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A Tale of Water and Fire: Modern Crisis and Health Crisis Management Analysis Tools Applied to the Minoan Palatial Collapse (ca. 1700–1450 BCE)

Student ID Number: 20063888 | studiofilippimarco@gmail.com

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Candidate

Marco FILIPPI — flpmrc77b24e625o

B.Sc. Civil Protection Management

M.Sc. Candidate Disaster and Crisis Health Management

Supervisor

Prof. Luca Ragazzoni

Firmato digitalmente da Luca Ragazzoni
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Organizzazione: UNIVERSITA' DEGLI STUDI DEL PIEMONTE ORIENTALE/01943490027

Co-Supervisors

Dr. Stefania Benetti, Researcher in Economic and Political Geography

Dr. Monica Trentin, PhD, Researcher in Sociology, Global Health, Humanitarian Aid and Disaster Studies

Firmato digitalmente da Stefania Benetti
Data: 13.07.2026 17:03:03 CEST
Organizzazione: UNIVERSITA' DEGLI STUDI DEL PIEMONTE ORIENTALE/01943490027

Stefania Benetti

Dedication

To my father, Duccio Filippi, who dedicated his life to culture, knowledge and their dissemination. His intellectual curiosity, his respect for learning, and his belief that knowledge only acquires meaning when shared with others remain a constant source of inspiration. Although he is no longer here to witness the completion of this journey, his example continues to guide every page of this work. This thesis is respectfully dedicated to his memory.

Thesis Nature and Purpose

This dissertation is presented as an original interdisciplinary research thesis developed within the Master of Science in Disaster and Crisis Health Management. The study investigates the collapse of the Minoan Palatial Civilization through the analytical lenses of Crisis Management, Disaster Risk Reduction, Human Geography, Political Ecology, Public Health, Environmental Anthropology, Palaeoclimatology, Environmental History and Complex Adaptive Systems Theory. Rather than focusing exclusively on traditional archaeological explanations, the thesis explores whether the Minoan collapse may be interpreted as the outcome of a prolonged socio-ecological crisis characterized by climatic deterioration, water insecurity, environmental stress, declining resilience, public health vulnerabilities, governance limitations and increasing geopolitical pressures.

Artificial Intelligence Disclosure

In accordance with the principles of academic integrity, transparency and responsible research practices, Artificial Intelligence tools may have been employed exclusively as support instruments for:

- linguistic revision
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Artificial Intelligence tools have not been used to generate original scientific findings, formulate conclusions, replace critical reasoning or substitute the intellectual contribution of the candidate.

All analyses, interpretations, methodological decisions, discussions and conclusions contained in this dissertation remain the sole responsibility of the author.

All references, quotations, datasets and factual claims have been independently verified through academic sources and scientific literature.

Methodological Disclaimer

The analytical frameworks employed throughout this dissertation derive primarily from contemporary Crisis and Disaster Management studies. Their application to an ancient civilization is intended as a heuristic and interpretive research tool and does not imply that modern concepts can be transferred uncritically to Bronze Age societies. Consequently, the conclusions presented herein should be interpreted as interdisciplinary analytical interpretations based upon currently available archaeological, environmental and geographical evidence rather than as definitive explanations of historical causality. Particular attention has been devoted to the integration of multiple independent lines of evidence, including archaeological findings, palaeoenvironmental records, climatological reconstructions, geographical analyses and anthropological interpretations.

Abstract

This study reconceptualises Late Bronze Age palatial decline through a socio-ecological and governance-centred lens, arguing that interacting environmental, institutional, and public-health stresses produced cascading failures rather than a mono-causal catastrophe. Integrating archaeological sequences, palaeoclimatic proxies, isotopic plant data, hydrological mapping, and comparative case studies from irrigated basins, mountain catchments, and epidemic-prone regions, it constructs multi-scalar scenarios linking spring behaviour, storage infrastructure, land use, and administrative reach. Methodologies combine GIS-based watershed delineation, remote-sensing change detection, stable isotope analysis of charred macro-remains, and relational excavation databases to map vulnerabilities in catchments and settlement hierarchies. The analysis highlights how gradual degradation of water reliability, repeated yield shocks, centralised control of storage and redistribution, and uneven access to health and sanitation could amplify modest hydroclimatic departures into long-term demographic and political reorganisation. Comparative evidence from modern basins shows how institutional lock-in, patronage, and short-term technical fixes can preserve production for elites while eroding ecosystem services and public welfare, producing crisis without transformative learning. A cascading-failure model is proposed that identifies coupled tipping domains in hydrology, agrarian productivity, and governance capacity, and which treats climatic variability as an amplifier of pre-existing fragilities. The study concludes by drawing cautiously modelled lessons for contemporary disaster risk reduction and environmental security, emphasising multi-sectoral governance, local buffering, distributed storage, and integrated early-warning logic as mechanisms more likely to stabilise complex socio-hydrological systems than isolated technical interventions.

Keywords

Minoan palatial collapse • socio-ecological systems • water security • cascading failure • disaster risk reduction • governance and resilience • palaeoclimatology • public health and food security • Bronze Age Aegean • complex adaptive systems

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1 Introduction

Interacting socio-ecological stresses, rather than single-factor shocks, increasingly appear central to food insecurity, public health emergencies, and institutional fragility in diverse settings. Studies of African food systems, for example, emphasise that zoonotic disease outbreaks intersect with longstanding vulnerabilities in nutrition, livelihoods, and governance, and that reactive strategies remain inadequate when complex nature–society feedbacks are not explicitly addressed (Khan & Sesay, 2015). Environmental health and public safety research likewise catalogues intertwined pressures from air, water, and soil pollution, waste management deficits, occupational hazards, and disaster risks, all of which demand multisectoral responses that integrate environmental and health governance (Adefemi et al., 2023). These contemporary perspectives motivate a re-examination of Bronze Age crises, including Aegean palatial decline, through a systemic, socio-ecological lens rather than through deterministic or monocausal explanations. Governance emerges as a critical mediator between environmental stress and societal outcomes. Work on food-related crises stresses that vulnerability assessments must grapple with spatial and temporal scaling issues, bio-complexity in disease ecology, and multi-actor interactions, and argues that these interactions are best framed within governance rather than purely biophysical models. Governance arrangements that span state and non-state institutions, and that attend to rules of decision-making and scale matching, are presented as mechanisms for managing food security under uncertainty and ecosystem shifts (Khan & Sesay, 2015). Similar arguments appear in analyses of water management reforms, where institutional change motivated by political or donor dynamics often fails to address underlying resource degradation, leading to ad hoc emergency responses to droughts

and floods and leaving systems vulnerable to recurrent shocks. These insights provide a comparative backdrop for interrogating Late Bronze Age polities as governance regimes embedded in fragile socio-ecological systems. Contemporary disaster studies underscore how extreme events can open windows for institutional learning yet frequently result only in short-term, reactive measures. In river-basin management, droughts or floods tend to trigger emergency councils, bans on particular crops, or temporary reductions in water allocations, but once the crisis passes, earlier practices resume and no long-term strategy for variability and scarcity is implemented (Schlüter & Herrfahrdt-Pähle, 2011). Analyses of epidemic response similarly highlight that previous Ebola virus disease interventions relied on rigorous isolation and surveillance protocols anchored in local authorities and external financial support, with key lessons centring on augmentation of local capacity and institutional infrastructure (Khan & Sesay, 2015). These cases illustrate the recurrent pattern of reactive crisis management without deeper transformation of vulnerability structures, a pattern that is analytically relevant for any reconstruction of prolonged ancient crises. A parallel body of work in environmental health and artificial intelligence documents how complex, multi-hazard pressures are increasingly monitored and managed through advanced sensing, predictive modelling, and data-driven governance, yet remain conditioned by structural issues of bias, equity, and regulatory capacity. Air-quality monitoring, for instance, is shifting from sparse, conventional stations to dense, AI-enabled sensor networks capable of high-frequency, real-time analysis, source attribution, and event prediction; nonetheless, data privacy, algorithmic bias, and the need for interdisciplinary collaboration remain significant challenges. Similar AI applications are deployed for disaster vulnerability assessment, critical

infrastructure maintenance, predictive policing, epidemic forecasting, and emergency medical dispatch, again illustrating how technical innovations sit within broader ethical and institutional debates (Adefemi et al., 2023). For this thesis, such contemporary configurations offer conceptual and methodological analogues for thinking about information flows, early warning, and decision-making in complex socio-ecological systems, even where ancient data constraints preclude direct comparison. Food security research framed through law, economics, and sustainability adds another set of reference points. Global assessments describe climate variability, resource depletion, and biodiversity threats as interacting drivers that compromise crop yields and alter growing conditions, while also highlighting how economic disparities, gender inequality, policy incoherence, implementation gaps, and technological access shape who is most vulnerable and who can adapt. Governments are depicted as pivotal actors whose policies on subsidies, trade, environmental regulation, and social protection collectively shape the trajectory and sustainability of food systems, yet whose efforts are hindered by sectoral silos, weak governance structures, and conflict or political instability (Agarwala et al., 2022). These findings foreground the importance of analysing ancient palatial economies not simply as production systems but as politically mediated food regimes whose resilience or fragility depended on multi-level institutional arrangements. Mountain regions, including the Himalayas, offer further illustration of how environmental change, water and food insecurity, and demographic responses interact. Research there links declining water availability, stressed local production systems, and heightened risks of natural disasters with increased male out-migration, intensified workloads for women, and gendered health vulnerabilities related to waterborne disease and nutritional deficiencies. Calls for gender-sensitive development agendas, recognition of traditional adaptation knowledge, and empowerment in natural resource governance highlight how social differentiation and power relations shape both exposure and adaptive capacity (Tiwari & Joshi, 2015). Although culturally and temporally distant from Bronze Age Crete, such work reinforces the need to treat social structure, labour distribution, and knowledge systems as integral components of any socio-ecological crisis analysis. Finally, scholarship on institutional responses to land and water degradation in large irrigated basins demonstrates that technical measures aimed at maintaining short-term productivity often proceed without addressing cycles of overuse and ecosystem service loss. Informal institutions such as patronage and corruption can further undermine implementation, leaving systems exposed to combined fast shocks and slow drivers (Schlüter & Herrfahrdt-Pähle, 2011). Taken together, these diverse strands of research justify an approach to ancient palatial decline that foregrounds interacting environmental, institutional, and public-health dimensions, and that seeks to derive cautiously modelled lessons for contemporary crisis management, disaster risk reduction, and environmental security.

1.1 Structure and Analytical Architecture of the Thesis

Analytical and methodological strands introduced earlier in the manuscript are operationalised through a stepwise structure that moves from conceptual framing to empirically grounded risk and vulnerability analyses for Bronze Age Crete and the wider eastern Mediterranean. Multi-scalar integration of archaeological and palaeoclimatic datasets provides the backbone for the early chapters, which adopt explicit assumptions that change is multi-causal, multi-scalar, and historically contingent, and that analysis must jointly examine supra-regional, regional, and local processes together with both long-term trends and short-term events such as natural disasters and

political decisions. These premises organise the initial theoretical and methodological exposition, where palatial Crete is defined as a complex socio-hydrological system and environmental settings are treated as co-produced by hydrology, land use, and institutions, rather than as passive backdrops. Subsequent chapters that address historical interpretations of collapse are structured around a critical reassessment of earlier monocausal models. Narratives that

once privileged singular catastrophes, such as earthquakes, invasions, or rapid aridification, are systematically evaluated against diachronic archaeological sequences and palaeoclimate syntheses, highlighting the limitations of frameworks that isolate a single destructive event from longer trajectories of socio-ecological change. Within this part of the thesis, formal resilience theory is introduced not as a deterministic template but as one heuristic among others for organising evidence on retention, loss, adaptation, and innovation in specific societal features. Chapters dealing with Mycenaean and wider Aegean contexts are arranged to demonstrate how earlier catastrophe-focused models are replaced by diachronically sensitive analyses that emphasise differential regional fortunes and shifting settlement hierarchies, preparing the ground for later work on Minoan Crete. The core empirical chapters focus on Late Bronze Age Crete and are explicitly designed so that direct archaeological evidence forms the primary empirical basis. Settlement data, destruction and rebuilding horizons, storage and hydrological installations, and indicators of administrative reach are first documented and spatially analysed using geographical information systems and stratigraphic correlations. Only once these archaeological sequences and proxy datasets have been laid out in detail are comparative modern case studies introduced, and then strictly as heuristic instruments. For instance, configurations from large irrigated basins in Central Asia, epidemic crises such as Ebola virus disease, and food-system research in African and Himalayan settings are employed to construct variable sets and coding schemes that help interpret ancient evidence on governance, food security, and health stressors without substituting contemporary data for ancient empirical records. This ordering ensures methodological transparency: inferential steps from modern analogues are clearly marked and always follow, rather than precede, the archaeological analysis. An important structural component is the integration of anthropological and public-health evidence through dedicated chapters that apply an evidence-synthesis strategy. These chapters translate insights from modern food-related crises and epidemic responses into risk-matrix logics that can be qualitatively applied to Bronze Age settings. Variables such as storage concentration, household buffering, ritual and healing spaces, and local autonomy within palatial hierarchies are coded from the archaeological record and then assessed against reconstructed climatic and hydrological stress episodes to generate envelopes of probable nutritional and epidemiological risk. Methodologically, this part of the thesis also incorporates analogues from nuclear winter studies and artificialintelligence based surveillance architectures, using them to shape the design of qualitative risk matrices and multi-source correlation procedures, while explicitly acknowledging issues of data incompleteness, uncertainty, bias, and equity. Through this sequence, the dissertation foregrounds socio-ecological interactions and governance regimes rather than simple environmental forcing. A further set of chapters situates ancient crises within wider comparative frames drawn from environmental health, disaster studies, and food security research. Here, analyses of reactive versus transformative crisis

management in river-basin governance, epidemic interventions, and AI-enabled monitoring are presented in order to build analogues for information flows, early warning, and decision-making in complex socio-ecological systems. Mountain-region studies that link declining water availability, gendered labour burdens, and health vulnerabilities, together with work on institutional responses to land and water degradation, are organised to underscore how social differentiation, informal institutions, and governance arrangements shape exposure and adaptive capacity. These comparative chapters follow the core archaeological analysis and are signposted as providing conceptual rather than evidential support, reinforcing the rejection of classical environmental determinism in favour of an approach that treats environment, institutions, technology, and culture as interacting components of resilience and collapse. The concluding chapter synthesises findings across these strands and explicitly returns to the critique of environmental determinism. Classical versions that posit environment as a sufficient and unilateral causal agent are rejected in light of evidence for multi-scalar, historically contingent interactions between climatic episodes, hydrological stress, governance regimes, and community-level adaptive strategies. Throughout the thesis, "environmental determinism" is therefore used in a precise sense to denote explanatory models that assign primary, overriding causality to environmental variables, treating social, political, and cultural dimensions as secondary or derivative. By contrast, the dissertation’s structure consistently implements a modern socio-ecological interpretation in which environmental change is one driver among many, mediated through governance, institutions, technology, and social organisation, and evaluated through empirically grounded, scale-sensitive analyses of Bronze Age Crete.

2 Background and Historical Context

2.1 Overview of the Minoan Palatial Civilization

2.1.1 Geographical extent and environmental setting

Reconstructing the geographical extent and environmental setting of any ancient palatial system must begin from clearly documented cases where landscape processes, hydrology, and settlement patterns have been analysed together. Studies of large irrigated basins in semi-arid Central Asia show how agriculture depends entirely on surface water from major rivers, with massive twentieth-century expansion of irrigated land driving soil salinization, waterlogging, and severe degradation of downstream delta ecosystems, culminating in the near-disappearance of a terminal sea and loss of associated fisheries and ecosystem services. In this system, an authoritarian post-Soviet regime continued to rely on irrigated cotton as a key source of revenue and rural employment, and institutional reforms in the water sector remained limited, reinforcing long-term overuse of land and water resources. Hydrological dependence on river flows, combined with low management standards and deteriorating infrastructure, left rural populations exposed to poverty, unsafe drinking water, and heightened vulnerability during drought years, thereby linking environmental change directly to social and health conditions. These insights underline how the spatial reach of a political economy is materially constrained by water availability, irrigation technology, and institutional choices. Work on wetland restoration in the same deltaic setting highlights a different configuration of geographic extent and environmental setting. Restoration projects re-established wetlands in parts of the degraded delta, providing new livelihood options and demonstrating substantial ecological recovery potential, yet their long-term sustainability remained uncertain because institutional arrangements for securing freshwater inflows and regulating use of biological resources were weak. Although technical measures increased local water storage and ecosystem services, the absence of integrated allocation rules meant that these wetlands were not fully embedded within basin-wide water management, especially as drought frequency and severity appeared likely to rise (Schlüter & Herrfahrdt-Pähle, 2011). This combination of promising ecological response and fragile governance illustrates how environmental setting cannot be characterised solely in biophysical terms but also depends on the reach and coherence of management institutions across a river basin. At smaller spatial scales, detailed case studies of single monumental sites demonstrate how groundwater dynamics and urban growth reshape local environmental settings. Analysis of the Ptolemaic Horus temple at Edfu, located on the west bank of the Nile in Upper Egypt, uses hydrological and hydrochemical studies of groundwater together with remote sensing and geographic information systems to identify causes and mechanisms of deterioration. Rising groundwater, urbanisation, and associated environmental changes around the site require spatial change detection, hazard mapping, and integration of remote sensing with in situ sampling to support cultural heritage management and to design protection models (A.Megahed, 2020). Here, the geographical extent of risk is defined by interactions between riverine hydrology, urban land use, and the micro-topography of a single temple complex, demonstrating the need to link local-scale environmental processes with broader regional water regimes. Remote sensing and GIS applications in other archaeological landscapes similarly connect environmental processes to the preservation and vulnerability of cultural sites. Research shows

that hydrological and hydrochemical analysis of groundwater, combined with spatial autocorrelation, radar data, and change-detection techniques, provides effective tools for monitoring environmental change around archaeological areas and for constructing predictive models within decision-support systems for preventive archaeology (A.Megahed, 2020; Tautenov et al., 2022). Low-cost, high-resolution satellite imagery allows repeated observation of landscape evolution, including urbanisation and groundwater rise, over large areas and multiple periods, thereby clarifying how regional geomorphology, land use, and hydrological shifts intersect at heritage locations (A.Megahed, 2020). Spatial analysis of water erosion using remote sensing in agricultural settings likewise demonstrates how snowmelt, residual soil moisture, and soil-management practices drive yearly changes in surface runoff networks, reinforcing the necessity of fine-grained environmental monitoring in sloping terrains (Tautenov et al., 2022). Together, these studies stress that any account of a palatial system's geographical extent must incorporate catchment-scale hydrology, local groundwater behaviour, and landscape change detectable only through synoptic observation. Environmental archaeology and historical geography also document how broader regional climatic and political regimes can reconfigure settlement patterns and centres of power. In the post-palatial Aegean, for instance, a shift to increasingly arid conditions coincided with

contraction of land use in some areas and declining spatial extent of occupation, even as certain nonpalatial regions prospered temporarily before experiencing downturns later in the millennium. Here, the completeness of collapse has been interpreted in terms of leaders' failure at urban centres to halt depopulation and re-establish stability, rather than simply as the destruction of palaces themselves. Changing political and settlement systems have been framed as a reversion to earlier, smaller-scale organisational forms that had previously coexisted with palatial structures, yet now operated within increasingly constrained environmental conditions (Molloy, 2022). This juxtaposition of shifting aridity, land-use contraction, and spatial reorganisation of power provides an important comparative template for considering how any palatial civilisation occupied, managed, and ultimately lost control over its wider environmental setting.

2.1.2 Chronology and phases of palatial development

Discussion of palatial development in the Aegean between 1700 and 1200 BC depends on securely dated destruction horizons, architectural sequences, and associated administrative practices. For southern Greece, a series of fire destructions at major urban centers around 1200 BC traditionally marks the end of the Mycenaean palatial system; these include Mycenae, Tiryns, Midea, Gla, Dhimini, Teichos Dymaion, and sites in Achaea. Comparable episodes of burning affected Ayios Vasileios around 1250 BC and earlier in the Argolid and Boeotia, indicating that major disruptions predate the final wave of destructions and point to recurring instability within the palatial era itself. In Crete, Knossos appears to have suffered a destruction in the late 14th century BC, although an administration using Linear B script persisted until at least 1250 BC, while the palatial center at Chania was destroyed around 1200 BC, roughly contemporary with mainland collapses. These chronological anchors delineate a long trajectory of palatial florescence, conflict, and reorganisation rather than a single terminal event. Evidence from settlement hierarchies clarifies how palatial phases emerged and evolved. In southern Greece, shaft graves at Mycenae were established around 1700 BC, with the richest tombs dating to the 16th century, marking an

early phase of elite consolidation that precedes formal palatial architecture. The first signs of urbanism appear around 1500 BC; between 1400 and 1300 BC, fortified citadels were constructed at Tiryns, Athens (possibly), Thebes, and Mycenae, while palaces at Pylos, Orchomenos, Dhimini, and Ayios Vasileios were built in the same general horizon, some without enclosing citadel walls. Teichos Dymaion in Achaea presents an enclosed fortification without a palace, indicating diversity in central-place forms within the broader palatial koine. These developments chart a middle palatial phase characterised by the consolidation of fortified centers, increasing regional hierarchy, and differentiated trajectories of individual polities. The functioning of a mature palatial system is best illuminated at Pylos, where well-preserved Linear B archives document a two-province polity with a possible four-level settlement hierarchy in the 13th century BC. Many settlements operated under palatial authority yet retained day-to-day autonomy, suggesting that administrative centralisation coexisted with localised management at lower tiers of the hierarchy. A destruction level at the neighbouring center of Iklaina, together with the Pylian texts, implies conquest or subjugation and the recent unification of two previously separate polities only decades before the wider collapse. This situation exemplifies a late palatial phase marked by expanding territorial control, administrative integration, and inter-polity conflict. Post-destruction sequences define a further phase of transformation rather than simple abandonment. After the fiery end of palaces around 1200 BC, rebuilding at Mycenae, Tiryns, and Midea eschewed canonical palatial architecture, even though these sites remained important power foci for several decades. Material and ideological disinvestment in central palatial forms unfolded over two to four generations, during which leaders failed to re-establish stability and halt regional depopulation. For a time, the loss of palatial authorities coincided with prosperity in previously non-palatial regions such as Achaea, Corinthia, Phokis, and the Euboean Gulf, where new commercial forms and settlement patterns emerged before declining around 1050 BC. In parallel, palynological evidence from some areas indicates increasing aridity, contraction of land use, and shrinking spatial extent of occupation, while places like Kotihi lagoon in Achaea show relatively stable environmental signals and continued prosperity until late in the millennium. These diachronic contrasts define a post-palatial horizon of regionalised trajectories and uneven responses to environmental and political stress. Across the 1700 to 1050 BC interval, there was no single stable or "classic" palatial condition; instead, urban centers and their hinterlands passed through successive phases of emergence, fortification, administrative expansion, conflict-driven reconfiguration, destruction, and reorganisation (Molloy, 2022). The sequence derived from Mycenaean Greece and Crete therefore provides an essential

chronological scaffold for any comparative interpretation of Minoan palatial development, including the analysis of shifting settlement hierarchies, changing land-use, and the timing of socio-ecological stresses relative to political transformations. (See Figures A.5–A.7 for the spatial distribution and chronological development of the principal Minoan palatial centres discussed above.)

2.1.3 Socio-political structure and governance systems

Accounts of Late Bronze Age southern Greece document settlement hierarchies in which farmsteads, villages, and minor urban centers were integrated into territories focused on palatial complexes, yet with marked regional variation in how central places were organised and how far their authority extended. Some communities

selectively engaged with the material culture and symbols of this wider koine while maintaining different political systems and hierarchies, indicating that palatial power did not amount to uniform territorial control across all regions. Within more densely settled areas, a spectrum ran from small palaces embedded in local networks to major citadels that anchored extensive hinterlands, underscoring the diversity of socio-political configurations even within a shared cultural horizon. This variability forms an essential comparative frame for any reconstruction of Minoan governance, as it demonstrates that palatial systems could coexist with, and rely upon, subordinate yet relatively autonomous communities. High-resolution administrative evidence from Pylos illuminates this multi-layered political organisation in exceptional detail. Linear B archives from the 13th century BC describe a polity composed of two provinces and a probable four-tier settlement hierarchy, through which many settlements answered to the palace but appear to have retained considerable day-to-day autonomy. These records also point to recent territorial expansion: the destruction level at the nearby center of Iklaina, when read alongside the Pylian texts, has been interpreted as evidence for conquest or subjugation and for the late unification of two formerly separate polities only decades before the wider collapse. Palatial governance in this case combined centralised oversight of labour, resources, and ritual with a dependence on existing local structures for routine management, implying that socio-political control operated through negotiated relations rather than through complete administrative penetration of the countryside. The uneven fortunes of different palaces, such as the apparent decline of Orchomenos by 1300 BC and alternating prominence between Mycenae and Tiryns, further indicate that regional power balances and patronage networks were unstable within the broader palatial system. Destruction horizons and their aftermath provide additional insight into institutional robustness and adaptability. A wave of burnings around 1200 BC at Mycenae, Tiryns, Midea, Gla, Dhimini, Teichos Dymaion, and other sites has long defined the end of the Mycenaean palatial order, yet closer chronological resolution reveals earlier episodes of fire damage in the Argolid and Boeotia and at Ayios Vasileios around 1250 BC. These events mark recurrent crises within the palatial era rather than a single terminal catastrophe, implying repeated tests of political authority and administrative resilience. Post-destruction sequences at Mycenae, Tiryns, and Midea show rebuilding that deliberately abandoned canonical palatial architectural forms even while these sites continued to function as significant power foci for several decades. Over two to four generations, leaders failed to reverse depopulation or restore the previous scale of centralised authority, indicating a gradual disinvestment in, or inability to sustain, the institutional apparatus associated with palace-centred governance. Regional trajectories after the palatial collapse further underline the fragmented and adaptive nature of socio-political systems. In formerly marginal or non-palatial zones such as Achaea, Corinthia, Phokis, and the Euboean Gulf, settlement expansion and commercial innovation followed the demise of palaces, with prosperity continuing until roughly 1050 BC. In parallel, some areas exhibit palynological signals of increasing aridity, land-use contraction, and shrinking spatial extent of occupation, while localities such as Kotihi lagoon in Achaea retain relatively stable environmental indicators and sustained prosperity late into the millennium. Analysis of these contrasts has argued that the "collapse" consisted less in the physical destruction of palaces than in the failure of urban leaderships to re-establish stability, maintain demographic levels, and manage environmental constraints, leading to a reversion toward earlier, smaller-scale organisational forms that had long coexisted with palatial authority. Together, these observations portray Aegean palatial societies as governance regimes embedded in complex settlement networks and subject to uneven,

regionally differentiated processes of political reconfiguration, institutional weakening, and localised resilience (Molloy, 2022).

2.1.4 Economic foundations and trade networks

Economic organisation in Late Bronze Age palatial societies can be approached through comparative cases in which agricultural production, resource management, and long-distance exchange have been reconstructed together with their institutional settings. Work on large irrigated basins in Central Asia shows how a regional economy built on cotton monoculture and extensive irrigation depended entirely on river flows, with state revenue and rural employment locked into continued overuse of land and water. Expansion of irrigated land generated soil salinization, waterlogging, and degradation of downstream delta ecosystems, including the near-disappearance of a terminal sea and loss of fisheries, while post-Soviet institutional reforms largely preserved production targets and quota systems. These conditions exposed rural communities to poverty, unsafe drinking water, and vulnerability in drought years, linking export-oriented agriculture, environmental decline, and social precarity within a single political economy. Responses to this degradation remained predominantly technical and short term. Institutional change in the water sector was driven by donor agendas, internal power struggles, and the dismantling of large farms, rather than by recognition of ecological limits. Emergency measures such as bans on rice planting, temporary reductions in water allocations, and ad hoc transboundary councils appeared during droughts or floods, but did not lead to structural diversification of crops or water use. Informal institutions such as patronage and corruption further undermined policy implementation, leaving the agrarian export system exposed to recurrent shocks. Wetland restoration in the degraded delta created new livelihood opportunities and demonstrated ecological recovery potential, yet lacked secure water allocations and integrated basin-wide rules, illustrating how promising resource-based initiatives can remain marginal to the dominant economic regime (Schlüter & Herrfahrdt-Pähle, 2011). Elsewhere, detailed reconstructions of chestnut and holm-oak rural forests document how multi-functional woodland economies combined staple food production, animal husbandry, fuelwood, charcoal, timber, and specialized products such as truffles. Chestnut landscapes supplied dried and fresh nuts for local markets, fodder for animals, and wood for construction and mining, while parallel activities included silk and wine production. Holm-oak forests, managed primarily as grazing grounds for large flocks, also yielded truffles for local consumption and for sale through brokers to urban processors, together with secondary products like mushrooms, aromatic plants, and game. Truffle exports reached approximately 2000 tons annually by the late 19th century, before declining to about 20 tons by 1996 and 40 tons by 2005, a collapse partially offset by technical innovations such as controlled inoculation of host trees by national agronomic institutes. Rising rarity contributed to escalating prices, from the equivalent of about 36 euros/kg in 1868 to over 800 euros/kg in 2012, illustrating how shrinking ecological production can transform a once widespread food into a luxury commodity. These woodland economies were not static. In the 20th century, semigovernmental institutions and research bodies fostered renewed interest in forestry and truffle cultivation, promoting hybrid chestnut varieties resistant to disease and certified inoculated seedlings for truffle plantations. Support programs encouraged planting on arable land rather than in traditional garrigue settings, yet field outcomes often failed to match expectations, revealing the path dependence of ecological knowledge and the limits of transferring production systems out of their long-evolved

socio-ecological contexts. Collective action by growers enabled interaction with scientific institutions and uptake of new varieties, but also reoriented trade networks and value chains, as self-produced planting material gave way to externally certified stock and more formalised market circuits (Aumeeruddy-Thomas et al., 2012). A separate comparative strand concerns food-system governance at national and international scales. Analyses of government policies emphasise that agricultural subsidies, trade agreements, and social safety nets shape food availability, access, utilisation, and stability, with subsidies influencing crop choices and land-use decisions, and trade regulations determining the affordability and diversity of imported foods. Climate variability, resource depletion, and biodiversity loss interact with income and gender inequalities, policy incoherence, and implementation gaps to create uneven vulnerabilities within ostensibly integrated food markets. Governments attempt to stabilise food supplies through strategic reserves, disaster preparedness, and insurance, but may simultaneously entrench environmentally damaging practices or disadvantage small-scale producers through unfavourable trade regimes. Integrated approaches that align agricultural production with environmental regulation, public health, and social protection are advocated as a way to reconcile economic objectives with sustainability and equity, although obstacles of sectoral silos, technological access, and political instability remain significant (Agarwala et al., 2022).

2.2 Historical Interpretations of Collapse

2.2.1 Early archaeological theories

Early explanatory models for Aegean Bronze Age collapse were strongly coloured by assumptions of monocausal triggers, often privileging singular catastrophes or narrowly framed environmental shocks. Subsequent work on later prehistoric and historic societies has exposed the limitations of such approaches by demonstrating that political economies are embedded in dynamic human–environment interactions operating across multiple spatial and temporal scales (de Haas, 2017; Molloy, 2022). These insights retrospectively cast doubt on any interpretation of the Minoan or wider Aegean palatial declines that isolates a single destructive event, such as an earthquake, invasion, or drought, from the longer trajectories of socio-ecological change within which these events occurred. Analyses of Mycenaean Greece provide a particularly clear window onto how collapse was once framed and how this framing has evolved. A wave of destructions around 1200 BC at major urban centres long served as the canonical marker of a sudden palatial "end," encouraging narratives that equated architectural burning layers with instantaneous systemic failure. More recent syntheses emphasise instead that these destructions were preceded by earlier fire events, differential regional fortunes, and shifting settlement hierarchies, implying a protracted sequence of stresses and reconfigurations rather than a single, terminal catastrophe. When set against these diachronic patterns, earlier catastrophe-focused models appear increasingly inadequate. Formal resilience theory, with its emphasis on adaptive cycles and panarchy, has been taken up as an alternative framework for conceptualising collapse as one phase within recurring cycles of growth and contraction. However, work on later second-millennium BC Europe warns that a rigid application of resilience theory risks reducing culture to material attributes and obscuring the ideological, political, and religious transformations that make crises historically distinctive. Instead, collapse is better approached through diachronic markers for retention, loss, adaptation, and innovation in specific societal features, an orientation that challenges earlier, more mechanistic accounts of

systemic failure. This critical stance undercuts simplistic readings of Minoan decline as a uniform transition from "high" to "low" complexity. Climate-centric explanations have constituted another influential early strand. Apocalyptic scenarios in which rapid aridification supposedly devastated agriculture, induced famine, and toppled political systems have been widely invoked for eastern Mediterranean and European contexts. Synthesis of palaeoclimate and archaeological data, however, highlights serious difficulties with such models, including the need for changes to be rapid, extreme, and sustained, and the frequent lack of chronologically sensitive archaeological proxies closely tied to local communities. Social-science research further indicates that few past societies were entirely inflexible or incapable of responding to environmental change, making it hard to sustain visions of populations passively overwhelmed by climate forcing alone. These critiques directly undermine earlier deterministic readings of Minoan collapse that treat climate deterioration as a sufficient causal agent. At the same time, arguments that sought to minimise external drivers in favour of purely local, agent-centred accounts have also proven problematic. A reassessment of post-processual tendencies to downplay broad structuring conditions notes that such moves risk neglecting the climatic and environmental contexts that shape, constrain, and channel human choices. For later second-millennium BC Europe, rapid climate change events around 1250 to 1150 BC are recognised as significant turning points, even though their onset, duration, and spatial expression remain debated. The challenge is framed as avoiding both an environmentally reductionist "causality trap" and an equally misleading detachment of societies from the wider environmental regimes within which they operated (Molloy, 2022). Early Minoan theories that fall into either extreme appear increasingly untenable in light of this balanced perspective. Parallel debates in Roman landscape studies and centuriation research also bear on older archaeological models of collapse. An integrated approach to the Pontine marsh centuriation, combining morphology, geophysics, coring, settlement archaeology, written sources, and palaeoenvironmental data, reconceptualises centuriation as both adaptation to changing environmental and socio-economic conditions and as an agent of environmental and cultural change. This work explicitly treats change as multi-causal, multi-scalar, historically contingent, and generated through reciprocal interactions between human and natural agents (de Haas, 2017). By implication, early narratives that interpreted Roman landscape transformations, and by analogy Aegean palatial crises, as straightforward consequences of singular political decisions or environmental events no longer withstand scrutiny when confronted with such complex, cross-scalar reconstructions. In sum, later comparative research on Mycenaean collapse, climate–society interactions, and large-scale landscape engineering collectively exposes the inadequacy of early archaeological theories that sought simple, monocausal explanations for Bronze Age crises. These findings support a shift towards models that embed palatial decline within long-term, multi-scalar socio-ecological processes, even as they caution against replacing one form of determinism with another (de Haas, 2017; Molloy, 2022).

2.2.2 Environmental determinism perspectives

Early climate-centric narratives of Aegean Bronze Age collapse exemplify a wider pattern in which environmental change is treated as a near-autonomous causal agent, capable of toppling complex societies with limited regard for institutional dynamics or social differentiation. Synthetic work on food systems and sustainability shows how

climate variability, resource depletion, and biodiversity loss undoubtedly compromise agricultural yields and alter growing conditions, but also stresses that economic disparities, gender inequality, policy incoherence, and governance capacity decisively shape who becomes food insecure under such pressures (Agarwala et al., 2022). When such multi-dimensional configurations are taken seriously, deterministic scenarios that equate climatic deterioration with inevitable societal failure lose much of their plausibility. Research on governance in food-related crises and epidemics reinforces this critique by foregrounding institutional mediation between environmental stress and social outcomes. Analyses of zoonotic disease such as Ebola virus disease and bovine spongiform encephalopathy argue that vulnerability emerges where food insecurity, inadequate health infrastructure, and weak governance intersect, and that effective responses require governance mechanisms linking sectors, scales, and actor networks rather than solely technical containment measures. Extreme events can open windows for institutional learning, yet case studies of epidemic response show that outcomes hinge on how far local capacity, institutional infrastructure, and decision-support tools are strengthened, not simply on the biophysical severity of the shock itself (Khan & Sesay, 2015). Read against these findings, any account that attributes Minoan decline straightforwardly to drought or other environmental change overlooks the mediating role of governance arrangements. This caution is consistent with the wider critical literature on the end of the Late Bronze Age in the eastern Mediterranean, which stresses that the available material, textual, climatic, and chronological evidence is too ambiguous and context-dependent to support any single overarching explanation, and cautions specifically against climatic accounts that outrun the precision of the underlying chronology (Knapp & Manning, 2016). At the same time, palaeoclimate and radiocarbon-based chronological work from Cyprus indicates that abrupt climatic deterioration around the twelfth century BC coincided closely with, and plausibly contributed to, famine and subsequent social and political disruption in parts of the eastern Mediterranean (Kaniewski et al., 2013); such findings are treated in this thesis not as evidence for climatic determinism but as one strand within the multi-causal, governance-mediated framework adopted throughout. Water management in large irrigated basins provides a further empirical challenge to simple environmental determinism. In Central Asia, decades of over-extraction for cotton monoculture produced severe salinization, ecosystem degradation, and increasing man-made water shortage, yet institutional reforms in the water sector were largely driven by donor agendas, internal power struggles, and the need to manage thousands of new farm entities, rather than by recognition of ecological limits. Droughts and floods triggered emergency measures such as bans on particular crops, temporary reductions in water limits, and ad hoc transboundary councils, but once extreme conditions passed, management reverted to previous practices, leaving the underlying cycle of overuse and degradation intact. Informal institutions including patronage and corruption further constrained implementation, producing a system that remained highly vulnerable to combined fast shocks and slow ecological drivers (Schlüter & Herrfahrdt-Pähle, 2011). These dynamics demonstrate that environmental stress does not mechanically generate either collapse or adaptation; outcomes depend on path-dependent institutional responses and power relations. Contemporary debates on environmental health and public safety similarly adopt non-deterministic framings. Reviews of air, water, soil pollution, waste management, occupational hazards, and disaster risk emphasise that these hazards interact within complex urban and regional systems, and that multidisciplinary, multisectoral approaches involving governments, local authorities, industry, and civil society are required to manage them.

Artificial intelligence is increasingly integrated into monitoring and response, from realtime air-quality sensor networks and water-quality analytics to predictive disaster planning and smart urban infrastructure, but these technical advances are explicitly situated within ethical, legal, and governance debates over data quality, privacy, bias, and accountability (Adefemi et al., 2023). Again, biophysical pressures are framed as part of socio-technical systems rather than as sole determinants of social trajectories. Finally, analyses of global and regional food security underscore that climate shocks interact with trade regimes, income distribution, gender relations, infrastructure, and political instability. Governments deploy subsidies, strategic reserves, social safety nets, and environmental regulations in attempts to stabilise availability, access, utilisation, and stability, yet often confront trade-offs in which measures that boost short-term production exacerbate long-term degradation or inequity. Stability in food systems emerges, or fails, from these interacting policy choices rather than from climate forcing alone (Agarwala et al., 2022). Collectively, these strands of evidence provide a comparative foundation for rejecting rigid environmental determinism in favour of explanations that embed environmental change within complex governance and socio-economic configurations, a move that directly informs the reinterpretation of Minoan palatial decline developed in this thesis.

Early explanatory schemes for Aegean Bronze Age crises crystallised around strongly monocausal narratives in which discrete environmental or physical shocks were treated as sufficient to account for palatial decline. Accounts that equated a single wave of destructions with a terminal "collapse" framed architectural burning layers and ruin horizons as direct, instantaneous reflections of systemic failure, thereby privileging abrupt events such as earthquakes, invasions, or droughts over longer socio-ecological trajectories. Within such schemes, environmental change frequently appeared as an autonomous agent whose impacts were assumed to propagate mechanically through agrarian production and political organisation, with limited attention paid to institutional dynamics, regional variation, or temporal sequencing. These assumptions provided the conceptual core of classical environmental determinism in Bronze Age studies, even when not labelled as such, and they continue to form a critical foil for the present dissertation’s methodological stance. Climate-centred formulations offer the clearest expression of this determinist tendency. Apocalyptic scenarios were advanced in which rapid aridification supposedly devastated agriculture, induced famine, and toppled complex palatial systems across the eastern Mediterranean and Europe. Such narratives depended on postulating environmental changes that were sufficiently rapid, extreme, and sustained to overwhelm any feasible adaptive capacity, yet they often lacked chronologically sensitive archaeological proxies closely tied to specific communities and sites. Subsequent syntheses of palaeoclimate and archaeological data have identified serious difficulties with these models, including mismatches between proposed climatic episodes and local stratigraphic sequences, and the

implausible assumption that societies were uniformly inflexible and passively overwhelmed by climate forcing alone. Evidence indicates that very few past political economies operated without at least some capacity to respond to environmental variability, making it difficult to maintain visions of deterministic climate collapse that bypass governance and social differentiation. Parallel strands of determinism emerged in earthquake-focused interpretations. Seismological research has quantified recurrence intervals and probabilities for large events over the last 13 ka, explicitly linking magnitudes and frequencies to archaeological contexts where instrumental records

are available (Jusseret & Sintubin, 2012, p. 4). Structural descriptions from Troy VI, with fortification walls "shaken out of plumb," curtain faces tilted sharply, and heaps of fallen stones lying in "utter disorder and confusion," provided an influential template for recognising earthquake damage in built environments (Nur & Cline, 2000, p. 15). Some classical models effectively extrapolated from such cases, implicitly treating major earthquakes as decisive and sufficient triggers of collapse, without extending analysis to the preceding and subsequent socio-ecological configurations. Research on long fault sequences and "earthquake storms" that unzip entire plate-boundary segments over decades has further deepened understanding of seismic clustering, but it also underscores that tectonic activity operates over long temporal horizons and interacts with settlement organisation and institutional capacity rather than dictating singular outcomes (Nur & Cline, 2000, p. 4). The determinist logic also appeared in early climate-centric and hazardcentric narratives that neglected governance, social structure, and regional differentiation. Environmental change was cast as a near-autonomous causal agent capable of toppling complex societies with little regard for institutional dynamics or multi-scalar interactions. Synthetic work on food systems and sustainability shows that climate variability, resource depletion, and biodiversity loss compromise agricultural yields and alter growing conditions, yet simultaneously stresses that economic disparities, gender inequality, policy incoherence, and governance capacity shape who becomes food insecure under such pressures. When these multi-dimensional configurations are taken seriously, scenarios equating climatic deterioration with inevitable societal failure lose much of their plausibility. Analyses of zoonotic disease and food-related crises likewise argue that vulnerability emerges at intersections of food insecurity, inadequate health infrastructure, and weak governance, demonstrating that environmental stress does not straightforwardly produce either collapse or adaptation but is mediated by institutional responses and power relations. In landscape archaeology, early models that privileged either environmental drivers or purely local agency have both been reassessed. Integrated studies of Roman centuriation reconceptualise large-scale land division as simultaneously adaptation to changing environmental and socio-economic conditions and an agent of environmental and cultural change, treating transformations as multi-causal, multi-scalar, and historically contingent, generated through reciprocal interactions between human and natural agents. This balanced perspective criticises environmentally reductionist "causality

traps" that attribute change solely to climate or geomorphology, while also warning against post-processual tendencies to detach societies from the broader environmental regimes within which they operate. These reassessments feed directly into the present thesis's critique of earlier Minoan theories that either overstated external environmental forcing or minimised it in favour of abstract agency. Within this dissertation, direct archaeological evidence from Bronze Age Crete is therefore defined as the primary empirical basis for any discussion of crisis or transformation. Stratified settlement sequences, destruction and rebuilding horizons, storage and hydraulic installations, and indicators of administrative reach must be documented and analysed before environmental proxies or modern comparanda are introduced. Comparative modern case studies from food systems, epidemic management, irrigated basins, and disaster governance are employed only after the archaeological record has been laid out and strictly as heuristic instruments to structure variables and risk-assessment logics, never as substitutes for ancient empirical data. On this foundation, "environmental determinism" throughout the dissertation is used in a precise sense to denote explanatory models that assign

primary, overriding, and near-sufficient causality to environmental variables such as climate change, earthquakes, or sea-level shifts, while treating social, political, institutional, and cultural dimensions as secondary or derivative. These models, exemplified by early climate-apocalyptic and hazard-centric narratives, are explicitly rejected in favour of a socio-ecological interpretation in which environmental change is one driver among many, co-produced with hydrology, land use, and institutions, and always analysed within multi-scalar, historically contingent configurations of governance, technology, and social organisation.

Critiques of environmental determinism in this project arise from multiple strands of research that collectively undermine any explanation of Bronze Age crises grounded in single, overriding environmental causes. Climate-centric narratives that posit rapid aridification as a sufficient agent of agricultural collapse and palatial failure are explicitly challenged by syntheses of palaeoclimate and archaeological data. These syntheses argue that such models demand climatic changes that are rapid, extreme, and sustained, yet often lack chronologically sensitive archaeological proxies closely tied to local communities, and further note that few past societies were entirely inflexible or incapable of responding to environmental variability. Deterministic readings that treat climate deterioration as a sufficient causal agent of Minoan collapse are therefore directly rejected, and arguments that sought to minimise external drivers in favour of purely local, agent-centred accounts are likewise criticised for detaching societies from the broader environmental regimes that shaped and constrained human choices. Alternative approaches emerge from work that embeds environmental change within complex socio-ecological and

governance configurations. Synthetic studies of food systems and sustainability, for example, show that climate variability, resource depletion, and biodiversity loss compromise agricultural yields and growing conditions, but insist that economic disparities, gender inequality, policy incoherence, and governance capacity decisively shape who becomes food insecure under such pressures. Under these multi-dimensional configurations, scenarios equating climatic deterioration with inevitable societal failure lose much of their plausibility. Analyses of governance in food-related crises and epidemics reinforce this critique by demonstrating that vulnerability arises where food insecurity, inadequate health infrastructure, and weak governance intersect, and that effective responses require mechanisms linking sectors, scales, and actor networks rather than purely technical containment measures. Read against such findings, any account that attributes Minoan decline straightforwardly to drought or other environmental change is understood as overlooking the mediating role of governance arrangements. Research on large irrigated basins in Central Asia further develops non-deterministic perspectives by detailing how decades of over-extraction for cotton monoculture produced severe salinisation and ecosystem degradation, yet institutional reforms in the water sector were driven primarily by donor agendas, internal power struggles, and the management of thousands of new farm entities. Droughts and floods triggered emergency bans on particular crops, temporary water-limit reductions, and ad hoc transboundary councils, but once extreme conditions passed, management reverted to earlier practices, leaving cycles of overuse and degradation intact. Informal institutions such as patronage and corruption constrained implementation, maintaining high vulnerability to combined fast shocks and slow ecological drivers. These dynamics demonstrate that environmental stress does not mechanically generate either collapse or adaptation; outcomes depend on path-dependent institutional responses and power

relations. Contemporary disaster studies and environmental health research broaden this alternative framework by treating hazards as elements within socio-technical systems. Reviews of pollution, waste management, occupational risks, and disaster vulnerability argue that multi-hazard pressures interact within complex urban and regional systems, and that multidisciplinary, multi-sectoral approaches involving governments, local authorities, industry, and civil society are required to manage them. Artificial intelligence is described as increasingly integrated into air- and water-quality monitoring, disaster planning, and smart infrastructure, but these technical advances are framed within ethical, legal, and governance debates over data quality, privacy, bias, and accountability. Food-security analyses similarly emphasise that climate shocks interact with trade regimes, income distribution, gender relations, infrastructure, and political instability, and that government policies on subsidies, strategic reserves, social safety nets, and environmental regulation create trajectories of stability or fragility. Stability in food systems is thus interpreted as emerging from interacting policy choices rather than from climate forcing alone. Within this thesis, these critiques and alternative approaches serve two explicit

methodological functions. First, they justify defining direct archaeological evidence from Bronze Age Crete as the primary empirical basis for interpreting crises and transformations; stratified settlement sequences, destruction and rebuilding horizons, and material indicators of storage and hydrological management must be analysed before any environmental proxy or modern comparison is introduced. Second, they authorise the use of modern case studies solely as heuristic instruments for variable selection, coding, and conceptual framing, not as substitutes for ancient data. Research on irrigated basins, epidemics, environmental health, and AI-enabled monitoring is therefore mobilised to structure risk-assessment logics and socio-ecological questions, while explanatory models that assign primary, overriding, and near-sufficient causality to environmental variables are systematically rejected in favour of an approach that treats environment, governance, institutions, technology, and social organisation as interacting components of resilience and collapse.

2.2.3 Socio-political and economic explanations

Socio-political and economic explanations for large-scale crises have increasingly shifted from monocausal accounts to configurations in which governance, policy, and market structures mediate environmental and health pressures. Analyses of food systems, for instance, underline how climate variability, resource depletion, and biodiversity loss compromise crop yields yet become critical only where economic disparities, inadequate infrastructure, or political instability restrict access to nutritious food. Governments shape these outcomes through subsidies, trade regimes, social safety nets, and environmental regulations, which collectively structure production, distribution, and consumption within national and regional food systems. Government policy thus appears as a central explanatory axis rather than a background condition. Studies of global and regional food security argue that agricultural subsidies can encourage or discourage particular crops, influencing land use and long term food availability, while land use regulations can either promote sustainable practices or drive environmental degradation. At the same time, social policies such as income support, minimum wages, and targeted safety nets determine economic access to food, and public health and nutrition programmes affect utilisation by shaping dietary awareness and addressing malnutrition. Stability is further conditioned by disaster

preparedness, insurance schemes, and climate smart agricultural policies that aim to buffer shocks; yet these same interventions can generate trade offs, for example when production boosting subsidies accelerate environmental decline or trade protections raise global food prices and constrain access elsewhere (Agarwala et al., 2022). From a socio political perspective, weakness or fragmentation in governance institutions emerges as a recurrent driver of vulnerability. Research on epidemic prone food systems stresses that vulnerability assessments must account for scale, bio complexity in disease ecology, and multi actor interactions, and proposes governance as the most appropriate rubric for organising these interactions. Here, governance is defined as encompassing state and non state institutions, rules of decision making, and mechanisms for matching scales of authority and ecological process. In contexts such as Ebola virus disease, food insecure populations with inadequate health care infrastructure signal potential crisis, and effective responses depend on governance mechanisms that link local food systems, environmental health, and public health agencies across jurisdictions and sectors. Historical case studies of Ebola in Uganda show that rigorous isolation protocols, surveillance, and treatment supported by local authorities and donor funding could be effective when they strengthened local institutional infrastructure and augmented capacity, rather than relying solely on externally driven technical fixes (Khan & Sesay, 2015). Comparative work on large irrigated basins in Central Asia provides a detailed example of how political economy, institutional design, and informal power relations structure exposure to environmental and economic shocks. There, an export oriented cotton monoculture locked state revenues and rural livelihoods into continued overuse of land and water, while institutional reforms in the water sector were driven mainly by donor agendas, farm restructuring, and internal power struggles rather than ecological limits. Environmental degradation and man made water scarcity were met with technical measures that sought to preserve existing productivity instead of addressing cycles of overuse. Extreme events such as droughts or floods triggered short term emergency measures, including bans on particular crops, temporary water reductions, and ad hoc transboundary councils, but management practices reverted once the crisis passed, and no long term strategy for water variability or scarcity was implemented. Informal institutions such as patronage and corruption further undermined policy execution, keeping the system highly vulnerable to future disturbances and illustrating how entrenched economic interests can block transformative adaptation (Schlüter & Herrfahrdt-Pähle, 2011). Government efforts to secure food supplies and promote sustainability face additional socio economic and political constraints. Studies detailing contemporary policy challenges enumerate climate variability, resource depletion, globalised trade asymmetries, income and gender inequalities, sectoral policy silos, implementation gaps, technological access barriers, and conflict or political instability as intertwined obstacles. Small scale farmers may be disadvantaged by unfavourable trade agreements and lack of market access, while global supply chain dependence can amplify vulnerability during systemic shocks such as the COVID 19 pandemic. Achieving policy coherence across agriculture, environment, and trade is repeatedly identified as difficult, with siloed bureaucracies generating conflicting goals and hindering integrated responses. In regions affected by geopolitical conflict, disrupted production and distribution, together with contested land use between agriculture, urbanisation, and industrialisation, further complicate sustainable management (Agarwala et al., 2022). These socio political and economic analyses collectively frame crises not as automatic outcomes of environmental change, but as the result of how governance arrangements, power structures, and policy regimes configure exposure, sensitivity, and

adaptive capacity within complex food and resource systems (Agarwala et al., 2022; Schlüter & Herrfahrdt-Pähle, 2011; Khan & Sesay, 2015).

2.3 Environmental History and Natural Hazards

Natural hazards enter this project primarily as historically situated phenomena whose impacts must be reconstructed through material and documentary traces rather than inferred from abstract models. Contemporary seismological studies provide an important benchmark for thinking about recurrence, magnitude, and probabilities, but are used here only as heuristic comparanda after the archaeological record has been established in detail. For example, earthquake-archaeology work calculates mean recurrence intervals and average rates of earthquake occurrence over the last 13 ka, and derives the probability of observing at least one event of given magnitude during a 100-year interval, explicitly linking seismological parameters to archaeological contexts (Jusseret & Sintubin, 2012, p. 4). Such quantified approaches highlight what is possible when instrumental and geological data are integrated, while simultaneously underscoring the contrast with Bronze Age Crete, where 13 ka

only indirect environmental and structural evidence can be mobilised. Studies of tsunami deposits in the Lefkada Lagoon illustrate how high-energy coastal hazards leave complex, multi-phase signatures in sedimentary archives. Detailed coring along transects reveals subunits characterised by changing grain-size spectra, from bioclastic sands to gravel-rich layers, with some sites showing well-defined bimodal patterns and others broader, less distinct peaks (May et al., 2012, p. 5). The Gyra washover structure, extending for more than and comprising approximately of material, is used as a diagnostic example for differentiating tsunami-related deposition from storm processes by combining spatial extent with internal stratigraphy (May et al., 2012, p. 10). Event reconstruction interprets lower bioclastic layers as the product of an initial, relatively low-energy inundation pulse that reworks lagoonal muds and bottom sediments, followed by thicker sand and gravel units associated with later, more turbulent waves and higher sediment loads, including phases of suspension fallout during slack water (May et al., 2012, p. 12). These results demonstrate that coastal hazard histories can be written as fine-grained environmental narratives when high-resolution coring and sedimentological analysis are available, but they also reveal the methodological distance between such modern examples and the fragmentary palaeoenvironmental record for Bronze Age Crete. In earthquakeprone regions, damage descriptions from excavated structures provide another strand of natural-hazard evidence. Work on Troy VI synthesises excavation reports noting tilted fortification walls, dislocated curtain faces, and masses of fallen stones that piled against citadel terraces and spread across intervening spaces in patterns consistent with abrupt structural failure (Nur & Cline, 2000, p. 15). Observations that walls originally built vertically have been "shaken out of plumb," that projecting tower flanks show numerous cracks attributed to foundation settling "perhaps induced by earthquakes," and that Cyclopean boulders lie displaced below corners of major buildings, are collated as qualitative indicators of seismic shocks affecting built environments (Nur & Cline, 2000, p. 14; 2000, p. 15). These descriptions, though tied to a specific Anatolian site, exemplify how archaeological documentation of wall tilting, differential displacement between superstructure and foundations, and concentrated rubble fans can inform the identification of earthquake damage

in the absence of instrumental records. For Late Bronze Age Crete, comparable structural pathologies would therefore be central to any attempt to reconstruct local natural-hazard histories, and the thesis consequently prioritises direct archaeological evidence of destruction horizons, wall deformation, and rebuilding sequences before engaging modern seismological analogues. Modern historical accounts of earthquakes further demonstrate how single events are embedded in wider social and environmental histories. Newspaper reports from on a devastating earthquake in northern Crete describe repeated shocks within a decade, severe housing damage in urban centres such as Heraklion and in rural villages, winter exposure of inhabitants forced into the streets, and significant government responses including emergency financial aid and provision of tents. These narratives, although far removed chronologically from 1 km 390, 000 m3

the Bronze Age, show how natural hazards become crises through their interaction with seasonality, building quality, state capacity, and social vulnerability. In addition, work documenting a more recent event that "devastated the north Cretan shores" and is still remembered by those who experienced shortages in goods underlines the persistence of hazard memory and its entanglement with economic disruption. Together, these materials reinforce the project's insistence that natural hazards must be analysed as socio-environmental episodes rather than isolated physical events. Quantitative reconstructions of past sea-level changes add another dimension to environmental history, particularly for coastal societies. Detailed compilations of radiocarbon-dated indicators from corals, depositional features, and archaeological markers provide time-bounded sealevel estimates spanning the Bronze Age and later periods, with uncertainties and multiple measurement types recorded for each data point (Pirazzoli et al., 1996, p. 4; 1996, p. 6). These datasets permit reconstruction of relative sea-level trajectories over millennia, including intervals relevant to – and subsequent phases, though the present thesis treats them primarily as contextual background when considering coastal site stability and potential exposure to marine inundation. Again, the emphasis remains on integrating such environmental histories with the stratigraphic and spatial evidence of Cretan sites, so that any inference about hazard impacts is rooted first in the archaeological record. Across these strands, natural hazards are consistently approached within a socio-ecological framework that rejects classical environmental determinism. Environmental determinism, as used throughout the dissertation, denotes explanatory models that assign primary, overriding causality to environmental variables such as earthquakes, tsunamis, or sea-level shifts, treating social, political, and cultural dimensions as secondary or derivative. By contrast, the thesis reads hazards through governance regimes, settlement organisation, and infrastructural choices, using modern case studies in seismology, tsunami sedimentology, and disaster response only after archaeological sequences have been established and strictly as heuristic instruments rather than substitutes for ancient empirical data.

2.4 Socio-ecological Systems and Resilience

Socio-ecological perspectives in this project emerge from interdisciplinary work that treats environmental and cultural change as reciprocally interacting processes rather than separate explanatory spheres. A key methodological strand aligns archaeological and palaeoclimatic datasets within a framework where change is explicitly conceived as multi-causal, multi-scalar, and historically contingent, and where supra-regional, regional,

and local dynamics, together with long-term trends and short-term events, are examined jointly. This orientation underpins the reconstruction of Bronze Age Cretan palatial systems as socio-hydrological configurations in which hydrology, land use, and institutional arrangements co-produce environmental settings instead of acting as independent 2110 1600 B.C.

background variables. Within this view, resilience is not a generic property of "the environment," but an emergent outcome of interactions between governance regimes, infrastructural choices, and settlement organisation. This usage follows the foundational ecological definition of resilience as the capacity of a system to absorb disturbance and persist through change rather than return to a single stable state (Holling, 1973), subsequently extended to social-ecological systems through the related concepts of resilience, adaptability, and transformability (Walker et al., 2004) and consolidated as a perspective explicitly concerned with non-linear dynamics, thresholds, and the interplay of gradual and abrupt change across scales (Folke, 2006). Analytical work on large irrigated basins in Central Asia illustrates how river dependence, irrigation infrastructure, and governance decisions together shape both ecological degradation and social vulnerability. Technical hydrological interventions in these basins remain precarious when basin-wide allocation rules and institutional mechanisms are weak, demonstrating that attempts to enhance resilience through engineering alone can fail if they are not embedded in wider regimes of territorial control and administrative reach. This configuration is directly relevant for thinking about palatial Crete as a complex socio-ecological system: hydrological stress is approached as mediated through political economy, not as an autonomous driver. The dissertation therefore rejects classical environmental determinism, understood as explanatory models that assign primary, overriding causality to environmental variables while treating institutions, technology, and social relations as secondary, and instead adopts an explicitly interactive conception of socio-ecological resilience grounded in co-production of environments and social orders. Resilience is further framed through research on crises that combine environmental and epidemiological pressures. Studies of Ebola virus disease and bovine spongiform encephalopathy conceptualise epidemics as multi-faceted phenomena whose entry points traverse local food systems, environmental health, and institutional capacity, and argue that these interactions are best organised under governance as a cross-cutting rubric. Vulnerability assessments in such work insist on attention to spatial and temporal scale, bio-complexity in disease ecology, and multi-actor interactions, treating governance as encompassing both state and non-state institutions, rules of decision-making, and scale matching. These insights are translated into coding schemes for Bronze Age Crete that draw on archaeological indicators of storage concentration, household buffering, ritual and healing spaces, and degrees of local autonomy within palatial hierarchies, which are then evaluated against reconstructed climatic and hydrological stress episodes to delineate envelopes of probable nutritional and epidemiological risk. In this way, resilience becomes a property of coupled food, health, and governance systems, not simply of environmental robustness. Methodologically, work on nuclear winter and global burden of disease modelling reinforces a risk-oriented understanding of socio-ecological resilience. In settings where direct empirical health data are absent, these studies propose combining climate and crop models within structured risk-assessment frameworks to estimate potential health impacts, using epidemiological forecasting tools to explore how environmental shocks may alter disease dynamics. By analogy, Bronze Age Cretan analyses employ risk matrices that bring together palaeoclimatic indicators, hydrological data, settlement density, storage capacity, and connectivity metrics to generate qualitative

envelopes of probable stress rather than quantitative morbidity estimates. These envelopes are explicitly framed as modelled risks, highlighting uncertainty and avoiding deterministic

causal chains, and thereby align with a resilience perspective that emphasises adaptive management under incomplete knowledge and contested institutional contexts. Contemporary studies of disaster management and environmental health provide additional perspectives on how socio-ecological resilience is shaped by information flows and institutional learning. In river-basin governance, droughts and floods frequently trigger short-term, reactive measures such as emergency councils or temporary allocation changes, yet long-term strategies for variability and scarcity are often not implemented. Epidemic interventions in Ebola outbreaks similarly relied on rigorous isolation and surveillance protocols anchored in local authorities and donor funding, with key lessons stressing the augmentation of local capacity and strengthening of institutional infrastructure. Parallel work on artificial-intelligence-enabled monitoring shows that technical innovations in sensor networks, predictive modelling, and data-driven governance operate within constraints of bias, equity, and regulatory capacity. Together, these findings illustrate recurring patterns in which socio-ecological systems absorb shocks through reactive responses but fail to transform underlying vulnerability structures, an insight that informs the thesis's reconstruction of prolonged ancient crises as sequences where resilience can erode or be reconfigured depending on institutional adaptation. Empirical studies in Himalayan mountain regions add a further dimension by showing how environmental change, water scarcity, and food insecurity interact with demographic processes and gendered labour burdens. Declining water availability and heightened disaster risk have driven male out-migration, intensified women's workloads in agriculture and livestock care, and increased women's vulnerability to water-borne and nutritiondeficiency health risks, with women forming a large proportion of disaster victims due to limited preparedness and information. Calls for gender-sensitive development agendas and recognition of traditional adaptation knowledge underscore that social differentiation and power relations are integral components of exposure and adaptive capacity. For this dissertation, such work reinforces a socio-ecological conception of resilience in which labour distribution, knowledge systems, and informal institutions are analytically central, even though direct Bronze Age evidence is fragmentary and must be reconstructed primarily from archaeological material. Across these strands, direct archaeological sequences for Late Bronze Age Crete remain the primary empirical basis, with modern case studies used only after the archaeological analysis and strictly as heuristic instruments for variable selection, coding, and conceptual framing. Within this design, environmental determinism is consistently rejected, and "environmental determinism" is used in a precise sense to denote models that posit environment as a sufficient and unilateral causal agent, in contrast to the socio-ecological interpretation adopted here, where resilience is understood as an emergent property of interacting environmental, institutional, technological, and cultural dimensions.

2.5 Crete and the Eastern Mediterranean: Comparative Geographical Framework

Locating Bronze Age Crete within its wider eastern Mediterranean setting requires explicit attention to the coastal and tectonic regimes that conditioned long-term environmental histories and the occurrence of extreme events. Quantitative reconstructions of relative sea level, based on radiocarbon-dated indicators such as corals,

depositional features, and archaeological markers, provide time-bounded estimates that span intervals from the late second millennium through the first millennium (Pirazzoli et al., 1996, p. 4). These datasets document ranges such as – and – for specific markers, together with later phases extending into Late Antique times, and they record uncertainties and multiple measurement types for each point. For this dissertation, such information is mobilised primarily as contextual background for evaluating the stability of coastal settings and the potential exposure of sites to marine inundation, rather than as direct drivers of social change. Consistent with the project's methodological stance, the environmental sequences reconstructed from sea-level indicators are integrated only after the archaeological evidence for settlement patterns, destruction horizons, and rebuilding episodes has been established, and they are treated as one strand within a broader socio-ecological framework that rejects classical environmental determinism (Pirazzoli et al., 1996, p. 4). Regional hazard regimes further situate Crete within a seismotectonic corridor characterised by repeated high-magnitude earthquakes and associated tsunamis. Work on the Lefkada–Preveza area in western Greece identifies this coastal zone as belonging to a region of remarkably high seismic activity and elevated tsunami recurrence rates, noting that tsunami events of variable magnitude are very likely. Sedimentary and geomorphological investigations of coastal geoarchives, including sand and shell-debris layers intercalated within lagoonal sequences and large washover structures dated to Classical–Hellenistic times or linked to the event, have been interpreted as records of repeated tsunami impact during the recent past (May et al., 2012, p. 3). In the Lefkada Lagoon, the Gyra washover structure provides a particularly detailed case: its subaerial portion comprises approximately of material and extends for more than inland from the modern barrier beach, dimensions that are used as diagnostic criteria for distinguishing tsunami-related deposition from storm-driven processes (May et al., 2012, p. 10). Grain-size analyses across coring sites reveal multiphase event stratigraphy, with lower bioclastic subunits interpreted as the product of an initial, relatively low-energy inundation pulse, followed by thicker sand and gravel units associated with later waves characterised by increased turbulence and sediment load (May et al., 2012, p. 12; 2012, p. 5). Although these studies concern areas north of Crete, they delineate a wider eastern Mediterranean coastal system in which extreme marine events can leave extensive and stratigraphically complex signatures. They therefore offer

methodological comparanda for thinking about potential tsunami exposure along Cretan shores and around neighbouring regions, while again being introduced only after the primary archaeological evidence has been assessed. In the dissertation's design, such geomorphological reconstructions serve as heuristic instruments for identifying what kinds of coastal deposits or landscape features might signal high-energy inundation, without displacing stratified Cretan site records as the principal empirical basis (May et al., 2012, p. 3). Seismological and earthquake-archaeology research further sharpens the picture of long-term tectonic activity within which Crete is embedded. Studies of plateboundary faults in the eastern Mediterranean argue that seismic activity has been ongoing for hundreds of thousands, and perhaps even a few million, years, with plate motions on the order of centimetres per year and slowly shifting fault patterns. During prolonged periods of relative inactivity, strain can accumulate on faults for centuries before being released either in a single large earthquake with numerous aftershocks or in a series of large events, each triggering the next. This latter pattern has been termed an "earthquake storm" or "earthquake sequence," describing situations in which an initial rupture along one segment of a fault increases stress on adjacent segments, leading to progressive failure and eventual "unzipping" of the

entire fault line over years or decades (Nur & Cline, 2000, p. 4). Modern examples along the North Anatolian Fault demonstrate sequences of large earthquakes that migrate spatially along the fault zone, releasing strain accumulated over or more years (Nur & Cline, 2000, p. 8). For the dissertation, such work defines plausible regional modes of seismic clustering rather than providing direct evidence for specific Bronze Age events, and it is employed to frame questions about how multiple destructive episodes might have been distributed in time and space across the Aegean, again only after Cretan archaeological sequences are laid out in detail (Nur & Cline, 2000, p. 4). Fine-grained archaeological documentation from Troy VI, though geographically in Anatolia, exemplifies the kinds of structural pathologies that can be associated with major earthquakes in eastern Mediterranean urban centres. Excavation reports describe fortification walls that were originally vertical but have been tilted sharply, inner faces "shaken out of plumb," and curtain walls that have been partially dislocated and tilted, together with huge masses of fallen stones spreading between citadel walls and terrace structures in "utter disorder and confusion". Specific buildings show easterly walls suffering greatest damage, with characteristic flat stones fallen in great numbers into houses and cascading into open areas, Cyclopean boulders lying below projecting corners of major structures, and pithoi sunk deep into heaps of collapsed wreckage, all interpreted as evidence for abrupt structural failure in a violent upheaval (Nur & Cline, 2000, p. 15). These observations, while tied to Troy, delineate a repertoire of damage patterns that can inform the recognition of comparable seismic impacts at Cretan and other eastern Mediterranean sites when combined with local stratigraphic and architectural data. Modern historical accounts of earthquakes on Crete itself provide a later chronological analogue for how hazard events interact with social and institutional contexts within the

island. Newspaper descriptions of an earthquake, following an earlier devastating event in [YEAR NOT STATED IN SOURCE], recount repeated shocks within less than a decade, severe housing damage in Heraklion and rural villages, and the plight of inhabitants forced into the streets in harsh winter conditions, together with governmental responses that included immediate financial assistance and the provision of tents for the affected population. Additional testimony recalls an event that "devastated the north Cretan shores" and is still remembered by those who experienced shortages in goods, underlining the persistence of hazard memory and its entanglement with economic disruption. While chronologically remote from the Bronze Age, these accounts situate Crete within an historically documented seismic zone and highlight how even single events become crises through their embedding in seasonality, building quality, and state capacity. Within the dissertation, they serve solely as contextual analogues for socio-environmental interactions, never as direct templates for Bronze Age conditions, and are consistently subordinated to archaeological evidence from earlier periods. Taken together, relative sea-level reconstructions, coastal tsunami archives, long-term fault dynamics, archaeologically documented earthquake damage, and modern Cretan hazard narratives delineate a geographically and historically specific eastern Mediterranean setting in which Bronze Age Crete formed part of a multi-hazard coastal and tectonic system. However, environmental determinism in its classical sense, understood as models that assign primary, overriding causality to environmental variables and treat social, political, and cultural dimensions as secondary, is explicitly rejected. In this dissertation, such environmental factors are treated as interacting components within socio-ecological systems, mediated through governance, institutions, technology, and settlement organisation, and

always interpreted through the primary empirical lens of Cretan archaeological sequences, with modern case studies used strictly as heuristic comparanda.

2.6 Regional Geomorphology and Tectonic Setting

Regional geomorphology and tectonics around Crete and the wider eastern Mediterranean are approached here through time-bounded coastal indicators and long-term fault dynamics, both of which are treated as interacting components of socio-ecological settings rather than unilateral drivers of historical change. Radiocarbon-dated markers such as corals, depositional features, and archaeological levels provide relative sea-level ranges that span key phases from the Bronze Age into the first millennium, including intervals whose precise boundaries were not recoverable from the source table (see Section 2.6, n. 1) (Pirazzoli et al., 1996, p. 4). These data points, together with associated depth and lithology information, outline millennial-scale trajectories of coastal stability and relative submergence or emergence. For the present dissertation, they are mobilised primarily as contextual constraints on shoreline configurationmorphology and tectonics around Crete and the wider eastern Mediterranean are approached here through time-bounded coastal indicators and long-term fault dynamics, both of which are treated as interacting components of socio-ecological settings rather than unilateral drivers of historical change. Radiocarbon-dated markers such as corals, depositional features, and archaeological levels provide relative sea-level ranges that span key phases from the Bronze Age into the first millennium, including intervals whose precise boundaries were not recoverable from the source table (see Section 2.6, n. 1) (Pirazzoli et al., 1996, p. 4). These data points, together with associated depth and lithology information, outline millennial-scale trajectories of coastal stability and relative submergence or emergence. For the present dissertation, they are mobilised primarily as contextual constraints on shoreline

configuration and the potential exposure of coastal settlements to gradual marine encroachment or relative uplift, not as direct causal explanations for social transformations. Consistent with the methodological framework that integrates palaeoenvironmental proxies only after archaeological sequences have been established, these sea-level ranges function as background parameters within which site-specific geomorphology and settlement histories on Crete are reconstructed (Pirazzoli et al., 1996, p. 4). More detailed insight into coastal hazard geomorphology comes from tsunami archives in western Greece, which provide comparanda for interpreting high-energy inundation features in eastern Mediterranean lagoons. Work in the Lefkada Lagoon documents the Gyra washover structure as a subaerial body comprising approximately of sediment and extending more than landward from the recent barrier beach (May et al., 2012, p. 10). Its spatial scale is explicitly used as a diagnostic criterion to differentiate tsunami-generated washover deposits from storm-related features, in conjunction with internal stratigraphy. Coring shows a lower bioclastic subunit associated with an initial, relatively low-energy inundation pulse that reworks lagoonal muds and bottom sediments, including a mud drape attributable to suspension fallout under slack-water conditions, followed by thicker sand and gravel units that correspond to later waves with increased turbulence and sediment load (May et al., 2012, p. 12). At some coring sites, grain-size spectra in these upper subunits appear broader and lack clear bimodal peaks, indicating spatial variability in flow energy and sediment sourcing within a single event (May et al., 2012, p. 5). Although these findings derive from a coastal

sector north of Crete, they define the kinds of geomorphological signatures that extreme marine events can inscribe in lagoonal settings across the eastern Mediterranean. In this dissertation, such evidence is used heuristically to sharpen expectations about possible tsunami-related features in Cretan coastal geomorphology once local cores and stratigraphies are available, but it does not substitute for direct archaeological and sedimentological data from the island itself (May et al., 2012, p. 10; 2012, p. 12). Tectonic setting is framed through long-term observations on plate-boundary faults and their modes of strain accumulation and release. Studies of active fault systems in the eastern Mediterranean argue that seismic activity has persisted for hundreds of thousands, and perhaps even a few million, years, with plate motions on the order of centimetres per year and slowly shifting fault patterns. During prolonged intervals of relative quiescence, strain can build on these faults for centuries before being discharged either in a single large earthquake with aftershocks or in a series of large events in which each rupture triggers the next. This latter pattern has been conceptualised as an "earthquake storm" or "earthquake sequence," in which an initial rupture affects only part of a fault zone and transfers additional stress to adjacent segments. Subsequent earthquakes then propagate along the fault until the entire length is "unzipped" and temporarily relieved of accumulated strain, after which the cycle of slow loading and episodic release begins anew (Nur & Cline, 2000, p. 4). A twentieth-century sequence along the North Anatolian Fault illustrates this dynamics: a chain of large events 390, 000 m3 1 km

with magnitudes exceeding migrated westward along the roughly -long fault, releasing strain that had built up over more than years (Nur & Cline, 2000, p. 8). For Bronze Age Crete, this conceptualisation provides a regional tectonic context in which multiple damaging earthquakes could have clustered over decades or centuries, but the dissertation strictly refrains from inferring specific ancient sequences in the absence of stratigraphically dated destruction horizons from Cretan sites. Instead, earthquake-storm models are employed as heuristic tools for formulating testable questions about temporal clustering once direct archaeological evidence is assembled (Nur & Cline, 2000, p. 4). At the site scale, earthquake archaeology on Troy VI supplies detailed descriptions of structural deformation patterns that are relevant for recognising seismic damage in eastern Mediterranean urban architecture. Excavation reports note fortification walls whose inner faces, originally vertical, have been "shaken out of plumb" and partially dislocated, tilting sharply towards the interior, together with masses of fallen stones that accumulated between citadel walls and terrace structures in "utter disorder and confusion". House walls show greatest damage on particular orientations, with characteristic flat stones fallen in large numbers into rooms and cascading into open areas, Cyclopean boulders lying below projecting corners of major buildings, and large pithoi sunk deep into heaps of collapsed wreckage indicative of abrupt structural failure in a violent upheaval (Nur & Cline, 2000, p. 15). These qualitative indicators delineate a diagnostic repertoire of wall tilting, differential displacement between superstructures and foundations, and concentrated rubble fans that can be used to evaluate whether destruction levels at Cretan sites plausibly result from seismic shocks once their stratigraphy and architecture are documented. In keeping with the broader research design outlined earlier, such comparative use of Troy VI evidence is explicitly heuristic: it aids in interpreting Cretan geomorphological and structural data but never overrides or replaces the primary empirical role of local archaeological sequences (Nur & Cline, 2000, p. 15). Later historical records from Crete itself underscore the island’s position within an active seismic corridor and illustrate how tectonic events intersect with built environments and social vulnerability. Newspaper accounts of the earthquake,

following a devastating event in [YEAR NOT STATED IN SOURCE], describe widespread housing collapse in villages such as Ano and Kato Vathia, Anopolis, Skalani, Kainourgio Horio, Aetania, and Makrys Toichos, fatalities in multiple settlements, and the plight of inhabitants forced into the open fields and winter streets before returning to unearth injured and dead from the ruins. Government responses included immediate financial assistance and the provision of tents, while reports note severe damage to houses, shops, and government buildings in Rethymnon and Chania. Additional testimony refers to an earthquake that "devastated the north Cretan shores" and is remembered for subsequent shortages in goods. These narratives, though modern, situate Crete within a geomorphologically and tectonically dynamic region where earthquakes have repeatedly reshaped urban and rural landscapes. Within this dissertation, they are used solely to exemplify socio-environmental entanglements in hazard episodes; they do not serve as analogical templates for Bronze Age conditions and remain subordinate to archaeological evidence from earlier periods. Across these strands, environmental determinism in its classical sense is explicitly rejected. Relative sea-level change, tsunami geomorphology, and tectonic fault behaviour are treated as components of regional settings that interact with settlement organisation, infrastructure, governance, and social practices rather than as sufficient, overriding causal agents. As in Section 2.1, direct archaeological evidence from Bronze Age Crete forms the primary empirical basis for interpreting geomorphological and tectonic influences, while modern coastal, seismological, and earthquake-archaeology studies are introduced only after those sequences and strictly as heuristic instruments for sharpening questions and identifying possible signatures of environmental stress.

A detailed chronology of relative sea-level and tectonic uplift episodes for the eastern Mediterranean coast, compiled from Morhange et al. (2006) and Pirazzoli (2005), is presented in Table A.1 (Appendix A).[1] (See Figures A.2 and A.3 for comparative multi-layer timelines situating this chronology within the wider Late Bronze Age context.)

[1] The specific radiocarbon-dated interval labels originally cited from Pirazzoli et al. (1996, p. 4) in an earlier draft of this section could not be reliably re-paired with their source values and have accordingly been superseded here by Table A.1 (Appendix A), an independently compiled and fully sourced chronology of relative sea-level and tectonic uplift episodes for the region, drawing on Morhange et al. (2006) and Pirazzoli (2005). The interpretive discussion in this section does not depend on the specific figures from the 1996 source and is retained in full.

3 Methodological Framework

3.1 Interdisciplinary Research Design

3.1.1 Integration of archaeological and palaeoclimatic data

Aligning archaeological and palaeoclimatic datasets in this project builds on existing multi-scalar frameworks that treat environmental and cultural change as reciprocally interacting rather than as separate explanatory spheres. Work on Roman centuriated landscapes in the Pontine marshes adopts four explicit assumptions: change is multi-causal, multi-scalar, and historically contingent; analysis must integrate archaeological, historical, ecological, and ethnographic data; processes at supra-regional, regional, and local scales must be jointly examined; and temporal perspectives must accommodate both long-term environmental trends and short-term events such as natural disasters and political decisions. These assumptions provide a methodological template for integrating palaeoclimate reconstructions with archaeological sequences in the Cretan palatial context, guiding the combined use of settlement data, landscape history, and environmental proxies. Implementing such integration requires explicit attention to spatial and temporal scaling. In the Pontine case, supra-regional climatic and political conditions are related to regional field survey and palaeoenvironmental data, while micro-studies based on geophysics, coring, excavation, and ecological work clarify how centuriation reshaped drainage and settlement organisation (de Haas, 2017). A comparable strategy for Bronze Age Crete links regionally dated climatic episodes with catchment-scale hydrology, localised geomorphology, and site-specific cultural sequences. High-resolution destruction and rebuilding horizons at Aegean palatial centres demonstrate that even within a shared cultural koine, political trajectories diverged over centuries, so any correlation with climatic proxies must operate with chronologically precise archaeological phases rather than undifferentiated "collapse" events (Molloy, 2022). Methodologically, this study adopts the view that environmental settings are co-produced by hydrology, land use, and institutions. Analyses of large irrigated basins in Central Asia show how river dependence, irrigation infrastructure, and governance choices together determine both ecological degradation and social vulnerability. Environmental reconstruction for Minoan Crete therefore combines palaeoclimatic indicators with evidence for water-management practices and institutional arrangements, treating hydrological stress as mediated through political economy rather than as an autonomous driver. Wetland restoration experiments in the same Central Asian delta further illustrate how technical hydrological improvements remain precarious without basin-wide allocation rules, underscoring the need to embed climate and water data in reconstructions of territorial control and administrative reach (Schlüter & Herrfahrdt-Pähle, 2011). Because food systems and epidemic vulnerability are shaped by multiple, interacting drivers, research on zoonotic disease and food security provides additional guidance for structuring the integration of climatic and archaeological datasets. Work on Ebola and other epidemics argues that vulnerability assessments must attend to spatial and temporal scale, bio-complexity in disease ecology, and multi-actor interactions, and that governance offers the most appropriate rubric for organising these dimensions (Khan & Sesay, 2015). Translating this to a Bronze Age setting, palaeoclimatic series are not interpreted in isolation but are read through contemporaneous evidence for settlement hierarchies, administrative reach, and possible public-health stressors, using governance as a cross-cutting category that links environmental

proxies to social outcomes. Public health research on extreme scenarios such as nuclear winter likewise informs the analytical design. Studies there propose adapting global burden of disease methodologies, integrating climatic and crop models to assess health impacts where direct empirical data are absent, and using epidemiological forecasting tools to explore how environmental shocks could alter disease dynamics (Vilhelmsson & Baum, 2023). By analogy, this thesis employs a structured risk-assessment logic for Bronze Age Crete, iteratively combining palaeoclimate indicators with archaeological evidence on food production, storage, and habitation to map plausible envelopes of risk rather than to assert direct causal chains. Finally, integrated studies of sustainable food systems demonstrate that government policies promoting agroecological practices, crop diversification, and sustainable land management can measurably alter greenhouse-gas emissions and biodiversity, while support for small-scale farmers and rural infrastructure shapes economic resilience and social equity (Agarwala et al., 2022). These findings are methodologically important because they show that similar

levels of climatic stress can yield contrasting socio-ecological trajectories depending on institutional responses. In this thesis, palaeoclimatic reconstructions for the Late Bronze Age are therefore systematically compared with regionally differentiated archaeological sequences of prosperity, contraction, and reorganisation, operationalising a non-deterministic integration of environmental and cultural datasets (Molloy, 2022; de Haas, 2017; Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022).

3.1.2 Incorporating geographical and hydrological analyses

Geographical and hydrological components in this study are structured around multi-scalar spatial analysis, hydrological modelling, and remote-sensing driven change detection applied to Cretan landscapes, in dialogue with the integrated approaches outlined for Roman centuriation, irrigated basins, and heritage sites. In the Pontine marsh case, centuriation is evaluated through the combined use of morphological analysis, geophysical prospection, coring, archaeological settlement data, written sources, and palaeoenvironmental reconstruction, enabling assessment of both environmental and cultural agents in landscape change (de Haas, 2017). This thesis adopts a comparable integration by combining field-based geomorphological observation in Crete (Appendix A) with archival cartography, elevation models, and coring data where available, in order to reconstruct drainage structures, sedimentation, and abandonment processes in palatial hinterlands. Hydrological analysis for Cretan palatial regions follows methodologies developed for large irrigated basins where river dependence, irrigation infrastructure, and institutional context jointly shape degradation and vulnerability. In Uzbekistan, dismantling of state farms, maintenance of state order systems for cotton and wheat, and path-dependent quota regimes created economic disincentives for efficient water use, undermining Water User Associations and leading to overuse and high water losses (Schlüter & Herrfahrdt-Pähle, 2011). These insights inform a Cretan protocol that links mapped hydraulic features such as cisterns, terrace walls, and channels (Appendix A) with reconstructed water-allocation regimes, treating hydraulic networks as socio-political artefacts rather than purely technical installations. For site-specific hydrological risk, procedures mirror those applied at the Ptolemaic Horus temple at Edfu. There, hydrological and hydrochemical analysis of groundwater is combined with remote sensing indices, hydrogeological settings, spatial autocorrelation, and integration of remote sensing with geographic information

systems to build protection models for cultural heritage threatened by rising groundwater and urbanisation. In this thesis, DEMs derived from SRTM and high-resolution elevation data are used to delineate watersheds around Cretan palatial centres, identify low-lying zones prone to waterlogging, and locate optimal points for drainage or pumping infrastructures, applying tools such as watershed delineation, Getis-Ord statistics, and hot-spot analysis to quantify clustering of hydrological hazards. Remote sensing and GIS routines draw directly on established archaeological applications. At Edfu, layer stacking, geometric correction, unsupervised and supervised classifications, and postclassification comparison in ENVI and ArcGIS permitted detection of changes in urban and agricultural areas through time, while conversion of raster outputs to vector polygons facilitated statistical analyses of land-use dynamics. Comparable workflows are applied to multi-date satellite imagery of Cretan catchments, allowing the reconstruction of agricultural expansion or contraction, urban sprawl around heritage zones, and encroachment into floodplains documented during the 2025 field campaign (Appendix A). Spatial statistics using Getis-Ord and hot-spot tools are then deployed to map significant clusters of land-use change that intersect with known hydraulic installations (A.Megahed, 2020). Broader landscape appraisal builds on Himalayan mountain research, where digital interpretation of multi-date satellite data, supported by intensive ground validation, underpins land, water, and forest resource mapping. In that study, PAN and LISS-3 merged data and Cartosat-2 imagery at metre to sub-10-metre resolution are interpreted, converted into land-use maps for two time slices, and then transformed into spatial layers that are cross-tabulated in a GIS to identify trajectories of change and associated socio-economic impacts (Tiwari & Joshi, 2015). The present work applies an analogous change-matrix approach to Cretan valleys, with land-cover classes tailored to Bronze Age agrarian regimes and modern analogues, and with cross-comparison to field-observed water availability, spring behaviour, and soil erosion indicators recorded in Appendix A. Several studies in environmental health and disaster risk underscore that effective management of hazards such as floods, pollution, and infrastructure failures depends on dense, high-quality spatial data and decision-support systems (Adefemi et al., 2023). In line with these findings, the Cretan geographical and hydrological datasets are assembled into a decision-support style database, linking DEM-derived drainage networks, classified land use, hydraulic feature inventories, and settlement distributions. This structure is intended to facilitate

subsequent risk and vulnerability analyses that treat palatial Crete as a complex socio-hydrological system rather than as a static backdrop, while remaining grounded in empirically validated spatial methods (de Haas, 2017; Schlüter & Herrfahrdt-Pähle, 2011; A.Megahed, 2020; Tiwari & Joshi, 2015).

3.1.3 Anthropological and public-health evidence synthesis

Anthropological and public-health strands are incorporated through an evidence-synthesis strategy that treats food security, disease ecology, and governance as co-constituted rather than as parallel domains. Work on Ebola virus disease (EVD) and bovine spongiform encephalopathy (BSE) frames epidemics as multi-faceted phenomena whose entry points traverse local food systems, environmental health, and institutional capacity, and argues that these interactions are most appropriately organised under the rubric of governance. For this thesis, such studies supply conceptual templates and variable sets for reading archaeological evidence on diet, subsistence, and

institutional arrangements in tandem with reconstructed health stressors. A first component involves translating insights from African food-related crises into a coding scheme for Minoan data. Research on EVD identifies vulnerable, food-insecure populations with inadequate health-care infrastructure as signalling potential crisis, and stresses that governance mechanisms must link sectors, jurisdictional scales, and interest groups to generate effective responses. Vulnerability assessments are described as needing to address spatial and temporal scale, bio-complexity in disease ecology, and multi-actor interactions, with governance conceived as encompassing state and non-state institutions, rules of decision-making, and scale matching. In this project, comparable variables are extracted from the Cretan archaeological record (Appendix A), including indicators of storage concentration versus household-level buffering, evidence for centralised versus dispersed ritual and healing spaces, and proxies for local autonomy within palatial hierarchies, and are then assessed against reconstructed climatic and hydrological stress episodes using the same scale-sensitive logic. A second component adapts contemporary models of crisis management and adaptive cycles. Studies of EVD and BSE note that disasters can open windows for institutional learning and transformation, yet often yield only short-term, reactive measures, and that effective interventions in Uganda relied on rigorous isolation, surveillance, and treatment protocols supported by local authorities and donor funding, with the key lesson of augmenting local capacity and strengthening institutional infrastructure (Khan & Sesay, 2015). Methodologically, these findings are used to construct a set of heuristic scenarios for Late Bronze Age Crete, distinguishing between purely reactive palatial responses to shocks and more adaptive patterns in which local communities retain or develop capacities outside central control. Archaeological sequences of destruction, rebuilding, and reorganisation are therefore read through an analytical lens that asks where evidence points to capacity augmentation versus erosion, rather than assuming automatic systemic failure. Third, the integration of public-health risk assessment tools informs the treatment of incomplete or indirect evidence. Work on nuclear winter proposes adapting the Global Burden of Disease framework to combine climate and crop models in order to estimate health impacts where direct empirical data are lacking, and highlights epidemiological forecasting as a way to anticipate disease outbreaks on the basis of environmental threats and demographic patterns (Vilhelmsson & Baum, 2023). By analogy, this thesis employs a structured risk-matrix approach: palaeoclimatic and hydrological indicators are combined with settlement density, storage capacity, and connectivity metrics to generate qualitative envelopes of probable nutritional and epidemiological stress, rather than quantitative morbidity estimates. These envelopes are explicitly framed as modelled risks, not as direct readings of disease prevalence. Contemporary public-health applications of artificial intelligence provide further guidance on data integration and early-warning logics. AI-enabled disease surveillance systems analyse diverse data sources, including electronic health records, social media, and environmental information, to detect unusual symptom clusters, identify early indicators of outbreaks, and forecast spread based on population density, travel patterns, and environmental factors. Parallel AI systems in environmental health use real-time air-quality sensor networks and predictive modelling to issue alerts and support targeted interventions, while stressing challenges of data privacy, algorithmic bias, transparency, and inclusivity (Adefemi et al., 2023). Although such technologies have no ancient equivalent, their architecture informs how heterogeneous archaeological, palaeoenvironmental, and geographical datasets are combined here: emphasis is placed on multi-source correlation, anomaly detection across proxies, and explicit documentation of uncertainty and potential bias in both data and interpretive models.

Finally, work on integrating food studies, epidemiology, and environmental governance in African contexts argues for combinations of community-based production systems, public–private partnerships,

and centralised public-health agencies, as well as for early-warning networks, environmental-health monitoring, and strengthened food-security institutions to promote adaptive capacity (Khan & Sesay, 2015). These governance arrangements serve as comparative scaffolds for interpreting Cretan evidence on local agrarian strategies, supra-local redistribution, and coastal–hinterland linkages (Appendix A). Rather than inferring specific diseases, the synthesis focuses on how different configurations of authority, resource control, and information flow would have conditioned the capacity of Minoan communities to detect, absorb, and adapt to cascading socio-ecological stresses (Khan & Sesay, 2015; Vilhelmsson & Baum, 2023; Adefemi et al., 2023).

3.1.4 Interdisciplinary design and evidence hierarchies

Interdisciplinary design in this project is organised around explicitly articulated evidence hierarchies that regulate how archaeological, palaeoenvironmental, anthropological, publichealth, and technological strands are combined. At the core lies a multi-scalar framework originally developed for Roman centuriated landscapes, which assumes that change is multi-causal, multi-scalar, and historically contingent, that supra-regional, regional, and local processes must be examined jointly, and that long-term environmental trends and short-term events such as natural disasters and political decisions require integrated analysis across archaeological, historical, ecological, and ethnographic data. These assumptions are adopted here as methodological rules rather than general inspiration, and they underpin the evidence hierarchy that places stratified archaeological sequences for Bronze Age Crete at the top of the empirical pyramid, with other datasets introduced only in clearly defined ways and at specific analytical stages. Within this hierarchy, direct archaeological evidence is explicitly designated as the primary empirical basis for reconstructing Cretan palatial systems. Settlement data, landscape history, destruction and rebuilding horizons, storage and hydraulic installations, and indicators of administrative reach are treated as foundational, and must be documented and analysed before palaeoclimate series or modern comparanda are brought into the discussion. The integration of palaeoclimatic reconstructions is then carried out using the Pontine template: supra-regional climatic and political conditions are related to regional field survey and palaeoenvironmental data, while micro-studies based on geophysics, coring, and excavation clarify local drainage and settlement organisation. For Bronze Age Crete,

regionally dated climatic episodes are therefore linked to catchment-scale hydrology, site-specific geomorphology, and detailed cultural sequences only after these archaeological phases have been chronologically refined, avoiding undifferentiated "collapse" events and maintaining a clear ordering of evidence types. Environmental settings in this design are treated as co-produced by hydrology, land use, and institutions, not as passive backdrops or unilateral drivers of change. Analyses of large irrigated basins in Central Asia show that river dependence, irrigation infrastructure, and governance choices jointly determine ecological degradation and social vulnerability, and that technical hydrological improvements remain precarious without basin-wide allocation rules and robust territorial control. These findings are used methodologically to justify embedding climate and water data within reconstructions of political economy and administrative reach for Minoan Crete, rather than reading

hydrological stress as an autonomous causal agent. In the evidence hierarchy, hydrological and palaeoclimatic proxies are consequently subordinated to, and interpreted through, institutional and settlement evidence, reinforcing the thesis's rejection of classical environmental determinism and its adoption of a socio-ecological perspective in which environment, governance, technology, and institutions interact. Anthropological and public-health strands are incorporated through a dedicated evidence-synthesis strategy that preserves this hierarchy while widening the disciplinary scope. Work on Ebola virus disease and bovine spongiform encephalopathy frames epidemics as multi-faceted phenomena whose entry points traverse local food systems, environmental health, and institutional capacity, and argues that governance offers the most appropriate rubric for organising spatial and temporal scale, bio-complexity in disease ecology, and multi-actor interactions. These studies are not treated as analogical templates for Bronze Age Crete, but as sources of conceptual variables and coding schemes. Indicators of storage concentration versus household buffering, centralised versus dispersed ritual and healing spaces, and proxies for local autonomy within palatial hierarchies are extracted from the Cretan archaeological record and only then evaluated against reconstructed climatic and hydrological stress episodes using a scale-sensitive logic derived from contemporary vulnerability assessments. Modern case studies thus occupy a strictly heuristic position in the hierarchy: they structure variables and interpretive questions, but never substitute for ancient empirical data. Riskassessment tools from public health further refine the design. Nuclear-winter research proposes adapting global burden of disease methodologies by combining climate and crop models to estimate health impacts where direct empirical data are absent, and highlights epidemiological forecasting to explore how environmental shocks might alter disease dynamics. In this thesis, these approaches are translated into qualitative risk-matrix logics that combine palaeoclimate indicators with archaeological evidence on food production, storage, settlement density, and connectivity to generate envelopes of probable nutritional and epidemiological stress, explicitly framed as modelled risks rather than direct readings of morbidity. Contemporary artificial-intelligence-enabled surveillance and environmental-

health monitoring, which integrate electronic health records, social media, air-quality sensors, and environmental data to detect anomalous symptom clusters and emerging hazards, provide further analogues for multi-source correlation, anomaly detection, and early-warning architectures. Their methodological value lies in demonstrating how heterogeneous datasets can be combined while documenting uncertainty, bias, privacy, and equity concerns, all of which are mirrored in the careful treatment of incomplete and uneven ancient datasets through transparent interpretive protocols. Finally, disaster-management and food-security research contributes comparative governance lenses that sit beneath archaeological data in the evidence hierarchy but above purely physical proxies. Studies of river-basin management show that droughts and floods often trigger short-term emergency councils, bans on particular crops, and temporary reductions in water allocations, after which systems revert to previous practices and long-term strategies for variability and scarcity are not implemented. Parallel analyses of epidemic response highlight that Ebola interventions depended on rigorous isolation and surveillance anchored in local authorities and donor funding, with lessons centring on augmenting local capacity and institutional infrastructure. Environmental-health and AI studies, together with work on large irrigated basins, demonstrate that technical innovations and management measures operate within structural constraints of bias, equity, informal institutions, and regulatory capacity. Within the thesis, these strands collectively justify an evidence hierarchy in which socio-

ecological interpretations of Bronze Age crises foreground interacting environmental, institutional, and public-health dimensions, while classical environmental determinism, in the sense of models assigning primary and near-sufficient causality to environmental variables, is systematically rejected in favour of an integrated, governance-centred reading that remains anchored in direct Cretan archaeological sequences.

3.2 Data Sources and Analytical Techniques

3.2.1 Archaeological datasets and excavation records

Archaeological information used in this study is structured around geospatially explicit datasets that integrate excavation records, survey results, and environmental observations within dedicated geographic information systems. Multi-site projects in western Asia demonstrate that long-term excavation and survey campaigns can generate large, heterogeneous corpora spanning millennia, and that such corpora are most effectively managed through relational geodatabases built in open-source platforms such as QGIS. In the Helawa–Aliawa micro-region, for example, stratigraphic, ceramic, radiocarbon, and geoarchaeological data from Late Neolithic to Islamic occupations are stored in a project GIS that underpins multi-scalar and cross-correlated analyses of human–environment interaction; this model informs the organisation of excavation-derived data for Cretan palatial centres in this thesis. Data management protocols from the MAIPE project in the Erbil plain provide a concrete template. There, base cartography, satellite and historical imagery, and digital elevation models are first assembled to define the topographic and environmental context. Unmanned Aerial Vehicle (UAV) imagery is then acquired and processed to refine surface models and plan excavation strategies. Field documentation proceeds through standardised stratigraphical unit and locus sheets, sample lists, and laboratory records for pottery and small finds. These records are digitised into survey, excavation, and geoarchaeological databases, saved as .CSV files, and uploaded into a QGIS-based Geopackage as attribute tables linked to shapefile layers representing features such as stratigraphic units, loci, and geomorphological forms. A comparable workflow is adopted for the Cretan datasets in Appendix A, ensuring that trench-level observations, architectural features, and environmental samples are consistently georeferenced and available for spatial analysis. Geomorphological and environmental components of archaeological datasets receive particular emphasis in this thesis. In the southwestern Erbil plain, geomorphological mapping combines remote sensing and field survey to discriminate between old and recent modifications of landforms, and to clarify how tectonics, climate, and human agency shaped Late Quaternary processes. Satellite sources such as Google Earth, Landsat, WorldView2, and declassified Corona imagery are processed in QGIS and GRASS GIS to trace channel shifts, sediment bodies, and anthropogenic surfaces around sites, while targeted fieldwork validates interpretations and refines the mapping. This integrated procedure guides the compilation of Cretan geomorphological layers used to contextualise palatial sites within catchment-scale hydrological and sedimentary systems, as documented in Appendix A. Within excavation datasets, explicit linkage between spatial entities and stratigraphic information is critical. At Helawa, shapefile layers representing stratigraphic units and loci are associated with attribute tables that record occupational phase, stratigraphic relations, elevation, dimensions, and associated material culture. Micromorphological samples taken from section faces are positioned by total station, imported into the GIS, and connected to the relevant stratigraphic units

through shared identifiers. This relational structure permits rapid querying of sequences, distributional analyses of artefact classes, and assessment of associations between geomorphological features and archaeological deposits (Oselini et al., 2023). Similar principles are applied to Minoan contexts, where excavation records from palatial buildings, associated terraces, and hydraulic installations are encoded to allow correlation between architectural phases, depositional environments, and indicators of environmental stress. Digital archaeology initiatives in the Jezreel Valley further illustrate how excavation and survey data can be embedded within high-resolution terrain and imagery frameworks. There, extensive and intensive landscape survey and excavation at multiple spatial scales are supported by remote sensing, three-dimensional photogrammetry, and high-precision spatial control. Raster and vector datasets are integrated to visualise complex landscapes, and UAV-based Structure-from-Motion workflows are used to generate dense point clouds, digital elevation models, orthophotos, and textured three-dimensional models at landscape scale. These methods not only increase spatial precision but also produce time-efficient, cost-effective, and high-quality digital archives, an approach mirrored in the photographic and topographic documentation procedures described for Crete in Appendix A. High-resolution spatial analysis is also necessary to recognise and correct for taphonomic and survey biases. In the Jezreel Valley, colluvial deposition during the late Roman to Byzantine period buried earlier surfaces beneath one or more metres of sediment, skewing surface artefact distributions toward hills and plain margins where visibility is higher. Archaeologists there deliberately incorporate varied topography, landforms, and vegetation into survey strategies, and rely on detailed spatial patterning to isolate phenomena of genuine archaeological interest despite these biases (Homsher et al., 2017). This awareness informs the interpretation of uneven artefact visibility and preservation in Cretan valley bottoms and slopes, where modern erosion, colluviation, and agricultural practices documented in Appendix A complicate straightforward readings of surface assemblages. Finally, archaeological datasets in this thesis are explicitly designed to support multi-scalar human–environment analysis. The MAIPE GIS integrates geomorphological layers with artefact distributions to identify points of interest and generate new research questions, while tools such as QField enable direct field recording into the GIS, streamlining data management and reducing post-processing time (Oselini et al., 2023). These practices align with the emphasis in digital archaeology on building robust geospatial datasets that can sustain complex analyses of socio-ecological dynamics across space and time, a requirement that is central to the cascading-failure and complex adaptive systems perspectives applied to Minoan Crete in subsequent chapters (Homsher et al., 2017; Oselini et al., 2023).

3.2.2 Palaeoclimate proxies and isotope records

Palaeoclimatic reconstructions in this study draw on proxy classes whose formation processes, temporal resolution, and uncertainties have been explicitly characterised. Stratified archives such as cave speleothems, peat bogs, lake sediments, and tree rings provide incrementally laid down records from which climatic variables can be inferred, yet each proxy offers only partial "estimates" that differ in statistical treatment, spatial representativeness, and chronological control. For Late Bronze Age contexts, speleothem and ice-core series from the North Atlantic realm illustrate both the potential and limits of such data. A Crag Cave speleothem in southwest Ireland registers a warming after 1200 BC, but sparse absolute dating for the Bronze Age produces total chronological uncertainties exceeding 1000 years between 2700 and 5000 cal. BP, so that any apparent 12th century signal rests on cautious

correlation with nearby proxies rather than on precise annual alignment. Greenland ice cores similarly indicate a warming 12th century and a cool spike in the 11th century BC, with one study identifying an exceptional cold event of about 29 years in the 11th century BC within a 7000-year Holocene transect. These examples underscore that even tightly sampled archives carry dating uncertainties and seasonal biases that must be respected when comparing with archaeological phases. Peat-bog and chironomid records from Ireland further exemplify the type of palaeotemperature information available. Synthesised bog data suggest mean summer temperatures peaking between 1310 and 1100 BC, followed by a drop of roughly 1.5 °C between 1150 and 960 BC, although conditions in this cooler phase remained warmer than in bracketing centuries. Chironomid head analyses indicate increased summer temperatures and aridity in the 12th century BC, succeeded by lower temperatures but relatively reduced rainfall, complementing the peat-bog signal. Annually resolved Irish bog-oak series add another layer of evidence: a sharp downturn in oak numbers around 1180 BC has been interpreted as reflecting long-term climatic forcing, while reduced growth between 1159 and 1141 BC has been argued to represent a cold episode, most clearly expressed in oaks growing in bog environments rather than on mineral soils. However, researchers emphasise that even when ring sequences are absolutely dated, the climatic meaning of individual rings is debated, and ecological niche differences can modulate the climatic signal, again reinforcing the need for cautious, context-specific interpretation. Across these archives, several methodological cautions are salient for the present project. Temporal resolution is constrained not only by sampling intervals but also by the least precise dataset included; many proxies average conditions over several years and may be seasonally biased, for example towards summer temperatures in chironomid or tree-ring records, or towards winter hydroclimate in continental speleothems. Geoarchaeological case studies that capture genuinely short-term weather anomalies, such as sluggish rivers in parts of the Pannonian Plain or brief arid summer phases in the Po Valley during the 12th century BC, remain rare, and their signatures are often bundled together with longer-term trends in regional syntheses. Authors therefore argue against using event horizons, such

as discrete destruction levels, as primary tools for aligning archaeological and palaeoclimatic datasets in the absence of secure, independent chronologies, and they caution against "blurring" often precise archaeological sequences in order to force a match with less precise environmental records (Molloy, 2022). These principles directly inform how external palaeoclimate series are mobilised here: as broad envelopes of hydroclimatic variability rather than as year-exact triggers. Within this framework, stable isotope analysis of plant macro-remains provides a higher-resolution, locality-specific complement to regional climate proxies. Carbon and nitrogen isotopic compositions of charred seeds and wood are widely used to infer photosynthetic pathways, water conditions during grain filling, and aspects of the nitrogen cycle. Differences between C3 and C4 plants arise from distinct enzymatic carbon-fixation pathways (Calvin–Benson with RUBISCO versus Hatch–Slack with PEPC and RUBISCO), making δ 13C an effective discriminator between these groups and a recognised proxy for water-use efficiency, with higher δ 13C in drier or colder regimes due to stomatal conductance responses. Nitrogen isotopic ratios (δ 15N) reflect complex nitrogen biogeochemistry; elevated plant δ15N values have been associated with limited rainfall, saline soils, and, in agricultural settings, manuring, whereas low values occur in moist forests or legumes fixing atmospheric N2. Recent work highlights the value of soil and crop δ 15N in palaeoecology and in detecting manured systems, which can substantially raise crop δ 15N relative to unmanaged contexts.

Methodological protocols for charred-seed isotopic analysis have been refined over several decades. Current best practice favours rinsing with ultrapure water rather than acid-based treatments, in order to minimise isotopic fractionation, and avoids ultrasonication because of associated mass loss. After rinsing, samples are dried at 40 °C, crushed, homogenised, and weighed into tin capsules, with carbon, nitrogen, and sulphur contents and isotopic ratios measured by elemental analyser coupled in continuous-flow mode to an isotope-ratio mass spectrometer. Analytical precision can reach better than 0.1‰forbothδ13C and δ 15N under such conditions. Corrections for changing atmospheric δ 13C, charring effects, and the calculation of carbon isotopic discrimination (Δ 13C) using established equations are standard considerations, although some studies choose not to adjust raw values where the time span is short and atmospheric composition assumed stable, instead applying corrections only in comparative analyses (Speciale et al., 2020). Models linking Δ 13C to water input during grain filling, expressed in millimetres, provide a means to translate seed isotopic values into semi-quantitative estimates of past water availability, provided that atmospheric baselines and species-specific parameters are adequately constrained (Speciale et al., 2020; Diffey et al., 2020). A case study from Case Bastione illustrates the interpretive potential of such datasets. There, δ 13C values for C3taxa, including cereals, legumes, and woody plants, are relatively high compared with typical forested environments (around −27) and average near −22 during the 4.2 ka BP event. This pattern has been interpreted as indicating drier conditions in that phase, coupled with an opening of the landscape, while a subsequent short phase with lower δ 13C values suggests wetter conditions, albeit on the basis of few samples. An anomalously low δ 15N in Pistacia during this wetter interval has been linked to a capacity for atmospheric nitrogen fixation in this genus. In the latest phase, slightly drier conditions appear to coincide with higher crop δ 15N, consistent with hypothesised manuring and improved water management that buffered plants against the most extreme moisture stress despite ongoing aridity. Importantly, the authors emphasise that, even across the 4.2 ka BP episode, their combined archaeological, isotopic, and pollen evidence points to limited climatic impact on local inland communities, with any demographic or settlement shifts interpreted cautiously and framed as hypotheses requiring further regional testing (Speciale et al., 2020). Analytical protocols developed for other large archaeological assemblages, such as cereal macro-remains from Hattusha, reinforce the technical standards adopted here. There, 64 subsamples of homogenised cereal grains were analysed for δ 13C and δ15N to infer water availability and soil nitrogen conditions under different crop management regimes. Individual-sample errors were calculated from within-run variability and the known uncertainty of reference standards, yielding accuracies of approximately ±0.091 for δ 13C and ±0.

3.2.3 Hydrological and water-management studies

Hydrological and water-management components of this study are informed by contemporary analyses in large irrigated basins, heritage protection, and mountain catchments, which together specify the types of data, scales, and institutional variables that must be documented in Appendix A. In Uzbekistan, phased land and water reforms retained a state order system for cotton and wheat, with lowered formal procurement quotas offset by increased per-hectare output requirements and limited alternative markets. Farmers were obliged to deliver most of their harvest to the state at low prices,

which curtailed their ability to pay Water User Association fees and contributed to overuse and high water losses in irrigation infrastructure. Institutional changes in water allocation planning were implemented top-down through presidential decrees, often resulting in mere renaming of organisations while khokims remained responsible for meeting district quotas and intervened directly in allocation decisions. For the Cretan case, these findings motivate systematic recording of who would have controlled hydraulic installations, how obligations might have been structured, and how such arrangements could have shaped both maintenance and over-extraction risks. Institutional responses to environmental degradation and hydrological shocks in the same basin further refine the analytical focus. Technical measures aimed at preserving agricultural productivity addressed symptoms of man-made water shortage, yet the underlying cycle of overuse and ecosystem-service loss remained intact. Droughts and floods triggered emergency bans on specific crops, temporary reductions in water limits, and ad hoc transboundary emergency councils, but management reverted to earlier practices once crises subsided, and no long-term strategy for variability or scarcity emerged. Informal institutions such as patronage and corruption constrained implementation, leaving the system vulnerable to future disturbances and slow drivers like loss of fish and reed production and dust-storm protection. Wetland restoration polders in parts of the former Aral Sea were initiated partly in response to ecological deterioration, again without fully embedding these measures in basin-wide allocation rules (Schlüter & Herrfahrdt-Pähle, 2011). On Crete, hydrological mapping in Appendix A is therefore coupled with an explicit search for evidence of episodic versus sustained interventions, considering whether palatial authorities likely pursued reactive, short-term measures or more durable reconfigurations of water use. Site-scale hydrological and hydrochemical analysis at the Ptolemaic Horus temple in Edfu provides a template for linking groundwater dynamics, urbanisation, and heritage risk. There, groundwater studies are integrated with historical and archaeological research, remote sensing indices, hydrogeological settings, and spatial autocorrelation to detect environmental changes threatening the temple. Remote sensing and GIS support change detection in urbanisation and rising groundwater, aided by low-cost, high-resolution satellite imagery capable of covering large areas and multiple time slices. Optical and radar data, together with GIS techniques, are used to develop zoned archaeological hazard maps that guide where building activity should be regulated, while decision-support systems incorporate these spatial analyses to reduce archaeological risks (A.Megahed, 2020). For Minoan sites, analogous workflows in Appendix A employ digital elevation models, multi-date imagery, and hotspot statistics to delineate watersheds, identify zones prone to waterlogging or erosion, and prioritise sectors where hydrological stress may have compromised palatial architecture and surrounding settlements. Mountain catchment research in the Himalayas adds methods for integrating hydrology with land use and socio-economic data. Appraisal of land, water, and forest resources relies on digital interpretation of multi-date satellite data, supported by intensive ground validation, with PAN and LISS-3 merged products and Cartosat-2 imagery used to map land use in 2001 and 2011. These land-use maps are converted into spatial layers and cross-tabulated in a GIS to quantify trajectories of change, while village registers and detailed household surveys supply information on water availability, resource deficits or surpluses, and links between resource depletion, migration, workload, and community health (Tiwari & Joshi, 2015). In Appendix A, comparable cross-layer analyses combine Cretan land-use classifications with mapped springs, cisterns, and channels to evaluate how shifts in cultivation or grazing might have altered runoff, recharge, and exposure to drought. Snow-hydrology work in Kazakhstan illustrates

additional techniques relevant to runoff modelling. Repeated snow surveys under different stubble and fallow conditions measure snow depth, density, and water equivalent, and are paired with remote sensing for monitoring snow accumulation and melt. Radar and RGB imagery support visualisation of snow deposition and thaw over a precision-agriculture polygon, demonstrating how remote sensing can complement in situ measurements in forecasting spring floods, crop yields, and avalanche risk on sloping terrain (Tautenov et al., 2022). Although no direct snow data exist for Bronze Age Crete, this combination of field measurement and radar-based observation informs how modern remote-sensing products in Appendix A are interpreted when reconstructing seasonal water inputs into Cretan catchments. Across these studies, hydrological and water-management analysis emerges as irreducibly socio-ecological. Economic incentives, governance structures, informal power relations, technical infrastructure, and multi-scalar spatial processes jointly determine how water is allocated, how infrastructure is maintained, and how systems respond to shocks. By adopting similar data structures, GIS-integrated workflows, and institutional variables for Minoan Crete, the hydrological component of this thesis grounds cascading-failure analysis in empirically attested configurations

of water use, control, and vulnerability (Schlüter & Herrfahrdt-Pähle, 2011; A.Megahed, 2020; Tiwari & Joshi, 2015; Tautenov et al., 2022).

3.2.4 Theoretical and methodological literature on geographical sources

Analytical work on spatial evidence in this project is underpinned by methodological frameworks that insist on integrating environmental proxies with archaeological data through explicit, multi-scalar strategies. One core template derives from studies of Roman centuriated landscapes in the Pontine marshes, which articulate four assumptions: change is multi-causal, multi-scalar, and historically contingent; archaeological, historical, ecological, and ethnographic data must be jointly analysed; supra-regional, regional, and local processes are examined together; and temporal perspectives must accommodate both long-term trends and short-term events such as natural disasters and political decisions. These premises guide the way palaeoclimate reconstructions and geomorphological

indicators are related to settlement evidence and landscape history in the Cretan palatial context, including spatially explicit datasets on destruction and rebuilding horizons. Within this framework, environmental settings are treated as co-produced by hydrology, land use, and institutions, which is methodologically significant for geographical sources: river systems, coastal geomorphology, and lagoonal archives are interpreted through the lens of water-management practices and governance arrangements, rather than as independent physical backdrops. Sea-level indicators and coastal stratigraphies exemplify how spatial environmental data are mobilised. Compilations of radiocarbondated markers such as corals, depositional features, and archaeological levels provide relative sea-level ranges that bracket key first-millennium and early intervals whose precise boundaries were not recoverable from the source table (see Section 2.6, n. 1), as well as later phases between – and – (Pirazzoli et al., 1996, p. 4). For this dissertation, these time-bounded ranges constrain reconstruction of coastal stability and potential exposure of sites to gradual marine encroachment, but they are explicitly subordinated to stratified archaeological sequences for Bronze Age Crete, which constitute the primary empirical basis. Spatial

environmental data are thus brought into the analysis only after settlement patterns, destruction horizons, and rebuilding episodes have been documented; they function as contextual parameters rather than as autonomous drivers of social change (Pirazzoli et al., 1996, p. 4). Coastal geomorphological studies of the Lefkada Lagoon further illustrate methodological approaches to high-energy inundation archives that inform spatial analysis. Detailed mapping and coring of the Gyra washover fan show that its subaerial portion comprises approximately of sediment and extends more than inland from the recent barrier beach, dimensions that have been used as diagnostic criteria for distinguishing tsunami-induced washover deposition from storm-generated features. Stratigraphic work identifies a lower bioclastic subunit interpreted as the product of a first, relatively low-energy tsunami inundation pulse, characterised by erosion and reworking of lagoonal muds, shell-debris selection, and a mud drape documenting suspension fallout under slack-water conditions. Overlying sand and gravel layers (subunit II), together with a distinct gravel unit (subunit III), are attributed to subsequent waves with increased turbulence and sediment load, producing thicker event deposits. Grain-size spectra at some coring sites reveal broader, less clearly bimodal distributions in upper subunits, highlighting spatial variability in flow energy and sediment sourcing within a single event (May et al., 2012, p. 2; 2012, p. 5; 2012, p. 10; 2012, p. 12). For the dissertation's spatial methodology, these findings provide heuristic expectations about the kinds of geomorphological signatures that tsunami exposure might leave in coastal lagoons and plains around Crete. However, they are not used to infer specific Bronze Age events in the absence of locally dated sediments; instead, they serve as comparanda for interpreting any Cretan cores and fan structures once those empirical records are assembled. Tectonic and seismological research contributes another theoretical strand for spatial evidence, but again within clearly delimited methodological

roles. Work quantifying mean recurrence intervals and average earthquake rates for the last 13 ka, and deriving the probability of observing at least one event of given magnitude during a 100-year interval, demonstrates how instrumental and geological data can be statistically related to archaeological contexts where both types of evidence are available (Jusseret & Sintubin, 2012, p. 4). Earthquake-archaeology studies of Troy VI supply detailed descriptions of spatial damage patterns: fortification curtains whose inner faces, originally vertical, have tilted sharply, masses of fallen stones lying in "utter disorder and confusion" between citadel and terrace walls, Cyclopean boulders found below projecting corners of major buildings, and large pithoi sunk deep into collapsed wreckage, all interpreted as signatures of abrupt structural failure in a violent upheaval (Nur & Cline, 2000, p. 15). These observations form a methodological repertoire for recognising potential seismic impacts in architectural and spatial collapse layers, including those on Crete, once local stratigraphy and wall orientations are carefully recorded. Long-fault "earthquake storm" models that describe sequential rupturing over decades, such as the mid-twentieth-century sequence unzipping the North Anatolian Fault, provide regional tectonic context but are used strictly to frame questions about possible temporal clustering, not to assert specific Bronze Age seismic histories (Nur & Cline, 2000, p. 8; 2000, p. 15). Modern historical accounts of Cretan earthquakes add a socio-spatial dimension to methodological thinking about hazard impacts on landscapes and settlements. Newspaper reports on the and events describe inhabitants fleeing to the countryside, spending nights outdoors to avoid collapsing structures, and returning at daylight to assess damage; they detail villages where most houses collapsed or became uninhabitable, fatalities across multiple settlements, and governmental interventions including immediate

financial aid and provision of tents. Additional testimony refers to an earthquake that "devastated the north Cretan shores" and is remembered for ensuing shortages in goods. These narratives show how spatial patterns of damage and relief intersect with seasonality, building quality, transport networks, and state capacity. In methodological terms, they reinforce the interpretive stance that natural hazards must be read as socio-environmental episodes embedded within specific spatial configurations of infrastructure and governance, even though they are chronologically distant and are used here only as contextual analogues, never as templates for Bronze Age conditions. Across these theoretical and methodological strands, the project explicitly rejects classical environmental determinism in geographical analysis. Relative sea-level trajectories, tsunami geomorphology, and tectonic fault behaviour are treated as interacting components of socio-ecological systems, mediated through institutions, technology, and settlement organisation, rather than as primary, near-sufficient causal agents of crisis. Direct archaeological evidence from Bronze Age Crete, including spatially resolved settlement and destruction data, is consistently defined as the primary empirical basis, with modern coastal, seismological, and hazard case studies deployed only after those sequences and strictly as heuristic instruments for

variable selection, spatial pattern recognition, and the formulation of testable questions.

3.2.5 Empirical geographical evidence for Bronze Age Crete

Geographical reconstruction for Bronze Age Crete in this project is constrained by proxy datasets whose spatial and temporal characteristics have been explicitly evaluated, yet these environmental archives are consistently subordinated to stratified site evidence. Relative sea-level indicators provide one important class of empirical geographical data. Compilations of radiocarbon-dated markers, including corals, depositional features, and archaeological levels, yield time-bounded ranges whose precise boundaries were not recoverable from the source table (see Section 2.6, n. 1), together with multiple late first-millennium and early first-millennium intervals up to – (Pirazzoli et al., 1996, p. 4). These ranges delineate long-term trajectories of relative coastal stability and vertical land movement around eastern Mediterranean shorelines. Within the present thesis, they serve as contextual constraints for considering the stability of Cretan coastal plains and harbours, but they are not treated as direct causal drivers of settlement change. Their chronological envelopes are instead used to frame questions about whether Bronze Age shoreline configurations were broadly comparable to later documented positions or whether gradual emergence or submergence might have altered local geomorphological settings that are archaeologically attested (Pirazzoli et al., 1996, p. 4). High-energy coastal inundation features provide a second empirical strand that informs geographical assessment of tsunami exposure in eastern Mediterranean lagoonal environments. Work on the Gyra washover fan in the Lefkada Lagoon documents a subaerial deposit of approximately extending more than landward from the recent barrier beach, dimensions which are explicitly employed as diagnostic criteria for differentiating tsunami-generated washover from storm-induced systems (May et al., 2012, p. 10). Coring transects across the fan identify two to four subunits separated by erosional unconformities, with the overall sequence thinning and fining landward. Sedimentological analysis reveals massive bedding, fining-upward trends, heterogeneous layers with possible sub-stratification, and both unimodal and bimodal grain-size distributions. In particular, bimodal spectra combining fine to medium sand with very coarse sand to medium gravel are interpreted

as signatures of multiple sediment sources, notably sublittoral sands and littoral gravels, mobilised within single tsunami events (May et al., 2012, p. 11; 2012, p. 12). Event reconstruction distinguishes a lower bioclastic subunit formed during an initial, relatively low-energy inundation pulse, characterised by erosion and reworking of lagoonal muds and bottom sediments, separation of shell debris by strong currents, and the deposition of a mud drape documenting suspension fallout under slack-water conditions. Overlying sand and gravel layers, together with distinct gravel units, correspond to later pulses in the tsunami wave train marked by increased turbulence and sediment load, producing thicker event deposits.

At certain coring sites, upper parts of subunits lack clear bimodal patterns and show broader grain-size spectra, indicating spatial variability in flow dynamics and sediment transport. Mud layers and rip-up clasts within the fan are interpreted as physical attributes typical of tsunami deposits and rare in storm strata, supporting the conclusion that at least one tsunami event was responsible for the Gyra washover sequence (May et al., 2012, p. 5; 2012, p. 11; 2012, p. 12). For Bronze Age Crete, these findings do not provide direct evidence of specific events, but they establish empirical criteria for recognising comparable tsunami signatures in Cretan lagoonal and coastal deposits once local cores are obtained, including landward-fining sequences, discrete subunits with erosional boundaries, bimodal grain-size distributions pointing to mixed littoral and sublittoral sources, and internal mud drapes formed during slack-water phases. Regional tectonic context is informed by long-term observations of plate-boundary faults and their seismic behaviour. Studies of eastern Mediterranean fault systems argue that seismic activity has persisted for hundreds of thousands, and possibly a few million, years, with plate motions on the order of centimetres per year and slowly shifting fault patterns. Strain accumulation during intervals of relative quiescence over centuries can be released either in a single large earthquake with numerous aftershocks, or in a series of large events in which each rupture triggers the next, conceptualised as an "earthquake storm" or "earthquake sequence" (Nur & Cline, 2000, p. 4). Empirical documentation of the mid-twentieth-century sequence along the North Anatolian Fault shows a chain of large earthquakes with magnitudes greater than 6.5, migrating westward along a fault zone roughly 1000 km long, between 1939 and 1967, releasing strain accumulated over more than 200 years (Nur & Cline, 2000, p. 8). At the site scale, structural deformation patterns at Troy VI provide another empirical basis for recognising seismic effects in urban architecture. Excavation reports describe fortification curtains whose inner faces, originally vertical, have been "shaken out of plumb" and tilted sharply, masses of fallen stones lying in "utter disorder and confusion" between citadel and terrace walls, Cyclopean boulders found below projecting corners of major buildings, and large pithoi sunk deep into collapsed wreckage, all interpreted as signatures of abrupt structural failure in a violent upheaval (Nur & Cline, 2000, p. 15). These qualitative indicators form a diagnostic repertoire for evaluating destruction levels at Cretan palatial centres, once wall orientations, collapse patterns, and rubble distributions are empirically documented. Modern hazard descriptions for Crete itself add an historically grounded, though much later, perspective to empirical geographical evidence. Testimony records an earthquake that "devastated the north Cretan shores" and is still remembered for the shortages in goods that followed, underscoring the spatial extent of coastal damage and its entanglement with supply networks and everyday life. In the methodological framework adopted here, such modern accounts are used only as contextual analogues for socio-environmental impacts and not as templates for Bronze Age conditions. Across these

empirical strands, environmental determinism in its classical sense is explicitly rejected. Relative sea-level changes, tsunami geomorphology, and fault dynamics are treated as 6.5 1000 km 1939 1967

components of regional settings that interact with, but do not unilaterally determine, Cretan settlement histories. Direct archaeological evidence from Bronze Age Crete remains the primary empirical basis, and the geographical proxies and comparative case studies summarised here are introduced only after those sequences and strictly as heuristic instruments for identifying potential signatures of environmental stress and formulating testable questions about spatial vulnerability and resilience (May et al., 2012, p. 10; Nur & Cline, 2000, p. 4; Pirazzoli et al., 1996, p. 4).

4 Climatic and Environmental Stressors

4.1 Palaeoclimatic Trends in the Eastern Mediterranean

4.1.1 Temperature variability and extreme events

Speleothem, peat-bog, ice-core, and tree-ring archives together document pronounced temperature variability around the close of the Late Bronze Age, but also expose substantial chronological and interpretive uncertainties. A speleothem from Crag Cave in southwest Ireland records a warming phase after 1200 BC, yet Bronze Age intervals in this archive suffer from sparse absolute dates, with total age uncertainties exceeding 1000 years between 2700 and 5000 cal. BP; recognition of a 12th century signal therefore depends on correlation with nearby proxies rather than precise independent dating. Greenland ice cores similarly register a warm 12th century and a cool spike in the 11th century BC, and a 7000-year North Atlantic Holocene transect isolates an exceptional cold event of ∼ 29 years during the 11th century BC, underscoring that short but sharp deviations occurred within otherwise moderate Holocene variability. These high-latitude records frame the eastern Mediterranean within a wider field of North Atlantic climate shifts, but temporal uncertainty precludes simple year-on-year alignment with archaeological horizons. Peat-bog stratigraphies from Britain and Ireland provide more regionally constrained signals of temperature change. Synthetic analyses indicate that mean summer temperatures peaked between 1310 and 1100 BC, followed by a decline of about 1.5 °C between 1150 and 960 BC, to values still warmer than those of preceding and subsequent centuries. Chironomid head capsule studies from Irish lakes reinforce this pattern, pointing to increased mean summer temperatures and aridity in the 12th century BC, then decreasing temperature but relatively lower rainfall thereafter. Annually resolved Irish bog-oak series add yet another layer: a sharp downturn in oak numbers around 1180 BC has been interpreted as reflecting long-term forcing consistent with a climate-driven shift, and ring-width data suggest a cold phase between 1159 and 1141 BC that is most clearly expressed in trees growing in bog environments, with much weaker expression in oaks rooted on mineral soils. Even in this ostensibly high-resolution archive, ecological niche effects and uncertainties in the climatic meaning of individual rings complicate attempts to read these changes as discrete "events" directly impacting human societies. Across continental Europe and the Mediterranean, comparative synthesis of diverse proxies identifies a distinct inflection in temperature–wetness regimes in the decades around 1200 BC. Analyses of lake and marine cores, speleothems, ice bodies, bogs, tree rings, pollen, and chironomids reveal a relatively coherent niche in the 16th to 13th centuries BC, followed by increased aridity in the 12th century in most study regions. A north–south contrast emerges, with rising temperatures around 1200 BC across much of continental Europe and the Atlantic islands, while proxies from the Mediterranean indicate cooling tendencies. In every region, a distinct shift is detectable near 1200 BC and climate variables approach the margins of Holocene conditions, yet these changes are not characterised as extreme in absolute terms. For Greece specifically, most proxies document increasingly arid conditions in the 12th century BC, possibly following a drier spike in the later 13th century, though the magnitude and duration of these anomalies remain debated. Closer to the core Bronze Age settlement zones of the Po Valley, multi-proxy records illuminate how modest but abrupt hydroclimatic shifts translated into local water stress. Lake Ledro shows high water levels from about 1600 BC, then lower levels

indicative of increased aridity after roughly 1200 BC, while pollen and sediment data from Lake Lucone point to substantial reductions in anthropogenic markers and lake level after ∼ 1100 BC. Geoarchaeological investigation at Terramare sites identifies stratified soil horizons dated 1330–1170 cal. BC that reflect a drop in the water table, directly affecting large wells and interconnecting ditches and thereby restricting access to drinking water. A drier phase between 1200 and 1150 BC is also recorded at Montale, Casinalbo, and Fondo Paviani; however, these intervals are explicitly described as neither extreme nor long-lasting climatic perturbations. Such case studies emphasise that what might appear as modest shifts in regional temperature or precipitation can nonetheless manifest as critical local hydrological stress when superimposed on particular geomorphological and infrastructural configurations. Several methodological cautions from these studies are central for later interpretation of Cretan evidence. Many proxies are seasonally biased, often towards summer conditions, and average climatic states over multi-year windows; event-scale anomalies are

rarely captured unambiguously. Chronological precision is constrained by the least precise archive in any comparison, and attempts to align archaeological destruction levels with climatic "events" risk forcing correlations across mismatched temporal resolutions. Authors therefore warn against relying on event horizons as primary synchronising tools, and against diluting archaeologically well-resolved sequences to fit coarser environmental timelines. In the analysis developed here, palaeoclimatic series are consequently treated as defining envelopes of temperature variability and episodes of relative aridity or cooling, rather than as single, date-specific triggers, and are integrated with archaeological, hydrological, and governance data only within these explicitly bounded uncertainty ranges (Molloy, 2022).

4.1.2 Precipitation patterns and drought frequency

Evidence for hydroclimatic change around the close of the Late Bronze Age is clearest where multiple proxy series converge on shifts in effective moisture rather than in temperature alone. A synthetic review of lake and marine cores, speleothems, bog deposits, tree rings, pollen, and chironomid assemblages across Europe delineates a distinctive temperature–wetness niche in the 16th to 13th centuries BC, followed by a transition toward more arid conditions in the 12th century in most regions examined. Within this broad pattern, a north–south contrast emerges: while continental Europe and the Atlantic islands experienced increasing temperatures in the decades around 1200 BC, Mediterranean proxies tend to register cooling, implying regionally differentiated combinations of precipitation and evaporative demand. Across all regions a marked shift is detected in the decades straddling 1200 BC, with hydroclimatic variables approaching the margins of Holocene variability, although not reaching truly extreme values. For Greece specifically, most proxy records point to increasingly arid conditions in the 12th century BC, possibly preceded by a drier spike in the later 13th century. These findings frame any discussion of eastern Mediterranean drought frequency as an issue of altered baseline wetness and seasonality within a relatively narrow but consequential Holocene envelope. Regional case studies in the Po Valley illustrate how such "moderate" aridification translated into tangible reductions in water availability and, by implication, more frequent or protracted drought episodes affecting agrarian communities. At Lake Ledro, high water levels between roughly 1600 and 1200 BC give way to lower stands indicative of increased aridity thereafter, while sediment and pollen

from Lake Lucone show both declining anthropogenic indicators and reduced lake level after about 1100 BC. Geoarchaeological observations in large Terramare settlements document a drop in the water table between 1330 and 1170 cal. BC that directly impacted wells and interconnected ditches, constraining access to drinking water. Additional evidence from sites such as Montale, Casinalbo, and Fondo Paviani points to a drier phase between 1200 and 1150 BC. Crucially, these intervals are characterised as neither extreme nor very long-lasting climatic perturbations, yet they were sufficient to induce sluggish river flow, silting, and peat formation in valley bottoms, reflecting significant shifts in seasonal runoff and groundwater recharge. Such examples caution against equating "non-extreme" climatic departures at regional scale with negligible hydrological consequences at settlement scale. Heterogeneity in rainfall histories within single macro-regions further underscores that drought frequency and intensity varied across short distances. In the Carpathian and Pannonian domains, speleothem δ 18O records, lake sediments, and bog sequences collectively suggest wetter conditions in earlier Late Bronze Age centuries, followed by a 14th century turning point, a 13th century aridity peak, and continued dryness into the 11th century BC. Within this framework, a bog at Fenyves-tető documents an exceptional dry spell between about 1440 and 1070 BC, whereas pollen from the Gutaiului Mountains indicates cooling and increased precipitation after 1200 BC. Pollen around the fortified site of Corneşti Iarcuri records reduced anthropogenic activity between 1200 and 1000 BC, consistent with settlement contraction, while another core at Sarló Hát shows limited change before 1000 BC and later woodland clearance. These contrasting signatures reveal that even where a general trend toward increased aridity is recognised, local catchments could experience divergent precipitation trajectories, implying spatially uneven exposure to drought stress for Late Bronze Age communities. Methodological reflections arising from these studies are directly pertinent for interpreting precipitation signals in relation to Aegean palatial decline. Many archives preferentially register summer conditions; bogs and chironomids are biased toward growing-season moisture, while some speleothems reflect winter hydroclimate, so reconstructed "aridity" or "wetness" often refers to seasonally specific water balances rather than annual totals. Temporal resolution also varies: some speleothems offer 7–18-year sampling but carry century-scale age uncertainty; peat and lake cores frequently average over decades; tree-ring series

are annually resolved yet encode complex ecological responses. Analysts therefore warn against synchronising short-lived archaeological destruction horizons with single "event" layers in palaeoclimate records and argue for focusing instead on decadal to centennial envelopes of hydroclimatic change. Within such envelopes, increased drought frequency can be conceptualised not as isolated failures of rainfall but as a raised probability of multi-year sequences in which seasonal deficits, groundwater lowering, and reduced baseflow recurrently stress water-dependent systems. For Greece, the 12th century BC falls within precisely such an aridity-biased window, with a possible precursor spike in the later 13th century, providing a cautiously constrained temporal frame for situating Minoan and Mycenaean socio-hydrological vulnerabilities without collapsing them into simple climate determinism (Molloy, 2022).

4.2 Environmental Degradation

4.2.1 Deforestation and vegetation change

Vegetation change in socio-ecological systems emerges not only from climate forcing but from sustained human exploitation of land and water resources. Work on irrigated cotton regimes in Central Asia shows how decades of over-extraction and salinization degraded semi-natural ecosystems that had previously supplied fish, reeds, and dust-storm protection. Wetland restoration polders in parts of the former Aral Sea delta were initiated as partial responses to this deterioration, yet remained weakly integrated into basin-wide allocation rules. As a result, land-cover mosaics shifted from diverse wetland and riparian vegetation towards simplified, degraded assemblages associated with man-made water shortage, even as technical projects attempted to reconstruct fragments of lost habitats (Schlüter & Herrfahrdt-Pähle, 2011). This configuration of progressive ecosystem simplification under exportoriented agriculture provides an important comparative backdrop for thinking about woodland and scrub trajectories in Bronze Age Crete, particularly in contexts where palatial political economies might have incentivised intensive land use without robust mechanisms for landscape regeneration. Deforestation and reforestation dynamics have also been investigated in mountain regions where climate change, water scarcity, and livelihood stresses intersect. In the Himalayas, declining water availability and increasing risks of natural disasters place severe pressure on local production systems, driving male out-migration and leaving women with increased workloads in agriculture, livestock care, and fuelwood collection. These burdens reduce time for personal and child care and increase exposure to water-borne and nutrition-related health risks, while women constitute a disproportionately high share of disaster victims due in part to limited access to information and preparedness measures (Tiwari & Joshi, 2015). Although specific vegetation trajectories are not quantified, this analysis links social differentiation, gendered labour, and environmental change in ways that are directly relevant to reconstructing how forest clearance, shrub encroachment, or terrace abandonment around Cretan palatial centres may have been experienced unevenly across social groups. Environmental health research underscores that vegetation change is tightly coupled to broader hazard landscapes. Urban and peri-urban regions face interacting challenges from air, water, and soil pollution, inadequate waste management, occupational hazards, and disaster risk, all of which demand multisectoral governance arrangements. Artificial intelligence is increasingly applied to air-quality monitoring, water-quality analysis, and disaster vulnerability assessment via dense sensor networks, predictive models, and decision-support tools, yet technical solutions remain conditioned by questions of equity, data quality, and institutional capacity (Adefemi et al., 2023). Vegetation loss or transformation in such settings can both reflect and reinforce these hazards, for example through diminished buffering of dust and pollutants or through conversion of green space to built-up land, suggesting that arboreal and shrub cover around ancient palatial sites should be treated as part of a wider environmental-health assemblage rather than an isolated variable. At the scale of individual heritage landscapes, remote sensing and GIS-based change detection reveal how urban expansion and groundwater rise alter vegetation structure and, indirectly, archaeological preservation conditions. Around the Ptolemaic Horus temple at Edfu, hydrological and hydrochemical analysis of groundwater is combined with optical and radar imagery, spatial autocorrelation, and hazard mapping to track environmental change. Low-cost, high-resolution satellite data make it possible to observe landscape evolution, including

urbanisation and shifting groundwater levels, across multiple time slices and large areas. These techniques are used to construct zoned hazard maps that inform where building activity should be restricted to protect archaeological remains (A.Megahed, 2020). Although focused primarily on hydrological and urban drivers, such workflows necessarily register

associated vegetation changes, for instance replacement of agricultural plots or riparian strips with impervious surfaces, and thus offer a methodological template for reconstructing long-term land-cover transformations in Cretan valleys using the imagery and geomorphological observations reported in Appendix A. Forest-plantation studies in arid Western Kazakhstan further clarify how deliberate vegetation interventions can both respond to and reshape degraded environments. Research on artificial cultivation of black saxaul aims to develop low-cost, durable forest plantations that increase forest cover and improve living conditions in desert regions. Field investigations involve reconnaissance surveys, trial plots, soil profile descriptions to depths of 150–160 cm, and analysis of water-physical and chemical properties in order to define optimal soil preparation, planting methods, seedling spacing, and agrotechnical care. The stated goal is to design socially significant plantations that enhance soil protection, climate regulation, and productivity, with monitoring of vegetation–habitat relationships used to refine recommendations (Tautenov et al., 2022). This case demonstrates that in severely degraded settings even sparse shrub-forest cover functions as critical green infrastructure, and that its successful establishment depends on fine-grained knowledge of soils, hydrology, and management regimes. In interpreting Bronze Age Cretan pollen and charcoal signals for woodland clearance or regeneration, this modern example cautions against treating "forest" as a simple binary category; instead, attention must be paid to structural and functional attributes of vegetation, including its role in soil stabilisation, microclimate moderation, and fuel provisioning. These diverse studies collectively show that deforestation and vegetation change are best understood as outcomes of interacting climatic, hydrological, socio-economic, and governance processes, often producing path-dependent ecological states that can be only partially reversed. By anchoring palaeoecological interpretations of Cretan landscapes in such empirically documented socio-ecological configurations, this thesis seeks to avoid deterministic readings of vegetation decline and instead position arboreal and shrub dynamics as both indicators and drivers of longer-term shifts in palatial resilience and vulnerability (Schlüter & Herrfahrdt-Pähle, 2011; Tiwari & Joshi, 2015; Adefemi et al., 2023; A.Megahed, 2020).

4.2.2 Impact on agricultural productivity

Shifts in climatic and environmental conditions alter agricultural productivity through combined effects on yields, resource bases, and food-system stability. Climate variability in the form of erratic droughts and floods disrupts crop growth and harvest schedules, directly lowering yields and compromising the reliability of food availability; over time, such disruptions force governments to adapt food systems to increasingly unpredictable weather regimes. Resource depletion further constrains productive capacity. Progressive soil degradation, intensifying water scarcity, and biodiversity loss together narrow the ecological space within which agriculture can function, making it harder to meet nutritional needs as competition for key inputs increases. Impacts on productivity cannot be understood independently of governance. Agricultural subsidies and land-use policies shape crop choices,

production levels, and long-term soil and water conditions. Subsidies can incentivise particular crops and management practices, sometimes enhancing aggregate output but also risking environmental degradation when they promote input-intensive monocultures or expansion into marginal lands. Land-use regulations can support sustainable practices that stabilise productivity, or alternatively accelerate degradation that erodes future yields. Evidence also shows that policies promoting agroecological methods, such as crop rotation and polyculture, contribute to enhanced environmental resilience and a shift toward more diversified, climate-resilient systems, thereby sustaining productivity under stress. Food-system productivity extends beyond farm-level yields to encompass access, utilisation, and stability. Income inequality and poverty limit effective demand even where production is adequate, constraining the profitable scale of agriculture and reducing incentives for sustainable investment. Gender inequality in access to resources and decision-making restricts the productive potential of women farmers, weakening household-level food security and the aggregate performance of agrarian sectors. Social policies such as income support, minimum wages, and safety nets directly influence economic access to food, while public-health and nutrition programmes affect utilisation by determining how far available calories translate into improved nutritional status. These dimensions feed back into productivity: malnourished, impoverished populations have reduced labour capacity, deteriorating human capital, and limited ability to adopt improved practices (Agarwala et al., 2022). Environmental degradation linked to unsustainable production practices exerts a cumulative drag on yields. Land degradation, including salinization, waterlogging, soil acidification, and erosion, illustrates how productivity gains achieved through intensive cultivation can be reversed when ecological limits are exceeded. In Australia, unsustainable practices have produced widespread land degradation, with millions of hectares at risk or already affected by salinity, alongside increasing soil acidification and erosion, all threatening future food supply unless farming methods are adjusted. Agriculture also contributes substantially to greenhouse gas emissions, while climate change in turn feeds back negatively on agricultural output. Projections for Australia estimate an overall decline in food production of 15–30 % over four decades as a result of climate-driven changes, including more frequent heatwaves and altered rainfall patterns, despite any potential fertilisation effect of higher atmospheric CO2(Selvey & Carey, 2013). At global scale, additional pressures arise from market and trade structures. Unfavourable trade agreements and market-access barriers disadvantage small-scale producers, weakening their economic resilience and capacity to invest in soil and water conservation measures that could stabilise yields. Reliance on extended supply chains increases vulnerability to systemic shocks, such as pandemics, which disrupt labour availability, logistics, and market demand, further undermining effective agricultural productivity even where biophysical conditions remain adequate. Governments attempt to buffer these impacts through strategic reserves, disaster-preparedness policies, agricultural insurance, and climate-smart agriculture initiatives, yet trade-offs persist: policies that boost production in the short term may intensify resource depletion or entrench inequities that erode long-run productivity (Agarwala et al., 2022). Integrated sustainability agendas explicitly target these intertwined constraints. Sustainable food-system strategies emphasise regenerative agriculture that enhances soil health, biodiversity, and water conservation, alongside climate-resilient crops and water-efficient irrigation, in order to mitigate the negative productivity impacts of climate change and resource depletion. Economic sustainability measures, including support for small-scale farmers, fair prices, rural infrastructure investment, and fair-trade

arrangements, are designed to maintain productive capacity while improving livelihoods. Social sustainability, through policies that guarantee affordable, nutritious food and promote gender equality in agriculture, aims to strengthen the human and institutional foundations of productive systems. Nonetheless, analysis warns that scaling such approaches remains difficult, as conventional input-intensive methods and globalised trade regimes continue to dominate, creating persistent tensions between immediate yield maximisation and the maintenance of the ecological and social conditions on which long-term agricultural productivity depends (Agarwala et al., 2022; Selvey & Carey, 2013).

5 Water Security and Hydraulic Systems

5.1 Hydrological Resources in Minoan Crete

5.1.1 Spring systems and aquifer availability

Discussion of spring systems and aquifer availability in karstic landscapes benefits from detailed hydrogeological reconstructions in comparable regions where subsurface flow, recharge, and discharge points have been systematically mapped. In the southern Petén Plateau, drainage is controlled by karst hydrologic features, including seasonal swamps (bajos), dolines, intermittent lakes, subsurface conduits, and springs, which together define karst drainage basins contributing to outlet springs. Geographic Information System methodologies integrate multiple remote-sensing datasets to map these features, model subsurface flow paths, and delimit basin boundaries, demonstrating that karst basins can be characterised as coherent hydrological units defined by surface landforms and inferred conduit networks. Such an approach underpins the identification of the Mirador-Calakmul Karst Basin (MCKB) as a fluviokarst landscape in which solution-enhanced conduits funnel recharge from thousands of dolines and swallow holes toward springs at the basin margin. Hydrogeological analysis of the MCKB specifies how groundwater movement structures spring availability. Groundwater recharged in upland bajos and karst valleys flows west and east from central anticlines, with bidirectional patterns documented by regional modelling that integrates more than 4000 natural water points. Within the MCKB, subsurface flow is inferred to follow a dendritic network of trunk conduits and tributaries trending west to northwest, underdraining major karst valleys and resurfacing at lines of exsurgence springs at the base of low hills along the western margin. This mapping shows that springs can mark the downstream boundary of a karst basin, while topographic divides and structural highs delimit upstream limits where direct tracer data are lacking. These observations provide a comparative framework for conceptualising Cretan palatial territories as embedded within analogous, if smaller-scale, karst basins whose spring distributions and aquifer geometries conditioned reliable access to groundwater. Seasonal variability in such systems is critical for assessing water security. In the MCKB, dry-season conditions

lower the water table so that water persists mainly in civales and residual lagoons along the western margin, indicating that only certain parts of the aquifer remain expressed at the surface for sustained periods. With the onset of the rainy season, thousands of dolines and swallow holes rapidly funnel water into the subsurface, and solution-enhanced fractures and conduits channel groundwater westward to numerous springs at the base of the marginal hills. Heavy rain events can overwhelm conduit capacity, activating overflow springs and generating surface flow in channels and arroyos, while closed depressions in the bajo system act as temporary storage, with some overflow crossing the basin margin. These dynamics show that spring discharge regimes depend jointly on recharge intensity, conduit capacity, and basin morphology, and that perennial versus ephemeral behaviour reflects both seasonal forcing and longer-term aquifer configuration. Empirical data from Himalayan micro-watersheds demonstrate how changes in aquifer recharge and spring discharge translate into community-level water scarcity. In the Upper Kosi catchment, long-term deforestation has reduced groundwater recharge, contributing to decreased streamflow, diminishing spring discharge, and altered surface run-off and channel capacity. Field surveys document that approximately 33.75 % of natural springs have completely dried and about

10.8 % have become seasonal over three decades, while a total of 736 km of stream length has dried, with 61 % of villages facing significant water scarcity, particularly during dry months. Associated declines in biomass supply to agro-ecosystems (up to 58 % in some micro-watersheds), irrigation potential (up to 21 % loss of irrigated area), and agricultural productivity (overall decline of 25 %) highlight how reduced spring and aquifer availability cascade into lower agrarian output and heightened livelihood vulnerability (Tiwari & Joshi, 2015). These contemporary cases illustrate several parameters that must be considered when reconstructing spring systems and groundwater access in karstic island settings: the spatial organisation of recharge zones and conduit networks, structural controls on basin-scale groundwater flow, the position and seasonality of discharge points along basin margins, and the sensitivity of springs to land-cover change and prolonged environmental stress. They also emphasise the importance of basin-scale drainage maps, integrating surface karst features, inferred subsurface flow paths, and spring lines, as key tools for any attempt to model how ancient communities might have utilised, managed, or contested access to aquifer-fed springs under changing climatic and land-use regimes (Tiwari & Joshi, 2015; Agarwala et al., 2022; Adefemi et al., 2023). (See Figures A.10–A.12 for the hydrological atlas of Minoan Crete referenced throughout this chapter, and Figure A.13 for the underlying physical and geographical map.)

5.1.2 Impact of climatic change on water resources

Climatic variability alters water resources through coupled effects on river flow regimes, groundwater recharge, and the persistence of surface and subsurface storage, with consequences that depend strongly on institutional responses and land-use trajectories. In the Amudarya basin, semi-arid conditions already require that virtually all agriculture be irrigated from surface water, so changes in flow directly affect both ecological systems and rural livelihoods. Massive twentieth-century expansion of irrigated land to more than 4 million ha, combined with low management standards, deteriorating infrastructure, and frequent lack of drainage, generated soil salinization, waterlogging, and severe degradation of the Aral Sea delta, including collapse of fisheries and loss of semi-natural ecosystems that had buffered salt and dust storms. Although this degradation is largely anthropogenic, projected changes in river flow linked to climate change are explicitly noted as factors that may aggravate already constrained water availability, underscoring how climatic forcing can compound existing hydrological stress in irrigation-dependent systems. Hydrological consequences of climatic shifts are particularly visible where groundwater-fed features and wetlands respond sensitively to changes in effective moisture. In Central Asia, wetland restoration projects in sections of the former Aral Sea delta re-established lakes and marshes and demonstrated substantial ecological recovery potential, yet their long-term sustainability remains uncertain because institutional arrangements do not guarantee freshwater inflows, especially given expectations that the number and severity of drought years might increase. Restoration increased local water storage and ecosystem services but did not secure their position within basin-wide allocation rules, so potential climate-driven reductions in flow threaten to undermine these gains (Schlüter & Herrfahrdt-Pähle, 2011). This combination of high ecological restoration capacity and vulnerability to future drought illustrates how climatic shifts in runoff interact with governance gaps to determine whether water-related interventions enhance or erode resilience. Mountain catchments provide another set of observations on how changing precipitation and temperature regimes reshape

spring discharge, stream length, and resource availability. In the Upper Kosi basin, long-term deforestation has reduced groundwater recharge, contributing to decreased streamflow, falling spring

discharge, and modified surface run-off and channel capacity. Over roughly three decades, approximately 33.75 % of natural springs have dried completely and about 10.8 % have become seasonal, while about 736 km of stream length has vanished and 61 % of villages now experience significant water scarcity, particularly in dry months. These hydrological changes cascade into reduced biomass supply to agro-ecosystems by up to 58 % in some micro-watersheds, loss of irrigated area by up to 21 %, and an overall decline in agricultural productivity of about 25 %, illustrating how altered recharge and discharge regimes under environmental change reverberate through food production and livelihoods (Tiwari & Joshi, 2015). Although deforestation is central here, climatic variability modulates recharge and thus amplifies or dampens spring decline. Broader climate–security analyses frame such hydrological impacts as elements in complex chains of risk. Global heating is described as a "risk multiplier" that disturbs interactions between natural and social systems, with linkages from local to global levels. Among key pathways, climate change affects critical infrastructures and supply networks, intensifies the water–energy–food nexus, and contributes to production losses and price rises that can propagate through global markets. Loss or degradation of vital resources such as water, arable land, forests, and biodiversity threatens human security, particularly in fragile regions characterised by weak governance and limited management capacity. In such contexts, climate-induced water stress interacts with poverty, institutional fragility, and social conflict to undermine problem-solving capacity and degrade infrastructures, including health systems, thereby increasing vulnerability to further shocks (Scheffran, 2023). Governmental efforts to manage these compounded pressures in food systems highlight the difficulty of adapting water management under climatic variability. Policy analyses emphasise that erratic droughts and floods disrupt agricultural production, while overexploitation of soil and water resources and biodiversity loss further constrain the ecological basis of food supply. As resource competition intensifies, meeting nutritional needs becomes more challenging, particularly where income inequality, gender disparities, and weak infrastructure restrict access to food even when aggregate production is sufficient. Attempts to stabilise food systems through strategic reserves, trade agreements, and environmental regulation must therefore operate within an increasingly volatile hydroclimatic regime and confront implementation gaps, sectoral silos, and political instability that limit effective responses to water-related climate risks (Agarwala et al., 2022). Across these diverse cases, climatic change does not operate as an isolated driver of hydrological crisis; instead, shifts in runoff, groundwater recharge, and drought frequency interact with land-use decisions, institutional arrangements, and socio-economic inequalities. For the Cretan material examined in Appendix A, these findings justify treating changes in spring behaviour, stream intermittency, and storage reliability as outcomes of coupled climatic and governance dynamics, rather than as straightforward reflections of climatic forcing alone (Schlüter & Herrfahrdt-Pähle, 2011; Tiwari & Joshi, 2015; Scheffran, 2023; Agarwala et al., 2022).

5.2 Minoan Hydraulic Infrastructure

5.2.1 Cisterns and storage systems

Cisterns and related storage installations must be understood against wider patterns of hydrological stress, institutional control of water, and long-term degradation of land and aquatic ecosystems. Work on large irrigated basins in Central Asia documents how path-dependent, state-directed agricultural regimes can generate chronic man-made water shortage, soil salinization, and collapse of downstream wetlands, even before projected climate-driven reductions in river flow are fully realised. In that system, irrigation infrastructure and on-farm storage effectively became instruments for sustaining cotton and wheat quotas rather than for buffering variability, with low farm-gate prices undermining the ability of producers to finance maintenance of canals and associated facilities, leading to overuse and high conveyance losses. By analogy, any assessment of Minoan cisterns and storage basins must consider not only their technical capacity but also their embedding in fiscal and political arrangements that determined who could invest in upkeep and who benefited from stored water. Institutional responses to hydrological shocks in the same basin further expose the limitations of storage-focused strategies when they are not accompanied by structural reform. Droughts and floods triggered short-term emergency measures, including bans on particular crops and reductions in water limits, as well as ad hoc transboundary emergency councils, but once extreme conditions passed, management reverted to prior practices and no long-term strategy for coping with high flow variability or increasing scarcity was implemented (Schlüter & Herrfahrdt-Pähle, 2011). Such persistence of prior practice may reflect the kind of institutional fragility and resistance to systemic reform described in studies of university

transformation, where deliberate transformational intent, flatter governance, and a shift from defensive to facilitative leadership are argued to be necessary to reorient mission and practice (Stewart et al., 2022). Absent such organizational change, storage infrastructure can be co-opted to perpetuate existing distributions of power and resource access rather than to deliver equitable, durable adaptation. Storage infrastructure in such a context served chiefly to prolong the viability of an unsustainable regime. For Minoan Crete, this suggests that large cisterns, terrace reservoirs, or rock-cut basins documented in Appendix A should be interpreted within a similar spectrum between reactive buffering and transformative adaptation, rather than as inherently stabilising features. Hydraulic storage also appears centrally in heritage-protection studies, where rising groundwater and changing land use threaten monumental sites. At the Ptolemaic Horus temple at Edfu, hydrological and hydrochemical analyses of groundwater, integrated with remote sensing, spatial autocorrelation, and GIS, are used to characterise deterioration risks and to design protection models. Hazard maps derived from optical and radar data delineate zones where building activity should be restricted, and low-cost, high-resolution satellite imagery allows repeated observation of waterlogging, urban expansion, and associated landscape changes over time (A.Megahed, 2020). Although the focus at Edfu is on subsurface moisture rather than deliberately engineered cisterns, the methodological framework is directly applicable to Cretan contexts: DEM-based watershed analysis, classification of land use, and hot-spot statistics (Appendix A) can be combined to identify sectors where cisterns would experience chronic recharge, seasonal desiccation, or accelerated structural decay under shifting hydrological regimes. Mountain micro-watersheds in the Himalayas illustrate how loss of small-scale storage and

declining spring discharge cascade into reduced irrigation capacity and crop yields. In the Upper Kosi basin, long-term deforestation reduced groundwater recharge, contributing to the drying of approximately 33.75 % of natural springs and the seasonalisation of a further 10.8 %, with about 736 km of stream length disappearing and 61 % of villages experiencing significant water scarcity, especially in the dry months. Consequent reductions in biomass supply (up to 58 %), irrigated area (up to 21 % loss), and agricultural productivity (about 25 % overall decline) demonstrate that when aquifer-fed sources falter, any cistern or tank system reliant on them will face diminishing inputs and rising competition between domestic and agricultural uses (Tiwari & Joshi, 2015). These observations inform the interpretation of Cretan storage installations in Appendix A: their effectiveness as buffers would have depended critically on the resilience of karstic spring systems feeding them, which in turn were vulnerable to land-cover change and broader climatic shifts (Tiwari & Joshi, 2015). Contemporary work on sustainable food systems underscores that infrastructure for storage, whether of water or crops, operates within a larger governance field. Government policies on land use, subsidies, disaster preparedness, and agricultural insurance shape the extent to which storage mitigates shocks or entrenches unsustainable practices. Strategic reserves and improved storage facilities can enhance stability, but without attention to equity, gendered access, and smallholder constraints, such investments may reproduce existing vulnerabilities (Agarwala et al., 2022). For Minoan Crete, cisterns and storage pits mapped around palatial centres and secondary sites (Appendix A) can thus be read as physical manifestations of redistributive and control mechanisms in which decisions over siting, capacity, and integration into terrace and field systems reflected political priorities as much as hydrological opportunity. Finally, studies of environmental health and AI-enabled monitoring emphasise that contemporary decision-support systems for floods, pollution, and infrastructure risk rely on dense spatial datasets, predictive models, and continuous feedback between sensors, planners, and communities (Adefemi et al., 2023). While no such technologies existed in the Bronze Age, the logic of integrating multiple data streams to assess hazard exposure and to plan protective interventions is transferable. In practical terms, this thesis constructs a geospatial database of Cretan cisterns, reservoirs, and associated catchments (Appendix A) modelled on digital-archaeology and environmental-health workflows, enabling the analysis of storage systems as nodes within a complex socio-hydrological network rather than isolated architectural features (Adefemi et al., 2023; Oselini et al., 2023).

5.2.2 Irrigation networks and agricultural water use

Irrigation networks in semi-arid agrarian systems cannot be analysed in isolation from feedbacks between water use, soil degradation, institutional control, and livelihood vulnerability. Work on the Amudarya and Syrdarya basins in Central Asia shows how complete dependence of agriculture on surface-water irrigation, combined with massive twentieth-century expansion from 0.42 to over 4 million ha of irrigated land, generated soil salinization, waterlogging, and near-collapse of downstream aquatic ecosystems, culminating in the disappearance of the Aral Sea and loss of fisheries and other ecosystem services. Poor-quality and deteriorating infrastructure, frequent lack of drainage, and low standards of water management meant that roughly 40 % of water diverted for irrigation disappeared into surface drains without contributing to plant growth, while 95 % of irrigated land in parts of Karakalpakstan became salinized to some degree by 1999. These dynamics illustrate how extended canal networks and field-distribution systems, if operated under production-maximising but ecologically blind regimes, can

simultaneously sustain short-term agricultural output and erode the very resource base on which irrigation depends. Institutional arrangements around irrigation water prove at least as consequential as hydraulic hardware. In Uzbekistan, state order systems for cotton and wheat locked producers into meeting centrally imposed quotas. District khokims, whose careers depended on quota fulfilment, intervened directly in allocation decisions, while successive "reforms" of water-management organisations largely amounted to renaming without substantive change in mandates or accountability. Presidential decrees, rather than deliberated legislation, drove water-sector restructuring, and external donor agendas, farm break-up, and intra-ministerial power struggles shaped institutional change more than recognition of ecological limits. Under these conditions, irrigation networks became instruments of top-down control, and technical measures such as drainage construction and soil leaching were deployed to preserve export-oriented productivity, even though leaching itself consumed large volumes of water and intensified salinization feedbacks. Responses to hydrological shocks further expose the limitations of such irrigation regimes. Droughts and floods in the basin triggered emergency measures such as bans on rice planting, temporary reductions in regional water limits, and ad hoc transboundary councils for flood mitigation. Once extreme events passed, however, management reverted to previous practices, and proposed long-term strategies such as diversification to less water-intensive crops, reuse of drainage water, or broader diversification of water use were not implemented. Informal institutions, including patronage and corruption, constrained enforcement and fostered continued overuse, leaving irrigated agriculture highly vulnerable to any increase in drought frequency or reduction in river flow (Schlüter & Herrfahrdt-Pähle, 2011). For comparative purposes, these patterns highlight the distinction between irrigation networks that function as adaptive infrastructures capable of buffering variability, and networks that entrench path-dependent exposure by amplifying resource depletion. At the field scale, soil-moisture and nutrient regimes mediate how irrigation translates into yield. Experiments in dry-steppe environments link crop productivity primarily to soil-water reserves, with nitrogen and phosphorus regimes also playing important roles. Comparative evaluations of cultivation technologies and fertiliser backgrounds demonstrate strong correlations among available water, nutrient contents, and yields, yet in many variants, nitrate nitrogen remains low and phosphorus only moderate despite differing tillage and input regimes. Zero-fertiliser backgrounds sometimes show advantages in productive moisture, but do not consistently outperform more intensive treatments in overall yield, and cereal harvests range widely between 9.3 and 24 centners/ha depending on crop, rotation, and fertiliser application. Nitrogen–phosphorus additions can produce gains of roughly 3.7 centners/ha in wheat following legumes or in continuous wheat relative to zero-input baselines, yet no single technology yields clear, universal superiority (Tautenov et al., 2022). These findings underscore that irrigation networks interact with fertiliser strategies and rotation structures; over-reliance on water without attention to nutrient balance risks diminishing returns, while fertiliser inputs without adequate soil moisture similarly limit productive potential. Climate change and land degradation introduce an additional layer of stress on irrigated systems. In Australia, unsustainable production practices have degraded millions of hectares through salinity, acidification, and erosion, threatening future food supply. Agriculture accounts for about 16 % of national greenhouse-gas emissions, and climate projections point to more frequent heatwaves and shifts in rainfall patterns. Modelling suggests an overall decline in food production of 15–30 % over four decades despite any potential fertilisation effects of elevated atmospheric CO2, reinforcing arguments that farming must adjust to minimise

further land degradation and emissions while maintaining nutritional adequacy (Selvey & Carey, 2013). Integrated analyses of sustainable food systems extend this reasoning by advocating agroecological practices, climate-resilient crops, and water-efficient irrigation as ways to reduce environmental impacts while preserving or enhancing yields. Regenerative agriculture is highlighted for improving soil health, biodiversity, and water conservation; smart irrigation and precision agriculture can lower water demand and associated pressure on rivers and aquifers; and circular-economy approaches such as recycling organic waste for compost are promoted as means to close nutrient and water loops within food systems (Agarwala et al., 2022). Taken together, these contemporary cases

provide a comparative framework for evaluating Minoan irrigation and agricultural water use. They show that canal and field-distribution systems are embedded in broader political economies, that short-term gains from expanded irrigation can mask accumulating salinization and ecosystem loss, and that institutional path dependence often favours technical fixes over transformative change. They also demonstrate that climate variability and land degradation reshape the operating space of irrigation networks, and that sustainable configurations require alignment between hydraulic infrastructure, agronomic practices, and governance arrangements oriented toward long-term socio-ecological resilience rather than narrowly defined production targets (Schlüter & Herrfahrdt-Pähle, 2011; Tautenov et al., 2022; Selvey & Carey, 2013; Agarwala et al., 2022).

5.3 Hydrological Infrastructure and Water Governance: Comparative Archaeological Evidence

Hydraulic arrangements in this project are analysed within the broader socio-hydrological framework already established for palatial Crete, where environmental settings are treated as co-produced by hydrology, land use, and institutions rather than as passive backdrops. This analytical stance derives from multi-scalar work on Roman centuriated landscapes and Central Asian irrigated basins, which collectively demonstrate that river systems, drainage structures, and wetland interventions cannot be understood apart from the governance regimes that organise territorial control and resource allocation. Direct archaeological sequences for Bronze Age Crete, including hydraulic installations and settlement configurations, are therefore defined as the primary empirical basis. Modern hydrological and governance case studies are introduced only after those sequences and strictly as heuristic instruments for thinking about water infrastructure and its political embedding, not as substitutes for ancient data. Methodological integration of palaeoclimatic and hydrological proxies into the analysis of water infrastructure is guided by explicit scaling procedures. In the Pontine marshes, supra-regional climatic and political conditions are related to regional field survey and palaeoenvironmental data, while microstudies based on geophysics, coring, excavation, and ecological work clarify how centuriation reshaped drainage and settlement organisation. A comparable strategy for Bronze Age Crete links regionally dated climatic episodes with catchment-scale hydrology, localised geomorphology, and site-specific cultural sequences, ensuring that any interpretation of hydraulic installations is chronologically precise and situated within multi-scalar processes. Environmental settings are thereby reconstructed as outcomes of interactions between hydrological engineering, land-use patterns, and institutional arrangements rather than unidirectional responses to climate forcing. Evidence from large irrigated basins in Central Asia offers a detailed comparative frame for understanding how water

infrastructure and governance co-constitute vulnerability and resilience. Analyses show that river dependence, canal networks, and reservoir systems

were expanded to support cotton monoculture, leading to severe salinisation, ecosystem degradation, and increasing man-made water shortage. Yet institutional reforms in the water sector were driven primarily by donor agendas, internal power struggles, and the need to manage thousands of new farm entities, not by recognition of ecological limits. Droughts and floods triggered emergency measures such as bans on particular crops, temporary reductions in water limits, and ad hoc transboundary councils; once crises passed, management reverted to prior practices, leaving the underlying cycles of overuse and degradation intact. Informal institutions including patronage and corruption further constrained implementation, maintaining high vulnerability to combined fast shocks and slow ecological drivers. These dynamics underscore that hydrological infrastructure alone cannot secure resilience; outcomes depend on how governance regimes regulate access, distribution, and maintenance of water systems. This comparative material is used in the dissertation to shape questions about Bronze Age Cretan water governance rather than to impose specific models. For instance, Central Asian basin studies justify asking whether palatial hydraulic installations were accompanied by basin-wide allocation rules and mechanisms of territorial control, and whether short-term responses to hydrological stress were embedded in longer-term strategies or confined to reactive interventions. The same work highlights the analytical importance of informal institutions and power relations in structuring access to irrigation and drinking water, prompting attention to archaeological indicators of differential storage, local autonomy, and infrastructural investment within and beyond palatial centres. In all cases, the comparative insights remain heuristic: they guide variable selection and interpretive lenses but are always subordinated to the stratified Cretan archaeological record. Public-health and epidemic studies further extend the analysis of water infrastructure into the domain of health governance. Research on Ebola virus disease and bovine spongiform encephalopathy conceptualises epidemics as phenomena whose entry points traverse local food systems, environmental health, and institutional capacity, and argues that governance is the appropriate rubric for organising interactions between water supply, sanitation, and disease ecology. Vulnerability assessments emphasise spatial and temporal scale, bio-complexity, and multi-actor interactions, with governance conceived as encompassing state and non-state institutions, rules of decision-making, and scale matching. In this thesis, such findings inform coding schemes that relate archaeological evidence for hydraulic installations and water-storage facilities to potential public-health stressors, constructing qualitative envelopes of probable nutritional and epidemiological risk associated with water access and quality. Risk matrices combine palaeoclimatic and hydrological indicators with settlement density, storage capacity, and connectivity metrics, producing modelled stress envelopes that explicitly acknowledge uncertainty. Contemporary environmental-health and artificial-intelligence-enabled monitoring architectures supply additional analogues for how information about water systems and hazards can be integrated into governance decision-making. Studies document the use of dense sensor networks, predictive modelling,

and data-driven governance to manage air and water quality, disaster vulnerability, and critical infrastructure, while insisting that these technical innovations remain conditioned by structural issues of bias, equity, and regulatory capacity. For this dissertation, such cases validate the construction of multi-source analytical

frameworks in which hydrological proxies, archaeological indicators, and reconstructed governance arrangements are jointly evaluated for their implications for community resilience. They also reinforce the need to document interpretive uncertainty and possible biases arising from incomplete or uneven ancient data, mirroring debates over algorithmic transparency and data quality in modern systems. Across all these strands, classical environmental determinism is explicitly rejected. Hydrological infrastructure and water governance are not treated as channels through which autonomous environmental forces impose fixed outcomes on societies. Instead, environmental change, hydraulic engineering, institutional arrangements, and social differentiation are analysed as interacting components of socio-ecological systems. In the precise conceptual sense used throughout the dissertation, "environmental determinism" denotes explanatory models that assign primary, overriding, and near-sufficient causality to environmental variables such as climate or hydrology, treating governance, technology, institutions, and culture as secondary or derivative. By contrast, the thesis adopts a modern socio-ecological interpretation in which water systems are both shaped by and shape political economy, health vulnerability, and adaptive capacity, and in which resilience or collapse emerges from the configuration of these interacting dimensions rather than from hydrological conditions alone.

6 Political Ecology and Resource Governance

6.1 Resource Control and Hydro-hegemony

6.1.1 Water governance structures

Governance of water in heavily managed river basins illustrates how authority, incentives, and informal power relations configure access to and control over critical hydrological resources. In the Amudarya basin, all agriculture in the semi-arid Turan lowlands depends on surface-water irrigation, with cultivated area increasing from 0.42 million ha in 1913 to over 4 million ha by 1990 and remaining around 4.2 million ha thereafter. Low management standards, deteriorating infrastructure, and missing drainage produced extensive soil salinization, waterlogging, and severe degradation of downstream ecosystems, culminating in the disappearance of the Aral Sea and loss of fisheries, pasture, and protection from salt and dust storms. An authoritarian post-Soviet regime with a strong executive maintained heavy dependence on irrigated agriculture, particularly export-oriented cotton, for foreign exchange, revenue, and rural employment, while a significant proportion of the population remained below the poverty line and health conditions deteriorated in environmentally degraded areas with limited access to safe drinking water. These conditions define a hydro-hegemonic setting in which central political and economic interests dominate allocation decisions across the basin. At subnational level, district governors (khokims) are held personally responsible for meeting cotton and wheat quotas in their districts and thus have a direct stake in water management. They intervene in allocation, using their influence to secure flows necessary to achieve production targets, which adds uncertainty and reduces transparency in the water management system. Institutional reforms in water allocation planning, formally intended to improve efficiency, largely resulted in renaming organisations without substantive change, reflecting weak ownership of reform goals within the broader governance structure. Since the early 2000s, water-sector reforms have been implemented via presidential decrees rather than parliamentary legislation, reinforcing a centralised, top-down mode of rule. Similar reliance on decrees characterises agricultural reforms, entrenching a governance pattern in which executive fiat rather than participatory deliberation defines water and land policy. Such arrangements exemplify hydro-hegemonic governance in which vertical accountability to central authorities outweighs horizontal accountability to water users or local communities. Institutional responses to environmental degradation and hydrological shocks further characterise the prevailing governance regime. Growing deterioration of land and water resources and loss of ecosystem services were not primary drivers of institutional change. Instead, external events such as donor funding, dismantling of large farms into many small entities, and internal ministerial power struggles shaped reforms. Resource problems were addressed mainly through technical measures aimed at maintaining short-term productivity rather than breaking cycles of overuse and degradation. Only in the case of extreme events, such as droughts and floods, did ecological dynamics trigger direct institutional responses, typically ad hoc emergency measures like bans on rice planting, temporary reductions in regional water limits, or creation of transboundary emergency councils for flood mitigation. Once crises passed, management reverted to previous practices, and no long-term strategy for coping with high flow variability and increasing scarcity, such as reuse of drainage water, diversification to less water-intensive crops, or broader diversification of water use, was implemented. This

pattern illustrates crisis management without structural transformation, a configuration directly relevant to assessing Late Bronze Age water governance in Section 3.1.2. Informal institutions intensify these governance deficits. Patronage and corruption severely constrain implementation of formal measures; Uzbekistan is ranked among the ten most corrupt countries in the world according to the Corruption Perception Index. These feedbacks

between vested interests and centralised governance impede learning and adaptive change, maintaining vulnerability to future disturbances, particularly when fast shocks such as droughts or floods coincide with slow drivers like ecosystem-service loss. Analyses of potential transformation in this basin argue that moving towards less water-intensive production would require abandoning low-productivity soils, shifting to other crops, and diversifying economic sectors, but current power constellations and rent structures make such change unlikely. Key ingredients for successful transformations identified elsewhere, including acceptance of the need for change, trust and leadership, removal of perverse incentives, political capacity for structural reform, and strategic investment in social and human capital, are largely absent. Stakeholder involvement, social entrepreneurship, and institutional support that might promote renegotiation of water-use regimes are also missing. Although bottom-up processes such as emerging trust in Water User Associations and increasing farmer resistance to the state order system show some potential, realisation of transformative change would require self-organisation around these nuclei despite resistance from higher governance levels (Schlüter & Herrfahrdt-Pähle, 2011). Comparative perspectives from food-security governance reinforce the centrality of state structures in shaping water-related vulnerabilities. Governments are portrayed as pivotal actors whose policies on agricultural subsidies, trade, environmental regulation, and social protection collectively influence resource depletion, greenhouse-gas emissions, and biodiversity loss, as well as income and gender inequalities that condition access to food and water. Sectoral silos, implementation gaps, and limited institutional capacity often hinder integrated responses, while climate variability, resource scarcity, and geopolitical conflict complicate sustainable land and water management. In regions facing water scarcity and political instability, conflicts over land use between agriculture, urbanisation, and industrialisation further challenge sustainable allocation (Agarwala et al., 2022). Together, these studies show how water governance structures, from centralised decree-based regimes to fragmented policy fields, can lock socio-ecological systems into maladaptive pathways in the face of climatic and environmental stress (Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022; Adefemi et al., 2023). (See Figure A.8 for the socio-ecological systems layered structure and Figure A.9 for inter-site connectivity discussed in this chapter.)

6.1.2 Competition for water and agricultural land

Struggles over water and cultivable land in intensively managed basins emerge where irrigated agriculture, ecological limits, and hierarchical governance intersect. In the Amudarya system, all agriculture in the semi-arid Turan lowlands depends on surface-water irrigation from the Amudarya and Syrdarya, with irrigated area in Uzbekistan expanding from 0.42 million ha in 1913 to over 4 million ha by 1990 and remaining around 4.2 million ha thereafter. Low standards of water management, deteriorating infrastructure, and frequent lack of drainage led to soil salinization, waterlogging, and severe degradation of downstream semi-natural ecosystems, including the disappearance of the Aral Sea and loss of fisheries, pasture, and dust-storm protection. These processes effectively

converted large tracts of land and water from multi-functional commons into heavily controlled, degraded production space for cotton and wheat, constraining alternative land uses and livelihoods and heightening competition over what remained of productive soils and clean water. Allocation conflicts are shaped by state-led production targets. An authoritarian post-Soviet regime maintained heavy dependence on irrigated agriculture, particularly export-oriented cotton, for foreign exchange, revenue, and rural employment. District governors (khokims) are personally responsible for meeting cotton and wheat quotas in their districts and thus intervene directly in allocation decisions to secure sufficient water, increasing uncertainty and reducing transparency in the management system. Land and water reforms since independence largely preserved the state order system; institutional "reforms" in allocation planning often amounted to renaming organisations, while decrees rather than parliamentary laws drove sectoral change. Under these conditions, irrigation networks and associated lands function as instruments of centralised control, with powerful actors able to secure flows needed to meet quotas, while poorer users face the consequences of salinity, waterlogging, and declining soil productivity, which are cited as key drivers of rural poverty. Episodes of hydrological stress expose and intensify these underlying competitions. Droughts and floods trigger emergency bans on specific crops such as rice, temporary reductions in regional water limits, and ad hoc transboundary emergency councils for flood mitigation. Once extreme conditions pass, however, management reverts to prior practices, and proposed strategies such as diversification to less water-intensive crops, reuse of drainage water, or broader diversification of water use are not implemented. Informal institutions, including patronage and corruption, further constrain implementation, entrenching a cycle in which declining agricultural productivity provokes technical countermeasures that in turn accelerate environmental degradation and lock the system into an undesirable regime.

Analyses of this basin emphasise that strong feedbacks, path dependence, and rents from irrigated agriculture generate a form of hydro-hegemony, understood here in the sense developed for trans-boundary river basins as control over a shared water resource achieved through an asymmetric combination of resource capture, integration, and containment strategies rather than through overt conflict alone (Zeitoun & Warner, 2006), that resists transformation toward less water-intensive land use, even as ecological and social vulnerabilities rise (Schlüter & Herrfahrdt-Pähle, 2011). Comparable tensions appear at the food-system scale where land-use conflicts and resource scarcity intersect. Global assessments of food security identify climate variability, resource depletion, and biodiversity loss as key pressures that reduce yields and alter growing conditions, while arable land and water become increasingly scarce. As competition for these resources intensifies, the ability to meet nutritional needs is jeopardised, especially for vulnerable populations. Governments deploy agricultural subsidies, trade agreements, and environmental regulations that structure which crops are profitable, where they are grown, and how land is allocated between agriculture, urbanisation, and industrialisation. Conflicts over land use, particularly where expanding cities and industries encroach on fertile land, are recognised as major obstacles to sustainable land management and complicate efforts to reconcile food security with environmental protection. Social and economic disparities, including income and gender inequalities, shape who gains access to high-quality land and reliable water, and who bears the burden of degraded environments and food insecurity (Agarwala et al., 2022). Environmental degradation feeds back into these competitions by reducing the effective supply of productive land and usable water. In Australia, unsustainable food production practices have contributed to land

degradation, with an estimated 5.7 million ha at risk of or affected by salinity, along with increasing soil acidification and erosion. Agriculture accounts for about 16 % of national greenhouse-gas emissions, and climate change is projected to produce more frequent heatwaves and altered rainfall patterns, with an estimated overall decline in food production of 15–30 % over the next 40 years. Protecting future food supply requires adjusting farming practices to minimise further land degradation and emissions. Dietary and production guidance that encourages shifts away from high-impact commodities such as red meat, reduces food waste, and promotes more plant-based diets is framed as part of an integrated response to these land and water pressures, explicitly linking consumption patterns, agricultural land use, and environmental impact (Selvey & Carey, 2013). Finally, competition for water and land is embedded within broader governance and infrastructure constraints. Governments attempting to stabilise food systems face erratic droughts and floods, overexploitation of soils and water, and geopolitical conflicts that disrupt production and distribution. Market-access disparities, dependence on long supply chains, and technological divides disadvantage small-scale producers and limit adoption of more sustainable, water-efficient practices. Sectoral policy silos and implementation gaps hinder coherent responses, so that even where policy frameworks acknowledge competing demands on land and water, they struggle to resolve them in practice, leaving many regions caught between intensifying agricultural production and escalating ecological and social costs (Agarwala et al., 2022; Schlüter & Herrfahrdt-Pähle, 2011; Selvey & Carey, 2013; Adefemi et al., 2023).

6.2 Ecological and Geopolitical Pressures

6.2.1 Maritime trade vulnerabilities

Vulnerability of maritime trade in Bronze Age Crete can be approached through contemporary cases where food systems, resource bases, and governance depend on long and complex supply chains. Global assessments of food security describe how reliance on extended distribution networks exposes societies to disruptions from climate variability, pandemics, and geopolitical conflict, with consequences for both availability and access to food. Market-access disparities and unfavourable trade agreements disadvantage small-scale producers, while dependency on global supply chains, as starkly illustrated during the COVID–19 pandemic, magnifies the impact of shocks on local food security. These dynamics provide an analogue for Late Bronze Age maritime circuits in which island polities such as Crete likely depended on external grain, metals, and prestige goods transported along vulnerable sea routes. Evidence indicates that climate change and resource scarcity function as overarching pressures that reshape trade-dependent systems rather than acting as isolated triggers. Analyses of global food systems emphasise that erratic droughts and floods disrupt agricultural production, while depletion of arable land, rising water scarcity, and biodiversity loss narrow the resource base available for export and import alike (Agarwala et al., 2022). As competition for land and water intensifies, the ability to sustain surplus production for trade diminishes, especially where governance and infrastructure are weak. In modern regions facing water scarcity and political instability, conflicts over land use between agriculture, urbanisation, and industrialisation complicate sustainable management and can

constrain both domestic provisioning and export capacity, a configuration that parallels potential Late Bronze Age tensions between coastal port complexes, inland agrarian zones, and emerging rival powers. Recent work on climate, conflict, and security provides additional framing for maritime vulnerability. Global heating is characterised as a risk multiplier that disturbs interactions between natural and social systems, including critical infrastructures and supply networks. Systemic crises, from armed conflict to economic downturns and pandemics, combine with reactive, short-term political responses to undermine preventive problem-avoidance and to push societies into crisis-management modes. Within this context, energy-security and climate–conflict–migration nexuses are analysed as cascades in which disruption of resource flows triggers further political and social instabilities (Scheffran, 2023). Although not specific to maritime transport, this framework is directly applicable to sea-based trade: interruptions of shipping due to conflict, piracy, or naval blockades can propagate rapidly into food insecurity, fiscal strain, and social unrest in import-dependent regions. Governance structures play a decisive role in determining whether trade-dependent systems absorb or amplify such perturbations. Studies of contemporary food-security governance show that policies on subsidies, trade, and environmental regulation shape not only domestic production but also a country's position within global supply chains and its exposure to international price volatility (Agarwala et al., 2022). Efforts to stabilise food systems through strategic reserves, social safety nets, and climate-smart agriculture are frequently undermined by sectoral silos, implementation gaps, and limited institutional capacity, especially where conflict and political instability are present. In maritime terms, weak or fragmented governance can translate into inadequate port infrastructure, insufficient regulation of shipping safety, and limited capacity to reroute flows when primary corridors are disrupted. Public-health emergencies illustrate a further dimension of maritime trade vulnerability. Research on Ebola virus disease argues that vulnerable, food-insecure populations with inadequate health-care infrastructure signal potential crisis during epidemics and that governance mechanisms must link food systems, environmental health, and public-health response across multiple scales. Mobility of coastal fishers, cross-border land travel, and global airline networks are identified as pathways for disease spread that require robust regional monitoring, travel protocols, and risk mapping to manage effectively (Khan & Sesay, 2015). By implication, maritime trade routes function both as lifelines for food and resource flows and as vectors for pathogens. Where governance fails to integrate food security, transport regulation, and epidemic preparedness, seaborne exchanges can exacerbate crises rather than mitigate them. Environmental health and public-safety studies that incorporate artificial intelligence underline how complex, interdependent infrastructures shape vulnerability. Critical infrastructures such as bridges, roads, and smart urban systems are increasingly monitored using sensors and predictive analytics, while AI-enabled tools support disaster vulnerability assessment and emergency response (Adefemi et al., 2023). At the same time, growing recognition of data-quality, privacy, and governance challenges highlights that technical systems cannot compensate for weak institutional frameworks. For maritime networks, this contemporary configuration suggests that resilience depends not only on physical port and fleet capacities but also on integrated monitoring, early-warning, and decision-support architectures, features that are analytically useful when reconstructing the susceptibility of Bronze Age sea-lanes to cascading socio-ecological and geopolitical shocks. Taken together, these strands of evidence support a view in which maritime trade is embedded within broader socio-ecological systems shaped by climate stress, resource scarcity, governance arrangements, and public-health risks. Rather than

treating seaborne exchange as a neutral conduit, these comparative cases show that vulnerabilities emerge where external shocks intersect with internally fragile institutions and uneven access to land and water, a perspective that informs the subsequent analysis of Cretan coastal networks and harbours based on 2025 field observations in Appendix A (Agarwala et al., 2022; Khan & Sesay, 2015; Scheffran, 2023; Adefemi et al., 2023).

6.2.2 Impact of external threats and invasions

External threats in complex socio-ecological systems rarely operate as purely exogenous shocks; their impacts are conditioned by pre-existing governance structures, resource dependencies, and infrastructural vulnerabilities. Analyses of large irrigated basins in Central Asia show that even without formal invasion, externally induced pressures such as donor-driven reform agendas and global market demands for cotton reshaped institutional arrangements around land and water in ways that reinforced existing power hierarchies and environmental degradation. Water-sector "reforms" were introduced by presidential decree, often amounting to renaming organisations rather than altering mandate or

accountability, while state order systems for cotton and wheat persisted because they underpinned political control and rent extraction (Schlüter & Herrfahrdt-Pähle, 2011). In such a setting, any future geopolitical coercion or trade embargo targeting export crops would intersect with already degraded soils, salinized fields, and a population locked into irrigation-dependent livelihoods, greatly magnifying the disruptive potential of ostensibly external actions (Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022). Hydropolitical tensions in this basin further illustrate how ecological interventions can become security issues for downstream actors. Construction of polders and wetland restoration polders in bays of the former Aral Sea partially mitigated ecological deterioration but did not resolve basinwide allocation conflicts or overuse, leaving downstream communities exposed to increasing drought frequency and ecosystem-service loss (Schlüter & Herrfahrdt-Pähle, 2011). Contemporary security analysis notes that large dam projects in countries such as Turkey, Ethiopia, and Laos have raised concerns in downstream states, as water control infrastructure becomes entangled with questions of territorial sovereignty and resource rights (Scheffran, 2023). These examples underscore that manipulation of flow regimes functions as a de facto external pressure on dependent regions, even in the absence of overt hostilities, and that such pressures are particularly destabilising where governance remains centralised and unresponsive. Climate change operates as a higher-order driver that modulates the intensity of external threats by destabilising critical infrastructures and supply chains. Global heating is characterised as a risk multiplier that disturbs the balance between natural and social systems, affecting critical infrastructures, the water–energy–food nexus, and global markets. Production losses and price spikes induced by climatic extremes can propagate through trade networks, undermining human security and political stability far from the initial shock (Scheffran, 2023; Agarwala et al., 2022). Security-oriented assessments argue that military and geopolitical institutions increasingly treat climate change as a threat multiplier that complicates operations, resource access, and territorial claims, with the potential to trigger downward spirals of securitisation and militarisation around resource corridors. In such contexts, embargoes, naval blockades, or disruptions to maritime trade could act as external shocks that reverberate through already strained food systems and water infrastructures, a configuration comparably relevant for Late Bronze Age maritime polities. Conflict-

focused research stresses that the relationship between climate risk and violent confrontation is contingent on political and socio-economic context. Many empirical studies find statistically significant links between climate risk and conflict, but others report only ambivalent or unproven associations; outcomes depend on factors such as agricultural dependence, exposure to weather extremes, and levels of external aid. Particularly critical are fragile regions with weak governance, fragmented societies, and inadequate management capacities, where environmental change can erode problem-solving ability, degrade infrastructures including health systems, and precipitate spirals of poverty, hunger, corruption, crime, violence, and forced displacement (Scheffran, 2023). In these settings, cross-border movements of climate- and conflict-displaced populations may be perceived as external threats by neighbouring states, even though they originate in shared climatic drivers. Food-system analyses reinforce that geopolitical conflict and political instability function as major external stressors on agrarian economies and trade. Regions affected by geopolitical conflicts experience disruptions in food production and distribution, while dependency on global supply chains heightens vulnerability to shocks such as the COVID-19 pandemic, which interrupted labour availability, logistics, and market access. Land-use conflicts between agriculture, urbanisation, and industrialisation intensify competition for fertile land and water, particularly in water-scarce regions like the Middle East and North Africa, where political instability and conflict amplify food-import dependence and insecurity (Agarwala et al., 2022). Under such circumstances, external blockades, sanctions, or regional warfare can rapidly translate into domestic shortages and social unrest, demonstrating how invasions or coercive actions intersect with structural food-system weaknesses. Public-safety and emergency-management studies add a technological dimension to this picture. Integration of artificial intelligence into disaster response, critical-infrastructure monitoring, smart urban systems, and predictive policing aims to enhance resilience through early warning, optimised resource allocation, and rapid intervention (Adefemi et al., 2023). However, challenges of data privacy, algorithmic bias, and uneven institutional capacity mean that such tools may be least available in precisely those fragile settings most exposed to climate-linked security threats. Where surveillance and decision-support architectures are incomplete, societies remain highly susceptible to cascading failures initiated by external shocks, whether in the form of cyberattacks on infrastructure, targeted strikes, or sudden disruptions of maritime and overland trade routes (Adefemi et al., 2023; Scheffran, 2023). Together, these contemporary cases demonstrate that "external threats," including

invasions, blockades, or hydropolitical coercion, cannot be analytically separated from internal socio-ecological vulnerabilities. Their impact is conditioned by patterns of resource dependence, institutional rigidity, corruption, and prior environmental degradation, and is amplified by climate-driven stresses on water and food systems (Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022; Scheffran, 2023; Adefemi et al., 2023).

7 Symbolism, Ritual and Cultural Ecology

7.1 Water in Minoan Religion and Symbolism

7.1.1 Sacred springs and ritual use of water

Ritualised engagement with springs presupposes socially mediated control over water, and modern comparative cases from semi-arid irrigation regimes clarify how such control is embedded in political economies and institutional logics. In the Amudarya basin, irrigation from a single major river underpins almost all agriculture; expansion from 0.42 to more than 4 million ha of irrigated land, combined with low management standards and missing drainage, led to salinization, waterlogging, and collapse of downstream aquatic ecosystems, including the disappearance of the Aral Sea and its fisheries. State order systems for cotton and wheat, backed by presidential decrees and enforced by district governors whose careers depended on quota fulfilment, produced a highly centralised water governance structure in which allocation served political and fiscal priorities rather than local needs. Under such conditions, any sites where clean or reliable freshwater emerges, such as springs or restored wetlands, acquire heightened strategic and symbolic significance because they stand out against a wider landscape of man-made water shortage and ecological degradation. Emergency responses to droughts and floods in this basin further illuminate how episodic hydrological crises intersect with institutional authority. Severe drought in 2000–2001 and later dry years prompted ad hoc bans on specific crops, temporary reductions in regional water limits, and the creation of emergency councils for transboundary flood mitigation. These measures were reactive, short-lived, and did not alter path-dependent overuse of land and water; once crises passed, management reverted to former practices and no long-term strategy for variability or scarcity was implemented. Informal institutions such as patronage and corruption constrained enforcement, leaving the social–ecological system vulnerable to future disturbances, especially when fast shocks combined with slow drivers like loss of ecosystem services (Schlüter & HerrfahrdtPähle, 2011). In such a governance setting, any ritualised protection or sacralisation of particular water sources would be occurring within, and potentially reinforcing, a broader hydro-hegemonic order that privileges central actors over local communities. Hydrological studies in Himalayan micro-watersheds provide a second comparative axis for thinking about how springs function simultaneously as material and cultural foci. In the Upper Kosi basin, long-term deforestation and associated environmental change reduced groundwater recharge, producing decreased streamflow, declining spring discharge, and altered run-off and channel capacity. Over roughly three decades, about 33.75 % of natural springs dried completely, 10.8 % became seasonal, and 736 km of stream length vanished, leaving 61 % of villages with significant water scarcity in dry months. These hydrological changes cascaded into reduced biomass supply to agro-ecosystems (up to 58 % in some micro-watersheds), loss of irrigated area (up to 21 %), and an overall decline in agricultural productivity of around 25 %, with disproportionate burdens falling on women through increased labour for water and fuel collection and heightened exposure to water-borne and nutritional health risks (Tiwari & Joshi, 2015). Springs in this context are not merely technical assets: they are focal points of everyday practice, gendered labour, and community vulnerability, and thus plausible loci for ritual intensification when scarcity grows. Karst-basin analysis in the Mirador–Calakmul region illustrates the geomorphological logic that frequently underlies such focality. There, thousands of dolines,

swallow holes, and seasonal swamps funnel recharge into subsurface conduits that resurface as exsurgence springs along basin margins. Groundwater flows bidirectionally from central anticlines, yet only specific lines of springs at structural boundaries provide dependable surface access during dry seasons. Heavy rainfall can temporarily activate overflow springs and surface flow, but baseline water security depends on the configuration of conduits and discharge points. This form of fluviokarst organisation implies that communities may cluster social and ritual institutions around structurally constrained spring lines, where access can be monitored, negotiated, or symbolically framed, rather than around diffuse and easily privatised wells. Public-health and disaster-governance research on epidemics adds a further dimension to the potential

sacralisation of water sources. Studies of Ebola virus disease and bovine spongiform encephalopathy emphasise that vulnerable, food-insecure populations with inadequate health-care infrastructure signal potential crisis in epidemic settings. Governance mechanisms linking local food systems, environmental health, and public health are described as necessary for effective response, with past interventions in Uganda relying on rigorous isolation, surveillance, and treatment supported by local authorities and donors. Windows for institutional learning appear after extreme events, yet often close without deeper transformation; the key lesson identified is the importance of augmenting local capacity and strengthening institutional infrastructure (Khan & Sesay, 2015). Where springs constitute primary drinking-water sources, such governance failures would translate directly into heightened health risks, particularly under conditions of water scarcity and pollution. Ritualised restrictions on access, purity rules, or sacral narratives around specific springs can therefore be understood, in comparative perspective, as potential community-level attempts to regulate exposure pathways in the absence of formal water-quality management, even though the sources summarised here do not document such practices explicitly. Finally, AI-enabled environmental-health monitoring demonstrates how modern societies are beginning to re-inscribe meaning and control around water through new technological assemblages. Agencies such as the U.S. Geological Survey use AI to analyse water-quality data from satellites and ground-based sensors, improving detection of pollution sources and informing management strategies. Broader AI deployments in environmental health and public safety include real-time air-quality networks, disaster-vulnerability modelling, and smart infrastructure such as adaptive street lighting. These systems deliver predictive capacity and fine-grained surveillance but raise ethical and legal issues concerning data privacy, algorithmic bias, transparency, and accountability; guidelines stress the need for inclusivity, public engagement, and robust regulatory frameworks to ensure that AI deployments serve all segments of society equitably (Adefemi et al., 2023). In symbolic terms, the transformation of springs, rivers, and aquifers into dense arrays of monitored variables marks a contemporary reconfiguration of how water is "seen" and governed, one that parallels earlier ritual codifications of water access insofar as both embed hydrological processes within broader regimes of authority, trust, and vulnerability (Adefemi et al., 2023; Schlüter & Herrfahrdt-Pähle, 2011; Tiwari & Joshi, 2015; Khan & Sesay, 2015).

7.1.2 Ceremonial architecture and water features

Architectural settings that organise movement, visibility, and access around water are today documented most clearly where hydrological analysis, remote sensing, and cultural-heritage management intersect. Work at the

Ptolemaic Horus temple at Edfu shows how a monumental complex can be materially conditioned by groundwater behaviour and surrounding urbanisation. Hydrological and hydrochemical studies of groundwater are integrated with archaeological and historical research to identify deterioration mechanisms affecting the temple fabric, while spatial autocorrelation, remote sensing indices, and hydrogeological mapping delimit zones of heightened risk around the sanctuary. Although Edfu concerns rising rather than scarce water, this configuration demonstrates how ritual architecture and water form a coupled system in which aquifer dynamics, surface hydrology, and built space must be analysed together. Remote sensing and GIS are central to reconstructing how such complexes sit within evolving urban and environmental settings. Around Edfu, low-cost, high-resolution satellite imagery is used to document temporal changes in land use and rising groundwater levels, and to derive zoned archaeological hazard maps indicating where building activity should be restricted to protect sacred precincts (A.Megahed, 2020). Techniques originally developed to monitor environmental pressures on temples and their immediate surroundings therefore provide a transferable toolkit for examining Cretan ceremonial structures with adjacent basins, channels, or terraces documented in Appendix A, where similar interactions between architectural layout, water presence, and encroaching settlement are at issue. Environmental health and public-safety research framed around artificial intelligence adds a further layer of insight into how water-related installations within built environments are now conceptualised. Contemporary strategies treat air, water, and soil quality, waste management, and disaster risk as interdependent challenges that require multisectoral collaboration among governments, local authorities, industry, academia, and civil society. AI-enabled monitoring of water quality by agencies such as the U.S. Geological Survey relies on satellite imagery and ground-based sensors to detect pollutants and track trends, feeding into management responses that aim to safeguard public health and infrastructure (Adefemi et al., 2023). Conceptually, these systems reframe fountains, reservoirs, and distribution networks as nodal points in risk-governance architectures, an orientation

that is analytically relevant when interpreting Minoan courts or rooms with basins as potential foci of both symbolic practice and hazard exposure, especially under conditions of water insecurity. Research on food systems and sustainability shows how water- and land-related infrastructures, including irrigation and storage, are embedded within broader policy and governance frameworks that influence availability, access, utilisation, and stability. Government interventions through subsidies, land-use regulations, and environmental policies shape where and how water is mobilised for agriculture, while disaster-preparedness and insurance instruments seek to buffer climatic shocks. These arrangements condition which hydraulic installations become critical for collective security and therefore plausible candidates for ceremonial investment. In contexts where climate variability and resource depletion heighten competition over water, architectural focal points that materialise control, redistribution, or ritualised allocation can acquire intensified socio-political significance (Agarwala et al., 2022). Comparative epidemic-governance studies underline how localised water access and institutional arrangements feed into public-health vulnerability. Analyses of Ebola virus disease emphasise that vulnerable, food-insecure populations with inadequate health-care infrastructure signal potential crisis, and that governance mechanisms linking food systems, environmental health, and public health across scales are essential. Windows for institutional learning after extreme events often close without structural change, unless local capacity and infrastructural robustness are deliberately strengthened (Khan & Sesay, 2015). In settlements where communal

points of water collection coincide with high-density social interaction, such as springs or cistern-fed courtyards, ceremonial architecture concentrating gatherings around water could mitigate or exacerbate disease risks depending on how access, cleanliness, and crowding are organised. Finally, mountain case studies documenting environmental change, spring decline, and gendered labour in the Himalayas illustrate how everyday engagement with water sources is structured by social power relations. Long-term reductions in spring discharge and stream length have generated significant water scarcity in 61 % of surveyed villages, reduced irrigated area by up to 21 %, and lowered agricultural productivity by about 25 %, while increasing women's workloads in agriculture and water collection and raising their exposure to water-borne and nutrition-related health risks (Tiwari & Joshi, 2015). Springs here serve as nodal points in both subsistence and social life, and any ritual or architectural elaboration around them must be read against this background of unequal labour and vulnerability. When Cretan ceremonial spaces with water installations are examined in Appendix A, a similar analytical lens that foregrounds how built form mediates differentiated access, labour, and risk will be applied, drawing on these comparative socio-hydrological and publichealth configurations rather than treating water features as merely decorative or symbolically generic (A.Megahed, 2020; Adefemi et al., 2023; Agarwala et al., 2022; Khan & Sesay, 2015).

7.2 Fire and Destruction in Minoan Context

7.2.1 Evidence for conflagrations in palatial sites

Burnt destruction layers at Late Bronze Age palatial centres in the Aegean are among the best documented material traces of crisis, yet they cluster in time and space in ways that undermine any notion of a single synchronous catastrophe. In the Argolid, urban centres including Mycenae, Tiryns, and Midea were destroyed by fire around 1200 BC, while across the Taygetus range the palace at Ayios Vasileios suffered an earlier destruction by fire around 1250 BC. Boeotian evidence from the Copaic Basin shows a similar pattern of conflagration embedded in longer trajectories of political reorganisation: drainage of the basin and construction of the large citadel at Gla in the later 14th century BC coincided with decline at nearby Orchomenos and a destruction horizon at Thebes, followed by rebuilding. These episodes collectively delineate repeated fiery destructions at major administrative sites over at least half a century rather than a single, terminal burning event. Regional comparison clarifies how conflagrations were integrated into cycles of fortification, expansion, and shifting centrality. In the Argolid, the citadel of Midea was constructed around 1250 BC in the core area of Mycenae and Tiryns, raising questions about the autonomy of citadels as centres of distinct states. After 1250 BC Mycenae shows a visible decline in prosperity but an increased emphasis on defensibility, while Tiryns expanded its fortifications to enclose the lower town, only for all major Argolid urban centres to be destroyed by fire around 1200 BC. North of the Isthmus, centres at Gla, Dhimini, and Teichos Dymaion in Achaea share similar fiery destruction horizons at approximately the same date. Fire thus appears as the immediate mechanism of palatial destruction across a wide geography, but its timing and association with earlier phases of investment in defences and hydraulic works point to prolonged

instability and conflict rather than an abrupt, exogenous catastrophe. Cretan palatial trajectories intersect with this pattern without replicating it exactly. The palace at Knossos, already diminished, may have experienced destruction towards the end of the 14th century BC, but administrative activity using Linear B script continued

there until at least 1250 BC. In western Crete, the palatial centre at Chania was destroyed around 1200 BC, broadly contemporary with the Argolid and Achaean burnings. These data anchor Minoan palatial conflagrations within a wider Aegean horizon of late 13th to early 12th century BC destructions, yet also show that fire at individual Cretan sites occurred against differing local chronologies of administrative endurance and decline. Interpretive frameworks that equate burnt palace levels with instantaneous systemic collapse are challenged by post-destruction sequences. At Mycenae, Tiryns, and Midea, rebuilding after the fiery destructions eschewed canonical palatial architecture even though these sites continued to function as important power foci for several decades. Material and ideological disinvestment in central palatial forms unfolded over two to four generations after 1200 BC, during which leaders failed to re-establish stability or arrest depopulation. From this perspective, conflagrations at palatial sites mark dramatic episodes within longer processes of political weakening and social reorganisation rather than the end-point of a stable regime. Assessments of causation for these fires also resist reduction to purely natural agents. Destructions of urban centres in the middle of the 13th century at Thebes, Mycenae, and Tiryns are interpreted as part of a regular cycle of conflict, and are explicitly distinguished from explanations that would treat them as natural disasters such as earthquakes or accidental fires. Within this conflictual landscape, it was specifically the palatial system, with its entourages of craftworkers, scribes, and priestesses, that collapsed. Conflagrations materially expressed this collapse in the loss of Linear B archives, canonical palatial buildings with central hearths, monumental civic and mortuary architecture, and organised military structures. The fiery end of palaces thus appears as a symptom of contests over territorial control and hierarchy in increasingly stressed socio-ecological settings, rather than as a sufficient cause in itself. Finally, diachronic correlations between conflagrations and environmental trends are framed cautiously. Analyses situate increasing aridity and strain on rain-fed agriculture after 1200 BC within a context where palatial land-use regimes may have rewarded specialisation and weak buffering, but explicitly avoid treating climate as an automatic trigger for burning events. Within this thesis, conflagrations at Cretan palatial sites documented in Appendix A are therefore interpreted through this comparative lens: as nodal points in longer sequences of conflict-driven reorganisation, environmental stress, and governance failure, rather than as isolated catastrophic episodes (Molloy, 2022).

7.2.2 Cultural memory and post-destruction narratives

Interpretations of Late Bronze Age fires at Aegean palatial centres already embed a rudimentary form of cultural memory, because scholars distinguish recurrent conflagrations from a single apocalyptic "end." In southern Greece, destructions by fire at Mycenae, Tiryns, Midea, Gla, Dhimini, Teichos Dymaion, and Ayios Vasileios span at least from the mid 13th to the early 12th century BC, and are explicitly framed as part of a regular cycle of conflict rather than as isolated natural disasters. This framing itself functions as a narrative that remembers fire as an index of political struggle, territorial realignment, and contestation over centrality, rather than as an undifferentiated catastrophe. Postdestruction architectural and demographic trajectories constitute a further narrative layer. Following fiery destructions around 1200 BC, rebuilding at Mycenae, Tiryns, and Midea abandoned canonical palatial forms even while these sites remained important power foci for several decades. Over two to four generations, leaders did not manage to restore previous levels of centralised authority or halt

depopulation, and this protracted disinvestment in palatial architecture has been interpreted as a historically specific sequence of decline rather than an instantaneous collapse. Cultural memory, in this sense, inheres in the material record as a stratified story in which fire marks a turning point, followed by selective reuse, reoccupation, and eventual reconfiguration of both built space and political order. Narratives of the wider "collapse" have themselves undergone critical reassessment that mirrors changing understandings of memory and trauma. Earlier monocausal models that treated the destructions around 1200 BC as a single terminal episode have been displaced by accounts that stress diachronic variability, conflict-driven change, and the absence of any stable "classic" Mycenaean condition (Molloy, 2022). This historiographical shift repositions fire from a definitive end to one moment in longer, unpredictable developmental arcs, aligning with broader socio-ecological perspectives that view crisis as embedded in ongoing processes rather than as a discrete, externally imposed rupture. Environmental historians working on Middle and Recent Bronze Age Terramare settlements in the Po Plain similarly

argue against climatic determinism and emphasise bi-directional interactions between climate, environment, and people (Cremaschi et al., 2018). Their reconstruction of crises as outcomes of long-term imbalances between land use, water management, and resource exploitation, rather than of single rapid climate events, provides an explicit comparative narrative frame. Terramare communities are presented as both shapers and victims of their landscapes, with episodes of population relocation and societal disruption emerging from cumulative overuse of natural resources. This narrative logic parallels reinterpretations of Aegean fires as expressions of unsustainable socio-ecological configurations rather than as passive responses to external shocks (Cremaschi et al., 2018; Molloy, 2022). Policy-oriented analyses of food security and sustainability contribute yet another stratum of post-destruction storytelling, this time focused on contemporary systems. Government efforts to secure stable food supplies, mitigate vulnerabilities through social safety nets, and promote nutritional security are acknowledged as only partially successful; unintended consequences such as environmental degradation from intensive farming or market distortions from subsidies repeatedly appear (Agarwala et al., 2022). These accounts effectively construct a narrative in which crises are remembered as products of interacting climatic, economic, and governance pressures, reinforcing the view that destructive episodes open windows for reflection on maladaptive trajectories but do not guarantee transformative change. Research on governance in food-related crises and epidemics makes this point explicit. Work on Ebola virus disease and bovine spongiform encephalopathy stresses that windows of opportunity for institutional learning arise during disasters, yet outcomes depend on whether local capacity and institutional infrastructure are strengthened or whether responses remain reactive and short term. Historical case studies from Uganda describe rigorous isolation, surveillance, and treatment protocols supported by local authorities and donors, with the key lesson framed as the need to augment local capacities rather than to rely on externally imposed technical fixes (Khan & Sesay, 2015). These reflections amount to contemporary post-crisis narratives that, like archaeological interpretations of Aegean fires, recast destructive events as tests of governance and social resilience rather than as isolated abnormalities. Analyses of institutional change in the Amudarya basin similarly narrate environmental degradation and hydrological shocks as catalysts for ad hoc emergency measures that rarely translate into long-term strategic adaptation. Droughts and floods provoke bans on particular crops, temporary reductions in water limits, or emergency councils for transboundary flood mitigation, but once extreme conditions pass, management reverts to previous practices and no durable strategy for variability and scarcity

emerges (Schlüter & Herrfahrdt-Pähle, 2011). This pattern of "crisis without transformation" resonates strongly with the post-palatial sequences in southern Greece, where conflagrations were followed by partial rebuilding and gradual institutional erosion rather than immediate systemic renewal (Molloy, 2022; Schlüter & Herrfahrdt-Pähle, 2011). Finally, work on AI-enabled disaster management and environmental health offers an emergent narrative in which advanced monitoring technologies are framed as tools for building more resilient, ethically informed societies. Recommendations stress adaptive regulatory frameworks, privacy-preserving methods, bias mitigation, and inclusive stakeholder engagement to ensure that AIdriven systems in public safety and environmental health enhance, rather than undermine, community resilience (Adefemi et al., 2023). Such forward-looking stories about learning from past failures and embedding ethical safeguards into new infrastructures echo, in a different technological register, the archaeological and policy-oriented narratives that reinterpret destruction as an impetus for rethinking socio-ecological relations. Read together, these diverse strands underscore that cultural memory of destruction, whether encoded in burned strata, institutional reforms, or ethical guidelines, is less about a singular moment of collapse than about ongoing struggles to narrate, understand, and reconfigure complex systems under stress (Molloy, 2022; Cremaschi et al., 2018; Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022).

8 Public Health and Societal Vulnerabilities

8.1 Nutrition and Food Security

8.1.1 Agricultural yield fluctuations

Yield variability in agrarian systems emerges from interacting climatic, environmental, and governance pressures rather than from a single driver. Governments confronting food-security challenges must adapt food systems to increasingly erratic droughts and floods that disrupt agricultural production, depress crop yields, and generate temporal instability in food availability. Simultaneously, overexploitation of soil and water resources, advancing soil degradation, and intensifying water scarcity constrain the ecological basis for production, so that fluctuations in annual output occur against a background of gradually shrinking productive capacity. These processes frame the Late Bronze Age Aegean comparison by showing how even moderate climatic anomalies, when superimposed on degraded or overused landscapes, can translate into large swings in harvest outcomes and thereby into nutritional stress. Policy regimes significantly modulate how such environmental shocks materialise as yield fluctuations. Agricultural subsidies influence which crops are planted and how intensively land is used, in turn affecting both short-term production levels and long-term soil and water conditions. When subsidies favour input-intensive monocultures or expansion into marginal land, they can raise yields in wet years but amplify inter-annual variability by increasing exposure to drought, floods, and pest outbreaks. Land-use policies that fail to prevent degradation further embed volatility: once salinization, erosion, or nutrient depletion have advanced, even small weather deviations can cause disproportionate yield declines. Evidence from contemporary systems thus supports an analytical stance in which Minoan and Mycenaean harvest fluctuations are read through the institutional logics of land and water allocation, rather than only through palaeoclimatic curves. Access, utilisation, and stability dimensions of food security feed back into productive performance. Income inequality and gender inequality restrict the ability of farmers to invest in soil conservation, improved seed, or water-saving technologies, thereby heightening sensitivity of yields to climatic variability. Social safety nets, income-support schemes, and minimum-wage regulations can buffer households from the immediate consequences of poor harvests, but they also alter labour availability and risk-taking behaviour, which in turn shape cropping strategies and input choices across seasons (Agarwala et al., 2022). In regions where such instruments are weak or absent, a sequence of bad years can precipitate rapid declines in both human and natural capital, locking systems into low-yield, high-variability trajectories that resonate with archaeological reconstructions of post-palatial contraction. Empirical case material from Australia details how unsustainable production practices translate into long-term declines and heightened variability in yields. Extensive land degradation in the form of salinity, rising soil acidification, and erosion is reported as a direct threat to future food supply, with millions of hectares at risk or already affected. Agriculture contributes about 16 % of national greenhouse-gas emissions, while projected climate change is expected to intensify heatwaves and alter rainfall patterns, together leading to an estimated 15–30 % decline in food production over four decades (Selvey & Carey, 2013). These figures do not simply describe a smooth downward trend; they imply larger inter-annual swings as systems operate closer to environmental limits and as extreme events become more damaging to already compromised soils. Such dynamics provide a quantitative

analogue for thinking about how repeated dry years in the 12th century BC could have interacted with overextended Bronze Age agrarian regimes to yield pronounced oscillations in surplus and deficit. Governmental attempts to stabilise food systems underscore both the possibilities and limits of policy in smoothing yield fluctuations. Investments in agricultural research and development, extension services, irrigation, and transport infrastructure aim to raise average productivity and reduce vulnerability to shocks. Disaster-preparedness policies, agricultural insurance, and climate-smart agriculture initiatives explicitly target the stability dimension, seeking to mitigate the impact of droughts, floods, and market disturbances on production. Yet analysis also records unintended consequences: subsidies designed to boost output may accelerate environmental degradation, while trade protections intended to secure domestic supply can influence global prices and access elsewhere. These trade-offs parallel the palatial tension, explored through Cretan field evidence in Appendix A, between short-term surplus extraction and the maintenance of resilient, low-variance agrarian systems. From a public-health perspective, fluctuations in yield propagate directly into nutritional and disease vulnerabilities. Policies that improve food utilisation through nutrition education, school feeding, and sanitation can partially decouple short-run harvest failures from malnutrition, but where such programmes are weak, each production downturn risks translating into impaired immune function and higher susceptibility to infectious disease (Agarwala et al., 2022). Governance in epidemic-prone settings shows that vulnerable, food-insecure populations with inadequate health-care infrastructure signal potential crisis during outbreaks such as Ebola virus disease, with food-system instability and health shocks reinforcing one another (Khan & Sesay, 2015). For Minoan Crete, this coupling suggests that sequences of poor harvests are best conceptualised as nodes within cascading socio-ecological failures that encompass agrarian output, nutrition, and epidemic susceptibility, rather than as purely economic perturbations. Finally, global and regional comparative work stresses that yield fluctuations are increasingly embedded in multi-scalar crisis chains. Climate-induced production

losses and price spikes can propagate through trade networks, interacting with geopolitical conflict, infrastructural fragility, and migration to erode human security (Scheffran, 2023; Agarwala et al., 2022). In fragile regions with weak governance and inadequate management capacity, environmental change undermines problem-solving ability and can precipitate spirals of poverty, hunger, and displacement (Scheffran, 2023). These contemporary patterns provide a risk-oriented template for interpreting Bronze Age agricultural volatility: rather than searching for a single "failure year," the analysis in this thesis tracks how repeated, medium-magnitude yield shocks, interacting with governance and health vulnerabilities, could cumulatively destabilise Minoan socio-ecological systems.

8.1.2 Impact of drought and crop failure

Episodes of drought and associated crop failure emerge in contemporary food-system analysis as multidimensional stressors that operate through intertwined biophysical and governance pathways. Policyoriented work on food security stresses that increasingly unpredictable climate patterns, including erratic droughts and floods, disrupt agricultural production, depress crop yields, and destabilise food availability over time. Simultaneously, overexploitation of soils and water resources accelerates degradation and scarcity, so that each

subsequent dry spell interacts with a progressively weakened resource base, amplifying the likelihood and severity of harvest shortfalls. Within the analytical framework adopted here, such dynamics provide a critical template for understanding how Late Bronze Age agrarian systems, including those on Crete, could have been pushed toward recurrent shortfalls rather than a single terminal failure. Government endeavours to safeguard food security under these conditions reveal the limits of technocratic responses when underlying vulnerabilities remain unaddressed. Studies identify droughts and floods as key drivers of yield volatility that force governments to balance the pursuit of increased output against sustainable resource management, often with only partial success. Interventions through subsidies, strategic reserves, and disaster-preparedness policies can smooth some shocks, yet they also risk entrenching input-intensive monocultures on marginal land, thereby heightening exposure to future drought-induced crop failures (Agarwala et al., 2022). In this sense, drought acts less as an exogenous anomaly than as a stress test on path-dependent production regimes, an insight that informs the crisis-management perspective applied to Minoan grain shortfalls in Appendix A. Empirical material from Australia offers a quantified view of how climatic drying and land degradation interact to depress yields over multi-decadal horizons. Unsustainable production practices have produced widespread salinity, increasing soil acidification, and erosion across millions of hectares, all of which threaten future food supply unless farming systems are substantially reconfigured. Agriculture accounts for about 16 % of national greenhouse-gas emissions, while climate change is projected to bring more frequent heatwaves and altered rainfall patterns, with modelled declines in food production of 15–30 % over the next 40 years (Selvey & Carey, 2013). These projections imply not only a downward trend but also greater inter-annual variance in yields as cropping takes place closer to ecological limits. When transposed heuristically to Bronze Age Crete, such findings underline that even moderate reductions in effective precipitation, if superimposed on overextended terraces or exhausted soils, could have produced marked swings between relative plenty and pronounced shortage. Yield instability under drought conditions has direct nutritional and public-health consequences. Food-security assessments emphasise that access and utilisation dimensions are as critical as aggregate availability; income inequality and gender inequality restrict the capacity of households to buffer crop failures through market purchases or social safety nets. Where social protection, public-health infrastructure, and nutrition programmes are weak, harvest failures more readily translate into undernutrition, impaired immune function, and greater susceptibility to infectious disease (Agarwala et al., 2022). Research on epidemic-prone food systems adds that vulnerable, food-insecure populations with inadequate health-care infrastructure "signal potential crisis" during outbreaks such as Ebola virus disease, because food-system instability and health shocks become mutually reinforcing. These coupled dynamics are central to the socio-ecological interpretation developed in this thesis: sequences of drought-induced crop failures are treated as triggers for cascading failures that propagate from fields through storage, diet, and disease ecology, rather than as purely economic events. Contemporary governance responses illustrate both opportunities and missed chances for learning from drought crises. Analyses of zoonotic disease management argue that extreme events can open windows for institutional transformation, yet often yield only short-term, reactive measures. Historical EVD interventions in Uganda, for example, relied on rigorous isolation, surveillance, and treatment supported by local authorities and donors, with the key lesson identified as the need to augment local capacity and

strengthen institutional infrastructure rather than to depend solely on externally imposed technical fixes (Khan & Sesay, 2015). In food systems, analogous principles apply to drought: without investment in local buffering capacity, diversified cropping, and equitable access mechanisms, each episode of crop failure primarily exposes governance weaknesses, echoing the pattern of crisis without structural adaptation diagnosed in other resource sectors (Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022). Finally, broader climate–security analysis conceptualises global heating as a "risk multiplier" that disturbs the water–energy–food nexus and critical infrastructures, generating production losses and price rises that propagate through global markets (Scheffran, 2023). Regions already facing water scarcity, land degradation, and weak governance are identified as particularly vulnerable to such compounded shocks, with drought-related crop failures acting as proximal drivers of poverty, hunger, and displacement (Scheffran, 2023; Agarwala et al., 2022). Although these studies concern modern states, their emphasis on interacting climatic, institutional, and socio-economic stressors directly supports the non-deterministic stance adopted here: in modelling Minoan drought and crop failure, climatic deterioration is treated as one component within a complex adaptive system whose behaviour depends on land use, hydrological infrastructure, and governance capacity documented in Appendix A, rather than as an autonomous cause of collapse (Agarwala et al., 2022; Khan & Sesay, 2015; Selvey & Carey, 2013; Scheffran, 2023).

8.2 Environmental Health Risks

8.2.1 Waterborne diseases

Water-related health risks in complex socio-ecological systems arise from intertwined changes in hydrology, land use, governance, and social structure rather than from isolated pathogenic events. Mountain communities in the Himalayas exemplify this configuration. Environmental transformations that have reduced water availability for both food production and domestic uses have "particularly" increased women’s vulnerability to water-borne and nutrition-deficiency health risks, as reduced access to safe drinking and sanitation water coincides with rising workloads in agriculture and livestock care and diminished time for personal and child care. These observations show how declining spring discharge and stream length, documented elsewhere in the same region, translate directly into exposure pathways for waterborne disease, embedded in gendered divisions of labour and uneven access to information and preparedness (Tiwari & Joshi, 2015). Comparable patterns appear in large irrigated basins where environmental degradation and institutional arrangements jointly shape water-quality conditions. In the Amudarya system, massive extension of irrigated agriculture, low standards of water management, deteriorating infrastructure, and frequent lack of drainage have produced widespread soil salinization, waterlogging, and collapse of semi-natural ecosystems. Rural populations in the most affected areas often lack access to good-quality drinking water, and environmental degradation has significantly impaired living conditions and health, increasing vulnerability to ecological, economic, and social stresses during droughts such as that of 2000/2001 (Schlüter & Herrfahrdt-Pähle, 2011). Although specific pathogens are not enumerated, these conditions describe classic determinants of waterborne disease: contaminated supplies, reduced buffering by wetland ecosystems, and poverty-linked constraints on treatment and prevention. Public health and environmental health research frames such vulnerabilities within a broader hazard landscape that includes water pollution,

inadequate waste management, and disaster risk. Water pollution arising from industrial, agricultural, domestic activities, natural disasters, and climate change is identified as a major challenge that undermines drinking-water quality and the health of aquatic ecosystems and dependent populations. Soil pollution, waste-management failures, and occupational and disaster hazards further complicate risk profiles, suggesting that waterborne disease in many settings co-occurs with multiple environmental stressors that share underlying governance deficits (Adefemi et al., 2023). In this thesis, such coupled hazards are relevant for interpreting archaeological evidence of drainage, waste disposal, and proximity between habitation areas and hydraulic features in Cretan settlements (Appendix A). Epidemic-focused studies emphasise that water-related health crises must be analysed through governance as well as biophysical pathways. Vulnerable, food-insecure populations with inadequate health-care infrastructure "signal potential crisis" in epidemics such as Ebola virus disease, which has multiple entry points across local food systems and environmental health. Governance mechanisms that link sectors, scales, and interest groups are described as necessary for making synergies between environmental health and public health, and for deploying decision-support tools within multi-level arrangements. Historical EVD responses in Uganda,

relying on rigorous isolation, surveillance, and treatment protocols supported by local authorities and donor agencies, are cited as successful where they augmented local capacity and strengthened institutional infrastructure (Khan & Sesay, 2015). Methodologically, these experiences demonstrate that even where waterborne transmission is only one component of broader disease ecologies, effective management depends on integrated, scale-sensitive institutions rather than on technical measures alone. Global climate–security analysis complements these perspectives by identifying water stress as a key conduit through which environmental change undermines human security. Loss or degradation of vital resources such as water, arable land, forests, and biodiversity, together with weather extremes that threaten livelihoods, can erode social order, degrade infrastructures including health systems, and contribute to spirals of poverty, hunger, and displacement, particularly in fragile regions with weak governance and inadequate management capacities (Scheffran, 2023). These impact chains suggest that waterborne disease risks will be most acute where climatic shifts in runoff and recharge intersect with prior degradation and institutional fragility, an analytical stance mirrored in this thesis for Late Bronze Age Crete. Contemporary environmental-health practice increasingly turns to artificial intelligence to monitor and manage water-related risks. The U.S. Geological Survey uses AI applications to analyse water-quality data from satellites and ground-based sensors, enhancing understanding of spatial and temporal trends and helping authorities identify pollution sources and formulate management strategies. Such systems operate alongside AI-enabled disaster-vulnerability modelling and real-time air-quality networks, but they also raise concerns about data quality, privacy, bias, and accessibility, leading to calls for transparent, inclusive, and ethically governed AI deployments (Adefemi et al., 2023). While no direct analogue existed in the Bronze Age, the decision-support logic underlying these systems informs the way heterogeneous archaeological, palaeoenvironmental, and hydrological datasets are combined in this thesis to infer zones of heightened waterborne-disease risk around Cretan springs, cisterns, and drainage features (Appendix A). Finally, food-system and policy analyses stress that water scarcity, resource depletion, and climate variability challenge governments' capacity to maintain safe and sufficient supplies, especially where income and gender inequalities, infrastructure deficits, and policy silos persist. Overexploitation of natural resources, including water, and inefficiencies in supply chains can compromise both availability and

quality of food and water, with vulnerable populations facing heightened risk of hunger and malnutrition (Agarwala et al., 2022). In combination with case-derived evidence on Himalayan and Central Asian water insecurity (Tiwari & Joshi, 2015; Schlüter & Herrfahrdt-Pähle, 2011), this reinforces the core assumption guiding the Minoan case study: waterborne disease must be situated within cascading socio-ecological failures that couple hydrological change, governance weakness, and social inequality, rather than being treated as an isolated biological phenomenon (Khan & Sesay, 2015; Scheffran, 2023; Adefemi et al., 2023; Agarwala et al., 2022).

8.2.2 Impact of environmental degradation on health

Environmental degradation in contemporary cases manifests as tightly coupled transformations of ecosystems, livelihoods, and morbidity patterns rather than as isolated biophysical shifts. In semi-arid Central Asia, massive expansion of irrigated agriculture on the Amudarya and Syrdarya, implemented through low management standards, deteriorating infrastructure, and frequent absence of drainage, drove soil salinization, waterlogging, and collapse of semi-natural delta ecosystems. Disappearance of the Aral Sea, loss of fisheries, reed resources, pasture, and protection from salt and dust storms eliminated key ecosystem services and livelihoods, while large rural populations in the most degraded regions were left without access to good-quality drinking water. Analyses explicitly link increasing soil salinity, declining soil productivity, and water-logging to rising rural poverty, and note that environmental degradation has "significantly impaired" living conditions and health, heightening vulnerability to ecological, economic, and social stresses during droughts such as that of 2000/2001 (Schlüter & Herrfahrdt-Pähle, 2011). These findings demonstrate how long-term land and water mismanagement translate into chronic health risk environments even in the absence of discrete disasters. Mountain regions in the Himalayas illustrate a different yet related nexus between environmental change and health. Declining water availability and stressed local production systems have increased out-migration of rural male youth, leaving women with intensified workloads in agriculture and livestock care and reduced time for personal and child care. Reduced availability of water for food production and diminished access to water for drinking and sanitation "particularly" elevate women’s vulnerability to water-borne and nutrition-deficiency health risks, while women constitute the highest proportion of disaster victims, partly because of limited preparedness and information and greater exposure (Tiwari & Joshi,

2015). Here, environmental degradation of springs, streams, and soils intersects with gendered labour and social marginalisation, reinforcing health inequities. Urbanising and industrial contexts add further layers of hazard. Reviews of environmental health and public safety identify air pollution, water pollution, soil contamination, inadequate waste management, occupational hazards, and disaster risk as interlinked challenges that undermine human health. Water pollution from industrial, agricultural, and domestic sources, compounded by natural disasters and climate change, degrades drinking-water quality and aquatic ecosystems, directly affecting populations dependent on these resources. Soil pollution through accumulation of heavy metals, pesticides, and radioactive materials compromises land fertility and food safety. Inadequate solid and liquid waste management, especially in urban areas, fosters environmental degradation, facilitates disease transmission, and can generate social conflict. Disaster risk reduction is complicated by increasing frequency and intensity of hazards and by

complex, interdependent infrastructures, so that failures in one domain can cascade into health crises across others (Adefemi et al., 2023). Public-health oriented work on extreme scenarios such as nuclear winter highlights the same core pathways via which environmental disruption threatens health. Global cooling analogues would compromise clean air, safe drinking water, nutritious food supply, and secure shelter, while secondary effects would include increased ultraviolet radiation, disease outbreaks associated with destroyed sanitary facilities and contaminated water, and infectious-disease epidemics of plague, typhus, malaria, dysentery, and cholera. Proposed research agendas explicitly call for integrating climate and crop models with epidemiological frameworks such as the Global Burden of Disease, and for developing forecasting tools that link environmental threats to spatial patterns of outbreak risk (Vilhelmsson & Baum, 2023). Although focused on hypothetical futures, these analyses codify the same impact chains observed in Central Asia and the Himalayas: environmental degradation undermines basic health determinants and amplifies epidemic vulnerability. Governance strongly modulates these relationships. Studies of food systems and sustainability argue that climate variability, resource depletion, and biodiversity loss reduce yields and alter growing conditions, while resource scarcity in land and water exacerbates competition and compromises the ability to meet nutritional needs. Government policies on subsidies, land use, trade, social safety nets, and environmental regulation shape both environmental trajectories and health outcomes by influencing production practices, access to nutritious food, and sanitation and health-care provision. Where policies promote unsustainable intensification, they may improve short-term availability but accelerate land degradation and pollution, generating longer-term health burdens (Agarwala et al., 2022). Climate–security analysis further stresses that loss of water, arable land, forests, and biodiversity, together with weather extremes, erodes social stability and can precipitate spirals of poverty, hunger, corruption, violence, and forced displacement, particularly in fragile regions with weak governance and inadequate management capacities (Scheffran, 2023). In such contexts, environmental degradation and institutional failure jointly degrade health infrastructures and problem-solving capacity, magnifying the health impacts of subsequent shocks. Across these cases, environmental degradation appears as a central driver within cascading socio-ecological failures that compromise water quality and availability, food security, income, and social cohesion, and thereby create multi-hazard health landscapes. This configuration provides the comparative template for reading Cretan evidence in Appendix A, where observed soil erosion, altered hydrology, and land-use pressures around Bronze Age settlements are analysed not only as ecological changes but as potential amplifiers of water-borne disease, nutritional stress, and differential vulnerability within Minoan communities (Schlüter & Herrfahrdt-Pähle, 2011; Tiwari & Joshi, 2015; Adefemi et al., 2023; Agarwala et al., 2022).

8.3 Community Resilience and Health Governance

8.3.1 Healthcare infrastructure and access

Access to effective health care emerges in contemporary studies as an outcome of interacting environmental, infrastructural, and governance conditions rather than of clinical capacity alone. Work on African food-related crises argues that vulnerable, food-insecure populations combined with inadequate health-care infrastructure "signal potential crisis" in the event of epidemics such as Ebola virus disease (EVD). Epidemics are described as

multi-faceted, with several entry points across local food systems and environmental health, so that governance mechanisms linking sectors, jurisdictional scales, and interest groups become indispensable for organising surveillance, isolation, and treatment capacities. This framing is central for the present thesis: Late Bronze Age Cretan communities with constrained

access to clean water and food, and lacking robust institutions for managing public health, would have been structurally similar to these modern high-risk configurations, even if specific pathogens and technologies differed. Historical EVD interventions in Uganda provide a concrete template for what "effective" infrastructure looks like under crisis. Successful containment relied on rigorous protocols for isolation, surveillance, and health-care treatment, supported by local authorities and international donors. The key lesson extracted is the need to augment local capacity and strengthen institutional infrastructure, rather than rely solely on external technical fixes or ad hoc emergency measures. Similar principles underpin proposed models for controlling disease and enhancing nutritional well-being in African settings, which include community-based production systems, public–private partnerships focused on sanitary research, and top-down central agencies responsible for monitoring and surveillance of pathogens (Khan & Sesay, 2015). Read through a political-ecology lens, these arrangements illustrate how clinical facilities, information systems, and local legitimacy must align if health-care infrastructure is to buffer shocks instead of amplifying them. Environmental change can erode these foundations from below. In the central Himalayas, declining water availability and stressed local production systems have increased rural male out-migration and shifted heavy agricultural and livestock workloads onto women. Reduced access to water for food production, drinking, and sanitation particularly heightens women’s vulnerability to water-borne and nutrition-deficiency health risks, while women constitute the largest share of disaster victims due to limited preparedness and greater exposure (Tiwari & Joshi, 2015). Here, physical infrastructure for water supply and health care is inseparable from social infrastructure: workload, time poverty, and gendered access determine who can reach clinics, latrines, or safe water points. This gendered vulnerability provides a crucial comparative template for interpreting Cretan evidence in Appendix A, where spatial relations between springs, habitation zones, and possible healing or cultic spaces must be evaluated in terms of differential access and labour burdens, not only hydraulic capacity. Large irrigated basins in Central Asia exhibit a different but related pattern of infrastructural fragility. Massive expansion of irrigation, low management standards, and deteriorating infrastructure generated soil salinization, waterlogging, and collapse of semi-natural ecosystems, leaving many rural communities without good-quality drinking water. Environmental degradation "significantly impaired" living conditions and health and increased vulnerability to ecological, economic, and social stresses during droughts such as that of 2000/2001 (Schlüter & Herrfahrdt-Pähle, 2011). Importantly, institutional responses focused on maintaining agricultural productivity through technical measures, while little attention was paid to restoring safe domestic water supplies or health services. This decoupling of production from public health underscores a risk for any palatial regime: irrigation and storage investments that privilege surplus extraction over potable water and sanitation may undermine community resilience to disease and famine. Public-health and environmental-health syntheses further specify the infrastructural domains that condition access. Key challenges include air and water pollution, soil contamination, inadequate waste management, occupational hazards, and disaster risk, each requiring multisectoral approaches and participation from governments, local authorities,

industry, academia, and civil society (Adefemi et al., 2023). Inadequate waste management in urban areas, for instance, contributes to environmental degradation, disease transmission, and social conflict, while water pollution from industrial, agricultural, and domestic sources compromises drinking-water quality and aquatic ecosystems. For Bronze Age Crete, this suggests that proximity of habitation to drainage lines, dumps, or livestock facilities documented in Appendix A would have shaped baseline disease loads irrespective of any specific "epidemic event." Governments' roles in structuring health-care access are elaborated in food-system analyses that link availability, access, utilisation, and stability of food with broader social-policy regimes. Income support, minimum-wage regulation, and social safety nets influence economic access to food, while public-health and nutritional programmes, together with sanitation and health-care access, determine whether consumed food leads to adequate nutritional outcomes. Social safety nets and disaster-preparedness policies are explicitly framed as critical for mitigating shocks, yet their effectiveness is constrained by income inequality, gender disparities, infrastructure deficits, and policy silos that hinder coherent responses across agriculture, health, and environment (Agarwala et al., 2022). These findings inform the governance dimension of Cretan health-care reconstructions: where archaeological evidence suggests concentrated storage, hierarchical redistribution, and limited local buffering (Appendix A), one may infer vulnerability patterns comparable to modern systems where weak safety nets and fragmented institutions leave marginal groups most exposed to health crises. Technological transformations in surveillance and decision support reshape what "infrastructure" entails. AI-enabled disease surveillance integrates electronic health

records, social media, and environmental data to detect unusual symptom clusters, predict outbreak spread, and optimise resource allocation. Real-time analysis, early-warning systems, and predictive modelling for both epidemics and disasters are increasingly embedded in public-health agencies and emergency-management organisations, though they raise serious concerns over data privacy, security, bias, transparency, and accessibility (Adefemi et al., 2023). In methodological terms, these architectures provide analogues for how this thesis integrates heterogeneous archaeological, hydrological, and palaeoclimatic datasets using GIS and risk matrices to identify "hot spots" of probable health vulnerability in Minoan landscapes (Appendix A), even in the absence of written medical records. Finally, crisis-management research stresses that biological hazards such as pandemic influenza can only be contained through combinations of medical interventions, social-distancing measures, quarantine, protective equipment, street and facility sanitisation, travel restrictions, and public advisories. Analyses of the 1918 pandemic note that where social-distancing and quarantine measures were implemented early and widely, morbidity and mortality declined, whereas in colonial India, reliance on voluntary relief amid inadequate health-care facilities and governmental apathy contributed to extremely high mortality among underprivileged populations. Barriers such as unsafe public transport, limited quarantine facilities, and insufficient vaccines and medications are identified as key factors that enhance morbidity and mortality (Nath & Nath, 2022). These modern cases sharpen a central argument of this thesis: health-care infrastructure and access are best conceptualised as multi-layered socio-technical systems whose capacity to absorb shocks from drought, food shortage, or epidemic depends on prior investments in local institutions, safe water and sanitation, and inclusive governance. In Late Bronze Age Crete, the spatial and material traces of such systems are fragmentary, but the comparative evidence assembled here provides a rigorous framework for interpreting how observed hydraulic,

architectural, and settlement patterns in Appendix A would have conditioned community resilience or vulnerability to cascading socio-ecological crises (Khan & Sesay, 2015; Tiwari & Joshi, 2015; Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022).

8.3.2 Adaptive strategies during environmental stress

Adaptive responses to environmental stress in contemporary systems are consistently portrayed as multi-layered, combining infrastructural, institutional, and community-level strategies rather than relying on single technical fixes. Work on Ebola virus disease (EVD) and bovine spongiform encephalopathy (BSE) argues that coping with epidemics in food-insecure settings requires anticipatory risk-reduction measures coupled with crisis management that integrates food security and environmental health. Governance is positioned as the key rubric for organising these interactions across sectors and scales, with emphasis on decision-support tools, multi-level arrangements, and social networks that can transmit new behaviours and norms supportive of local food security and well-being. In practice, this has included rigorous isolation and surveillance protocols, strengthening of local health infrastructure, and post-crisis food-production initiatives and stakeholder engagement, which together represent adaptive strategies under combined environmental and epidemiological stress. Scale-sensitive approaches to vulnerability assessment and adaptation are repeatedly stressed. Analyses of EVD highlight that spatial and temporal scale, bio-complexity in disease ecology, and multi-actor interactions complicate prediction of causal pathways and trends, yet also define entry points for intervention. Adaptive management is recommended where uncertainties due to climate change, incomplete knowledge, and institutional constraints are treated as the basis for iterative learning rather than as barriers to action. Proposed models include community-based production systems that prioritise sufficiency, public–private partnerships for sanitary research and health standards, and centralised agencies responsible for pathogen monitoring and surveillance, all of which are framed as cost-effective ways to move communities from "vulnerable" to "resilient" states during crises (Khan & Sesay, 2015). Empirical work in Himalayan mountain environments provides a contrasting but complementary view of adaptation under chronic environmental stress. There, declining availability of water for food production and domestic use, combined with heightened risks of natural disasters, has driven male out-migration and increased women’s workloads in agriculture and livestock care. These changes have reduced time available for personal and child care and have particularly increased women’s vulnerability to waterborne and nutrition-deficiency health risks, while women constitute the largest proportion of disaster victims due to limited preparedness and information. Authors call for gender-sensitive development agendas, empowerment of rural women in natural-resource governance, and recognition of traditional adaptation knowledge as core components of sustainable development strategies in the Himalayas, arguing that such measures are indispensable for ecological restoration and for building environmental, economic, and social sustainability (Tiwari & Joshi, 2015). These recommendations illustrate adaptive strategies that explicitly target social differentiation and power relations as levers for reducing health vulnerability under environmental stress. In large irrigated basins of Central Asia, adaptation efforts have largely remained reactive and technical, illustrating the difficulties of achieving transformative change. Massive expansion of irrigation led to soil salinization, waterlogging, and collapse of downstream ecosystems, yet institutional reforms were driven more by donor agendas, farm restructuring, and internal power struggles than by

recognition of ecological limits. Droughts and floods triggered emergency measures such as temporary bans on certain crops, reductions in regional water limits, and ad hoc transboundary councils, but once extreme events passed, water management reverted to previous practices, and no long-term strategy for variability and scarcity was implemented. This pattern, compounded by patronage and corruption, maintained high vulnerability to future disturbances and slow drivers like ecosystem-service loss, exemplifying crisis management without systemic adaptation (Schlüter & Herrfahrdt-Pähle, 2011). Research on food-security governance specifies additional arenas where adaptive strategies are being attempted. Governments seeking to address food security and promote sustainability confront climate variability, resource depletion, and biodiversity loss, together with globalisation-induced market-access disparities, income and gender inequality, policy incoherence, and conflict. Policy tools for adaptation include agricultural subsidies that can shift crop choices, investments in research and technology to increase yields and resilience, land-use regulations to support sustainable practices, social safety nets and income support to secure economic access, public-health and nutrition programmes to improve utilisation, and disaster-preparedness, agricultural insurance, and climate-smart agriculture to stabilise systems under shocks. Yet these interventions entail trade-offs: subsidies intended to boost production can accelerate environmental degradation, and trade policies aimed at protecting domestic markets can raise global prices and constrain access elsewhere. Integrated, cross-sectoral approaches that align agricultural, health, and environmental objectives are therefore recommended as adaptive strategies, even as implementation gaps and limited institutional capacity remain pervasive (Agarwala et al., 2022). Across these cases, adaptive strategies during environmental stress share several elements: efforts to build local institutional capacity and surveillance systems, use of crises as potential windows for governance innovation, attention to social differentiation and gender, and attempts to reconcile short-term crisis management with longer-term resource sustainability. At the same time, evidence indicates that without structural reforms in land and water governance, and without embedding health considerations in food and environmental policy, many responses remain reactive and path-dependent, a tension that is analytically central to interpreting Minoan responses to compounded climatic, hydrological, and public-health stress in Appendix A (Khan & Sesay, 2015; Tiwari & Joshi, 2015; Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022).

9 Security, Military Adaptation and Conflict

9.1 Defensive Strategies and Infrastructure

9.1.1 Fortifications and settlement defense

Archaeological syntheses of the later second millennium BC repeatedly associate fire destructions at major Aegean centres with cycles of conflict, fortification, and changing defensive priorities, providing a comparative template for analysing Minoan settlement defence. In the Argolid, the construction of the citadel at Midea around 1250 BC within the heartland of Mycenae and Tiryns coincided with a visible decline in prosperity but heightened emphasis on defensibility at Mycenae and expansion of fortifications at Tiryns to enclose the lower town. These architectural investments were followed, within roughly half a century, by conflagrations that destroyed all urban centres in the region, as well as Gla, Dhimini, and Teichos Dymaion to the north. Comparable burnings at Ayios Vasileios (∼ 1250 BC) and at the palatial centre of Chania on Crete around 1200 BC embed Cretan trajectories within this broader horizon of fortified settlement and fiery destruction. Evidence indicates that conflagrations formed part of a "regular cycle of conflict" rather than isolated disasters, and that they targeted urban centres that had become increasingly hierarchised and militarised. Linear B archives from the later 13th century BC document centralised administrations with ranked offices and organised military systems; archaeological analysis argues that it was specifically this palatial system, with its entourage

of craftworkers, scribes, and priestesses, which collapsed. Fortifications at citadels such as Mycenae, Tiryns, Gla, and Midea are therefore best read as components of a wider political–military infrastructure that sought to secure concentrated resources and administrative personnel within defensible nodes. The subsequent abandonment of canonical palatial architecture in post-destruction rebuilding at Mycenae, Tiryns, and Midea, despite continued occupation, underscores that settlement defence was dynamically reconfigured as part of longer trajectories of political weakening and social reorganisation rather than frozen in a "classic" form (Molloy, 2022). From a political-ecology perspective, these fortification programmes interacted with environmental and resource pressures that also shaped food security and public health. Global food-security analyses highlight that climate variability, resource depletion, and biodiversity loss reduce yields and alter growing conditions, while arable land and water become increasingly scarce; as competition for these resources intensifies, the capacity to meet nutritional needs is jeopardised, particularly for vulnerable populations (Agarwala et al., 2022). Where governments respond by prioritising strategic reserves, trade protection, or export-oriented production without addressing underlying degradation, defensive investments can concentrate in fortified centres tasked with securing access to shrinking resource frontiers and safeguarding critical stores. In this light, the late Mycenaean emphasis on citadel defensibility and enclosure of lower towns around palatial cores plausibly reflects a security logic in which settlement defence and resource control were tightly coupled, even though the specific resource configurations differ from modern cases (Molloy, 2022; Agarwala et al., 2022). Contemporary conflict and security research helps clarify how such defensive infrastructures fit into larger cascades of socio-ecological risk. Climate change is characterised as a "threat multiplier" that can destabilise critical infrastructures, intensify competition over land and water, and heighten conflict risk in agrarian, aid-dependent states exposed to weather

extremes. Environmental and resource policies, such as dam-building in transboundary basins, have already become explicit security issues, raising downstream concerns and stimulating militarised responses (Scheffran, 2023). Although these examples are geographically and temporally distant from Bronze Age Crete, they illustrate structurally similar dynamics: when environmental stress and resource competition intersect with hierarchical governance and uneven aid or trade relations, fortifications and militarised settlements emerge as spatial expressions of attempts to manage, control, or securitise vital flows. Environmental degradation further deepens the entanglement between defence and daily survival. In the Amudarya–Aral Sea system, large-scale irrigation expansion, salinization, and ecosystem collapse left rural populations without good-quality drinking water, deteriorated health conditions, and heightened vulnerability to ecological and economic shocks. Institutional responses remained largely technical and reactive, focused on maintaining short-term productivity rather than breaking cycles of overuse and degradation (Schlüter & Herrfahrdt-Pähle, 2011). These findings emphasise that secure walls cannot compensate for eroded environmental buffers; settlement defence that ignores water quality, ecosystem services, and public health risks reinforcing, rather than reducing, systemic vulnerability. Finally, public-health and disaster-governance work on epidemic-prone food systems demonstrates that windows for institutional learning after crises are often squandered. Historical Ebola interventions in Uganda show that rigorous isolation and surveillance protocols, anchored in strengthened local institutions and supported by external funding, can enhance resilience, whereas purely reactive measures leave underlying vulnerabilities intact (Khan & Sesay, 2015). Applied to Late Bronze Age fortified settlements, this suggests that the protective potential of walls and military infrastructure depended critically on accompanying adaptations in governance, resource management, and health provisioning. Where such adaptations failed, fortifications may have delayed but could not prevent cascading failures in socio-ecological systems under intensifying climatic, environmental, and political stress (Molloy, 2022; Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022; Scheffran, 2023).

9.1.2 Maritime defense and naval capabilities

Contemporary analyses of food systems and climate–security dynamics clarify how maritime infrastructures and naval capabilities sit within wider webs of environmental stress, trade dependence, and governance, providing analogical insight for reconstructing Bronze Age coastal defence. Government efforts to secure food under increasingly erratic droughts and floods must simultaneously cope with resource depletion, land-use conflicts between agriculture, urbanisation, and industrialisation, and geopolitical instability that disrupts production and distribution. Reliance on globalised supply chains heightens vulnerability to systemic shocks, vividly exposed during the COVID–19 pandemic, while unfavourable trade agreements disadvantage small-scale producers and constrain their resilience (Agarwala et al.,

2022). In such configurations, ports, shipping lanes, and coastal storage facilities function as critical nodes whose disruption by conflict, quarantine, or infrastructural failure can rapidly translate into shortages and social stress, an interdependence that is analytically relevant for assessing Minoan maritime defence within a risk-oriented framework. Security-oriented work on climate change characterises global heating as a "risk multiplier" that destabilises interactions between natural and social systems, including critical infrastructures and supply

networks. Loss or degradation of key resources such as water, arable land, forests, and biodiversity, together with more frequent weather extremes, is said to threaten human security and undermine political stability, particularly in fragile regions with weak governance and limited management capacity (Scheffran, 2023). Within this perspective, maritime routes and naval assets are not merely military instruments but integral components of the water–energy–food nexus: disruptions to seaborne grain imports or fisheries exports can cascade into domestic unrest, migration, and intensified securitisation of coasts and straits. Although the mechanisms differ, this cascade logic helps frame Late Bronze Age Cretan sea power as embedded in coupled socio-ecological and geopolitical stresses rather than isolated naval competition. Epidemic governance around Ebola virus disease (EVD) offers a further comparative view on maritime vulnerability. Coastal fisheries and seafood provide essential caloric intake, fatty acids, and micronutrients in affected West African countries, yet regional fish trade has been directly impacted by International Maritime Organization rules mandating 21-day quarantines for vessels exporting seafood, with documented effects on product quality, prices, and trade volumes. Authors argue that seafood security, public health, and environmental governance form an intertwined system, and that neglecting food and well-being as determinants of public health contributed to missing early warning signs of catastrophe. These findings underscore that maritime controls introduced for health reasons can inadvertently create food-security crises, illuminating how ancient naval blockades or disease-related port closures around Crete would have interacted with already stressed agrarian bases. Crisis-management recommendations for EVD explicitly call for early-warning networks, environmental-health monitoring, and strengthened foodsecurity institutions, combined with cross-border collaboration, institutional partnerships, and creative governance arrangements at regional and international levels. Such proposals implicitly assume robust coastal surveillance, information-sharing across maritime jurisdictions, and the capacity to regulate flows of people and goods by sea. They also highlight that reactive strategies, such as lockdowns or the narrow focus on drug trials, are insufficient without integrating food security, risk mapping, and environmental monitoring into long-term, multi-pronged approaches (Khan & Sesay, 2015). Translating these insights heuristically to a Late Bronze Age context suggests that sea-going polities that invested only in military hulls and not in information networks, redundancy in supply hinterlands, or diversified provisioning would have been especially exposed to cascading failures. Environmentalhealth research detailing AI-enhanced public-safety strategies extends this systems view. Disaster response, emergency medical dispatch, smart-city surveillance, and critical-infrastructure monitoring increasingly rely on real-time data streams, predictive modelling, and automated resource allocation to manage hazards, including disease outbreaks and extreme weather events. Maritime analogues include AI-supported monitoring of coastal flooding, port safety, and ship movements, along with AI-based disease surveillance that uses health data and social media to forecast outbreak spread and inform travel protocols (Adefemi et al., 2023). Ethical concerns over data privacy, bias, and unequal access, however, indicate that such capabilities may be weakest in precisely those regions most vulnerable to climate and conflict shocks. For Bronze Age Crete, the structural lesson is that naval strength must be analysed alongside information and governance infrastructures; fleets operating without early warning, situational awareness, or integrated crisis decision-making are poor guarantors of systemic resilience. Finally, food-security scholarship emphasises that conflict and political instability in water-scarce regions, such as parts of the Middle East and North Africa, amplify dependence on global food imports and on secure trade corridors, while land-use

conflicts and resource scarcity complicate sustainable management (Agarwala et al., 2022). Maritime chokepoints in such settings acquire disproportionate strategic importance, and their militarisation or disruption can rapidly escalate into wider crises. In the interpretive framework adopted here, Minoan maritime defence is therefore treated as one dimension of a broader security regime that tied naval capabilities, coastal provisioning hubs, and long-distance exchange tightly into climate-sensitive agrarian and hydrological systems, making naval failure both a symptom and a driver of wider socio-ecological breakdown (Agarwala et al., 2022; Scheffran, 2023; Khan & Sesay, 2015; Adefemi et al., 2023).

9.2 Geopolitical and Security Challenges

9.2.1 Regional rivalries and alliances

Regional competition over land and water emerges clearly in contemporary semi-arid irrigation regimes and provides an instructive analogue for Late Bronze Age Aegean rivalries. In the Amudarya basin, all agriculture in the Turan lowlands depends on surface-water irrigation, with irrigated area in Uzbekistan expanding from 0.42 million ha in 1913 to more than 4 million ha by 1990 and remaining at roughly 4.2 million ha thereafter. Low standards of water management, deteriorating infrastructure, and lack of drainage produced soil salinization, waterlogging, and collapse of downstream ecosystems, culminating in the disappearance of the Aral Sea and its fisheries. An authoritarian post-Soviet regime preserved heavy dependence on irrigated cotton and wheat for foreign exchange and rural employment, while large rural populations in degraded areas lacked access to good-quality drinking water and experienced significant health deterioration. Within this setting, competition for control of river flows and irrigable land is embedded in a broader political economy rather than expressible as simple upstream versus downstream antagonism, a configuration that parallels how Minoan and Mycenaean polities likely competed for fertile plains, springs, and maritime outlets documented in Appendix A. Allocation struggles in the Amudarya basin are mediated through hierarchical governance structures that configure de facto alliances and rivalries among regions and actors. District governors (khokims) are personally responsible for meeting state cotton and wheat quotas and therefore intervene directly in water allocation, adding uncertainty and reducing transparency. Institutional reforms in water allocation planning, introduced via presidential decrees rather than parliamentary laws, often amounted to mere renaming of organisations, reflecting weak ownership and reinforcing centralised control. Informal institutions such as patronage and corruption severely limit implementation of formal measures; Uzbekistan ranks among the ten most corrupt countries worldwide according to the Corruption Perception Index. These arrangements sustain a hydro-hegemonic order in which powerful actors secure water for quota crops while marginal communities bear the costs of salinization, waterlogging, and declining soil productivity that are key drivers of rural poverty. For Bronze Age Crete, this pattern suggests that regional alliances around palatial centres may have coalesced not only through kinship or military force but also through shared interests in maintaining particular hydraulic regimes, with subordinate communities experiencing analogous marginalisation when flows were redirected to elite-controlled terraces and cisterns mapped in Appendix A. Extreme events in this Central Asian case act as catalysts that temporarily reconfigure rivalries and spur short-lived cooperation. Droughts and floods trigger emergency measures such as bans on rice planting,

temporary reductions in regional water limits, and creation of emergency councils for transboundary flood mitigation. Once the immediate crisis passes, management reverts to prior practices, and no long-term strategy for dealing with high flow variability or increasing scarcity is implemented; options such as reuse of drainage waters, diversification to less water-intensive crops, or broader diversification of water use remain unadopted. Environmental degradation and socio-political crises, including the collapse of Aral Sea fisheries, have produced regime shifts in subsystems but have not triggered structural transformations at basin scale (Schlüter & Herrfahrdt-Pähle, 2011). This oscillation between ad hoc cooperation and entrenched rivalry under external stress offers a comparative template for interpreting how Aegean polities might have formed temporary alliances in response to drought or crop failure, without fundamentally altering competitive structures over land and maritime routes. Food-system research at global and regional scales reinforces the role of state policy in structuring rivalries and alliances over resources. Climate variability, resource depletion, and biodiversity loss reduce yields and narrow the resource base, while economic disparities and gender inequality restrict access to nutritious food. Governments deploy a range of instruments, including agricultural subsidies, trade agreements, social safety nets, and environmental regulations, that shape which regions gain or lose from particular production and trade regimes. Market-access disparities and unfavourable trade agreements disadvantage small-scale producers, especially in developing countries, while dependency on global supply chains, as starkly revealed during the COVID–19 pandemic, exposes both importing and exporting regions to disruptions in food distribution, labour, and prices. Conflicts over land use between agriculture, urbanisation, and industrialisation further complicate sustainable land management, particularly in water-scarce regions such as the Middle East and North Africa where political instability and conflict heighten dependence on food imports (Agarwala et al., 2022). These dynamics demonstrate how regional alliances may form around shared exposure to trade and climate shocks or around complementary positions in supply chains, while rivalries intensify where states compete for

limited arable land, water, and market access. Climate–security analysis situates such competitions within larger geopolitical configurations. Global heating is conceptualised as a "threat multiplier" that destabilises interactions between natural and social systems, including critical infrastructures and supply networks. Weak countries that depend heavily on agriculture, are highly exposed to weather extremes, and receive low levels of aid are identified as hotspots where conflict factors can intensify. Military institutions increasingly treat climate change as a driver of national and international insecurity, from disaster control to assertion of resource interests in a world of "climate chaos," and large infrastructure projects such as dams in Turkey, Ethiopia, and Laos have already raised downstream security concerns. Securitisation and militarisation of climate policy risk generating counterproductive actions that exacerbate both climate and conflict risks, while environmental and resource policies themselves become security issues (Scheffran, 2023). Although the sources do not describe Bronze Age alliances directly, these contemporary examples clarify how environmental stress, resource dependence, and militarised responses can align to produce shifting coalitions and antagonisms, a logic that informs the crisis-management and political-ecology reading of Minoan inter-polity relations developed on the basis of field observations in Appendix A (Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022; Scheffran, 2023; Adefemi et al., 2023).

9.2.2 Resource-related conflicts

Resource-related conflicts in semi-arid irrigation oases offer a detailed template for understanding how competition over water and land can become structurally embedded in political economies and governance regimes. In the Amudarya basin, all agriculture in the Turan lowlands depends on surfacewater irrigation from the Amudarya and Syrdarya, with irrigated area in Uzbekistan increasing from 0.42 to more than 4 million ha between 1913 and 1990. Low management standards, deteriorating infrastructure, and lack of drainage produced extensive soil salinization, waterlogging, and the collapse of downstream semi-natural ecosystems, including disappearance of the Aral Sea and loss of fisheries, reed resources, pasture, and dust-storm protection. These changes effectively transformed diverse hydrosocial landscapes into degraded monocultural production zones, intensifying competition for the remaining productive land and clean water. Distributional consequences of this regime are pronounced. Rural populations in the most degraded areas lack access to good-quality drinking water, and environmental deterioration has "significantly impaired" living conditions and health, making households more vulnerable to ecological, economic, and social stresses, as illustrated during the 2000/2001 drought. Soil salinity, falling soil productivity, and waterlogging are explicitly identified as main reasons for growing rural poverty, indicating that resource-related conflict is not only inter-regional but also social, pitting better-positioned actors who can secure irrigation flows against marginalised farmers on degraded plots. In basin-scale terms, the disappearance of the Aral Sea and loss of associated ecosystem services signal a severe contraction of shared resource space, sharpening latent conflicts around access and compensation. Formal governance structures channel and, in many respects, institutionalise these conflicts. An authoritarian regime with a strong executive maintains heavy dependence on irrigated agriculture, especially cotton, for foreign exchange, revenue, and rural employment. District governors (khokims) are personally responsible for meeting state cotton and wheat quotas and therefore intervene directly in allocation decisions, using their power to secure water for quota crops, which increases uncertainty and reduces transparency for other users. Reforms in water allocation planning, introduced via presidential decrees, have largely resulted in renaming organisations without altering underlying incentives or accountability, so institutional change does not address resource degradation or inequitable access. Informal institutions such as patronage and corruption further constrain implementation, leaving Uzbekistan among the ten most corrupt countries by the Corruption Perception Index and reinforcing a hydro-hegemonic pattern in which powerful actors capture scarce resources while environmental and social costs are externalised. Extreme hydrological events act as flashpoints in this contested setting. Droughts and floods trigger emergency reactions such as bans on rice planting, temporary reductions in regional water limits, and formation of transboundary emergency councils for flood mitigation. These measures temporarily reallocate water and may generate short-lived cooperation across administrative or national boundaries, yet management reverts to prior practices once the crisis passes, and no long-term strategy for variability or scarcity is implemented (Schlüter & Herrfahrdt-Pähle, 2011). Proposed pathways such as diversification to less water-intensive crops, reuse of drainage water, or broader diversification of water use remain unadopted; thus, resource-related conflicts are repeatedly managed rather than transformed. Food-system analysis at global and regional scales situates such basin-specific tensions within a wider field of resource competition. Climate variability, soil degradation, water scarcity, and biodiversity loss reduce yields and alter growing conditions, while arable land is depleting and water scarcity is rising. As

competition for land and water intensifies, the capacity to meet nutritional needs becomes more precarious, especially for vulnerable populations already constrained by income and gender inequalities. Conflicts over land use between agriculture, urbanisation, and industrialisation present additional challenges to sustainable management, particularly in water-scarce regions where political instability and conflict heighten dependence on food imports (Agarwala et al., 2022). In such contexts, resource-related conflicts are expressed not only as local struggles over irrigation flows but also as tensions between sectors, regions, and states embedded in uneven trade regimes and supply-chain dependencies (Agarwala et al., 2022; Scheffran, 2023). Climate–security research conceptualises these patterns as part of a broader cascade in which global heating acts as a "threat multiplier," destabilising interactions between natural and social systems, including critical infrastructures and supply networks. Weak countries highly dependent on agriculture, vulnerable to weather extremes, and with low levels of aid are particularly prone to intensified conflict factors, with unfair distribution of climate-change costs between those who cause and those who suffer them. Environmental and resource policies, such as large dams in Turkey, Ethiopia, or Laos, have already become security issues for downstream states, illustrating how hydrological interventions generate transboundary resource-related tensions. Military and political responses that securitise climate and resource issues risk triggering downward spirals, diverting resources from cooperative solutions and potentially reinforcing structural inequalities that underlie conflicts (Scheffran, 2023). These contemporary configurations provide a rigorous comparative framework for analysing Bronze Age Aegean resource-related conflicts as socio-ecological struggles over land, water, and maritime routes embedded in hierarchical governance and exposed to climatic variability, rather than as isolated episodes of "invasion" or "collapse." In subsequent chapters, spatial patterns of Cretan terracing, cistern distribution, and spring access documented in Appendix A will be interpreted through this lens of entrenched competition and hydro-hegemony (Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022; Scheffran, 2023; Adefemi et al., 2023).

10 Minoan Collapse within Late Bronze Age Systemic Crisis

10.1 Network Theory and Trade Dependency

10.1.1 Maritime trade routes and hubs

Contemporary food-system and security research provides the clearest empirical basis for analysing maritime trade routes and hubs as vulnerable components of wider socio-ecological networks. Global assessments of food security argue that dependence on long and complex supply chains exposes regions to disruptions from climate variability, geopolitical conflict, and public-health emergencies. Erratic droughts and floods destabilise agricultural production and can reduce exportable surpluses, while land and water scarcity, biodiversity loss, and environmental degradation narrow the resource base available for trade. Market-access disparities and unfavourable trade agreements further disadvantage small-scale producers, and reliance on global supply chains, starkly revealed during the COVID–19 pandemic, amplifies vulnerability to transport and logistics shocks. Ports and maritime corridors thus emerge as critical chokepoints where environmental, economic, and political stresses converge, with interruptions rapidly translating into shortages and price spikes for import-dependent populations (Agarwala et al., 2022). Climate–security analysis frames these dynamics as part of a broader cascade in which global heating acts as a "risk multiplier" that destabilises critical infrastructures and supply networks. Loss or degradation of water, arable land, forests, and biodiversity, together with more frequent weather extremes, threatens human security and undermines political stability, particularly in fragile regions with weak governance and limited management capacity. In this context, maritime trade routes form part of the water–energy–food nexus: constrained grain exports, whether through war, sanctions, or climatic crop failures, can trigger global food crises, as documented for disruptions to Russian and Ukrainian grain and fertiliser exports that generated agricultural crises in parts of Africa and Latin America. Energy and food transport corridors become contested strategic assets, and blockades or naval threats can propagate far beyond their immediate theatres, illustrating how trade hubs function within multi-scalar networks of risk and dependence (Scheffran, 2023; Agarwala et al., 2022). Epidemic-governance work on Ebola virus disease (EVD) sharpens this picture by detailing

how maritime regulations directly affect food flows. Coastal fisheries and seafood supply essential calories, fatty acids, and micronutrients in West African countries affected by EVD, yet International Maritime Organization rules have required vessels exporting seafood to undergo 21-day quarantines, degrading product quality, reducing fish prices, and disrupting regional trade. Authors argue that seafood security, public health, and environmental governance form an intertwined system, and that neglecting food and well-being as determinants of public health delayed recognition of early warning signs. They call for early-warning networks, environmental-health monitoring, and strengthened foodsecurity institutions, together with cross-border collaboration and creative governing arrangements at regional and international levels. Maritime trade routes here appear simultaneously as lifelines for nutrition, vectors for pathogens, and objects of regulatory control, with quarantine regimes reconfiguring the effective connectivity of ports and shipping hubs in real time (Khan & Sesay, 2015). Environmental-health and AI-based public-safety studies extend this network perspective by stressing the need for dense, real-time monitoring of infrastructural vulnerability, including coastal and urban systems. AI-enabled tools

now support disaster vulnerability assessment, emergency response, and smart infrastructure management through continuous data collection and predictive modelling. For water and air quality, sensor networks integrated with satellite data provide real-time alerts and support targeted interventions, while raising concerns about data privacy, algorithmic bias, and unequal access. Port cities and maritime hubs, as nodes where pollution, flooding, and industrial hazards intersect, are prime candidates for such monitoring architectures, yet governance and ethical constraints can limit deployment precisely where vulnerability is highest (Adefemi et al., 2023). For the Bronze Age Aegean analysis developed in this thesis, these findings help conceptualise maritime hubs not simply as static points on trade maps but as dynamic intersections of risk information, institutional capacity, and socio-ecological exposure. Comparative insights from food-system governance underline that maritime connectivity interacts with domestic production regimes and social inequality. Governments use trade agreements, strategic reserves, and environmental regulations to shape their position within global supply chains, but sectoral silos, implementation gaps, and limited institutional capacity often hinder coherent responses. Regions facing water scarcity, political instability, and conflict, such as parts of the Middle East and North Africa, become heavily dependent on food imports, making secure maritime corridors and port infrastructures central to human security. Land-use conflicts between agriculture, urbanisation, and industrialisation further complicate efforts to maintain coastal agrarian hinterlands that support export and import activities, and resource scarcity sharpens political contestation over harbour-adjacent land and freshwater (Agarwala et al., 2022; Scheffran, 2023). Within the network-theoretic and political-ecology framework of this thesis, these contemporary cases motivate treating Late Bronze Age Cretan maritime routes and hubs, mapped from 2025 field observations in Appendix A, as embedded in analogous cascades of environmental stress, food-system dependence, and governance capacity. Rather than positing linear "sea-people" invasions or single-event trade collapses, the comparative material suggests that small perturbations in multiple linked subsystems (agricultural yields, coastal water security, port health, regional politics) could have collectively driven non-linear reconfigurations of Aegean maritime connectivity, with island polities such as Crete particularly exposed due to their structural reliance on sea-borne exchange for both subsistence and elite reproduction (Agarwala et al., 2022; Khan & Sesay, 2015; Scheffran, 2023; Adefemi et al., 2023).

10.1.2 Supply-chain resilience and vulnerabilities

Resilience and fragility of supply chains emerge in current food-system analysis as properties of coupled production, distribution, and governance networks rather than of transport links alone. Structural dependence on increasingly unpredictable climate regimes, depleting soils, and rising water scarcity constrains the stability of crop yields and hence the reliability of upstream nodes that feed into trade and provisioning systems. Erratic droughts and floods disrupt agricultural production, alter growing conditions, and generate crop failures that compromise global and regional food supplies, while degradation of arable land and biodiversity intensifies competition for key resources. Under such conditions even well-developed trade corridors can only buffer variability if sourcing regions retain ecological capacity and institutional flexibility. Governmental interventions significantly reconfigure this resilience landscape. Subsidies, land-use regulations, and investments in agricultural research and technology influence which crops are cultivated, where production is concentrated, and how

intensively soils and water are exploited. These instruments can raise average yields and diversify supply, but they may also incentivise monocultures on marginal land, accelerate environmental degradation,

and therefore increase long-term volatility. Policies that promote intensive farming for short-term output can create path dependencies that reduce adaptive capacity when climate anomalies hit, illustrating how supply chains inherit vulnerabilities from policy regimes as much as from biophysical shocks. Similar trade-offs appear in trade policy, where efforts to secure domestic markets can modify global prices and access, redistributing risk along international chains rather than reducing it overall. Downstream segments of food systems transmit shocks through access, utilisation, and stability dimensions. Income inequality and gender inequality restrict households' ability to smooth consumption across bad harvest years, making them more exposed to supply interruptions and price spikes even where aggregate availability is adequate. Social safety nets, income support, and minimum-wage regulations partially mitigate these effects by stabilising purchasing power, while public-health and nutrition programmes shape whether available food translates into effective nutritional status. Yet implementation gaps, limited infrastructure, and sectoral policy silos often prevent coherent, crosssectoral responses, leaving critical nodes in the chain without robust redundancy or surge capacity (Agarwala et al., 2022). For Late Bronze Age Crete, where palatial redistribution likely channelled staple flows through a limited number of storage and administrative hubs (Appendix A), these patterns suggest a structural similarity to modern systems in which concentrated control and uneven buffering magnify the consequences of upstream perturbations. Climate–security research situates these supply vulnerabilities within multi-scalar crisis chains. Global heating is characterised as a risk multiplier that disturbs the balance between natural and social systems, affecting critical infrastructures and supply networks in ways that can lead to production losses, price rises, and financial crises transmitted through global markets. Loss or degradation of water, arable land, forests, and biodiversity, together with weather extremes, threatens livelihoods and human security, particularly in fragile regions with weak governance and inadequate management capacities. In such settings, erosion of social order and institutional collapse may compromise transport, storage, and market infrastructures, amplifying the impact of any disruption to agricultural output or trade. Security-relevant mechanisms explicitly include lack of water and food, storm and flood disasters that displace populations, and environmentally induced migration, all of which can disrupt both local distribution systems and longer-distance trade (Scheffran, 2023). Within a network-theoretic framework, these findings underscore that supply-chain resilience depends on the integrity of social and political institutions as much as on physical connectivity. Epidemic-focused work on Ebola virus disease (EVD) adds another axis of fragility. Vulnerable, food-insecure populations with inadequate health-care infrastructure are said to "signal potential crisis" in the event of epidemics, because disease shocks interact with and exacerbate existing weaknesses in food systems. In West African EVD-affected countries, coastal fisheries and seafood contribute substantially to nutritional well-being, yet International Maritime Organization rules mandating 21- day quarantines for seafood-exporting vessels have degraded product quality, lowered fish prices, and disrupted regional trade, revealing how public-health regulations can reconfigure maritime segments of food chains. Proposed responses emphasise early-warning networks, environmental-health monitoring, strengthened food-security institutions, and cross-border collaboration and governance innovations, highlighting that resilient supply under epidemic stress requires integration of health, environmental, and food-policy domains rather than reliance on reactive, single-sector

measures (Khan & Sesay, 2015). Technological initiatives around artificial intelligence (AI) in environmental health and public safety demonstrate both opportunities and new vulnerabilities for supply chains. AI-enhanced water-quality monitoring combines sensor networks, machine learning, and satellite imagery to provide real-time insights into contaminants, identify pollution sources, and support targeted remediation and regulatory action, thereby stabilising key inputs for agriculture and human consumption. At the same time, AI deployments raise issues of data quality, privacy, bias, transparency, and unequal access, implying that benefits may accrue unevenly and that failures or attacks on AI systems could introduce new points of fragility in monitoring-dependent infrastructures (Adefemi et al., 2023). These characteristics are analytically relevant when considering how information flows, early warning, and decision-support architectures condition Minoan supply resilience, even though ancient systems lacked digital technologies. Finally, sustainability-oriented analysis identifies strategies aimed explicitly at strengthening supply-chain resilience. Promoting localised and regional food systems can reduce dependency on global supply chains and associated exposure to distant shocks, while policies that support agroecological and climate-smart agriculture seek to maintain productive capacity under changing climatic conditions. Investments in rural infrastructure, including storage, transport, and market access, along with training programmes for farmers and public-awareness campaigns on sustainable consumption,

are presented as means to reinforce both environmental and economic dimensions of resilience. International collaboration around knowledge sharing, capacity building, and trade policies that incorporate environmental and social criteria is likewise framed as essential for building coordinated, robust responses to climate and market volatility (Agarwala et al., 2022). These contemporary configurations collectively provide a comparative matrix for evaluating the cascading vulnerabilities of Late Bronze Age Cretan supply networks reconstructed from Appendix A, and for formulating modelled lessons on how diversified production, distributed storage, and multi-scalar governance might mitigate systemic risk in both ancient and modern settings (Agarwala et al., 2022; Scheffran, 2023; Khan & Sesay, 2015; Adefemi et al., 2023).

10.2 Comparative Regional Collapses

10.2.1 Aegean and Eastern Mediterranean contexts

Patterns of crisis in the wider Aegean and eastern Mediterranean can only be reconstructed where climatic, environmental, and governance signals are explicitly traced. Multi-scalar analysis of a large irrigated basin in Central Asia shows how river-dependent agrarian systems respond to combined shocks: loss of a terminal sea and its fisheries, political reconfiguration after state breakup, and a severe drought in 2000/2001 interacted with deteriorating infrastructure and institutional rigidity to reduce the capacity of the social–ecological system to absorb and learn from disturbances. This configuration of cumulative environmental degradation, path-dependent irrigation, and low adaptability provides a comparative template for thinking about Late Bronze Age riverine and deltaic polities east of Crete, even though direct eastern Mediterranean case studies are not detailed in the available sources. Governance responses in Uzbekistan illustrate how crises across a basin translate into ad hoc measures without structural change. Droughts and floods triggered emergency bans on waterintensive crops, temporary reductions in regional water limits, and short-lived transboundary councils, but once hydrological extremes

abated, management reverted to earlier practices; no long-term strategy for variability, such as diversification to less water-intensive crops or reuse of drainage water, was implemented (Schlüter & Herrfahrdt-Pähle, 2011). Informal institutions such as patronage and corruption further constrained implementation, maintaining high vulnerability to future shocks. For Aegean and eastern Mediterranean polities reliant on complex irrigation or terraced agriculture, this pattern suggests that repeated episodes of climatic stress could have produced similar cycles of reactive intervention without fundamental reconfiguration of land and water regimes. Food-system research at global and regional scales provides additional context for eastern Mediterranean collapse narratives by specifying how climate variability, resource depletion, and biodiversity loss act through political economy. Governments face increasingly unpredictable droughts and floods that disrupt crop yields and food availability, while overexploitation of soils and water and rising scarcity intensify competition for land and freshwater. At the same time, economic and gender inequalities, policy silos, and weak infrastructure restrict equitable access to food, so that shortages disproportionately affect vulnerable groups. Conflict and political instability further disrupt production, distribution, and implementation of sustainable practices, particularly in water-scarce regions such as the Middle East and North Africa, where dependence on food imports is high (Agarwala et al., 2022). These findings indicate that eastern Mediterranean crises around the end of the Bronze Age cannot be plausibly framed as climate-driven alone when analogous modern regions exhibit strongly mediated outcomes. Maritime settings in the eastern Mediterranean share structural similarities with West African coastal systems affected by Ebola virus disease. In that region, seafood provides essential caloric intake and micronutrients, but International Maritime Organization rules imposing 21-day quarantines on vessels exporting seafood altered product quality, fish prices, and regional trade, demonstrating how public-health governance reconfigures maritime networks. Scholars argue that seafood security, public health, and environmental governance form an intertwined system and call for early-warning networks, environmental-health monitoring, and strengthened food-security institutions, combined with cross-border collaboration and innovative governance arrangements. For Late Bronze Age maritime hubs in the Aegean and Levant, this underscores that port and shipping vulnerabilities likely involved coupled food- and health-system stresses rather than simple military disruption. Epidemic-focused analyses in West Africa also emphasise that vulnerable, food-insecure populations with inadequate health-care infrastructure "signal potential crisis" under emerging zoonoses. Effective response to Ebola in Uganda depended on rigorous isolation, surveillance, and treatment protocols anchored in local authorities and donor support,

with key lessons centring on augmentation of local capacity and institutional infrastructure. More generally, adaptive management is proposed as a way to treat uncertainties from climate change, incomplete knowledge, and institutional constraints as a basis for iterative learning; proposed models integrate community-based production, public–private health partnerships, and centralised surveillance agencies within a unified governance framework (Khan & Sesay, 2015). These configurations highlight how public-health resilience in any eastern Mediterranean context would have depended on pre-existing institutional density and local capacity, not solely on the character of climatic or military shocks. Environmental-health and AI-enabled public-safety work helps to conceptualise eastern Mediterranean hubs as nodal points in complex risk networks. In contemporary systems, real-time monitoring of air and water quality, disaster vulnerability, and critical infrastructure increasingly relies on AI-driven sensor networks and predictive analytics, but these tools demand robust regulatory frameworks to address

privacy, bias, and accountability. Recommendations stress interdisciplinary collaboration, community engagement, and adaptive policy frameworks capable of responding to emerging environmental and health threats (Adefemi et al., 2023). While no ancient analogue exists, the emphasis on information integration, early warning, and ethical governance underpins the crisis-management and political-ecology lenses applied in this thesis when comparing Cretan palatial trajectories to other Aegean and eastern Mediterranean polities. Finally, resilience-oriented analysis of the Amudarya basin demonstrates that repeated shocks, including the collapse of Aral Sea fisheries, did not by themselves trigger structural transformation; strong vested interests, centralised governance, lack of stakeholder involvement, and weak learning processes prevented reorganisation toward less water-intensive production. Only modest bottom-up signs, such as emerging trust in Water User Associations and farmer resistance to state orders, hint at potential adaptive change (Schlüter & Herrfahrdt-Pähle, 2011). This pattern of "crisis without transformation" directly informs the comparative frame for Late Bronze Age Aegean and eastern Mediterranean collapses developed in this chapter, in which Minoan outcomes are interpreted alongside other regional trajectories as products of interacting environmental, institutional, and public-health vulnerabilities rather than of singular catastrophic events (Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022; Khan & Sesay, 2015; Adefemi et al., 2023).

10.2.2 Lessons from diverse societal trajectories

Comparative work on large irrigated basins, epidemic-prone coastal regions, mountain catchments, and globalised food systems allows several cross-cutting insights into how different societies navigate prolonged socio-ecological stress. In the Amudarya basin, a cascade of shocks including Aral Sea collapse, state breakup, and a severe 2000/2001 drought did not generate systemic transformation. Instead, hierarchical water management, fragmentation of responsibilities, and the political centrality of cotton kept the social–ecological system locked into an undesirable but resilient regime, with continued overuse, salinization, and loss of ecosystem services despite evident degradation. This trajectory illustrates how strong feedbacks, rents, and centralized authority can stabilise maladaptive configurations, an outcome that must be considered when interpreting the persistence of vulnerable arrangements in Late Bronze Age Crete. Institutional responses to environmental deterioration in this basin further specify what "non-learning" looks like. Land and water reforms were driven by donor agendas, farm restructuring, and intra-ministerial power struggles rather than by recognition of resource limits. Extreme events such as droughts and floods triggered bans on particular crops, temporary cuts in water limits, and emergency councils, but practices reverted once crises passed, and no long-term strategy for variability, reuse of drainage water, or diversification to less water-intensive crops was adopted. Wetland restoration schemes demonstrated high ecological recovery potential and local livelihood benefits but remained weakly embedded in allocation rules, so their contribution to basin-wide resilience stayed marginal (Schlüter & Herrfahrdt-Pähle, 2011). These patterns caution against assuming that episodes of destruction or stress in Aegean contexts automatically produced durable institutional innovation. Other trajectories underscore the importance of social differentiation and knowledge in adaptation. In the Himalayas, environmental change, declining water availability, and increased disaster risk have pushed male out-migration and shifted heavy agricultural and livestock workloads onto women. Reduced access to water for food production, drinking, and sanitation has particularly increased women’s vulnerability to water-

borne and nutrition-deficiency health risks, while women form the majority of disaster victims owing to limited preparedness and greater exposure. Authors argue that traditional adaptation knowledge held by rural women is crucial for ecological restoration and sustainable resource management, and call for gender-sensitive development agendas and empowerment in natural-resource governance as core elements of future climate adaptation (Tiwari & Joshi, 2015). This experience suggests that reconstructions of Minoan socio-ecological responses must pay attention to intra-community inequalities, not only elite decisions. Epidemic governance in West Africa offers a contrasting example where crises occasionally opened windows for partial learning. Analyses of Ebola virus disease emphasise that vulnerable, food-insecure populations with inadequate health-care infrastructure signal potential crisis, and that governance mechanisms linking local food systems, environmental health, and public health across scales are required. Effective EVD interventions in Uganda relied on rigorous isolation, surveillance, and treatment protocols supported by local authorities and donors, with the key lesson that augmenting local capacity and strengthening institutional infrastructure are central to resilience. Proposed African models for combining food and health security include community-based production systems focused on sufficiency, public–private partnerships for sanitary research and standards, and centralised agencies for pathogen monitoring and surveillance (Khan & Sesay, 2015). These configurations exemplify how multi-level governance can, under some conditions, shift a vulnerable system toward greater adaptive capacity. At the global scale, food-security research documents yet another family of trajectories shaped by climate variability, resource depletion, and policy regimes. Governments confront increasingly erratic droughts and floods that disrupt production, while soil degradation, water scarcity, and biodiversity loss erode the ecological basis of agriculture. Policy instruments such as subsidies, research investment, and land-use regulation influence yields and crop choices, but can also drive environmental degradation and inequitable access. Income and gender inequalities restrict the ability of vulnerable populations to buffer shocks, and sectoral silos plus implementation gaps undermine coherent, cross-sectoral responses. Conflict and political instability further disrupt production and distribution, particularly in water-scarce regions, while dependence on global supply chains, vividly exposed during the COVID–19 pandemic, magnifies vulnerability to distant disruptions (Agarwala et al., 2022). These findings highlight that similar climatic pressures can yield divergent outcomes depending on governance quality, equity, and infrastructural capacity. Security-oriented analyses extend this point by conceptualising climate change as a "threat multiplier" that destabilises critical infrastructures and supply networks. Loss of water, arable land, forests, and biodiversity, together with more frequent weather extremes, threatens livelihoods and human security, especially in fragile regions with weak governance. In such settings, environmental degradation undermines health systems and problem-solving capacity, increasing risks of poverty, hunger, violence, and displacement. Large dam projects in transboundary basins already function as security issues for downstream states, illustrating how resource interventions can generate or reconfigure regional rivalries (Scheffran, 2023). For the Late Bronze Age eastern Mediterranean, these patterns justify treating water and land interventions as potential axes of geopolitical tension, not merely technical adjustments. Together, these diverse cases suggest that socio-ecological crises unfold along multiple pathways: persistent maladaptation under strong path dependence; partial but socially uneven adaptation; and, more rarely, coordinated transformations leveraging cross-scale governance. In subsequent discussion, these lessons are used as comparative scaffolds for interpreting the Cretan evidence assembled in Appendix A, and for deriving modelled

scenarios in which Minoan collapse emerges from interacting failures of water management, social equity, and institutional learning rather than from single-factor shocks (Schlüter & Herrfahrdt-Pähle, 2011; Tiwari & Joshi, 2015; Khan & Sesay, 2015; Agarwala et al., 2022).

11 Cascading Failure Modeling

11.1 Complex Adaptive Systems Analysis

11.1.1 Panarchy and adaptive cycles

Panarchy and adaptive-cycle thinking, originally developed to describe nested cycles of growth, conservation, release, and reorganisation across interacting scales of ecological and social-ecological systems (Gunderson & Holling, 2002), are often invoked to frame collapse as a recurrent phase within such systemic oscillations. For later second-millennium BC Europe, this approach has been explicitly discussed as a way to conceptualise cycles of prosperity and contraction, with collapse treated as one stage among others in shifting configurations of social complexity. However, strict application of formal resilience theory has been criticised for reducing culture to material attributes and for downplaying ideological, political, and religious transformations that give crises their historically specific character. In that critique, resilience is instead assessed diachronically through markers of retention, loss, adaptation, innovation, and introduction of societal

features, rather than via a generic adaptive-cycle template (Molloy, 2022). For the present modelling framework, panarchy is therefore used heuristically rather than as a rigid schema. Analysis of the Amudarya social–ecological system demonstrates that repeated shocks, including Aral Sea collapse, post-Soviet state breakup, and the severe 2000/2001 drought, did not drive the system into a qualitatively new regime. Instead, path-dependent irrigation expansion, deterioration of infrastructure, and low management standards locked the basin into a highly irrigated, water-intensive mode despite mounting degradation and man-made water shortage. From a panarchy perspective, these developments illustrate a prolonged conservation phase in which reinforcing feedbacks, rents, and centralised governance inhibit release and reorganisation, producing what has been termed an "undesirable but resilient" regime. Institutional responses to ecological deterioration in this basin further clarify where adaptive cycles stall. Land and water reforms were motivated primarily by external donor agendas, farm restructuring, and power struggles in the Ministry of Agriculture and Water Resources, rather than by recognition of resource overuse. Extreme events such as droughts and floods triggered short-lived emergency measures, including crop bans, temporary reductions in water limits, and transboundary flood-mitigation councils, but once crises passed, management reverted to previous practices. Technical measures sought to maintain current productivity rather than to break the cycle of overuse and degradation; informal patronage and corruption constrained implementation. Despite a cascade of shocks and regime shifts in subsystems, including collapse of Aral Sea fisheries, no basin-wide structural transformation followed. In panarchical terms, these patterns exemplify crisis without systemic "release," and adaptation within, rather than transformation of, the dominant attractor. At the same time, small-scale signals of potential reorganisation appear. Decrees in 2007 and 2008 envisaged a reduction of cotton area by 5 % in favour of food crops, explicitly acknowledging increasing soil salinity and water scarcity. Introduction of Water User Associations (WUAs), though initially absorbed into patronage networks, created new organisational nodes that some farmers began to trust as water providers and training agents. Land reforms shifted political dynamics in favour of local actors, and growing resistance to the state order system, together with calls in stakeholder workshops for stronger formal institutions, human-capital investment, and improved planning and

adaptation procedures, indicate nascent bottom-up processes. These developments have been interpreted as modest nuclei of adaptive change that could, if self-organisation overcomes top-down resistance, initiate a transformation toward less water-intensive production (Schlüter & Herrfahrdt-Pähle, 2011). This configuration closely matches panarchy's emphasis on cross-scale interactions, where innovations at lower levels may, under favourable conditions, propagate upward and reconfigure higher-level regimes. Food-system research at national and global scales supplies complementary evidence on how adaptive cycles operate across interconnected subsystems. Governments confront increasingly unpredictable droughts and floods, resource depletion, and biodiversity loss, while simultaneously navigating globalised trade dynamics, income and gender inequalities, sectoral policy silos, and technological disparities. Policies such as subsidies, strategic reserves, social safety nets, and environmental regulations aim to stabilise availability, access, utilisation, and stability, yet often introduce trade-offs in which short-term production gains exacerbate long-term degradation or inequity (Agarwala et al., 2022). These findings show that food systems can exhibit resilience in some dimensions (e.g. availability) while eroding in others (e.g. equity, ecological integrity), complicating any simple mapping onto a single adaptive cycle. In this thesis, panarchy and adaptive cycles are therefore operationalised as diagnostic tools for identifying where Minoan socio-ecological subsystems, reconstructed from Appendix A, may have been caught in prolonged conservation phases, where local innovations or community practices could have functioned as incipient reorganisation, and how cross-scale linkages between hydrology, agriculture, governance, and health compare with documented modern cases of crisis without transformation or partial, uneven adaptation (Molloy, 2022; Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022; Adefemi et al., 2023).

11.1.2 Role of climate as threat multiplier

Evidence from contemporary social–ecological systems repeatedly shows climate variability acting less as an autonomous "cause" of crisis than as a factor that amplifies pre-existing vulnerabilities in water, food, health, and governance. In the Amudarya basin, semi-arid conditions and complete dependence on surface-water irrigation already tied agriculture, ecosystems, and institutions closely together; projected climate-driven changes in river flow are expected to aggravate what is explicitly described as a man-made water shortage within a degraded, salinized landscape. Here, climate change interacts with

entrenched overuse, deteriorating infrastructure, and path-dependent irrigated cotton regimes, lowering the capacity of the social–ecological system to absorb shocks such as the severe 2000/2001 drought. Rather than triggering collapse on its own, altered flow regimes intensify the impact of drought episodes on already stressed land, water, and livelihoods, illustrating a threat-multiplier role that is central to the complex adaptive systems perspective adopted in this thesis (Schlüter & Herrfahrdt-Pähle, 2011). Security-oriented analyses generalise this pattern to the global scale by conceptualising global heating as a "risk multiplier" that disturbs interactions between natural and social systems, including critical infrastructures and supply networks. Loss or degradation of vital resources such as water, arable land, forests, and biodiversity, together with more frequent weather extremes, is argued to threaten human security and undermine political stability, especially in fragile regions with weak governance and limited management capacity. In such settings, environmental change undermines problem-

solving capacities and health infrastructures, contributing to spirals of poverty, hunger, corruption, crime, violence, and displacement (Scheffran, 2023). Climate thus operates primarily by destabilising the conditions under which other drivers, such as inequitable land tenure, authoritarian resource governance, or inadequate health systems, become more likely to produce cascading failures rather than incremental stress (Scheffran, 2023; Schlüter & Herrfahrdt-Pähle, 2011). Food-system research offers a more disaggregated view of these cascades. Governments face increasingly unpredictable droughts and floods that disrupt agricultural production, affecting crop yields and food availability, while resource depletion in soils and water, and accelerating biodiversity loss, constrain the ecological basis of food supply. As arable land depletes and water scarcity rises, competition for resources intensifies, and the capacity to meet nutritional needs becomes more precarious, particularly for vulnerable populations already limited by income inequality, gender disparities, and inadequate infrastructure. Climate anomalies therefore magnify the consequences of policy failures, market-access barriers, and land-use conflicts, rather than acting as sufficient causal agents in their own right. Analyses of governmental efforts to address food security and sustainability further show how climate variability interacts with globalisation, social inequality, and institutional fragmentation. Disruptions to global supply chains during the COVID–19 pandemic, for example, exposed how dependency on distant production zones can convert local weather shocks elsewhere into domestic food-access crises, especially where safety nets and logistics are weak. Sectoral policy silos and implementation gaps hinder coherent adaptation, so that climate-related extremes translate into systemic stress across agriculture, trade, and social protection, again underscoring a multiplier logic in which environmental forcing amplifies vulnerabilities generated by governance arrangements (Agarwala et al., 2022). Epidemic-focused work on Ebola virus disease and other zoonoses introduces public health into this interaction. Vulnerable, food-insecure populations with inadequate health-care infrastructure are described as "signalling potential crisis" during epidemics; climatic variability and environmental degradation shape disease ecologies, but outcomes depend on whether governance mechanisms can link food systems, environmental health, and public health across sectors and scales. Suggested models for control and adaptation combine community-based production systems, public–private health partnerships, and centralised surveillance agencies, and are framed within adaptive-management logics that explicitly recognise uncertainties due to climate change and institutional constraints. In these accounts, climate-related hazards multiply epidemic risks by stressing food security and water quality, yet crisis trajectories are determined by institutional capacity, social networks, and decision-support tools (Khan & Sesay, 2015). Environmental-health syntheses reinforce this understanding by showing how air and water pollution, inadequate waste management, disaster risk, and occupational hazards constitute a dense hazard landscape in which climate change modifies baseline conditions. For disaster risk reduction, increasing frequency and intensity of floods, fires, and storms interact with complex, interdependent infrastructures, so that localised climatic events can cascade through energy, transport, and health systems. AI-enabled monitoring and predictive analytics are proposed as tools for early warning and targeted intervention, but their effectiveness hinges on ethical governance, data quality, and inclusivity, again placing climate within a broader assemblage of technological, institutional, and social determinants of risk (Adefemi et al., 2023). Together, these strands justify treating climate in this thesis not as a singular "cause" of Minoan collapse, but as a threat multiplier that perturbed hydrological regimes, agricultural yields, and disease ecologies in ways conditioned by land use, hydraulic infrastructure, and

governance capacities reconstructed for Crete in Appendix A. The complex adaptive systems and cascading-failure models developed here therefore operationalise climate as one driver among many, whose significance lies in how it amplified existing fragilities in water security, food systems, and public health rather than in any

deterministic capacity to produce collapse on its own (Schlüter & Herrfahrdt-Pähle, 2011; Scheffran, 2023; Agarwala et al., 2022; Khan & Sesay, 2015).

11.2 Failure Pathways and Critical Thresholds

11.2.1 Identification of tipping points

Identifying tipping points in a complex socio-ecological system requires locating moments when interacting subsystems jointly approach, or cross, critical thresholds rather than isolating singular causal events. Political-ecology analysis of the Amudarya basin shows how slow land and water degradation, culminating in the desiccation of the Aral Sea and collapse of its fisheries, marked a regime shift in which previously prosperous local economies and health conditions deteriorated sharply. Yet this ecological tipping point did not automatically trigger transformation of the wider governance regime; instead, strong feedbacks from cotton rents, hierarchical water-management culture, and fragmentation of responsibilities locked the system into an undesirable but resilient state, with continuing salinization, waterlogging, and poverty. In this case, a biophysical threshold (loss of a terminal sea and associated ecosystem services) was reached, but institutional thresholds for reorganisation were not, illustrating that multiple, partially decoupled tipping domains must be tracked within any cascading-failure model. The same basin reveals earlier, less visible thresholds in resilience. Progressive reduction of inflow, disappearance of most deltaic lakes, and a 90 % contraction of Tugai forest area over the 20th century constituted a slowly unfolding erosion of buffering capacity long before fisheries collapsed. Planners recognised the consequences of expansion and leaching, yet assumed future technical fixes, such as inter-basin diversions, would resolve them. This confidence sustained a "vicious cycle" in which environmental degradation prompted further irrigation expansion and technical mitigation, maintaining short-term cotton yields while steadily decreasing overall resilience. The 2000/2001 drought then exposed how far the system had moved toward a critical zone: grain output in Karakalpakstan dropped by 54 %, cotton by 30–40 %, and access to drinking water and other ecosystem services declined sharply. Within a panarchical framework, the combination of cumulative ecosystem loss and heightened sensitivity to a single drought can be read as an empirical signature of an approach to, or crossing of, a social–ecological tipping point. Resilience theory applied to this case further clarifies diagnostic criteria. The Amudarya system has undergone at least two regime shifts: collapse of Aral Sea fisheries and basin-wide soil salinization and waterlogging. Despite these shocks, powerful feedbacks from the state order system, cotton-based rents for elites, and a centralised governance regime prevented a transition to less water-intensive modes of production. Window-of-opportunity conditions after the Soviet breakup were missed, because acceptance of the need for change, trust and leadership, cutback of perverse incentives, and investments in social and human capital were absent. Stakeholder involvement, social entrepreneurship, and institutional support that might promote reframing of perspectives and adaptive governance were also missing. From a tipping-point perspective, this indicates that critical thresholds in ecological subsystems can be crossed without corresponding

tipping in governance subsystems; instead, path dependence and lock-in maintain the existing attractor. Nonetheless, very small but significant signals of potential new basins of attraction appear. Presidential decrees in 2007 and 2008 acknowledged increasing salinity and water scarcity and provided for a 5 % reduction in cotton area in favour of food crops. Land reforms and the emergence of Water User Associations created embryonic institutional forms that, in some localities, began to earn farmer trust and shift political dynamics towards local actors. Participatory workshops recorded calls from communities for stronger formal institutions, better planning, and improved adaptation procedures (Schlüter & Herrfahrdt-Pähle, 2011). In panarchy terms, these bottom-up processes can be interpreted as early indicators of reorganisation at lower scales, with the potential to cascade upward if self-organisation around them overcomes higher-level resistance. Climate–security analysis generalises this logic of interacting thresholds by conceptualising global heating as a risk multiplier that destabilises resource and infrastructure systems through complex impact chains. Losses of water, arable land, forests, and biodiversity, together with more frequent extremes, push vulnerable regions towards spirals of poverty, hunger, institutional erosion, and conflict, particularly where governance is weak and management capacities are low. Under such conditions, the ability to solve problems and maintain health systems can itself pass tipping points, yielding qualitatively different dynamics of insecurity and displacement (Scheffran, 2023). Food-system research adds that when climate variability, land and water scarcity, and biodiversity loss converge with income and gender inequalities, policy silos, and infrastructure

deficits, food systems may cross from relatively stable, though inequitable, configurations into states marked by chronic volatility and widespread food insecurity (Agarwala et al., 2022). These comparative trajectories suggest operational criteria for identifying tipping points in the Minoan case: progressive erosion of ecological buffers (e.g. spring reliability, soil quality), increasing sensitivity of agricultural output to climatic anomalies, repeated but non-transformative crisis responses in water and food governance, and emergent but constrained local initiatives analogous to Water User Associations. In the cascading-failure model developed here, critical thresholds are therefore defined not solely by climatic indices, but by co-occurring inflections in hydrological reliability, production volatility, and institutional adaptability, interpreted in light of the systemic lock-in and limited transformation documented for other socio-ecological regimes (Schlüter & Herrfahrdt-Pähle, 2011; Scheffran, 2023; Agarwala et al., 2022; Adefemi et al., 2023). (See Figure A.16 for a qualitative summary of socio-ecological vulnerability zones across Crete, complementing the risk matrix in Figure A.15.)

11.2.2 Recovery limitations and adaptive capacity loss

Empirical work on large irrigation systems and food-related crises documents how recovery from major shocks can stall, leading to progressive loss of adaptive capacity rather than renewal. In the Amudarya basin, three large shocks since the late 20th century (Aral Sea collapse, Soviet breakup, and the 2000/2001 drought) exposed severe vulnerability, yet did not generate a transition toward less water-intensive production. Instead, the social–ecological system remained locked into an irrigated cotton regime despite widespread soil salinization, waterlogging, ecosystem collapse, and deteriorating health conditions for rural populations deprived of safe drinking water. Continued reliance on the state order system for cotton and wheat, enforced through low

procurement prices and quota obligations, left farmers with little incentive or capacity to invest in maintenance of Water User Associations or in alternative practices, thereby undermining the very institutions that might have supported adaptive change. This configuration exemplifies "recovery" that restores core structures of production while further eroding long-term resilience. Institutional responses to environmental degradation and hydrological shocks in the same basin deepen this picture of adaptive capacity loss. Land and water reforms were driven largely by donor agendas, farm dismantling, and power struggles within the Ministry of Agriculture and Water Resources, rather than by recognition of ecological limits. Environmental problems were addressed with technical fixes aimed at preserving short-term productivity; the underlying cycle of overuse and degradation remained intact. Extreme events such as droughts or floods triggered ad hoc emergency measures, including temporary crop bans, reductions in water limits, and creation of transboundary emergency councils, but management rapidly reverted to earlier practices once the crisis passed. Informal institutions, notably patronage and corruption, further constrained implementation, leaving the system vulnerable to future disturbances and slow drivers such as ecosystem-service loss. From a complex-systems perspective, such patterns illustrate how repeated shocks can reduce the range of viable responses, as institutional inertia and vested interests crowd out transformative options. Ecological restoration projects in this context show that technical recovery of biophysical subsystems need not translate into enhanced adaptive capacity. Wetland restoration in parts of the former Aral Sea delta re-established lakes and marshes and generated new livelihood opportunities, demonstrating high restoration potential. Yet institutional arrangements failed to secure freshwater inflows or regulate exploitation of biological resources, particularly in the face of likely increases in drought frequency and severity. Because water requirements of restored wetlands were not integrated into basin-wide allocation rules, these projects did not significantly increase the resilience of the regional social–ecological system, and their long-term sustainability remains uncertain (Schlüter & Herrfahrdt-Pähle, 2011). Superficial ecological recovery thus coexists with strategic vulnerability whenever governance does not adapt alongside hydrological interventions. Public-health and food-security analyses in African epidemic settings trace a similar erosion of adaptive capacity where crises are treated through reactive, short-term measures. Vulnerable, food-insecure populations with inadequate health-care infrastructure are described as signalling potential crisis during events such as Ebola virus disease, yet most studies still focus on single causal factors instead of multiple pathways and feedbacks. Evidence indicates that failures to address interactions among climate variability, pests, disease ecology, livelihoods, and institutional decision-making hinder the development of early warning, robust response strategies, and effective post-crisis management. Reactive strategies that ignore these complex nature–society interactions are deemed inadequate for building long-term resilience. Governance-oriented work on Ebola nonetheless identifies elements that can counteract adaptive capacity loss. Historical interventions in Uganda combined rigorous isolation, surveillance, and treatment protocols with support from

local authorities and donor agencies, and are interpreted as windows in which local capacity and institutional infrastructure were strengthened. Proposed models for controlling disease and attaining nutritional well-being emphasise community-based production systems oriented to sufficiency, public– private partnerships for sanitary research and health standards, and centralised agencies for pathogen monitoring and surveillance (Khan & Sesay, 2015). Where such integrative arrangements emerge, recovery can expand the future option space instead of

narrowing it. Food-system research framed through law and economics confirms that many contemporary policy regimes reproduce vulnerability rather than alleviate it. Governments grappling with climate variability, soil degradation, water scarcity, and biodiversity loss often pursue increased production through subsidies and technological intensification, while market-access barriers, global supply-chain dependence, income and gender inequalities, sectoral policy silos, and implementation gaps persist. Conflicts over land use between agriculture, urbanisation, and industrialisation, along with geopolitical conflicts and pandemics that disrupt production and distribution, further compromise sustainable management (Agarwala et al., 2022). In such settings, each drought, flood, or price spike is more likely to precipitate ad hoc crisis management than to induce structural reform, gradually eroding adaptive capacity across water, food, and health subsystems. These comparative trajectories collectively demonstrate that recovery limitations and adaptive capacity loss often originate not in the magnitude of environmental stress alone, but in governance structures that restore pre-crisis configurations, reinforce path dependencies, and marginalise bottom-up initiatives. The cascading-failure modelling for Minoan Crete adopts these empirically documented mechanisms as analogues when interpreting sequences in which palatial systems may have repeatedly "recovered" in a narrow sense while progressively losing flexibility in water management, food provisioning, and public-health response (Schlüter & Herrfahrdt-Pähle, 2011; Khan & Sesay, 2015; Agarwala et al., 2022).

12 Lessons for Modern Crisis Management

12.1 Disaster Risk Reduction Insights

12.1.1 Early warning and preparedness

Early warning and preparedness in coupled food, health, and environmental systems are consistently framed as governance problems that must integrate multiple data streams, scales, and actors. Work on Ebola virus disease (EVD) stresses that vulnerable, food-insecure populations with inadequate health-care infrastructure already "signal potential crisis," implying that early warning requires continuous assessment of socio-economic and institutional indicators, not just biomedical surveillance. Because EVD is described as a multi-faceted phenomenon with several entry points across local food systems and environmental health, proposed strategies combine anticipatory risk-reduction with crisis management, embedding surveillance and response within adaptive-management cycles that explicitly recognise uncertainties due to climate change, limited knowledge, and institutional constraints. Several concrete models illustrate what such preparedness entails. Suggested configurations for controlling disease and attaining nutritional well-being in African contexts include: community-based production systems focused on sufficiency; partnership arrangements between governments and private-sector actors for sanitary research and health standards; and centralised agencies charged with public health policy and pathogen monitoring and surveillance. These models are explicitly intended to strengthen linkages between food security and environmental health and to create governance architectures where early warning, planning, implementation, monitoring, and evaluation of action plans are tightly coupled. Historical EVD responses in Uganda, in which rigorous isolation, surveillance, and treatment were implemented with support from local authorities and donor agencies, are cited as examples where crises opened "windows of opportunity" for institutional learning, with the key lesson framed as augmenting local capacity and institutional infrastructure rather than relying on one-off technical fixes. Attention to marine-based food systems reveals additional dimensions of early warning. In EVD-affected West African states, seafood provides essential calories and micronutrients, yet International Maritime Organization rules requiring 21-day quarantine for vessels exporting seafood disrupted quality, prices, and regional trade, showing how public-health measures can reconfigure food-security risks along maritime corridors. Long-term recommendations emphasise creating early-warning networks, monitoring environmental health, and strengthening local and national food-security institutions to promote adaptive capacity, together with cross-border collaboration, institutional partnerships, and creative governing

arrangements at regional and international levels. These proposals foreground early warning as an inherently transboundary task in which maritime regulations, fisheries governance, and terrestrial wildlife management must be coordinated to avoid unintended crises such as zoonotic spillover and trade collapse (Khan & Sesay, 2015). Digital surveillance and AI-based analytics are increasingly deployed to operationalise such early-warning logics. AI-supported disease surveillance systems integrate electronic health records, social media, and environmental data to identify unusual symptom clusters, detect early indicators of potential outbreaks, and predict spread based on population density, travel patterns, and environmental factors. Comparative discussion of "traditional" manual reporting versus AI-enabled real-time analysis stresses that machine-learning models can identify precursory

signals by jointly analysing historical data, climate conditions, and social variables, thereby enabling earlier and more targeted interventions. Integration of AI tools with existing public-health systems is presented as crucial for overcoming siloed information flows and building a more comprehensive surveillance infrastructure. At the same time, ethical and practical challenges shape the reliability and legitimacy of AI-enabled warning systems. Robust privacy protections, anonymisation, and informed consent are required for handling sensitive health data; algorithmic bias must be regularly audited and mitigated; explainability and transparency are needed to build trust in automated alerts; and inclusivity in design and deployment is emphasised to avoid reproducing socio-economic inequities in access to warning information and protective measures. Legal questions regarding liability for AI-related errors, lack of standardised regulation for AI in environmental health and public safety, and risks of cyberattacks on AI systems add further constraints, underscoring that preparedness must include cybersecurity and governance safeguards for the very infrastructures used in warning. Environmental-health case studies from the United States offer concrete institutional models. AI-powered urban air-quality sensor networks jointly deployed by the Environmental Protection Agency and technology companies provide real-time pollutant data, enabling proactive mitigation and informing targeted policy interventions. The U.S. Geological Survey uses AI to analyse multi-source water-quality data to identify pollution sources and guide water-management strategies, while the Centers for Disease Control and Prevention employ predictive models for influenza based on historical, demographic, and climatic variables to support vaccination planning and resource allocation. FEMA integrates AI into disaster response by modelling regional vulnerability to natural hazards to inform proactive planning, resource deployment, and evacuation strategies (Adefemi et al., 2023). Collectively, these initiatives demonstrate institutionalised early-warning architectures that link environmental monitoring, epidemiological forecasting, and emergency management. For the Minoan case study, these contemporary configurations justify designing early-warning reconstructions that combine hydrological indicators from springs, cisterns, and catchments in Appendix A with food-system and health proxies, and that treat governance capacity as a central component of preparedness. They also support the thesis-wide argument that effective warning and preparedness emerge where multi-scalar data integration, ethically governed surveillance, and locally grounded institutions converge, rather than from climate or technology alone (Khan & Sesay, 2015; Adefemi et al., 2023; Scheffran, 2023; Agarwala et al., 2022).

12.1.2 Resilience building in complex systems

Resilience building in complex socio-ecological systems hinges on recognising how shocks, slow degradation, and governance arrangements interact to either lock regimes into maladaptive trajectories or open possibilities for transformation. Analysis of the Amudarya basin shows a case in which repeated major shocks, including Aral Sea collapse, post-Soviet state breakup, and the severe 2000/2001 drought, did not produce a shift toward less water-intensive production. Instead, path dependence, Soviet legacies, strong central control, and vested interests maintained an irrigated cotton regime despite extensive salinization, waterlogging, ecosystem loss, and deteriorating rural health conditions. This configuration demonstrates that high resilience of a social system can actively block needed transformation and erode the resilience of the encompassing social–ecological system. Adaptive capacity in this basin has been undermined by reforms that were largely superficial. Water-sector changes amounted mainly to renaming organisations, with presidential decrees preserving top-down authority and

leaving core allocation logics intact. Extreme events prompted emergency bans on selected crops, temporary reductions in water limits, and short-lived transboundary councils, but practices reverted as soon as hydrological conditions improved. Informal institutions such as patronage and corruption further constrained effective implementation. The result is a system where adaptability of subsystems for the benefit of powerful actors has led to loss of resilience at SES scale, illustrating a classic maladaptive

pathway. Even within this locked system, small nuclei of potential transformation can be identified. Decrees in 2007 and 2008 that acknowledged increasing salinity and water scarcity and envisaged a 5 % reduction of cotton in favour of food crops mark a modest recognition of ecological limits. Emergence of Water User Associations has altered local political dynamics, with some farmers beginning to trust these bodies and resist the state order system, while participatory workshops recorded calls for stronger formal institutions, investments in human capital, and better planning and adaptation procedures (Schlüter & Herrfahrdt-Pähle, 2011). In complex adaptive systems terms, such bottom-up processes represent incipient self-organisation that could, under favourable conditions, shift feedbacks and move the system toward a new basin of attraction. Public-health and food-security work on Ebola virus disease (EVD) provides complementary evidence that resilience building requires integrated governance across sectors and scales. Vulnerable, food-insecure populations with inadequate health-care infrastructure are described as signalling potential crisis when epidemics arise. Because EVD has multiple entry points across local food systems and environmental health, governance mechanisms must link state and non-state institutions, decision rules, and scale-matching to address food security under uncertainty and ecosystem shifts. Adaptive management is advocated, in which uncertainties from climate change, limited knowledge, and institutional constraints become the basis for iterative planning, monitoring, and adjustment of interventions. Models proposed for African contexts include community-based production systems focused on sufficiency, public–private partnerships for sanitary research and health standards, and centralised agencies for pathogen surveillance and public-health policy, all conceived as contributions to movement from vulnerability to resilience (Khan & Sesay, 2015). Gendered mountain trajectories in the Himalayas show that resilience strategies must also address social differentiation. Declining water availability, reduced spring discharge, and increased disaster risk have driven male out-migration and intensified women's workloads in agriculture and livestock care, while diminishing time for personal and child care. Reduced access to drinking and sanitation water has particularly increased women's vulnerability to water-borne and nutrition-deficiency health risks, and women form the largest proportion of disaster victims due to limited preparedness and exposure patterns. Recommendations explicitly call for gender-sensitive development agendas, empowerment of rural women in natural-resource governance, and recognition of traditional adaptation knowledge as essential to ecological restoration and sustainable resource management (Tiwari & Joshi, 2015). These findings underscore that resilience building in complex systems depends on reworking power relations and knowledge regimes, not solely on technical measures. Food-system analyses at national and global scales outline further constraints and opportunities. Governments must adapt food systems to increasingly unpredictable climate patterns, soil degradation, water scarcity, and biodiversity loss while also confronting market-access disparities, dependence on global supply chains, income and gender inequalities, sectoral policy silos, and implementation gaps. Conflicts over land use between agriculture, urbanisation, and industrialisation, and geopolitical conflicts that disrupt production and distribution, complicate efforts to

implement sustainable practices. Suggested opportunities for improvement and innovation revolve around technological advances, integrated policy frameworks, strengthened governance structures, and social measures such as safety nets and gender equity, all oriented toward maintaining availability, access, utilisation, and stability under stress (Agarwala et al., 2022). Across these diverse cases, resilience building in complex systems emerges as a process of cultivating adaptive governance, embedding early warning and risk reduction in everyday institutions, tackling structural inequalities, and fostering bottom-up initiatives capable of reshaping feedbacks. For this thesis, such empirically grounded mechanisms provide the comparative backbone for interpreting the capacity, and limits, of Minoan socio-ecological systems to reorganise under climatic, hydrological, and geopolitical stress, and for deriving modelled lessons for contemporary disaster risk reduction and environmental security (Schlüter & Herrfahrdt-Pähle, 2011; Khan & Sesay, 2015; Tiwari & Joshi, 2015; Agarwala et al., 2022).

12.2 Environmental Security and Public Health Parallels

12.2.1 Modern Mediterranean water insecurity

Contemporary work on resource governance and food systems in regions climatically and institutionally comparable to the Mediterranean shows how water insecurity emerges from the interaction of climatic variability, structural scarcity, and fragmented policy fields. Analyses of government efforts to secure food supplies identify increasingly unpredictable droughts and floods as major stressors on agricultural

production, directly affecting crop yields and food availability. At the same time, overexploitation of soils and water resources and accelerating biodiversity loss further constrain the ecological basis of food supply, so that each additional dry spell or flood interacts with a progressively weakened resource base rather than a stable one (Agarwala et al., 2022). Within such contexts, arable land depletion and rising water scarcity intensify competition for key resources, making it more difficult to meet nutritional needs, particularly for vulnerable populations with restricted economic access to food. Economic disparities and income inequality limit households' capacity to buffer shortages through market purchases, while gender inequality in access to land, credit, and decision-making weakens the productive and adaptive potential of women farmers. These social gradients in access and power translate climatic and hydrological shocks into highly unequal human impacts, a configuration directly relevant to Mediterranean settings where smallholders and marginal communities often occupy the most waterstressed landscapes (Agarwala et al., 2022; Tiwari & Joshi, 2015). Regional assessments underscore that water-insecure conditions are especially acute in areas that resemble the modern Eastern and Southern Mediterranean in their combination of aridity, political instability, and import dependence. The Middle East and North Africa are described as facing "unique challenges" arising from structural water scarcity, recurrent conflict, and political instability, which together heighten the risk of food insecurity and lock countries into reliance on food imports that must traverse vulnerable maritime and logistical corridors. Land-use conflicts between agriculture, urbanisation, and industrialisation further complicate sustainable water allocation, as expanding cities and industrial zones encroach upon high-quality agricultural land and compete for limited freshwater, thereby constraining options for adaptation in already stressed basins (Agarwala et al., 2022). Climate–security research conceptualises these regional constellations as part of wider impact chains in which global heating functions as a risk multiplier. Loss or

degradation of vital resources such as water, arable land, forests, and biodiversity, together with more frequent weather extremes, is argued to undermine human security and social stability, particularly in fragile regions with weak governance and inadequate management capacities. In such settings, erosion of problem-solving ability and of infrastructures, including health systems, can trigger spirals of poverty, hunger, corruption, crime, violence, and forced displacement. Lack of water and food, weather extremes, and environmentally induced migration are explicitly identified as key conflict-relevant mechanisms, while storm and flood disasters that kill or displace people are observed to contribute to the spread of conflicts to neighbouring regions (Scheffran, 2023). Governmental attempts to address these intertwined pressures reveal both constraints and potential entry points for mitigation. Market-access disparities and unfavourable trade agreements disadvantage smallscale producers, reducing their economic resilience and ability to invest in water-saving technologies or soil conservation. Dependency on global supply chains for food distribution amplifies vulnerability, as disruptions like those seen during the COVID–19 pandemic expose the fragility of long-distance provisioning and complicate efforts to ensure consistent access to food. Sectoral policy silos between agriculture, environment, and trade hinder coherent responses, and implementation gaps linked to limited infrastructure and institutional capacity mean that even well-designed policies may fail to reach water-insecure communities in practice (Agarwala et al., 2022). Environmental-health and publicsafety research adds a further dimension by detailing how water pollution and inadequate waste management degrade both environmental and human health in urbanising regions. Water pollution from industrial, agricultural, and domestic sources, compounded by natural disasters and climate change, damages drinking-water quality and aquatic ecosystems, directly affecting populations dependent on these resources. Disaster risk reduction is complicated by increasing frequency and intensity of hazards and by the complexity and interdependence of urban systems and critical infrastructures. These conditions demand multisectoral approaches and participation from governments, local authorities, industry, academia, and civil society, highlighting again that water insecurity in Mediterranean-type settings is as much a governance and infrastructure problem as a climatic one (Adefemi et al., 2023; Agarwala et al., 2022). Taken together, these strands portray modern Mediterranean-adjacent water insecurity as a systemic phenomenon generated by climatic variability, chronic overuse and pollution of land and water, socio-economic inequality, policy fragmentation, and, in many areas, conflict and political instability. They provide the comparative baseline against which Late Bronze Age Cretan hydrological and food-system vulnerabilities, documented in Appendix A, are interpreted in this thesis, and from which modelled lessons for contemporary disaster risk reduction and environmental security are derived (Agarwala et al., 2022; Scheffran, 2023; Tiwari & Joshi, 2015; Adefemi et al., 2023).

12.2.2 Public health in environmental crises

Public-health outcomes in environmental crises depend not only on biophysical shocks but also on preexisting vulnerabilities in livelihoods, infrastructure, and governance. Mountain communities in the Himalayas illustrate this configuration: declining water availability for food production and domestic use, together with heightened risks of natural disasters, have stressed local production systems, driven male out-migration, and substantially increased women’s workloads in agriculture and livestock. Reduced time for personal and child care, coupled with diminished access to safe drinking and sanitation water, has "particularly" increased women’s vulnerability to

water-borne and nutrition-deficiency health risks, while women constitute the largest proportion of disaster victims due to limited preparedness and information and greater exposure (Tiwari & Joshi, 2015). These intertwined environmental and social shifts show how water and food insecurity translate directly into differentiated health impacts. Large irrigated basins undergoing severe land and water degradation present another pathway from environmental crisis to compromised health. In the Amudarya system, expansion of irrigation under low management standards and deteriorating infrastructure produced widespread soil salinization, waterlogging, and collapse of semi-natural ecosystems, culminating in desiccation of the Aral Sea and loss of fisheries, reeds, pasture, and dust-storm protection. Rural populations in the most degraded areas lack access to good-quality drinking water, and environmental degradation has "significantly impaired" living conditions and health, increasing vulnerability to ecological, economic, and social stresses during droughts such as in 2000/2001 (Schlüter & Herrfahrdt-Pähle, 2011). Here, chronic environmental mismanagement, rather than a single extreme event, has created a persistent disease-promoting landscape. Urbanising and industrial contexts compound these problems through multiple environmental health hazards. Reviews of environmental health and public safety catalogue air pollution, water pollution, soil contamination, inadequate waste management, occupational hazards, and disaster risk as major challenges that undermine human health. Water pollution from industrial, agricultural, and domestic activities, as well as natural disasters and climate change, degrades the quality and availability of drinking water and harms aquatic ecosystems and dependent populations. Soil pollution through accumulation of heavy metals, pesticides, and radioactive materials reduces land fertility and contaminates food and crops, while inadequate solid and liquid waste management, particularly in cities, facilitates environmental degradation, disease transmission, and social conflict. Increasing frequency and intensity of disasters, together with complex and interdependent urban infrastructures, further complicate disaster risk reduction, making cascading failures more likely (Adefemi et al., 2023). Public-health research on extreme scenarios such as nuclear winter clarifies generic mechanisms by which environmental perturbations threaten health. Work on abrupt global cooling uses analogies with global warming research to conceptualise how environmental change can undermine clean air, safe drinking water, nutritious food supply, and safe shelter. Anticipated secondary effects include increased ultraviolet radiation, disease following destroyed sanitary facilities and contaminated water, and outbreaks of infectious diseases such as plague, typhus, malaria, dysentery, and cholera. Proposed research pathways adapt the Global Burden of Disease framework for risk assessment and call for large-scale epidemiological forecasting integrating climate and crop models with disease dynamics (Vilhelmsson & Baum, 2023). Although focused on a hypothetical future, this agenda mirrors the pathways already documented in Himalayan and Central Asian cases, where environmental degradation and infrastructure failure increase exposure to water- and food-borne disease. Governance strongly shapes whether environmental crises become public-health disasters. Analyses of food-related crises and zoonotic epidemics such as Ebola virus disease argue that vulnerable, food-insecure populations with inadequate health-care infrastructure "signal potential crisis" when epidemics arise. Because EVD is characterised as a multi-faceted issue with several entry points across local food systems and environmental health, governance mechanisms that connect sectors, jurisdictional scales, and interest groups are identified as essential for effective early warning, response, and recovery. Historical interventions in Uganda relied on rigorous isolation, surveillance, and treatment protocols supported by local authorities and donor agencies; key lessons

emphasise augmenting local capacity and strengthening institutional infrastructure rather than relying solely on externally driven technical fixes. Proposed models for African contexts combine community-based production systems founded on sufficiency principles, public–private partnerships for sanitary research and health standards, and centralised government agencies responsible for public-health policy and pathogen monitoring (Khan & Sesay, 2015). In contrast, the Amudarya basin illustrates how crisis responses focused on maintaining short-term agricultural productivity, rather than reforming land and water governance, leave underlying drivers of health vulnerability intact (Schlüter & Herrfahrdt-Pähle, 2011). Food-system studies integrate these threads by showing how climate variability, soil and water degradation, and biodiversity loss interact with income and gender inequalities, infrastructure deficits, and fragmented policies to produce uneven exposure to hunger and disease. Government interventions through subsidies, land-use regulation, social safety nets, and public-health and nutrition programmes influence availability, access, utilisation, and stability dimensions of food security, and thereby condition nutritional and health outcomes. Where such policies neglect environmental sustainability or social equity, they can stabilise food supplies in the short term while exacerbating long-run health risks through continued degradation and exclusion (Agarwala et al., 2022). Together, these cases demonstrate that public health in environmental crises depends on the configuration of socio-ecological systems: water and land management, social differentiation, and governance architectures jointly determine whether environmental shocks translate into acute and chronic disease burdens (Tiwari & Joshi, 2015; Schlüter & Herrfahrdt-Pähle, 2011; Adefemi et al., 2023; Khan & Sesay, 2015).

13 Discussion

13.1 Integrative Interpretation of Minoan Collapse

13.1.1 Multi-causality versus single-event explanations

Interpretive models that attribute past crises to singular, abrupt shocks are increasingly untenable once complex socio-ecological interactions are foregrounded. Work on large irrigated basins in Central Asia documents how decades of land and water overuse, combined with deteriorating infrastructure and weak institutional ownership of reforms, produced a long-term degradation of soils, ecosystems, and drinking-water quality. Extreme events such as droughts and floods did elicit emergency responses, for example temporary crop bans, reductions in regional water limits, or ad hoc transboundary flood councils, yet once these extremes abated, managers reverted to existing practices and no durable strategy for variability or scarcity was implemented (Schlüter & Herrfahrdt-Pähle, 2011). This pattern demonstrates that shocks operate within, and are filtered by, pre-existing governance logics and path dependencies, rather than acting as singular causal switches. Food-system research further underlines that climate variability is only one component within broader resource and institutional configurations. Governments must adapt to increasingly erratic droughts and floods and to progressive soil and water depletion, while simultaneously managing globalised trade, income inequality, gender disparities, sectoral policy silos, and conflict. Resource scarcity in arable land and water, together with biodiversity loss, constrains production; market-access barriers and unfavourable trade agreements disadvantage small producers; and dependency on global supply chains, as exposed during the COVID–19 pandemic, magnifies vulnerability to distant disruptions (Agarwala et al., 2022). In such settings, there is no single "event" that explains food insecurity; instead, interacting climatic, economic, and political pressures yield cumulative vulnerability. Public-health oriented analyses of Ebola virus disease make an analogous argument in a different empirical arena. EVD is described as a multi-faceted phenomenon with several entry points, where vulnerable, food-insecure populations and inadequate health-care infrastructure "signal potential crisis" well before an outbreak is detected. Research criticises approaches that focus on single causal factors and calls for attention to multiple pathways, complex interactions, and contextual relationships between climate variability, disease ecology, livelihoods, institutional structures, and decision-making processes. Effective interventions in Uganda combined rigorous isolation, surveillance, and treatment protocols with support for local institutions, and subsequent proposals emphasise community-based production, public–private sanitary research, and centralised surveillance agencies as joint pillars of resilience (Khan & Sesay, 2015). Epidemics, in this framing, emerge from coupled failures of food systems, environmental health, and governance, not from a discrete biomedical "event" alone. Environmental-health syntheses that integrate artificial intelligence into monitoring likewise treat hazards as products of interacting domains. Air and water pollution, soil contamination, waste-management deficits, occupational risks, and disasters form an interconnected hazard landscape in which climate change modifies baselines and interdependencies among infrastructures. AI-enabled sensor networks, predictive modelling, and decision-support tools are proposed to enhance early warning and targeted intervention, yet challenges of data privacy, algorithmic bias, and uneven institutional capacity underscore that technical

innovations remain embedded within contested governance and ethical regimes (Adefemi et al., 2023). Here again, risk is multi-causal, arising from the co-evolution of environmental pressures, technological systems, and

regulatory frameworks. Mountain case studies in the Himalayas translate these insights into gendered lived experience. Environmental change, declining water availability, and increased disaster risk have stressed local production systems, driven male out-migration, increased women's workloads, and reduced time for personal and child care. Reduced access to water for drinking and sanitation has particularly heightened women's vulnerability to water-borne and nutrition-deficiency health risks, while women constitute the majority of disaster victims due to limited preparedness and information (Tiwari & Joshi, 2015). No single flood, drought, or landslide accounts for these outcomes; rather, cumulative environmental degradation intersects with social differentiation and marginalisation to produce layered vulnerabilities. Taken together, these contemporary configurations support the position adopted here that Minoan palatial decline is best conceptualised as a prolonged socio-ecological and socio-political crisis produced by interacting drivers. In the modern cases, climate variability acts as a threat multiplier that destabilises already stressed water, food, and health systems, but outcomes depend on governance structures, social inequalities, technological infrastructures, and institutional learning capacities (Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022; Khan & Sesay, 2015; Adefemi et al., 2023). Single-event explanations, whether framed as a decisive drought, flood, or epidemic, systematically misrepresent such dynamics. By analogy, the cascading-failure and complex adaptive systems analysis applied to Bronze Age Crete treats climatic shifts, hydrological stress, environmental degradation, governance weaknesses, and public-health vulnerabilities as co-evolving subsystems whose coupled behaviour must be reconstructed, rather than as a sequence of isolated triggers.

13.1.2 Implications for historical and modern contexts

Recurrent crises in semi-arid irrigated basins demonstrate that ecological tipping points and social tipping points do not automatically coincide, a finding with direct implications for how Late Bronze Age trajectories are framed. In the Amudarya system, loss of the Aral Sea, collapse of fisheries, and massive wetland degradation marked a profound ecological regime shift, yet hierarchical quota regimes for cotton and wheat, presidential decree governance, and entrenched patronage maintained the existing production model despite escalating salinization, waterlogging, and health deterioration among rural populations deprived of safe drinking water (Schlüter & Herrfahrdt-Pähle, 2011). For Aegean palatial societies, including Minoan Crete, this comparison underlines that even dramatic environmental change need not trigger institutional reorganisation; collapse or survival depend on how far political economies can decouple themselves from ecologically destructive path dependencies, a point that informs the cascading-failure interpretation advanced here. Food-system analyses in contemporary settings likewise stress that climatic shocks operate through policy and inequality filters rather than as autonomous drivers. Governments confronted with increasingly erratic droughts and floods must simultaneously navigate soil and water degradation, biodiversity loss, income and gender inequalities, market-access barriers, policy silos, and conflict, while managing dependence on global supply chains that proved fragile during COVID–19 (Agarwala et al., 2022). Under these conditions, crises emerge from interacting climatic, institutional, and socio-economic

pressures; no single drought or flood suffices as an explanation. The insistence in this thesis on multi-causality and on governance as mediator between environmental stress and social outcome (Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022) therefore aligns closely with current food-security and environmental-security debates. Epidemic-prone coastal systems in West Africa provide a further analogue for interpreting how health, food, and trade intersect in maritime polities. Ebola virus disease has multiple entry points across local food systems and environmental health; vulnerable, food-insecure populations with inadequate health-care infrastructure "signal potential crisis" well before outbreaks materialise. Effective interventions in Uganda combined rigorous isolation, surveillance, and treatment protocols with support from local authorities and donors, and inspired models that integrate community-based production, public–private sanitary research, and centralised surveillance agencies (Khan & Sesay, 2015). These findings inform the Minoan case by underscoring that public-health resilience depends on preexisting institutional density and local capacity, not only on the severity of climatic or military shocks. Environmental-health syntheses centred on artificial intelligence reveal analogous complexity in modern hazard landscapes. Air and water pollution, soil contamination, inadequate waste management, occupational risks, and disasters interact within increasingly interdependent infrastructure systems, so that climate change modifies baselines and interdependencies rather than creating isolated new risks. AI-enabled sensor networks and predictive models can enhance early warning and targeted intervention, but they also introduce challenges of data quality, privacy, bias, security, and unequal access

that must be addressed through transparent, inclusive governance (Adefemi et al., 2023). For Late Bronze Age Crete, where no such technologies existed, the methodological implication is nevertheless clear: risk assessment must integrate multiple environmental and social indicators, and early-warning capacity is inherently constrained by informational and institutional limitations that can themselves be modelled as nodes in cascading-failure pathways. Mountain case studies from the Himalayas add a crucial social-differentiation dimension. Environmental change, declining water availability, and increased disaster risk have driven male out-migration, intensified women’s workloads in agriculture and livestock care, reduced time for personal and child care, and "particularly" raised women’s vulnerability to water-borne and nutrition-deficiency health risks; women also form the majority of disaster victims due to limited preparedness and exposure patterns (Tiwari & Joshi, 2015). These observations make plain that any reconstruction of Minoan vulnerability that treats "the population" as homogeneous risks missing systematic asymmetries in exposure and adaptive capacity. They also highlight the importance, for modern policy, of gender-sensitive disaster risk reduction, echoing arguments for empowerment and recognition of traditional adaptation knowledge as prerequisites for sustainable resource governance (Tiwari & Joshi, 2015; Agarwala et al., 2022). Finally, climate–security scholarship formalises the role of global heating as a "threat multiplier" that disturbs interactions between natural and social systems, including critical infrastructures and supply networks. Loss of water, arable land, forests, and biodiversity, together with more frequent extremes, is seen to threaten human security and political stability in weakly governed, agriculture-dependent states, where spirals of poverty, hunger, institutional erosion, and displacement may develop (Scheffran, 2023). The modern Mediterranean and Middle East and North Africa, with structural water scarcity, land-use conflicts, and heavy foodimport dependence, exemplify such fragile configurations (Agarwala et al., 2022; Scheffran, 2023). By placing Minoan collapse within a long-term comparative field defined by these contemporary cases, the thesis not

only rejects monocausal climatic explanations but also argues that Bronze Age Aegean crises can serve as historically grounded laboratory scenarios for testing how interacting water insecurity, food-system stress, governance rigidity, and health vulnerability co-produce systemic failure, with direct relevance for present-day disaster risk reduction and environmental security agendas (Schlüter & Herrfahrdt-Pähle, 2011; Agarwala et al., 2022; Khan & Sesay, 2015; Adefemi et al., 2023).

13.2 Integrated Socio-ecological Analysis of Palatial Decline

Resource dynamics in this project are approached through proxy datasets that document environmental variability over centuries and millennia, but these archives are consistently interpreted within a socio-ecological framework that assigns primacy to stratified archaeological sequences from Bronze Age Crete. Relative sea-level indicators provide one important dimension of environmental stress with clear implications for coastal resource bases. Radiocarbon-dated markers such as corals, depositional features, and archaeological levels yield ranges whose precise boundaries were not recoverable from the source table (see Section 2.6, n. 1), together with multiple intervals extending into the first millennium (Pirazzoli et al., 1996, p. 4). These timebounded estimates delineate long-term trajectories of relative coastal stability and vertical land movement around eastern Mediterranean shorelines. Within the present analytical design, such trajectories constrain discussion of potential stress on marine-access resources, anchoring questions about whether gradual emergence or submergence altered local geomorphological settings relevant to Bronze Age harbours and coastal plains.

However, environmental determinism is explicitly rejected: these sea-level changes are treated as contextual parameters that interact with settlement organisation and governance, not as sufficient causal agents of palatial decline (Pirazzoli et al., 1996, p. 4). High-energy coastal inundation features add a second strand of environmental stress with direct consequences for land, water, and biotic resources. Work on the Gyra washover fan in the Lefkada Lagoon documents a subaerial deposit of approximately extending more than landward from the recent barrier beach (May et al., 2012, p. 10). Coring across this fan reveals a sequence of two to four subunits separated by erosional unconformities and thinning landward, with massive bedding, fining-upward trends, and grain-size spectra that in many cases display bimodal distributions combining fine to medium sand with very coarse sand to medium gravel. These bimodal spectra are interpreted as signatures of mixed sediment sources, notably sublittoral sands and littoral gravels mobilised during a single tsunami event. Mud layers, mud drapes, and rip-up clasts record suspension fallout during slack-water phases following major inundation impulses and erosion of previously terrestrial surfaces under high-energy turbulent flow. Comparative work argues that such intraclasts and internal mud drapes occur widely in tsunami deposits but rarely in storm-induced strata, and that storm washover systems are typically characterised by numerous thin laminae and foreset structures, in contrast to the limited number of thick subunits observed at Gyra. On this basis, at least one tsunami event is considered responsible for the Gyra washover fan, implying a short-lived but intense perturbation of coastal soils, freshwater access, and near-shore ecological communities (May et al., 2012, p. 11; 2012, p. 5; 2012, p. 12). For Bronze Age Crete, these findings function solely as heuristic comparanda: they help specify the kinds of geomorphological signatures by which extreme inundation might be recognised in Cretan lagoons and coastal plains, and thus frame

how sudden resource shocks in coastal zones would be investigated once local cores are available. Long-term tectonic activity constitutes another source of environmental stress that can reshape resource landscapes through repeated earthquakes and associated ground deformation. Studies of eastern Mediterranean plate-boundary faults argue that seismicity has persisted for hundreds of thousands, and possibly a few million, years, with plate motions on the order of centimetres per year and slowly shifting fault patterns. Strain accumulation during centuries of relative quiescence may be released either in single large earthquakes with aftershocks or in sequences of large events where each rupture triggers the next, conceptualised as "earthquake storms" that unzip entire fault zones (Nur & Cline, 2000, p. 4). Empirical documentation of the mid-twentieth-century sequence along the North Anatolian Fault shows a chain of earthquakes with magnitudes greater than 6.5, migrating westward over a fault zone roughly 1000 km long, between 1939 and 1967, releasing strain built up over more than 200 years (Nur & Cline, 2000, p. 8). Such patterns imply prolonged periods of heightened hazard, during which agricultural terraces, irrigation structures, and storage facilities could be repeatedly damaged. Earthquake-archaeology work at Troy VI 390, 000 m3 1 km 6.5 1000 km 1939 1967

provides detailed descriptions of how individual events can catastrophically affect built environments and thereby resource infrastructures. Fortification walls originally vertical have been "shaken out of plumb" and tilted sharply, masses of stones lie in "utter disorder and confusion" between citadel and terrace walls, Cyclopean boulders are found below projecting building corners, and large pithoi are sunk deep into collapsed wreckage, all interpreted as signatures of abrupt structural failure in a violent upheaval (Nur & Cline, 2000, p. 15). These qualitative indicators suggest that major earthquakes can instantaneously transform storage capacity, circulation routes, and access to productive land. The thesis uses such evidence to build diagnostic repertoires for identifying seismic impacts at Cretan palatial sites, but again insists that direct Cretan stratigraphic and architectural data are the primary empirical basis for any inference about resource dynamics under earthquake stress (Nur & Cline, 2000, p. 15). Modern accounts of Cretan earthquakes demonstrate how single events become resource crises through their interaction with seasonality, infrastructure, and governance. Newspaper reports on the earthquake, following a devastating event in [YEAR NOT STATED IN SOURCE], describe rural districts where most houses collapsed or became uninhabitable, inhabitants forced into fields and winter streets, and later returning to unearth injured and dead from the ruins. Government responses include immediate financial aid and tents for shelter, while additional testimony recalls an earthquake that "devastated the north Cretan shores" and is remembered for shortages in goods. These descriptions show that environmental stress translates into food, shelter, and commodity shortages only through specific socio-economic configurations. Within the dissertation, they are used strictly as late analogues to sharpen questions about how Bronze Age communities might have experienced similar multi-dimensional crises, not as templates for ancient conditions. Across these strands, environmental stress is consistently analysed as interacting with resource dynamics in non-deterministic ways. Relative sea-level trajectories, tsunami inundations, and earthquake sequences are treated as components of regional settings that may constrain or perturb land, water, and biotic resources, but they do not unilaterally dictate outcomes. Direct archaeological evidence from Bronze Age Crete, including settlement patterns, destruction and rebuilding horizons, hydraulic installations, and storage facilities, remains the primary empirical basis for reconstructing how resource systems responded to such stresses. Modern coastal, seismological, and earthquake-archaeology case

studies are introduced only after those sequences and strictly as heuristic instruments for identifying possible signatures of stress and framing testable questions about vulnerability and resilience. Within this precise conceptual usage, "environmental determinism" denotes explanatory models that assign primary, overriding, and near-sufficient causality to environmental variables such as sea-level change, tsunamis, or earthquakes while treating governance, institutions, technology, and social organisation as secondary. This dissertation explicitly rejects such models in favour of a socio-ecological interpretation in which environmental 1935 1926

stress is one driver among many within historically contingent resource regimes (May et al., 2012, p. 10; Nur & Cline, 2000, p. 4; Pirazzoli et al., 1996, p. 4).

13.3 Contributions to Resilience Theory, Archaeology and Medical Intelligence

Analytical strands developed in this dissertation contribute to socio-ecological and resilience theory by operationalising a multi-scalar framework in which environmental and cultural change are treated as reciprocally interacting rather than as separate explanatory spheres. Methodologically, this contribution rests on the explicit adoption of assumptions from work on centuriated landscapes: change is characterised as multi-causal, multi-scalar, and historically contingent; archaeological, historical, ecological, and ethnographic data are jointly analysed; supra-regional, regional, and local processes are examined together; and long-term trends are related to short-term events such as natural disasters and political decisions. Translated into the Bronze Age Cretan context, these premises allow resilience to be conceptualised not as a property of an abstract "environment" but as an emergent outcome of interactions among hydrology, land use, institutional arrangements, and settlement organisation. A central theoretical contribution is the consistent rejection of classical environmental determinism and the articulation of an alternative socio-ecological interpretation. Within the present work, environmental determinism is used in a precise sense to denote explanatory models that assign primary, overriding, and near-sufficient causality to environmental variables such as climate change, earthquakes, or sea-level shifts, treating social, political, institutional, and cultural dimensions as secondary or derivative. This position is challenged by integrating analyses of large irrigated basins in Central Asia, where river dependence, irrigation infrastructure, and governance choices jointly determine ecological degradation and social vulnerability, and where technical hydrological improvements remain precarious in the absence of basin-wide allocation rules and robust territorial control. In theoretical terms, these cases demonstrate that environmental stressors cannot be read as autonomous drivers but must be embedded in political economies and governance regimes when resilience or collapse is being evaluated. Another contribution lies in the way governance is foregrounded as a cross-cutting rubric for linking environmental proxies to social outcomes in both food systems and epidemic vulnerability. Studies of Ebola virus disease and bovine spongiform encephalopathy frame epidemics as multi-faceted phenomena whose entry points traverse local food systems, environmental health, and institutional capacity, and argue that vulnerability assessments must attend to spatial and temporal scale, bio-complexity in disease ecology, and multi-actor interactions. In this dissertation,

such work is translated into a coding logic in which archaeological indicators of storage concentration versus household buffering, centralised versus dispersed ritual and healing spaces, and proxies for local autonomy within

palatial hierarchies are assessed against reconstructed climatic and hydrological stress episodes. Conceptually, this moves resilience theory away from generic system robustness and towards a governance-centred understanding of how specific configurations of institutions, infrastructure, and social networks condition trajectories under stress. Risk-oriented contributions further extend socio-ecological theory by adapting public-health methodologies to contexts with incomplete empirical data. Nuclear-winter research, which proposes integrating climate and crop models within global burden of disease frameworks to estimate health impacts where direct data are lacking, is used as an analogue for constructing qualitative risk-matrix logics in Bronze Age Crete. Here, palaeoclimate indicators are combined with archaeological evidence on food production, storage, habitation, and connectivity to generate envelopes of probable nutritional and epidemiological risk rather than deterministic causal chains. This explicit framing of outputs as "modelled risks" rather than direct readings of disease prevalence underscores a resilience conception centred on adaptive management under uncertainty, iterative learning, and explicit acknowledgment of data incompleteness. The integration of artificial-intelligenceenabled surveillance architectures into the methodological toolkit also yields theoretical implications. Contemporary systems that merge electronic health records, social media, and environmental data to detect unusual symptom clusters and forecast outbreak spread are discussed in terms of real-time analysis, early warning, and predictive modelling, together with concerns over privacy, bias, transparency, and accessibility. Their architecture is used as a template for combining heterogeneous archaeological, hydrological, and palaeoclimatic datasets through geographical information systems and risk matrices to identify "hot spots" of probable health vulnerability in Minoan landscapes. Conceptually, this demonstrates that socio-ecological resilience theory can incorporate insights from complex, multi-hazard monitoring systems, while maintaining a strict evidence hierarchy in which direct archaeological sequences remain the primary empirical basis and modern case studies function only as heuristic instruments. Finally, comparative work on food security, disaster management, and environmental health contributes to a resilience narrative that distinguishes reactive crisis management from transformative adaptation. Analyses of river-basin governance show that droughts and floods often trigger emergency councils, crop bans, and temporary water-allocation changes, yet long-term strategies for variability and scarcity are rarely implemented; studies of institutional responses in large irrigated basins describe cycles of overuse and degradation maintained by informal institutions such as patronage and corruption; environmental-health and AI applications reveal technical innovations that remain constrained by bias, equity, and regulatory capacity. Read together, these strands provide a conceptual backdrop for interpreting post-destruction sequences and prolonged crises in terms of

"crisis without transformation", reinforcing the dissertation’s emphasis on governance, social differentiation, and institutional learning as key dimensions of socio-ecological resilience, in deliberate contrast to deterministic formulations that hinge on singular environmental shocks.

14 Conclusion

This study synthesises palaeoenvironmental, archaeological, hydrological, and comparative policy literature to argue that Minoan palatial transformation must be read as an extended socio-ecological sequence in which interacting slow and fast drivers produced cascades of stress rather than a single, isolable shock. Climatic fluctuations and shifts in effective moisture altered the baseline for productive agriculture and spring discharge, but their impacts became acute only through articulation with land-use practices, hydraulic infrastructure, and political economies that channelled control over water and staple flows. Evidence for repeated burnings, phased rebuilding, and regional divergence in settlement trajectories aligns with a model in which conflict, resource competition, and institutional fragility combined with environmental pressure to reconfigure settlement hierarchies over generations. Hydrological reconstruction emphasises the importance of karst catchment geometry, spring-line seasonality, and the interaction between recharge and engineered storage. Where cisterns, terraces, and channel works existed, their buffering capacity depended on sustained recharge and cooperative maintenance regimes; where governance concentrated extraction or degraded recharge areas, storage and irrigation became less effective and salinisation and waterlogging risks rose. Isotopic and palaeoecological proxies provide locality-sensitive signals of water stress that are best interpreted as envelopes of variability, rather than as instantaneous triggers for social rupture. Administrative concentration of surplus and centralized redistribution created pathways for provisioning that could both mitigate and magnify exposure: large-scale storage can smooth interannual scarcity when allocation is equitable and maintenance is feasible, but it can also produce vulnerability when used to sustain extractive production goals without attention to ecological limits. The interplay between food systems and public health emerges as a central axis of socio-ecological risk. Recurrent yield shortfalls, constrained dietary diversity, and compromised water quality raise the probability of nutritional stress and infectious-disease amplification in contexts of limited local health capacity. Comparative epidemic governance shows that outbreaks are most damaging where food insecurity, poor sanitation, and weak institutional linkages converge. Historical analogues indicate

that interventions which combine local capacity building, surveillance, and integrated food–health provisioning can reduce vulnerability; conversely, reactive, short-term technical fixes tend to preserve underlying fragility. Complex-systems perspectives, including adaptive-cycle and panarchy heuristics, clarify why some subsystems resisted transformation even after major perturbations. Path dependence in hydraulic regimes, rents derived from staple production, and centralised decision-making can stabilise an undesirable attractor, producing recovery that restores previous structures while eroding long-term resilience. Yet the record also contains micro-scale signals of reorganisation: shifts in settlement patterns, emergence of alternative provisioning nodes, and incremental institutional innovations that in other settings have served as nucleation points for more durable change. Recognising these uneven and scale-dependent dynamics is essential for any model that seeks to link environmental stress with political and demographic outcomes. Several analytic implications follow. First, causal narratives that privilege single agents, whether drought, earthquake, invasion, or pest, are insufficient; multi-causality, mediated through governance and social differentiation, provides a more coherent framework. Second, spatial heterogeneity matters: neighbouring catchments could experience different hydrological trajectories,

producing regionally divergent political outcomes that are visible archaeologically. Third, temporal framing must match proxy resolution: palaeoclimate series define decadal to centennial envelopes that should be compared with securely dated archaeological phases rather than with isolated destruction layers. Fourth, social differentiation, including gendered labour regimes and unequal access to resources, conditions both exposure and adaptive capacity and must be integrated into reconstructions of vulnerability. For contemporary policy-relevant reflection, the comparative cases mobilised here yield two broad lessons. One is methodological: reconstructing past crises profitably uses the same multi-scalar, multisectoral toolkit advocated for modern risk assessment, integrated GIS databases, proxy crosscorrelation, and institutional mapping that place technical features within political economies. The other is substantive: resilience is as much an institutional attribute as an ecological one. Investments in storage, irrigation, or monitoring will fail to reduce systemic risk unless accompanied by allocation rules, maintenance regimes, and inclusive governance that distribute costs and benefits and that maintain ecosystem buffering functions. In sum, the evidence supports a model of Late Bronze Age Aegean reconfiguration in which environmental drivers acted as amplifiers of pre-existing socio-political stresses. Collapse and reorganisation unfolded through interacting pathways linking water security, agrarian production, trade connectivity, and public health, all refracted through local power relations and institutional choices. Reconstructing those pathways with explicit attention to scale, chronology, and governance offers a disciplined route for learning from the past about how coupled human–environment systems respond to compounded stress.

The Integration to the Thesis synthesises these strands as follows.

This study synthesises archaeological sequences, palaeoclimatic proxies, and comparative case material to present a socio-ecological account of palatial societies in the eastern Mediterranean. It prioritises stratified settlement evidence, destruction and rebuilding horizons, and infrastructural indicators as the primary empirical basis, and then uses environmental and modern analogue data as explicitly heuristic complements. The result is an analytic architecture that treats environmental change as one of several interacting drivers rather than as a sole, overriding cause of institutional transformation. Methodologically, the work implements a multi-scalar framework that links supra-regional climatic patterns to catchment-scale hydrology and site-level geomorphology. Spatial analyses with geographical-information tools are combined with stratigraphic correlations to locate probable episodes of stress in time and space. Risk-matrix logics adapted from public-health and environmental assessment traditions translate combined indicators of storage distribution, settlement density, hydraulic investment, and connectivity into qualitative envelopes of probable nutritional and epidemiological exposure. These modelled risk envelopes are explicitly framed as contingent and uncertain, not as direct reconstructions of morbidity or deterministic statements about societal fate. Comparative material from irrigated basins, epidemic responses, tsunami sedimentology, and modern disaster governance supplies interpretive variables and diagnostic repertoires for recognising hydrological, seismic, and coastal hazard signatures in the archaeological record. That comparative strand is introduced only after the archaeological sequences are established, ensuring that analogues shape variable selection and hypothesis formation without substituting for ancient empirical data. Examples from large basin management and epidemic governance highlight how institutional arrangements, informal rules, and information flows mediate impacts of environmental shocks on food and health systems; these insights inform the coding

schemes used to evaluate Cretan contexts. The narrative that emerges emphasises how resilience and failure are outcomes of coupled environmental, technological, and institutional configurations. Hydraulic engineering, allocation rules, storage regimes, and administrative reach interact with landscape dynamics and episodic hazards to produce differential exposure across regions and communities. Repeated or clustered events may erode adaptive capacity when institutional learning, maintenance regimes, and local autonomy are weak; by contrast, diversified storage, distributed provisioning, and flexible decision-making reduce modelled risk across a range of scenarios. This governance-centred reading thus reframes episodes of destruction and reorganisation as historically contingent trajectories shaped by prior investments and social arrangements. Several methodological implications follow. First, assembling high-resolution, stratigraphically anchored archaeological datasets is essential before invoking environmental explanations. Second, multi-source correlation procedures and transparent coding protocols are needed to characterise uncertainty and avoid overstating causal links. Third, heuristic use of modern analogues is valuable for constructing testable variables, but such analogues must remain subordinated to the archaeological record. Finally, incorporating public-health risk logic and multi-hazard monitoring metaphors offers a productive way to synthesise heterogeneous proxies while making explicit the limits of inference. Future work should prioritise targeted palaeoenvironmental coring at key coastal and lagoonal sites, refined typologies of structural damage that distinguish seismic from anthropogenic collapse signatures, and expanded datasets on storage and distribution infrastructures across different settlement tiers. Comparative investigations of institutional mechanisms for water allocation and maintenance will further clarify how governance choices shaped long-term resilience. Iterative use of the risk-matrix approach, combined with improved chronological control, can refine the envelopes of probable stress and help map spatial patterns of vulnerability and adaptive response. Taken together, this integrated programme advances a socio-ecological perspective in which environment, technology, institutions, and social organisation co-produce trajectories of change. By resisting monocausal explanations and making evidence hierarchies explicit, the approach offers a framework for reconstructing past crises that is both empirically anchored and sensitive to the multi-dimensional processes that shape human-environment interactions.

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Bona medicina locis mali.

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Entries are listed alphabetically by first author surname. Entries marked [REFERENCE TO VERIFY] or [BIBLIOGRAPHIC DATA MISSING] are flagged in the accompanying Reference Audit Table and require completion by the author; no data has been invented to complete them.

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Appendix A

Field Observations, Photographic Documentation and Analytical Figures from Crete (2025)

Appendix A contains original observational material collected by the author during field research activities conducted in Crete in 2025, alongside a set of schematic analytical figures that visually summarise concepts already developed and cited in the main body of the thesis. No new archaeological, environmental or geographical claims are introduced in this appendix: every figure is either (a) a direct schematic rendering of material discussed and referenced in the preceding chapters, or (b) a placeholder for material that requires georeferenced source data or original photographs to be supplied by the author, which could not be generated without introducing unsupported assumptions.

Figure A.1 Chronological Timeline of Aegean Palatial Development and Destruction Horizons

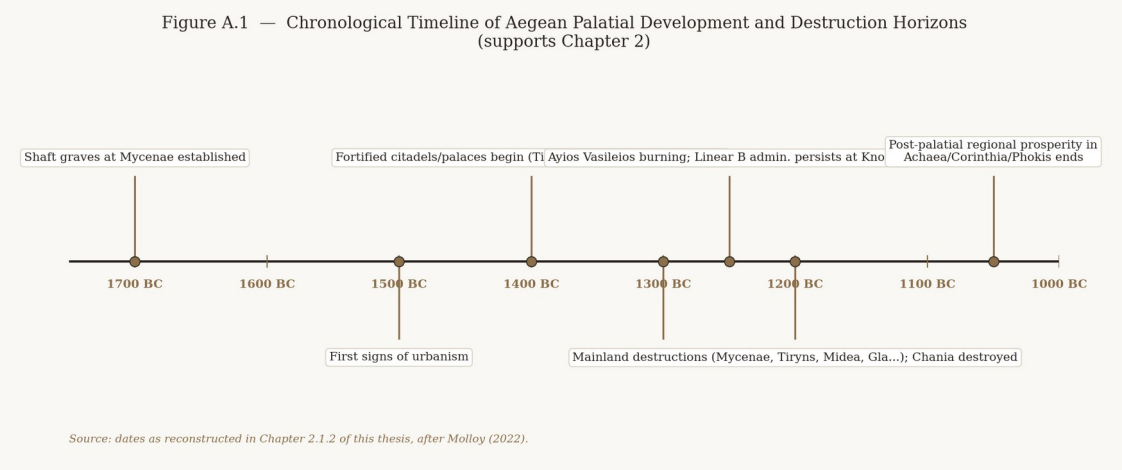


Figure A.1. Chronological Timeline of Aegean Palatial Development and Destruction Horizons. Supports Chapter 2. Source: Generated by the author from dates verified in Section 2.1.2 of this thesis, after Molloy (2022).

Figure A.2 Comparative Multi-Layer Gradient Timeline of the Minoan Crisis (Variant 1)

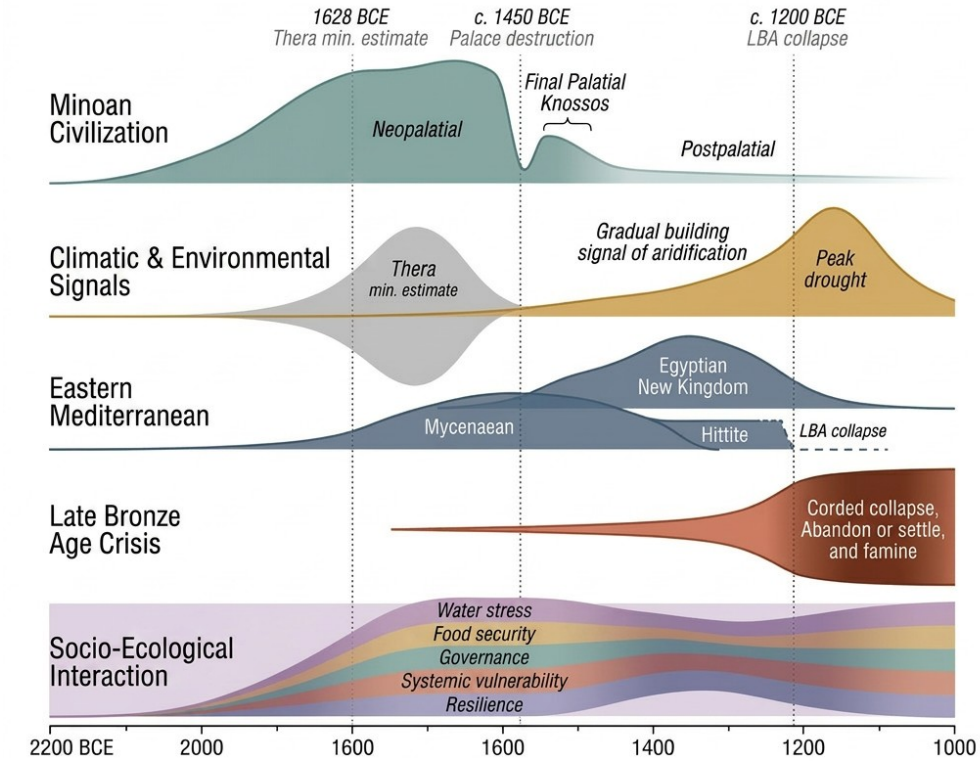


Figure A1. Comparative multi-layer gradient timeline illustrating the relative intensity of environmental, climatic, political and socio-ecological events during the Minoan crisis and the Late Bronze Age. The width and opacity of each band reflect the relative intensity of the phenomenon. Shaded intervals represent chronological uncertainty.

Figure A.2. Comparative Multi-Layer Gradient Timeline of the Minoan Crisis (Variant 1). Supports Chapters 2 and 10.

Source: Supplied by the author. Note on verification: general Aegean chronology is consistent with Section 2.1.2 of this thesis. Eastern Mediterranean bands (Egyptian New Kingdom, Hittite Empire, Levantine trade networks) are not sourced to citations in this thesis's bibliography, which does not cite dated Egyptian/Levantine synchronisms.

Figure A.3 Comparative Multi-Layer Timeline of the Minoan Crisis (Variant 2)

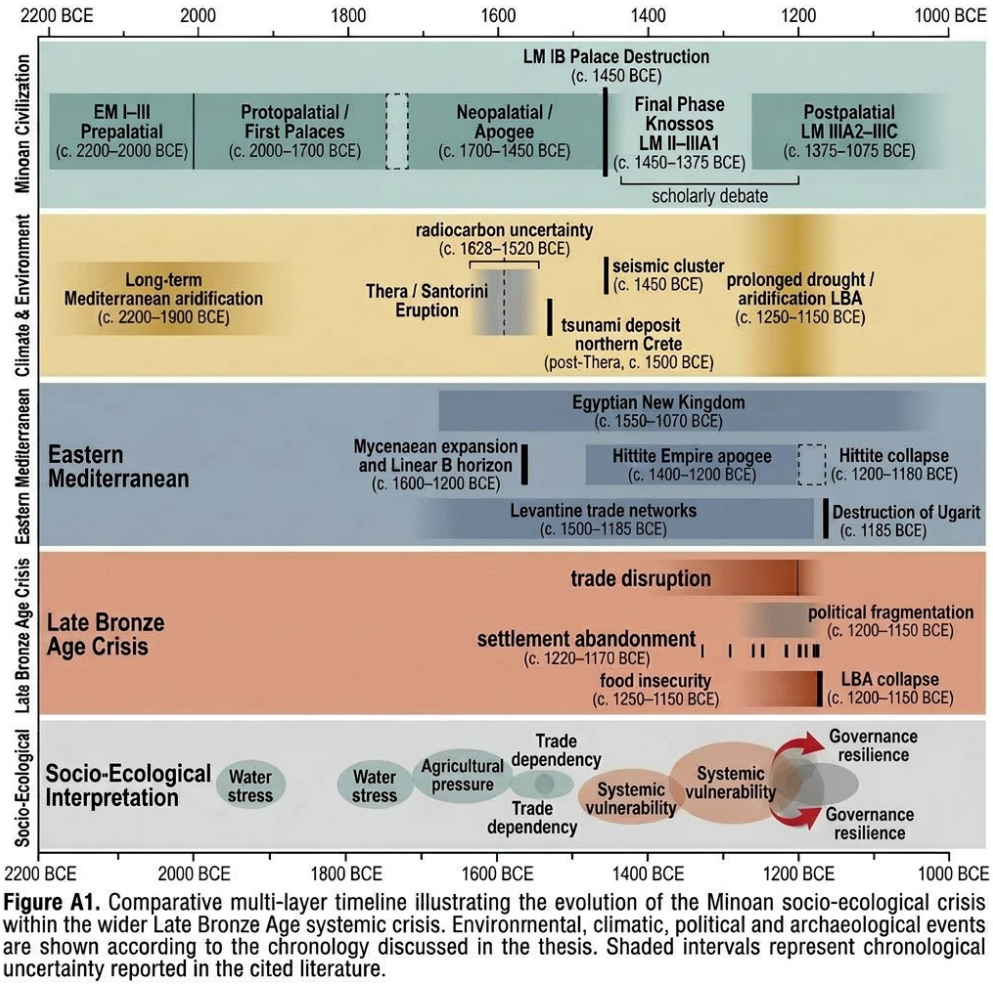


Figure A1. Comparative multi-layer timeline illustrating the evolution of the Minoan socio-ecological crisis within the wider Late Bronze Age systemic crisis. Environmental, climatic, political and archaeological events are shown according to the chronology discussed in the thesis. Shaded intervals represent chronological uncertainty reported in the cited literature.

Figure A.3. Comparative Multi-Layer Timeline of the Minoan Crisis (Variant 2). Supports Chapters 2 and 10.

Source: Supplied by the author. One of two comparative-timeline variants supplied; both are retained here. Note on verification: general Aegean chronology is consistent with Section 2.1.2 of this thesis. Eastern Mediterranean bands (Egyptian New Kingdom, Hittite Empire, Levantine trade networks) are not sourced to citations in this thesis's bibliography, which does not cite dated Egyptian/Levantine synchronisms.

Figure A.4 Explicit Evidence Hierarchy Applied Throughout the Thesis

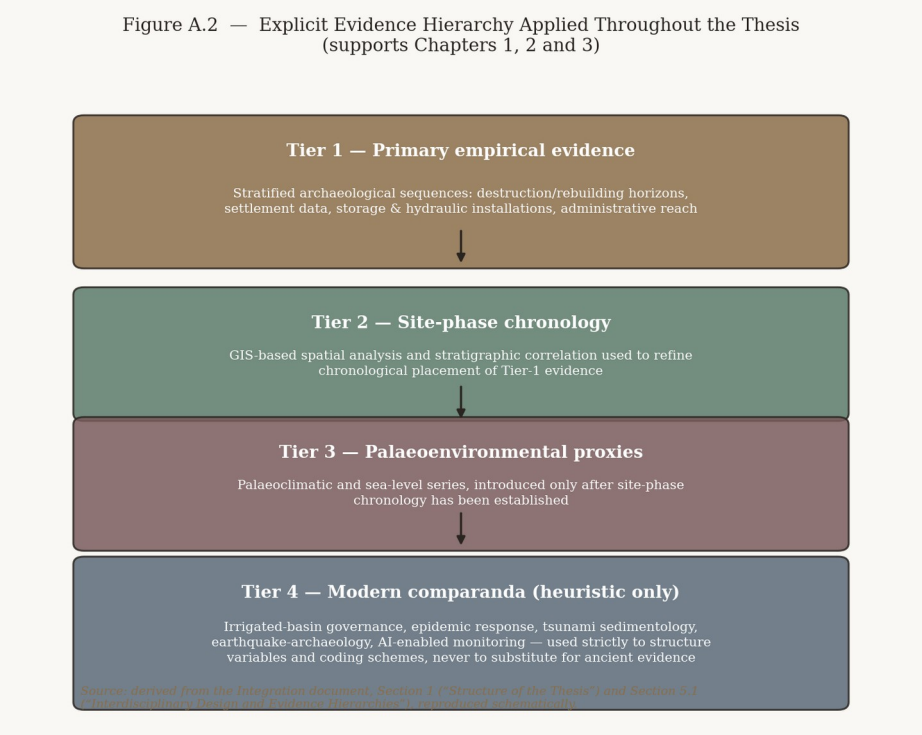


Figure A.4. Explicit Evidence Hierarchy Applied Throughout the Thesis. Supports Chapters 1, 2 and 3.
Source: Generated by the author from the Integration document, Sections 1 and 5.1, reproduced schematically.

Figure A.5 Spatial Distribution and Chronological Development of the Principal Minoan Palatial Centres (Variant 1)

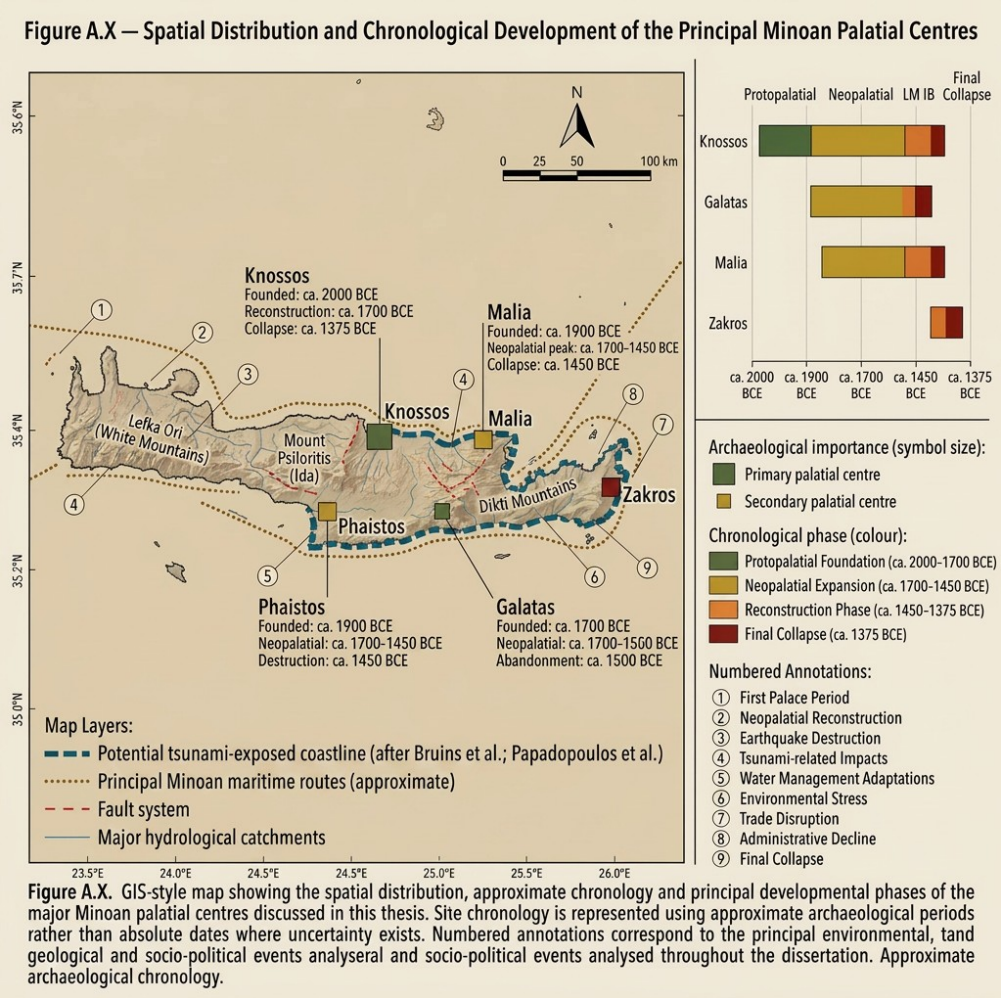


Figure A.5. Spatial Distribution and Chronological Development of the Principal Minoan Palatial Centres (Variant 1). Supports Chapters 2 and 10.

Source: Supplied by the author. Note on verification: specific founding/reconstruction/collapse dates shown for individual palatial centres on this figure are not sourced to citations in this thesis's audited bibliography.

Figure A.6 GIS Distribution and Chronological Phases of the Principal Minoan Palatial Centres (Variant 2)

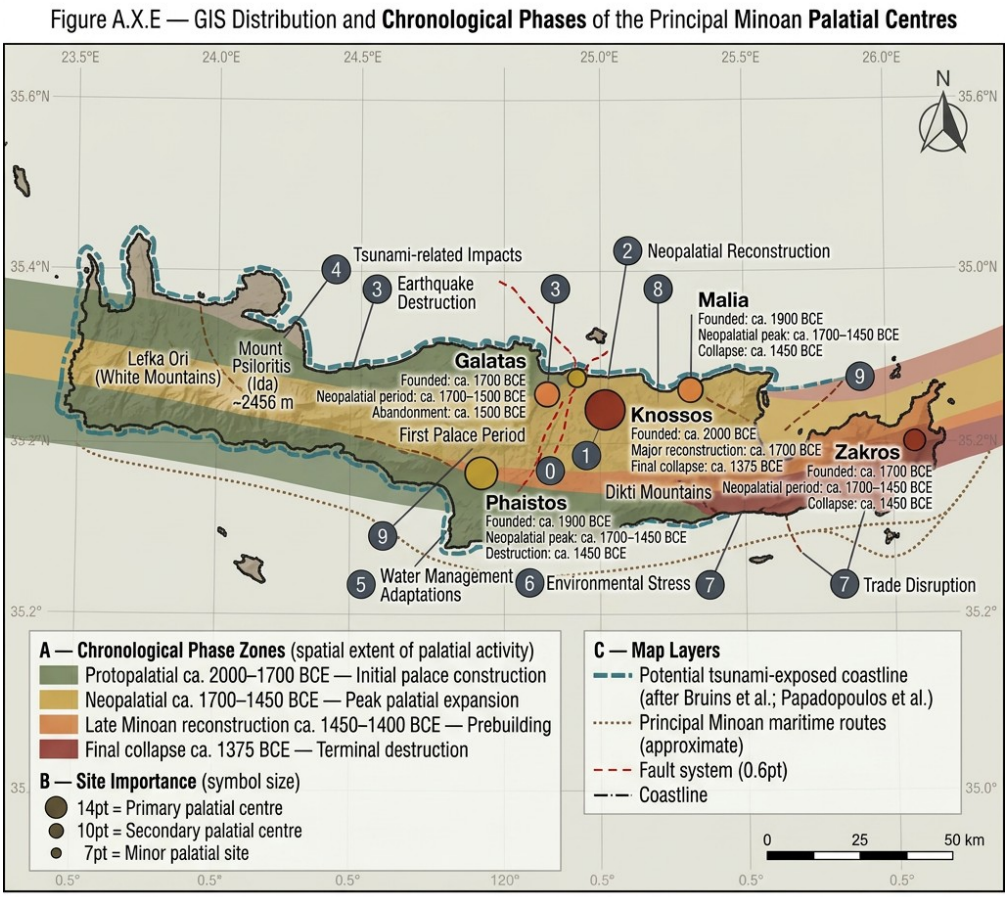


Figure A.X.E. GIS-style map showing the spatial distribution and principal chronological phases. major Minoan palatial centres discussed in this thesis. Coloured zones represent the approximate spatial extent of palatial activity during each chronological period. Symbol size indicates relative archaeological importanc of palatial centre. Site chronology is represented using approximate archaeological periods rather than absolute dates where uncertainty exists. Numbered annotations correspond to the principal environmental, geological and socio-political events analysed throughout the dissertation. Approximate archaeological chronology.

Figure A.6. GIS Distribution and Chronological Phases of the Principal Minoan Palatial Centres (Variant 2). Supports Chapters 2 and 10.

Source: Supplied by the author. Coordinate frame consistent with Crete's real geographic extent. Note on verification: specific founding/reconstruction/collapse dates shown for individual palatial centres on this figure are not sourced to citations in this thesis's audited bibliography.

Figure A.7 Territorial Network and Chronology of the Minoan Palatial Centres of Crete (Variant 3)

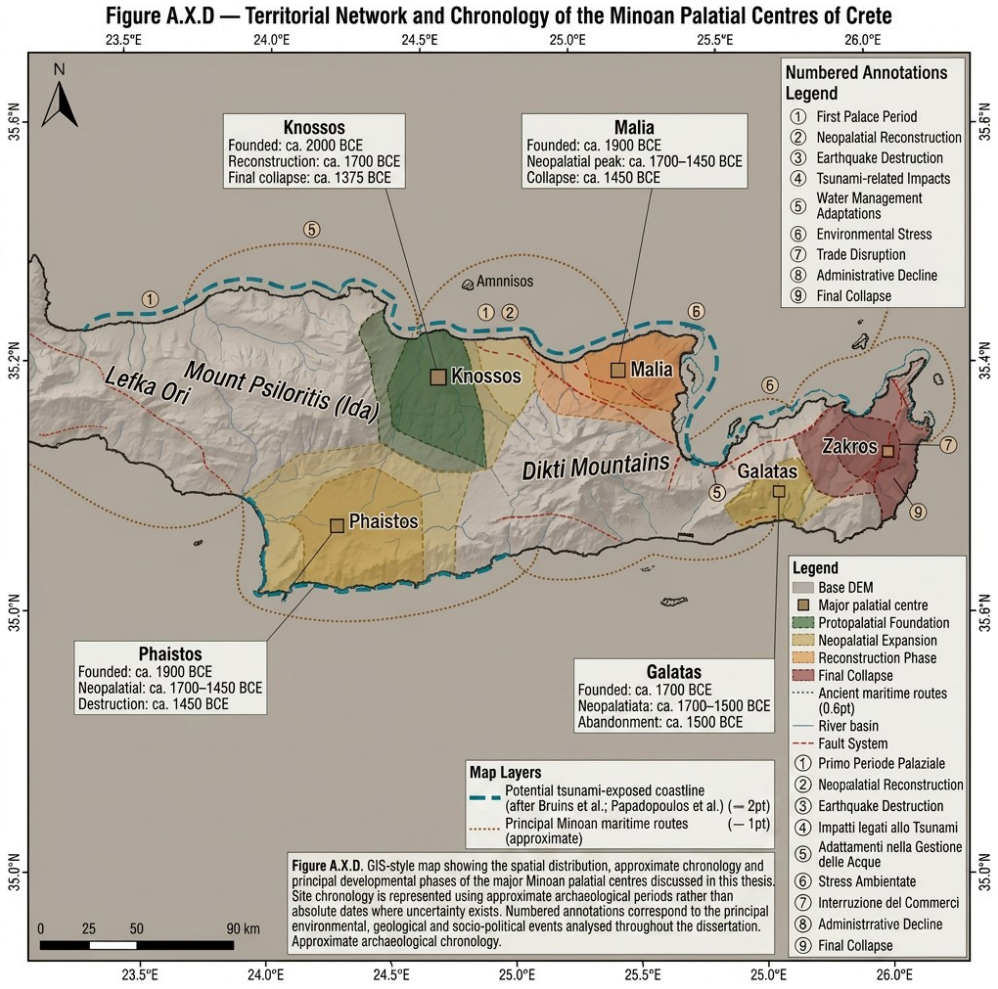


Figure A.7. Territorial Network and Chronology of the Minoan Palatial Centres of Crete (Variant 3). Supports Chapters 2 and 10.

Source: Supplied by the author. Coordinate frame consistent with Crete's real geographic extent. Third of three supplied variants of this concept, retained per full-integration instruction; captions on the figure itself mix English and Italian annotations for the same legend items. Note on verification: specific founding/reconstruction/collapse dates shown for individual palatial centres on this figure are not sourced to citations in this thesis's audited bibliography.

Figure A.8 Socio-Ecological Systems of Minoan Crete: GIS Layered Structure

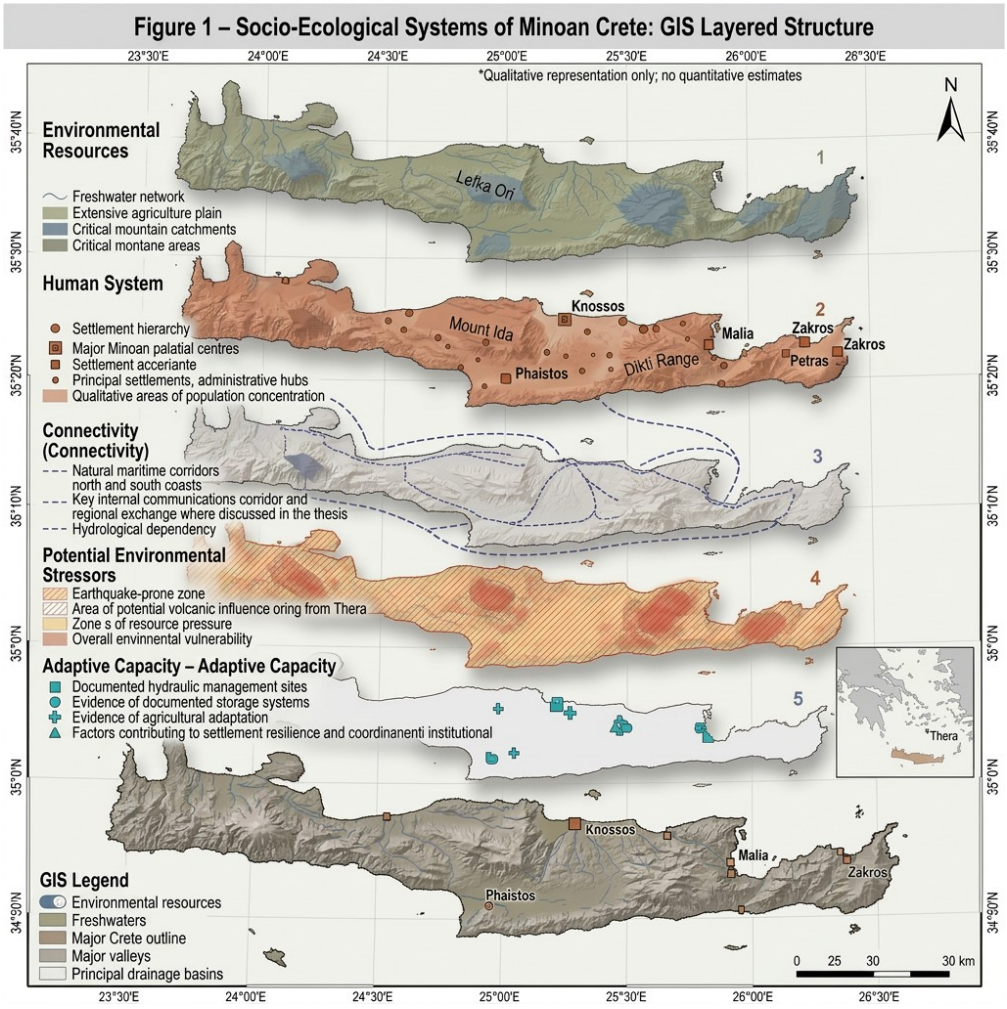


Figure A.8. Socio-Ecological Systems of Minoan Crete: GIS Layered Structure. Supports Chapters 6 and 10. Source: Supplied by the author. Coordinate frame consistent with Crete's real geographic extent.

Figure A.9 System Flows and Connectivity of Minoan Socio-Ecological Systems

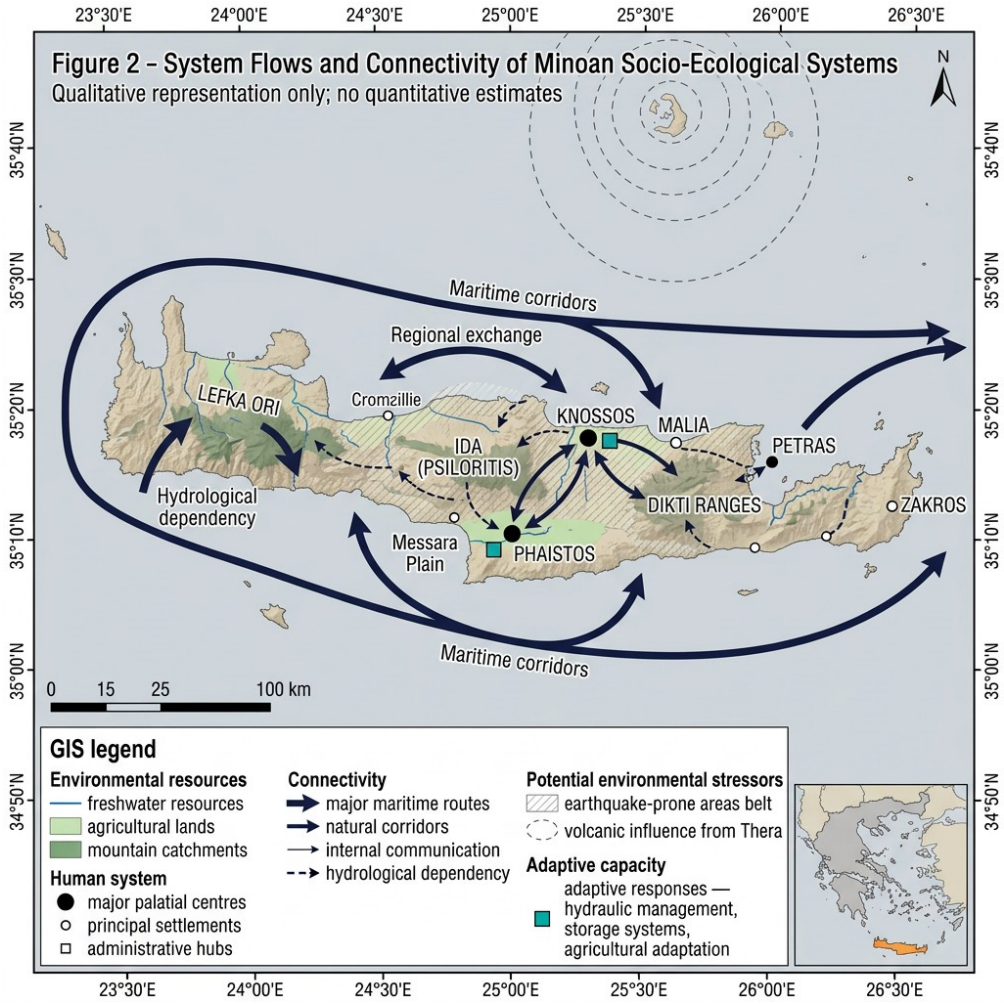


Figure A.9. System Flows and Connectivity of Minoan Socio-Ecological Systems. Supports Chapters 6 and 10. Source: Supplied by the author. Coordinate frame consistent with Crete's real geographic extent.

Figure A.10 Hydrological Atlas of Minoan Crete (Variant 1 of 3)

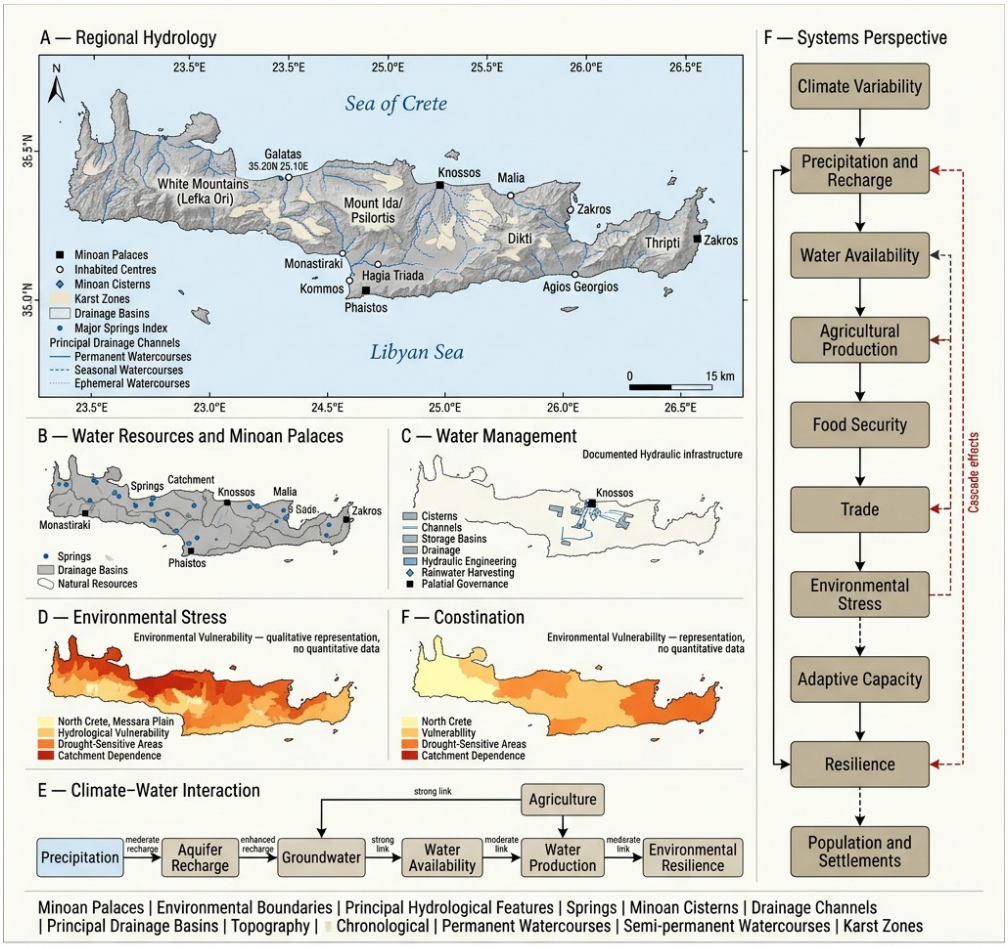


Figure A.X.C. GIS-based Hydrological Atlas illustrating the principal hydrological systems, water resources and environmental framework of Minoan Crete. The atlas integrates topography, drainage basins, archaeological settlements, documented hydraulic infrastructure and conceptual socio-ecological interactions discussed throughout the thesis. All mapped information derives exclusively from the literature cited in the dissertation.

Figure A.10. Hydrological Atlas of Minoan Crete (Variant 1 of 3). Supports Chapter 5.

Source: Supplied by the author. Coordinate frame consistent with Crete's real geographic extent. Includes real regional place names (Sea of Crete, Libyan Sea).

Figure A.11 Hydrological Atlas of Minoan Crete (Variant 2 of 3)

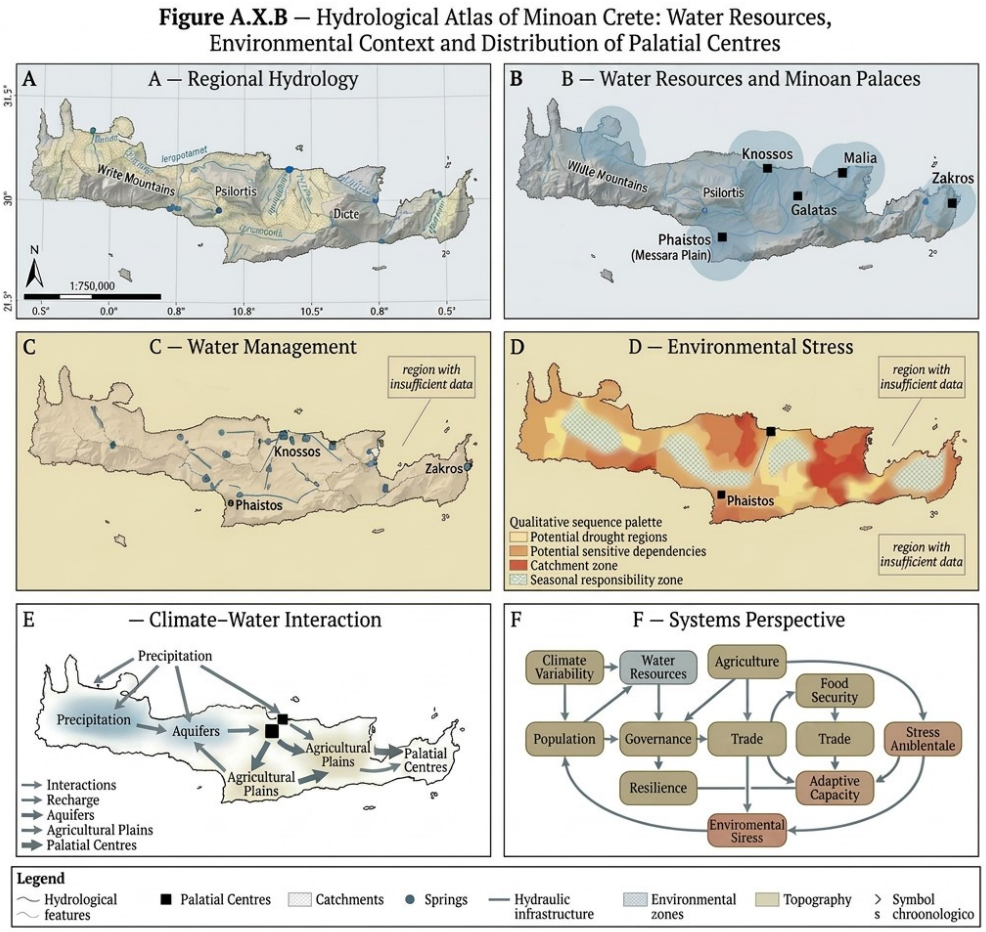


Figure A.X. GIS-based Hydrological Atlas illustrating the principal hydrological systems, water resources and environmental framework of Minoan Crete. The atlas integrates topography, drainage basins, archaeological settlements, docomented hydraulic infrastructure and conceptnal socio-ecological interactions discussed throughout the thesis. All mapped information derives exclusively from the literature cited in the dissertation.

Figure A.11. Hydrological Atlas of Minoan Crete (Variant 2 of 3). Supports Chapter 5.

Source: Supplied by the author. Note on verification: this variant's regional inset (panel A) uses a coordinate grid inconsistent with Crete's location, and contains the label "Write Mountains" (for "White Mountains") and "Environmental Siress" (for "Stress") in the original supplied graphic; retained as provided.

Figure A.12 Hydrological Atlas of Minoan Crete (Variant 3 of 3)

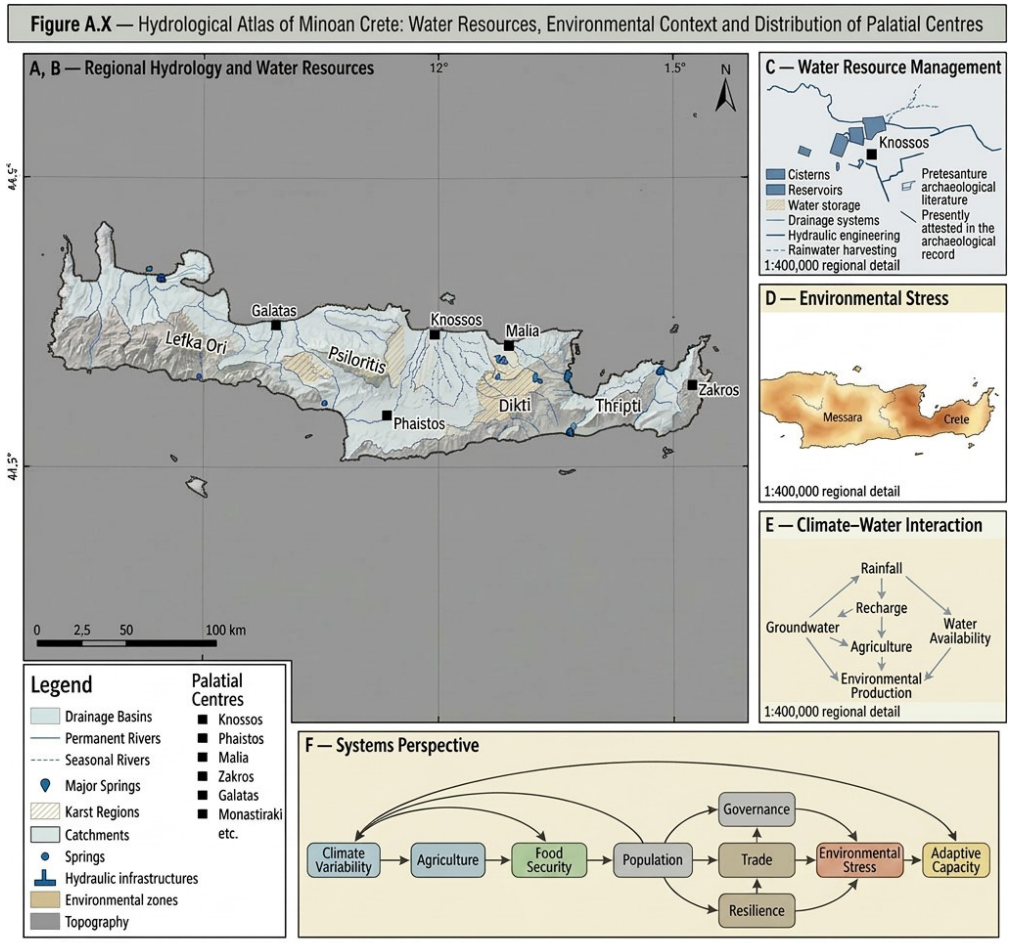


Figure A.12. Hydrological Atlas of Minoan Crete (Variant 3 of 3). Supports Chapter 5.

Source: Supplied by the author. Note on verification: this figure's coordinate grid does not correspond to Crete's actual location and has not been corrected, per the instruction to integrate all supplied material as provided. Latitude label "44.5°" appears twice on the same figure with contradictory positioning in the original supplied graphic; retained as provided.

Figure A.13 Physical and Geographical Map of Crete

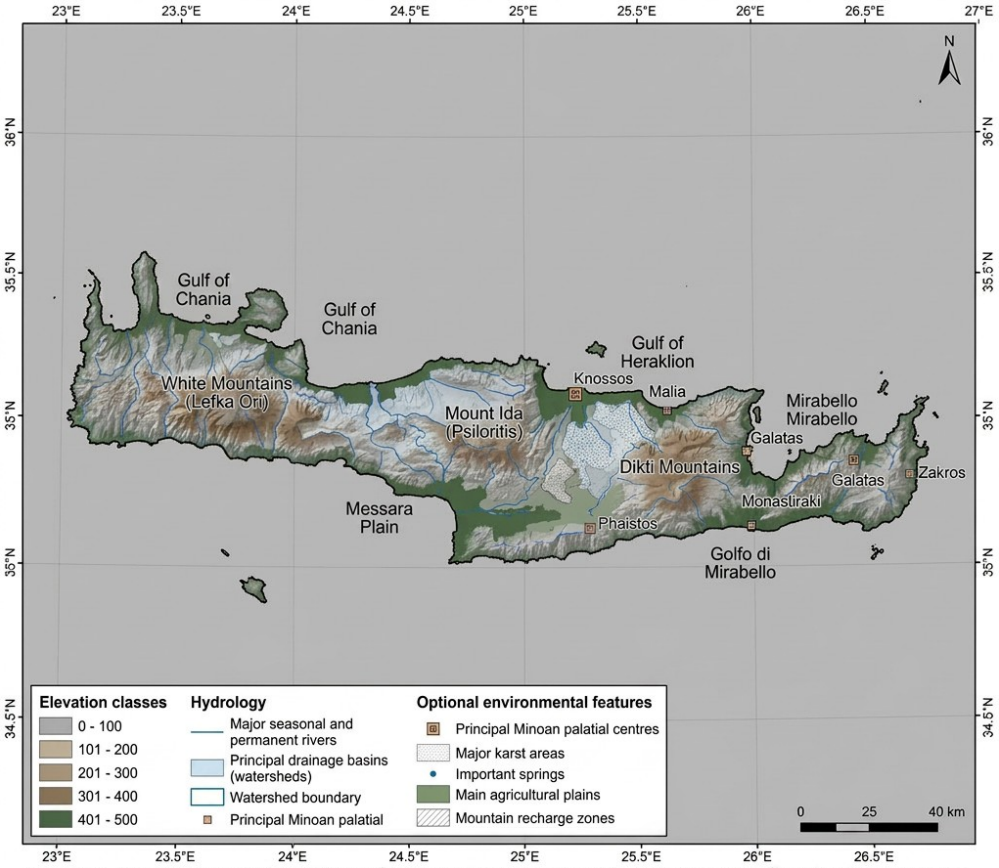


Figure A.9. Physical and geographical map of Crete showing the island's principal topographic features, drainage basins, major mountain systems and the location of the principal Minoan palatial centres discussed in this thesis. The figure provides the environmental framework supporting the analyses presented in Chapters 2 and 5 and does not imply archaeological interpretation beyond the evidence discussed in the dissertation.

Source: Physical geography is based exclusively on recognised cartographic and topographic datasets. Archaeological locations are based exclusively on the sites discussed in this thesis. Where precise GIS data are unavailable, the map is a schematic representation based on recognised physical geography and verified archaeological locations discussed in the thesis.

Figure A.13. Physical and Geographical Map of Crete. Supports Chapters 2 and 5.

Source: Supplied by the author. Coordinate frame consistent with Crete's real geographic extent.

Figure A.14 Schematic Complex Adaptive Systems Diagram of Coupled Socio-Ecological Domains

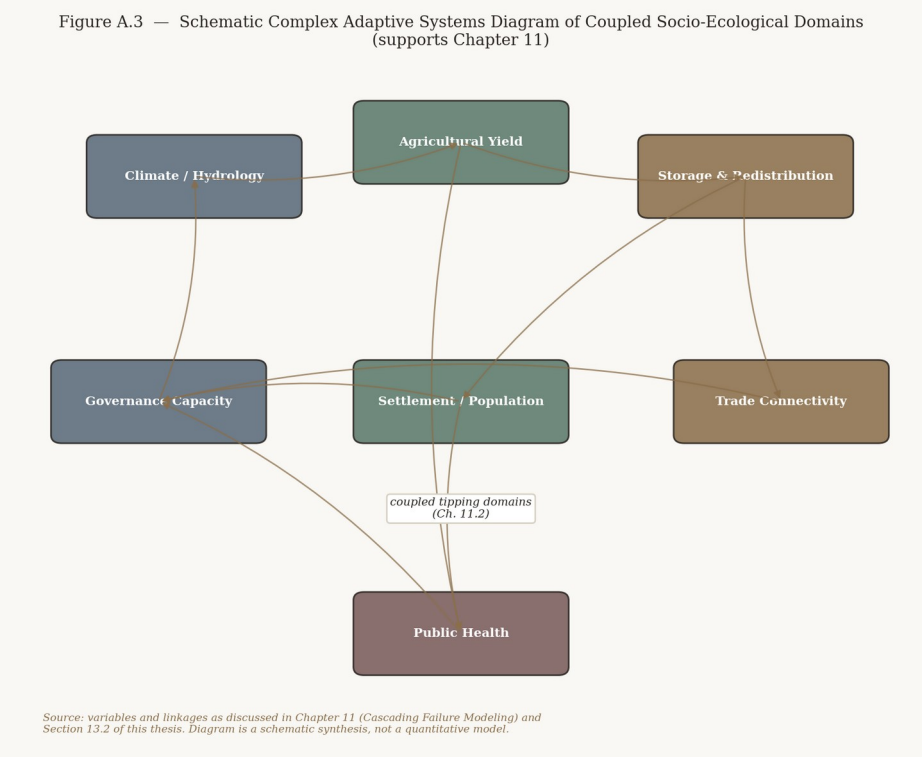


Figure A.14. Schematic Complex Adaptive Systems Diagram of Coupled Socio-Ecological Domains. Supports Chapter 11. Source: Generated by the author from Chapter 11 and Section 13.2 of this thesis.

Figure A.15 Qualitative Risk-Interaction Matrix (Hazard × Systemic Domain)

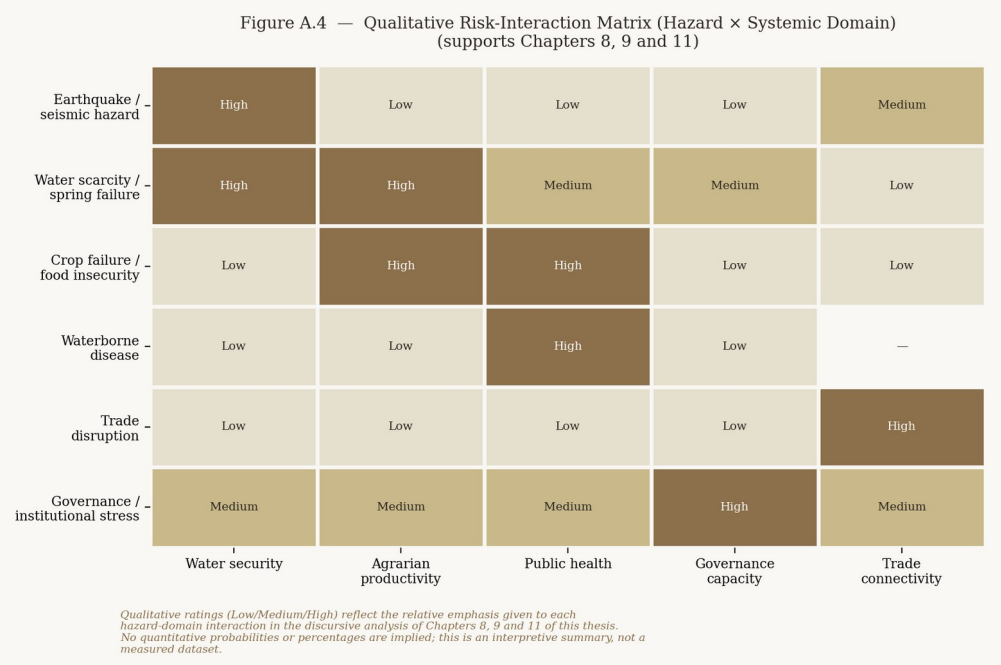


Figure A.15. Qualitative Risk-Interaction Matrix (Hazard × Systemic Domain). Supports Chapters 8, 9 and 11.

Source: Generated by the author from Chapters 8, 9 and 11 of this thesis.

Figure A.16 Socio-Ecological Vulnerability Zones: Minoan Crete

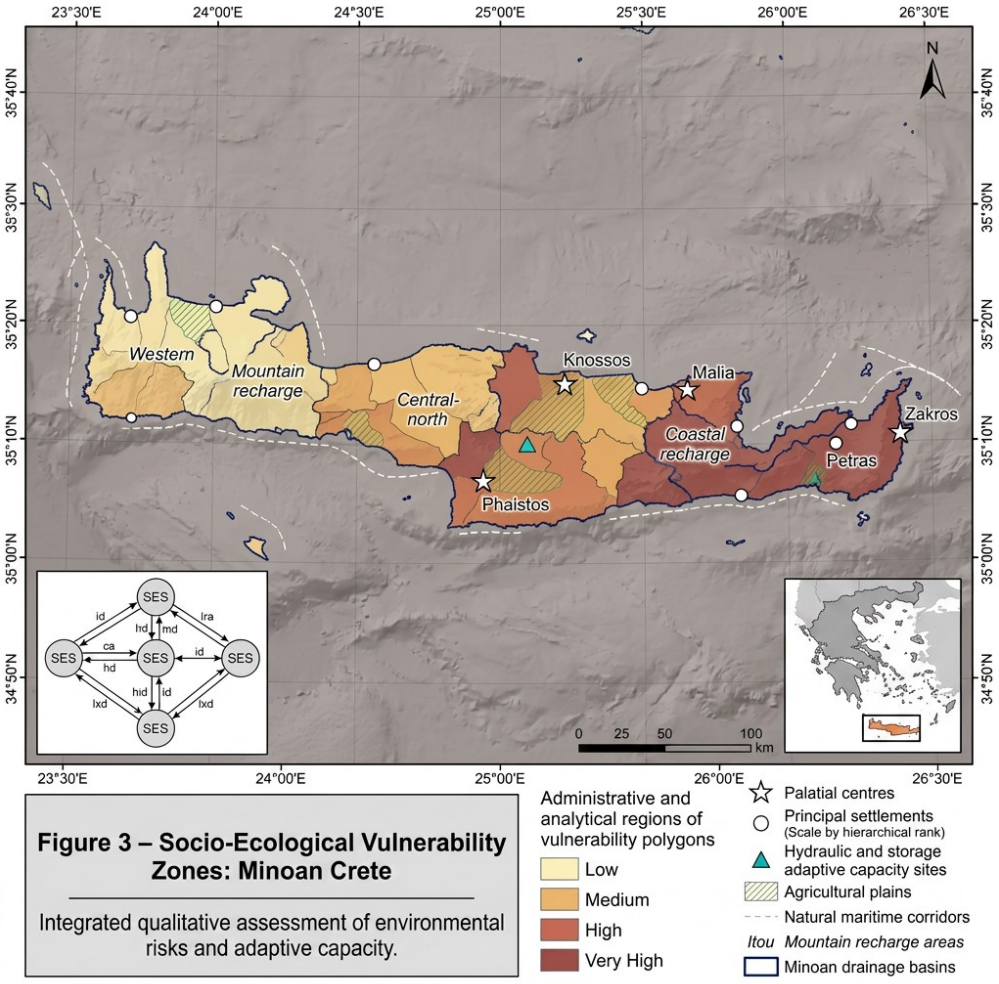


Figure A.16. Socio-Ecological Vulnerability Zones: Minoan Crete. Supports Chapters 8, 9 and 11.

Source: Supplied by the author. Coordinate frame consistent with Crete's real geographic extent. Vulnerability classes are qualitative and illustrative, consistent with the qualitative risk framework in Figure A.15.

Table A.1 Chronology of Relative Sea-Level Change and Tectonic Uplift Episodes on the Levant Coast

Supports: Section 2.6

Episode	Age	Elevation	Character / Evidence	Source
Upper shoreline ("Zennadian")	ca. 6000–3000 BP (density peak ca. 2700–2200 BP)	+120 to +140 cm	Long-lived stable shoreline predating the main tectonic episode; documented at Ile du Phare and Ile du Palmier, Tripoli	Morhange et al. (2006), §4, §5.1.1
Lower shoreline ("Tabarjan")	ca. 2100–1800 BP (5th c. BC – 6th c. AD, calibrated)	+80 ± 40 cm	Associated with the Early Byzantine Tectonic Paroxysm (EBTP) — fault movements on the Yammuneh and Roum-Tripoli Thrust dated ca. 1750–2000 BP	Morhange et al. (2006), §4, §5.1.2
Short Medieval episode	ca. 1100 BP	up to +80 cm (Bouar); +40 cm (Khaizerane)	Localised, rapid relative sea-level rise of probable tectonic origin, recorded near Bouar and north of Tyre	Morhange et al. (2006), §5.1.3
Historical stabilisation	ca. 1000 BP to present	present level	Relative sea-level stability along the Lebanese coast, evidenced by in-situ coastal archaeological remains (fish tanks, sea walls) at present sea level	Morhange et al. (2006), §5.1.4
Regional comparison — Levant coast	Lebanon: +1.3±0.1 m (6000–3200 BP) / +0.8±0.4 m (3000–1800 BP); Syria: +1.2 m / +0.6 m; Turkey (Hatay): +2 m / +0.8 m	—	Comparable two-shoreline pattern (older/higher, younger/lower, both ending in coseismic uplift) documented across the Levant coast	Pirazzoli (2005), §3.8

This table replaces an earlier author-supplied graphic that could not be verified against the cited literature. It is built directly from the findings reported in Morhange et al. (2006) — 33 radiocarbon-dated biological sea-level indicators from the Lebanese coast — and the cross-regional synthesis in Pirazzoli (2005). Both references are now confirmed and included in full in this thesis's bibliography. No values have been estimated or extrapolated beyond what these two papers report.

Field Photographs (2025)

The following pages provide a structured template for the author's original field photographs and observations collected in Crete in 2025, as described in the thesis front matter (“Section II – Appendix A: Field Observations and Photographic Documentation from Crete (2025)”). Image areas are left blank for insertion by the author.

Figure A.17.1

Photograph	
Location	Palace of Knossos, West Court sector, in front of the restored North Entrance.
GPS coordinates	Not embedded in the photograph (no EXIF GPS data present in the file). Published site coordinates, for reference only — not derived from this photograph: 35.2979° N, 25.1627° E.
Municipality	Knossos, Municipality of Heraklion.
Site	Palace of Knossos (open-air archaeological site).
Date	2025 field campaign; exact capture date not recorded (no EXIF date-time metadata embedded in the file).
Description	Three large ceramic pithoi shown in situ against the palace's western masonry, with the restored North Entrance visible in the background. Vessels of this class were used for bulk storage of grain, oil, wine and pulses.
Corresponding thesis chapter	Water Security and Hydraulic Systems; Security and Resilience Analysis.
Reference	Primary field photograph; cross-referenced with the storage discussion in the main body (§ Security and Resilience Analysis).
Author's analytical observations	The number and capacity of these vessels support the thesis's reading of storage infrastructure as a proxy for administrative surplus accumulation, and as a point of systemic fragility under supply-chain stress within the cascading-failure framework.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign.

Figure A.17.2

Photograph	
Location	Palace of Knossos, North Entrance Passage.
GPS coordinates	Not embedded in the photograph (no EXIF GPS data present in the file). Published site coordinates, for reference only: 35.2979° N, 25.1627° E.
Municipality	Knossos, Municipality of Heraklion.
Site	Palace of Knossos, North Entrance Passage (early-20th-century reconstruction by Arthur Evans).
Date	2025 field campaign; exact capture date not recorded (no EXIF date-time metadata).
Description	Tapering red-painted, wooden-type columns and ashlar door-jambs of the North Entrance Passage, one of the principal restored circulation routes into the palace. The visible fabric includes Evans's concrete reconstruction (c. 1900–1930s), not unaltered ancient material.
Corresponding thesis chapter	Late Bronze Age Systemic Crisis Framework; Fire and Destruction in Minoan Context.
Reference	Primary field photograph; reconstruction history per the established archaeological literature on Evans's restorations at Knossos.
Author's analytical observations	Used cautiously as illustrative material for palatial monumental architecture; the reconstructed status of this fabric is flagged explicitly so it is not read as unmediated primary evidence of destruction or seismic deformation.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign.

Figure A.17.3

Photograph	
Location	Palace of Knossos, North Entrance / Bastion sector.
GPS coordinates	Not embedded in the photograph (no EXIF GPS data present in the file). Published site coordinates, for reference only: 35.2979° N, 25.1627° E.
Municipality	Knossos, Municipality of Heraklion.
Site	Palace of Knossos (open-air archaeological site).
Date	2025 field campaign; exact capture date not recorded (no EXIF date-time metadata).
Description	Wide-angle view combining unrestored rubble and cut-stone wall stumps with the restored red-columned bastion in the middle distance; visitors provide scale.
Corresponding thesis chapter	Late Bronze Age Systemic Crisis Framework.
Reference	Primary field photograph.
Author's analytical observations	Provides broad documentary context for the site’s degree of ruin versus reconstruction, supporting the methodological caveat that destruction-horizon interpretation must distinguish original archaeological fabric from 20th-century concrete restoration before any seismic or fire-related inference is drawn.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign.

Figure A.17.4

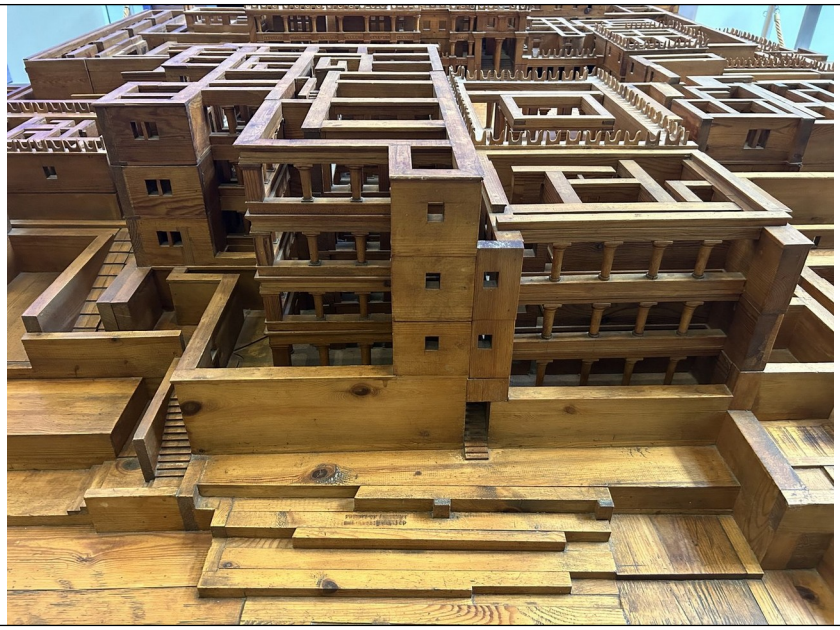
Photograph	
Location	Exhibition venue not independently confirmable from the photograph.
GPS coordinates	Not applicable / not available — no EXIF GPS data embedded, and no exhibition signage visible in frame to confirm venue.
Municipality	Heraklion (tentative; venue unconfirmed).
Site	Scale architectural model of the Palace of Knossos.
Date	2025 field campaign; exact capture date not recorded.
Description	Large wooden reconstruction model rendering the palace's dense, multi-storey, corridor-and-court plan, including piers, light wells and staircases.
Corresponding thesis chapter	Political Ecology and Human Geography (GIS and cartographic discussion of settlement complexity).
Reference	Primary field photograph; venue not independently confirmed — author to verify.
Author's analytical observations	Supports the discussion of multi-storey structural vulnerability and the labyrinthine plan referenced in the Symbolism, Religion and Environmental Dependency chapter. Recommended: author to confirm the exhibition venue for full caption completion.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign.

Figure A.17.5

Photograph	
Location	Heraklion Archaeological Museum (display); original findspot Phaistos.
GPS coordinates	Not embedded in the photograph (no EXIF GPS data present). Published museum (venue) coordinates, for reference only — not the artefact's findspot: 35.3390° N, 25.1370° E.
Municipality	Heraklion.
Site	Heraklion Archaeological Museum; artefact excavated at Phaistos.
Date	2025 field campaign; exact capture date not recorded.
Description	The Phaistos Disc: a fired-clay disc bearing forty-five pictorial signs stamped in a spiral sequence on both faces, one of the most discussed unresolved epigraphic problems of Aegean prehistory. Early 17th century BC (Protopalatial horizon), per the museum's own interpretive panel photographed in the same visit.
Corresponding thesis chapter	Political Ecology and Human Geography; Symbolism, Religion and Environmental Dependency.
Reference	Museum interpretive panel text, photographed by the author in the same field session (cross-referenced in the photographic-documentation audit).
Author's analytical observations	Illustrates the depth and limits of Minoan administrative/ritual literacy and underscores the thesis's methodological caution that undeciphered scripts cannot be used to reconstruct specific historical events.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign.

Figure A.17.6

Photograph	
Location	Heraklion Archaeological Museum, storage-vessels gallery.
GPS coordinates	Not embedded in the photograph. Published museum (venue) coordinates, for reference only: 35.3390° N, 25.1370° E.
Municipality	Heraklion.
Site	Heraklion Archaeological Museum; original findspot not individually labelled in frame.
Date	2025 field campaign; exact capture date not recorded.
Description	Two large relief-decorated pithoi, with inventory mark “3915” legible on one vessel, displayed beside the museum’s bilingual panel ‘Storage and Storage Pithoi’, explaining that vessel size and number increased during the Neopalatial period with population growth and organised production.
Corresponding thesis chapter	Water Security and Hydraulic Systems; Security and Resilience Analysis.
Reference	Museum panel text visible in the same photograph names subject and period directly.
Author's analytical observations	Directly corroborates, with primary museum-sourced text, the thesis’s argument that storage capacity is a proxy for administrative complexity and a point of systemic fragility under supply-chain stress; complements Figure A.17.1 with an independently documented example.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign.

Figure A.17.7

Photograph	
Location	Heraklion Archaeological Museum, Minoan religion gallery (attribution by stylistic/contextual consistency, not GPS-confirmed).
GPS coordinates	Not embedded in the photograph. Published museum (venue) coordinates, for reference only: 35.3390° N, 25.1370° E.
Municipality	Heraklion.
Site	Heraklion Archaeological Museum; findspot not confirmable from the image.
Date	2025 field campaign; exact capture date not recorded.
Description	Minoan female figurine with raised arms holding snakes, surmounted by a small feline figure, displaying the canonical iconographic type conventionally called ‘Snake Goddess/Priestess’. A small numeral (‘65’) is visible on the base, likely a display/inventory reference.
Corresponding thesis chapter	Symbolism, Religion and Environmental Dependency.
Reference	No catalogue cross-check performed; iconographic type identified from published comparanda, exact accession identity not independently verified.
Author's analytical observations	Provides visual evidence for the ritual/symbolic register discussed in this chapter, particularly the argument that cult imagery encoded relationships between fertility, protection and environmental risk.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign.

Figure A.17.8

Photograph	
Location	Heraklion Archaeological Museum, ritual pottery gallery (attribution by stylistic/contextual consistency, not GPS-confirmed).
GPS coordinates	Not embedded in the photograph. Published museum (venue) coordinates, for reference only: 35.3390° N, 25.1370° E.
Municipality	Heraklion.
Site	Heraklion Archaeological Museum; findspot not confirmable from the image.
Date	2025 field campaign; exact capture date not recorded.
Description	Composite pottery cult stand with several painted bird figures around a central column, a form associated with peak-sanctuary and domestic-shrine offering assemblages rather than utilitarian pottery.
Corresponding thesis chapter	Symbolism, Religion and Environmental Dependency.
Reference	General typological class identifiable; no label visible in frame; precise formal vessel-type term deliberately not assigned pending specialist confirmation.
Author's analytical observations	Supports the discussion of sacred landscapes and ecological symbolism, with birds as recurrent votive motifs linked to fertility and environmental renewal.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign.

Figure A.17.9

Photograph	
Location	Exhibition venue not independently confirmable; thematically consistent with the Roman-period gallery documented in the same field session.
GPS coordinates	Not embedded in the photograph. If displayed at the Heraklion Archaeological Museum (unconfirmed), published venue coordinates for reference only: 35.3390° N, 25.1370° E.
Municipality	Heraklion (tentative; venue unconfirmed).
Site	Findspot not confirmable from the image; NOT a Bronze Age artefact.
Date	2025 field campaign; exact capture date not recorded.
Description	Black-and-white tessellated mosaic pavement fragment depicting a scrolling vine issuing from a central krater, a decorative and symbolic motif typical of Roman-period Cretan viticultural iconography (c. 1st century BC – 4th century AD, stylistic dating).
Corresponding thesis chapter	Included only as later-period comparative/contextual material (cf. discussion of long-term regional wine economies); explicitly NOT part of the Bronze Age evidence base.
Reference	Style-based period attribution; precise site of origin not determinable from the image.
Author's analytical observations	Included with an explicit chronological caveat: this photograph must not be read as chronologically continuous with the Minoan-collapse discussion, consistent with the thesis's rejection of naive environmental/historical determinism.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign.

Figure A.17.10

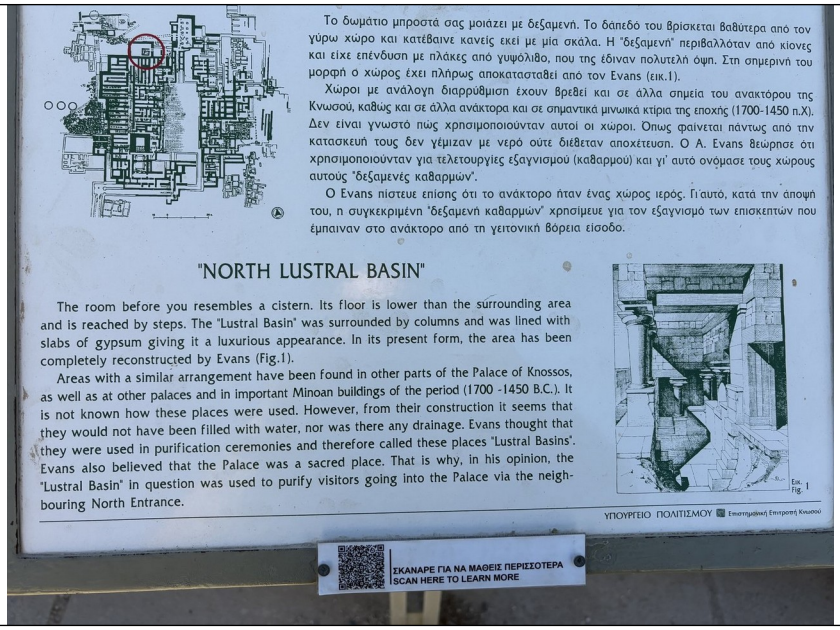
Photograph	
Location	Palace of Knossos, North Lustral Basin (on-site bilingual interpretive panel, illustrated with site plan and archival photograph).
GPS coordinates	Not embedded in the photograph (no EXIF GPS data present). Published site coordinates, for reference only: 35.2979° N, 25.1627° E.
Municipality	Knossos, Municipality of Heraklion.
Site	Palace of Knossos, North Lustral Basin (interpretive panel photographed in situ).
Date	2025 field campaign; exact capture date not recorded (no EXIF date-time metadata).
Description	On-site panel describing the ‘North Lustral Basin’: a sunken, column-lined chamber reached by steps, faced with gypsum slabs, fully reconstructed by Evans. The panel notes that similarly arranged sunken rooms occur elsewhere at Knossos and at other Minoan palatial buildings (1700–1450 BC), that their function is not established with certainty, and that they show no construction evidence of ever having held or drained water — Evans’s own reading was that they served ritual purification (‘lustral’) of visitors entering via the neighbouring North Entrance.
Corresponding thesis chapter	Symbolism, Religion and Environmental Dependency; Water Security and Hydraulic Systems.
Reference	On-site museum/site-authority interpretive panel (Hellenic Ministry of Culture / Knossos Scientific Committee), photographed by the author; content reproduced from the panel as displayed.
Author's analytical observations	This feature is included in the thesis primarily for the sacredness attributed to water in Minoan ceremonial architecture, rather than as evidence of functional water engineering: the panel itself states that the basin, despite its name and form, shows no constructional evidence of ever holding water. Read this way, the Lustral Basin illustrates how water could operate as a symbolic and purificatory reference even where it was not physically present or utilised, which is relevant to the thesis’s discussion of the ritual and ideological dimension of water alongside its practical hydraulic role. As with all Evans-attributed functional readings, this interpretation (‘purification’) is presented explicitly as his hypothesis, not as an established fact, consistent with the panel’s own cautious wording (‘it is not known how these spaces were used’).
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign; on-site interpretive panel text reproduced as displayed.

Figure A.17.11

Photograph	
Location	Palace of Knossos, corridor and stepped area adjacent to the North Entrance / North Lustral Basin sector (position corresponds to the area circled on the site plan reproduced on the North Lustral Basin panel).
GPS coordinates	Not embedded in the photograph. Published site coordinates, for reference only: 35.2979° N, 25.1627° E.
Municipality	Knossos, Municipality of Heraklion.
Site	Palace of Knossos (open-air archaeological site).
Date	2025 field campaign; exact capture date not recorded.
Description	Restored red-painted columns, striped pilasters and a descending staircase, photographed from within a corridor giving onto the area associated with the North Lustral Basin and North Entrance sector.
Corresponding thesis chapter	Symbolism, Religion and Environmental Dependency (architectural context for Figure A.17.10).
Reference	Primary field photograph.
Author's analytical observations	Provides the immediate architectural context for the North Lustral Basin (Figure A.17.10): the restored columned descent typical of this class of sunken room. As with other restored circulation spaces at Knossos, the fabric shown is a modern conservation intervention and is presented as architectural context only, not as unmediated ancient evidence.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign.

Figure A.17.12

Photograph	
Location	Palace of Knossos, stepped water/drainage channel beneath a modern protective boardwalk.
GPS coordinates	Not embedded in the photograph. Published site coordinates, for reference only: 35.2979° N, 25.1627° E.
Municipality	Knossos, Municipality of Heraklion.
Site	Palace of Knossos (open-air archaeological site); precise room/sector not individually labelled in frame.
Date	2025 field campaign; exact capture date not recorded.
Description	A carved stone channel and stepped conduit, part of the palace's water-supply or drainage infrastructure, preserved beneath a modern wooden walkway that protects the ancient fabric while allowing visitor access.
Corresponding thesis chapter	Water Security and Hydraulic Systems; Public Health Implications (waste-water management).
Reference	Primary field photograph; cf. the 'Water and Drainage Conduits' interpretive panel (Figure A.17.13) documented in the same field session.
Author's analytical observations	Directly evidences engineered water-management infrastructure at Knossos and is used in the thesis to support the discussion of wastewater and drainage as a public-health-relevant dimension of palatial infrastructure, distinct from the ceremonial/symbolic register illustrated by Figures A.17.10–A.17.11. Together with Figure A.17.13, it supports treating water security at Knossos as a dual system: engineered supply and drainage on one hand, and ritual/symbolic elaboration of water on the other, with the two registers not always coinciding spatially.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign.

Figure A.17.13

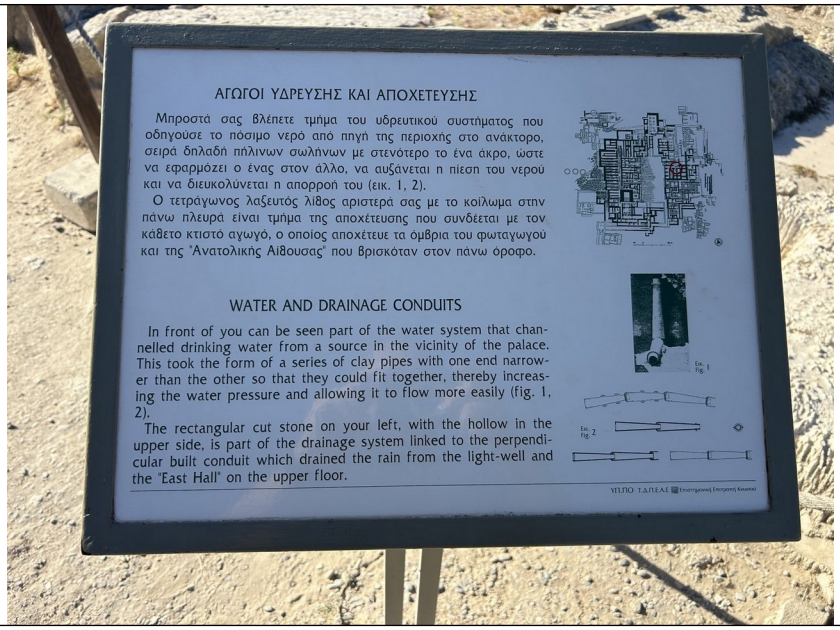
Photograph	
Location	Palace of Knossos, on-site bilingual interpretive panel ‘Water and Drainage Conduits’, with site plan, archival photograph and technical drawings of ceramic pipe sections.
GPS coordinates	Not embedded in the photograph. Published site coordinates, for reference only: 35.2979° N, 25.1627° E.
Municipality	Knossos, Municipality of Heraklion.
Site	Palace of Knossos (interpretive panel photographed in situ).
Date	2025 field campaign; exact capture date not recorded.
Description	Panel explaining the palace’s water-supply and drainage system: tapered terracotta pipe sections fitted end to end (increasing water pressure and flow), and a cut-stone drainage element linked to a built vertical conduit that drained rainwater from an upper-storey light-well and hall.
Corresponding thesis chapter	Water Security and Hydraulic Systems; Public Health Implications.
Reference	On-site interpretive panel (Hellenic Ministry of Culture / Knossos Scientific Committee), photographed by the author; content reproduced from the panel as displayed.
Author’s analytical observations	This panel is used in the thesis as primary, museum-sourced documentation of engineered wastewater and stormwater management at Knossos — tapered, self-tightening pipe joints and gravity drainage from upper floors — treated as an indicator of institutional capacity for public-health-relevant infrastructure (safe removal of run-off and waste) rather than of water supply alone. Read together with Figure A.17.12 (an in-situ stone channel of the same system), it supports the thesis’s argument that Minoan palatial administration invested in basic sanitation engineering, which is directly relevant to the Public Health Implications chapter’s discussion of infrastructure-dependent resilience.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign; on-site interpretive panel text reproduced as displayed.

Figure A.17.14

Photograph	
Location	Palace of Knossos, on-site bilingual interpretive panel ‘Magazine of the Medallion Pithoi’ / ‘Corridor of the Bays’, with site plan and archival photograph.
GPS coordinates	Not embedded in the photograph. Published site coordinates, for reference only: 35.2979° N, 25.1627° E.
Municipality	Knossos, Municipality of Heraklion.
Site	Palace of Knossos (interpretive panel photographed in situ).
Date	2025 field campaign; exact capture date not recorded.
Description	Panel describing a storage magazine named for pithoi with relief disc-and-rope decoration typical of the early Neopalatial period (1700–1450 BC), reused from the earlier Protopalatial period (1900–1700 BC), and the adjoining ‘Corridor of the Bays’, where three small storage openings yielded numerous vases and cult objects; the magazines were deliberately filled in at the end of the Neopalatial period.
Corresponding thesis chapter	Water Security and Hydraulic Systems (storage); Security and Resilience Analysis.
Reference	On-site interpretive panel (Hellenic Ministry of Culture / Knossos Scientific Committee), photographed by the author; content reproduced from the panel as displayed.
Author’s analytical observations	Provides museum-sourced evidence for continuity of storage function across the Old and New Palace periods and for a formal, deliberate closing/backfilling event at the end of the Neopalatial period. This last point is treated cautiously in the thesis: intentional infilling of storage magazines could equally reflect routine architectural remodelling, ritual closure, or response to systemic stress, and the panel itself does not attribute a cause; no single interpretation is asserted here.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign; on-site interpretive panel text reproduced as displayed.

Figure A.17.15

Photograph	
Location	Palace of Knossos, storage magazine sector (in situ pithoi, findspot consistent with the ‘Magazine of the Medallion Pithoi’ area documented on the adjacent panel, Figure A.17.14).
GPS coordinates	Not embedded in the photograph. Published site coordinates, for reference only: 35.2979° N, 25.1627° E.
Municipality	Knossos, Municipality of Heraklion.
Site	Palace of Knossos (open-air archaeological site).
Date	2025 field campaign; exact capture date not recorded.
Description	Three large storage pithoi of differing fabric and glaze tone, set into a stone-lined corner of a magazine, each bearing raised disc (‘medallion’) and rope-relief decoration.
Corresponding thesis chapter	Water Security and Hydraulic Systems (storage); Security and Resilience Analysis.
Reference	Primary field photograph; cross-referenced with the ‘Magazine of the Medallion Pithoi’ panel (Figure A.17.14) documented in the same field session.
Author’s analytical observations	Complements Figures A.17.1 and A.17.6 with a third, independently located storage assemblage, reinforcing the thesis’s reading of dispersed, large-capacity storage as a structural feature of the palatial economy and a potential point of both resilience (buffering shocks) and fragility (single point of administrative failure) within the cascading-failure framework.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign.

Figure A.17.16

Photograph	
Location	Palace of Knossos, small paved court with a circular stone base/emplacement, in a shaded area near restored walls.
GPS coordinates	Not embedded in the photograph. Published site coordinates, for reference only: 35.2979° N, 25.1627° E.
Municipality	Knossos, Municipality of Heraklion.
Site	Palace of Knossos (open-air archaeological site); precise room designation not visible in frame.
Date	2025 field campaign; exact capture date not recorded.
Description	A small, enclosed paved court with a low circular stone base at its centre, bounded by a bench-like stone ledge and restored ashlar walls.
Corresponding thesis chapter	Security and Resilience Analysis; Late Bronze Age Systemic Crisis Framework.
Reference	Primary field photograph; no on-site signage identifying this specific space was photographed, so the functional identification below is the author's own interpretation and is flagged as such.
Author's analytical observations	The author reads this small, enclosed, single-access space as consistent in scale and form with a minor guard post or sentry station rather than with a domestic or storage function — a tentative identification made on the basis of its size, position and layout, not confirmed by on-site interpretive signage. If correct, it would indicate that whatever organised security capacity existed at the palace was small in scale, oriented to controlling access and surveillance at a single point rather than to area-wide defence, and structurally incapable of the kind of coordinated relief or emergency-response function that a disaster (fire, earthquake, flood) would have required. In the thesis's crisis-management framework, this supports treating Minoan palatial 'security' primarily as a projection of authority and controlled access — reinforcing the symbolic and administrative order embodied in nearby ceremonial spaces such as the North Lustral Basin (Figure A.17.10) and in royal/ritual imagery such as the Prince of the Lilies fresco (Figure A.17.17) — rather than as an operational capability for disaster response. This reading is offered as an interpretive hypothesis for the author's own further verification against the excavation literature for this specific room, not as an established fact.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign.

Figure A.17.17

Photograph	
Location	Palace of Knossos, on-site framed reproduction of the ‘Prince of the Lilies’ (‘Priest-King’) relief fresco, displayed near its original findspot.
GPS coordinates	Not embedded in the photograph. Published site coordinates, for reference only: 35.2979° N, 25.1627° E.
Municipality	Knossos, Municipality of Heraklion.
Site	Palace of Knossos (on-site framed facsimile; the original fragments and the museum reconstruction are conventionally associated with the area of the South Propylaeum).
Date	2025 field campaign; exact capture date not recorded.
Description	A composite figural relief fresco showing a striding youthful figure wearing a feathered/lily crown and a kilt, set against a ground of papyrus/lily plants; conventionally known as the ‘Prince of the Lilies’ or ‘Priest-King’ relief. The composition and identification of the figure (whether a single individual, a composite of unrelated fragments, male or female, ruler, priest, boxer or athlete) have long been debated in the scholarly literature since Evans’s original restoration.
Corresponding thesis chapter	Symbolism, Religion and Environmental Dependency; Security and Resilience Analysis (governance authority).
Reference	On-site framed reproduction, photographed by the author; the fresco’s composite and much-restored character, and the long-standing scholarly debate over its correct reconstruction and identification, are well established in the archaeological literature and are noted here without attributing a specific citation, which the author should supply.
Author’s analytical observations	The author reads this image as a projection of authority through myth and symbol rather than as documentary evidence of an operational military or security apparatus: an idealised, crowned/plumed figure amid flowering vegetation communicates fertility, legitimacy and ceremonial status rather than martial capacity. Placed alongside Figure A.17.16 (the possible small guard post), the pairing illustrates a broader argument advanced in this thesis: that visible ‘security’ and authority at Knossos appear oriented toward ideological display and controlled ceremonial access rather than toward disaster-response capacity, which is consistent with the apparent absence, elsewhere in the archaeological and architectural record considered in this thesis, of dedicated emergency-response infrastructure. This interpretation is the author’s own and should be cross-checked against, and supported by, the relevant art-historical and archaeological literature on the fresco before being presented as a settled

	claim.
Source (if applicable)	Photograph by the Author (Marco Filippi), 2025 field campaign.

Author's Synthesis Note: Destruction Level and the Concept of 'Collapse' (Figures A.17.10–A.17.17)

The photographic evidence assembled in Figures A.17.10–A.17.17 — ceremonial water architecture, engineered drainage, dispersed storage, a possible minor guard post, and an idealised authority fresco — is read by the author as broadly consistent with the thesis's central argument that the Minoan 'collapse' should be understood as a systemic, cascading reorganisation rather than as the direct, sufficient consequence of any single destructive event. None of the standing or restored fabric documented here shows a level of physical destruction that would, on its own, have made rebuilding on the same site technically impossible: the palace's hydraulic infrastructure, storage capacity and monumental architecture evidently remained functional or repairable across multiple episodes of damage over its history. On this basis, the author suggests that even a hypothetical external destroyer or invader would have had no obvious material or engineering obstacle to reoccupying and rebuilding on the same site, as was in fact done repeatedly at Knossos itself after earlier Old Palace and Neopalatial destructions. The eventual abandonment of large-scale palatial reconstruction after the final Late Bronze Age destructions is therefore treated in this thesis as more plausibly linked to non-structural factors — cumulative ecological stress on the surrounding water, soil and agrarian systems, and the erosion or discrediting of the symbolic and ideological order (illustrated here by the ceremonial and authority-projecting material in Figures A.17.10 and A.17.17) that had underpinned palatial legitimacy — rather than to destruction levels that made physical reconstruction impossible.

This reading is not offered as a free-standing claim: it is corroborated by five points already established, with citations, in the main body of this thesis.

1. Physical rebuilding after fire was routinely possible and routinely happened. Following the fiery destructions of the Aegean palatial centres around 1200 BC, the thesis documents that 'rebuilding at Mycenae, Tiryns, and Midea eschewed canonical palatial architecture, even though these sites remained important power foci for several decades' (§2.1.3; §7.2.1). Reconstruction on the same sites is explicitly attested; what changed was the institutional form rebuilt, not the physical possibility of rebuilding (Molloy, 2022).

2. Fire functioned as a turning point within a longer sequence, not a terminal physical barrier. The thesis describes post-destruction trajectories as 'a stratified story in which fire marks a turning point, followed by selective reuse, reoccupation, and eventual reconfiguration of both built space and political order' (§7.2.1, following Molloy, 2022). Reuse and reoccupation, rather than permanent physical abandonment, are presented as the norm.

3. Disinvestment in palatial forms was gradual and generational, not instantaneous or structurally forced. The thesis states that 'material and ideological disinvestment in central palatial forms unfolded over two to four generations' after 1200 BC, during which 'leaders failed to re-establish stability and halt regional depopulation' (§2.1.3; §7.2.1). A multi-generational decline of this kind is inconsistent with a single destruction event having made reconstruction physically impossible.

4. The comparative governance literature cited in the thesis frames this same pattern as 'crisis without transformation': conflagrations were followed by 'partial rebuilding and gradual institutional erosion rather than immediate systemic renewal' (§7.2.2, citing Schlüter & Herrfahrdt-Pähle, 2011, on the Amudarya basin analogue). The barrier to renewal identified here is institutional learning capacity, not physical reconstruction capacity.

5. Independent ecological degradation is identified elsewhere in the thesis as a slow-moving driver operating 'against a background of gradually shrinking productive capacity' from soil overexploitation, degradation and water scarcity (§8.1.1). This supports treating cumulative ecological stress, rather than any single destruction horizon, as the more plausible long-term constraint on renewed palatial investment.

Taken together, these five points — already supported with citations elsewhere in this thesis — corroborate the author's reading of Figures A.17.10–A.17.17: the constraint on rebuilding at Late Bronze Age Cretan and wider Aegean palatial centres appears to have been institutional, ideological and ecological rather than a simple function of destruction severity. This synthesis remains the author's own interpretive argument, directing the reading of the photographic material in this appendix, and should be cross-referenced explicitly with §2.1.3, §7.2.1, §7.2.2 and §8.1.1 if incorporated into the main discussion or conclusions chapters.