COASTAL ARCHAEOLOGY AND CLIMATE CHANGE IN THE MIDDLE EAST AND NORTH AFRICA: CONTEXTUALISING GLOBAL PROJECTIONS

Abstract:

Recent global projections of climate change highlight alarming rates of flooding and erosion on the coastlines of the Middle East and North Africa (MENA). Though there are indisputable links between climate change and the deterioration of maritime cultural heritage (particularly coastal archaeology), deterioration is often the result of multiple compounding factors, central among which are anthropogenic landscape alterations. In this paper we attempt to disentangle these factors at a small scale, using the Gaza Strip, Libya and Oman as case studies. We examine the impact of accelerating coastal erosion, flooding, and increasing frequency of tropical cyclones to question predominant discussions on the impact of climate change on heritage. We instead emphasize methods and practices for the identification of sites that can expand and refine climate change research (often reliant on data from the twentieth and twenty first centuries) through the long-term perspective archaeology is uniquely placed to offer.

The impact of climate change on archaeological heritage has received increasing attention, reflected in an ever-growing number of academic studies, dedicated funding calls and inclusion in national and international policy-influencing efforts. The consensus is that archaeological sites, monuments and artefacts face a clear threat from climate change. The nature of the threat and its impact will vary depending on the type of heritage in question and the prevailing weather and climate where it is located. However, it is generally understood that climate change will either exacerbate existing processes of long-term decay and weathering , or introduce new processes where they previously did not operate. In the worst cases, this could lead to significant damage to, or the destruction and loss of, irreplaceable archaeological material. Consequently, there is an urgent need to identify and implement sustainable ways to protect or mitigate damage to archaeological sites and landscapes (Hambrecht and Rockman 2017; ICOMOS 2019; Sesana et al. 2021).

This paper will focus on maritime cultural heritage, with emphasis on coastal archaeology. Maritime archaeological sites provide testament to the engagement of people with the sea, offering opportunities to explore historical themes such as seafaring, migration, colonisation and international interaction, many of which continue to resonate in the modern world. In this respect maritime cultural heritage provides a vital link between regional archaeologies, particularly in the MENA region. It also offers palaeo-environmental evidence (e.g. sea-level change) with potential to inform global studies on climate change (e.g. Yasur-Landau et al. 2021).

Lying at the intersection of land and sea, coastal archaeology is particularly vulnerable to climate change, largely because coastal flooding and erosion can have a truly detrimental long-term impact on maritime cultural heritage. Episodic flooding and erosion may also intensify locally depending on changing storm and tropical cyclone patterns and can result in rapid destruction, or major damage, in a few hours (Wright 2016; Gregory et al. 2022). Both phenomena are projected to incrementally increase over the twenty-first century in response to climate change-driven sea-level rise (Vousdoukas et al. 2018; 2020). Although a precise global estimate does not presently exist, national and regional studies suggest that at least thousands of sites are vulnerable over the coming century (Anderson et al. 2017; Brooks et al. 2020; Li et al. 2022).

Because flooding and erosion are also hazards for coastal cities, communities and infrastructure, an extensive body of coastal management research has modelled their future impacts (Hinkel et al. 2021). The broader applicability of this research has reached archaeologists and historic environment managers to varying degrees. These range from simple application of future flood levels (Anderson et al. 2017; Li et al. 2022), to more complex studies seeking to quantify the effects of flooding and erosion (Vousdoukas et al. 2022, Reimann et al. 2018). The recent development of global–scale, open access geospatial models of twenty-first century erosion and flooding (Vousdoukas et al. 2018; 2020) has encouraged these latter types of studies. Such studies are an essential component of the archaeological response to climate change (Hambrecht and Rockman 2017). In theory, an inventory of vulnerable sites and associated frequency and intensity of climate change-related threats can enable appropriate prioritization of responses and resources. Prioritization is particularly relevant to coastal archaeology, where it is now accepted that not all sites can be saved (Dawson et al. 2021). Firstly, because of the scale of the problem; there are simply not enough resources to deal with every site which will be flooded or eroded. Secondly, because physically protecting sites, for example with sea defences, is unsustainable in the long-term given rising sea-levels. This strategy also runs counter to coastal management strategies which, for retreating shorelines, often advise “managed realignment” (removal of coastal defences to allow creation of natural intertidal or marsh areas) or “no active intervention”, particularly where there is no/little infrastructure to protect or where the ecological costs of protection outweigh the benefits (Williams et al. 2018).

In practice, the effectiveness of these models depends heavily on the quality of their inputs, including data availability and data resolution, all of which affect the scale of analysis and the questions that these models can answer. Thus, although the contribution of global models to broad-scale threat identification has been generally received positively in maritime archaeology (Andreou et al. 2022a), they are not without limitations. Recent studies have highlighted biases in global and regional models of climate change, particularly the relatively limited consideration of human adaptations that potentially slow down impacts and whose implementation may depend on financial resources (Hinkel et al. 2021). Moreover, the necessary simplification of coastal processes when modelling on a global scale has raised concern as it can result in inaccurate or lower confidence projections of future change (Cooper et al. 2020). For example, it has been projected that by 2100 large parts of the coast of the UAE and Bahrain will advance despite sea-level rise (Vousdoukas et al. 2020). This conclusion results from the fact that the historic pattern of shoreline change used to inform the model is based on satellite imagery from 1984 onwards; a period of massive and unprecedented land reclamation that has artificially extended the coastline. Therefore, the drivers for coastal advance in this context are more likely socio-economic rather than climate change-related and it is uncertain as to whether this trend will continue up till 2100, as modelled. This is not to say that projections are purposeless or ambiguous. Large-scale models are essential in providing information on general trends and impacts, which they do well in terms of the direction of future change. This can help raise awareness and, ideally, stimulate social, political and economic actions to tackle the climate crisis. Large-scale models also provide the foundation for more detailed studies which can examine the local impact of these general changes . These issues are, of course, known to the modelling community who for coastal areas recommend detailed studies at smaller scales that shed light on the compounding natural and anthropogenic processes which drive change (Vousdoukas et al. 2022).

This is particularly important in the coastal zone, where multiple processes originating from the atmosphere, land and sea interact with human activity to produce change over multiple spatial and temporal scales. The effect of coastal flooding and erosion can be influenced, for instance, by human actions that increase or decrease sediment supply, such as coastal construction, harbour development and upstream damming, as much as by sea-level rise resulting purely from global warming (IPCC 2022). Although there are indisputable links between climate change and the deterioration of maritime archaeological material (Gregory et al. 2022), there is a conceivable risk that these are examined without actively considering associated human actions that could aggravate flooding and erosion, or which may have driven changes that are inaccurately interpreted as a direct consequence of climate change.

In this paper we take a critical stance toward the projected impact of climate change on maritime archaeology with emphasis on coastal heritage. We argue that finding the root cause of coastal impacts such as flooding or coastal erosion can be difficult because both can be created by climate change-related sea-level rise, unrelated human actions or an overlapping combination of the two. Additional modifiers include physical processes such as waves, tides and storms, which also exhibit natural variability, but are themselves being modified by climate change. Nonetheless, identifying drivers of change is useful to understand the future trend of impacts and ultimately the most appropriate adaptation or mitigation response for a given location.

We illustrate this through case studies from the Gaza Strip, Libya and Oman. These areas are currently subject to in-depth study by the authors within the framework of a MENA-wide maritime archaeological threat assessment: the Maritime Endangered Archaeology (MarEA) project (Andreou et al. 2022a). Moreover, these areas all have multiple data sources ranging from satellite imagery to local knowledge which suggest that a combination of physical processes and anthropogenic actions has impacted coastal archaeological sites. We then discuss the implications of this complexity, in terms of projections of future impact, management considerations and mitigation strategies. Finally, we highlight the contribution of archaeology to wider climate change research.

COASTAL EROSION IN THE GAZA STRIP

The southern Levant benefits from an impressive array of scientific studies exploring long–term environmental dynamics and their intersection with maritime archaeology (Yasur–Landau et al. 2021). This reflects both the suitability of this region for such studies, but also underscores significant investment and expertise in the study and preservation of heritage, that is not necessarily available along the broader Levantine coast. A case in point is the Gaza Strip, widely discussed in conjunction with inter-linked ecological, humanitarian, and economic crises, all of which contribute to the rapid deterioration of cultural heritage.

As is the case at multiple Levantine coastal sites (e.g. Arsuf, Ashkelon, Byblos, Yavne-Yam: Galili and Rosen 2010; Deroin et al. 2017; Barkai et al. 2018) coastal erosion is affecting Gaza's maritime archaeology. Sites on the coast of Rafah, near the Iron Age site of Tell Ruqeish, and around the multiperiod site of Anthedon have lost over one meter of land every year between the 1990s and 2021 (Klinger and Knauer 2020; Andreou et al. 2022c) (figs. 1-2). Such rates are generally viewed as a twentieth century phenomenon, and the tendency has been to consider erosion >0.5 m/yr as anthropogenic, associated, among others, with the modernisation of traditional land-use practices, and the construction of dams, modern harbours and offshore structures (Anthony et al., 2014). This interpretation does not exclude the possibility of pre-modern erosion, for which the evidentiary record is limited but potentially significant (e.g. Marriner et al. 2012). It rather highlights the lack of environmental studies accompanying modern alterations, the impact of which appears more extensive. In this respect, there is abundant and relatively easily accessible evidence for erosion, including imagery from the 1950s onward (Anthropocene), while evidence from the Holocene relies on geo-archaeological studies within the small-scale of archaeological sites.

Along the Levantine coast, rapid coastal retreat has been linked to decreased deposition of Nile-sourced sediment caused by construction of the Aswan Dam in the 1970s (Abd–el Monsef et al. 2015). Unfortunately, the lack of reliable pre-1970s aerial imagery for Gaza (Andreou et al. 2022c) prevents a reconstruction of pre-Aswan coastal trends that would enable a systematic comparison of recent versus past erosion rates. At the same time, smaller-scale coastal assessments link erosion primarily with the construction of modern harbours and subsequently with agricultural activities, recreational development, and conflict–related damage (Abualtayef et al. 2012; 2021; Andreou et al. 2022c).

Erosion rates exceeding 1 m/yr are projected to continue, according to global models which rely on post-1980s satellite imagery (Vousdoukas et al. 2020). Though it is reasonable to suggest that climate change has increased the rate of erosion in Gaza, it is not possible to view it independently from extensive human interventions on the coastal landscape (fig.3). It is also not possible, at present, to quantify long-term land loss, due to the unknown impact of unpredictable human activities on the coast. Though landscape alterations are evident, the erosion rate during the Holocene remains to be determined in much of the Eastern Mediterranean.

COASTAL EROSION IN LIBYA

As in Gaza, erosion along the Cyrenaica coast (Eastern Libya) has damaged archaeological sites, notably the Hellenistic and Roman harbour cities of Apollonia and Tocra, but also many smaller and less well-studied ancient sites (Bennett et al. 2004; Nikolaus et al. 2022) (fig.4). Several natural factors conspire to make this coastal stretch susceptible to erosion: extensive deposits of unconsolidated sediment close to the shore, a largely open coastline exposed to some of the highest waves in North Africa (Barbariol et al. 2021), and tectonic subsidence within the last 2000 years, which has pulled archaeological structures originally built above high water closer to the water's edge (Flemming 2021).

Recent and twentieth century shoreline movements have been quantified using satellite imagery, historic aerial photos and declassified 1970s spy satellite (KH-9) images (Westley et al. in press). Erosion rates of >2 m/yr are present in the vicinity of Ptolemais, Tocra and Apollonia, as well as rates of up to 0.5 m/yr in locations where archaeological material is either built on, or buried within, unconsolidated backshore sediments (fig.5). This analysis also suggests that erosion rates have accelerated within the last 10–20 years. If such rates had prevailed since the abandonment of these settlements, it is unlikely that many of the visible structures would still be preserved, given that these are ancient harbours with structures built close to the water's edge. This is exemplified at Apollonia where an 1828 historic map shows a broadly similar shoreline, albeit with localized instances of retreat. If erosion rates of 0.2–0.5 m/yr (as observed recently) had operated since 1820, this would have resulted in 40–100m of coastal retreat, which does not seem to have been the case (fig.6). What, therefore, could have caused this acceleration?

Comparison of KH-9 images from 1974 with recent images highlights how actively eroding areas were once fronted by extensive beaches that no longer exist. Without the natural protection afforded by these beaches, waves can reach the vulnerable unconsolidated backshore during storms and, possibly, during moderate or fair-weather conditions**.** Though not all the drivers of this land-loss are known, one probable culprit is unregulated sand mining. This is suggested by satellite images and confirmed by local reports for the coast west of Ptolemais where erosion rates are highest **(**Elghazali 2019**)** (fig.7). Another possible factor is disruption of wadi-supplied sediment by urbanization and infrastructure that interferes with natural water flow; e.g. roads, bridges, buildings and culverts. Such features are evident from comparison of KH-9 and recent satellite images (fig.8). These observations tally with wider studies from North Africa which link widespread twentieth century beach loss and coastal retreat to human factors operating independently of climate change, such as upstream damming and urbanization **(**Hzami et al. 2021).

TROPICAL CYCLONES AND FLOODING IN OMAN

In recent years, countries in the Arabian Peninsula, particularly Yemen and Oman, have experienced the catastrophic impact of tropical cyclones on an almost yearly basis. Many have associated the increasing frequency and intensity of cyclones with climate change (Knutson et al. 2010; Al-Awadhi et al. 2019; Wehner et al. 2019).

The resulting coastal flooding is sufficiently serious that a warning system has been installed in Oman to mitigate future impacts. References to cyclone frequency that inform future projections rely on existing documentation by the National Oceanic and Atmospheric Administration (Knapp et al. 2010), which has recorded 36 “hurricanes” affecting the Omani coastline in the past 129 years (fig.9). Though only hurricanes with sustained winds >150 mph are classified as tropical cyclones, hurricanes with lower intensity have had a catastrophic impact on Oman’s infrastructure and environment (Mansour et al. 2021).

Problematically, information on cyclone activity before the mid-twentieth century is scarce. Historical descriptions of strong winds that could classify as hurricanes or cyclones date to 1286 CE, 1325 CE and 1853 CE (Newton and Zarins 2019), whilst historic flooding events (1600-1700 CE) have been identified in the sedimentary record near known sites, for example at Al–Baleed in Dhofar (Reinhardt 2000) - the governorate with the highest exposure to tropical cyclones (fig.10). Extreme sea level events have also been noted in the geoarchaeological record of Ras al–Hadd in NE Oman, dating to 4450 cal BP (Hoffman et al. 2015). Though the deposits at Ras al-Hadd are tentatively ascribed to a tsunami, there is a general understanding that more evidence for extreme wave events and flooding can and will be identified in future excavations.

Based on the available evidence, it appears that the precise relation between the increasing frequency and intensity of cyclones and climate change requires further historical, archaeological and geological input, to minimise any reasonable hypothesis that increasing frequency is the result of more effective documentation (e.g. Blount et al. 2009). Similarly, further investigation is required to quantify the contribution of extensive construction of modern impervious surfaces (Al–Awadhi et al. 2016; 2018), particularly in coastal urban centres in Oman, which locally enhance the impact of flooding events.

Considerable attention given to the impact of tropical cyclones on Oman’s urban infrastructure (Hereher 2020; Mansour et al. 2021) has opened the way for assessments of the condition of archaeological sites located within the cyclone tracks through satellite imagery analysis (Andreou et al. 2022a; 2022b). Importantly, the identification of site clusters that are highly vulnerable to cyclone activity, particularly in the NE (Muscat, Ash Sharqiyah) and SW (Dhofar), lends themselves well to the exploration of the pre–modern frequency of such events (e.g. Hoffmann et al. 2015; Ermertz et al. 2019). New geo–archaeological information will not only elucidate the frequency and intensity of historic cyclones, but also has the potential to inform risk management strategies. Though heritage perspectives are often incorporated in risk management strategies, these perspectives tend to serve as cautionary tales within the scope of protection and preservation. With archaeology uniquely placed to add much-needed historical depth to increase the accuracy of climate change projections (see also Wright 2016), there is scope for geoarchaeological studies to not only confirm, but also to inform existing vulnerability models, thereby contributing more actively to heritage policies.

CONTEXTUALISING MARITIME ARCHAEOLOGY IN CLIMATE CHANGE RESEARCH

Climate change involves a dense network of inter-dependencies, including cultural heritage and modern human societies. We examine these inter-dependencies by reference to the coastal zone and the commonly-cited destructive impacts of flooding and erosion, both of which will be aggravated by sea-level rise and changing storm patterns (ICOMOS 2019). The discussed case studies show that contemporary erosion and flooding impacts on coastal heritage are not solely attributable to climate change impacts but also include a strong contribution from human action. More specifically, activities that restrict coastal sediment supply, including sand mining, construction, and damming, can aggravate erosion on local and regional scales. Similarly, the extent and impact of flooding is contingent on human action: reduction through artificial flood defences but exacerbation via impervious surfaces created by urbanization. In short, many coastal changes we see today which damage or destroy coastal archaeological sites, in the MENA region at least, result from human actions related to urban and economic development. A direct link between these changes and climate change-driven sea-level rise is, at present, less clear. However, as we show below, this link will probably strengthen over the twenty-first century. Nonetheless, we emphasize that this observation is specific to our study region. Other parts of the world show clearer and stronger links with climate change, for instance the vastly accelerated erosion of polar and sub-polar coastlines due to permafrost melting.

Consideration of the above suggests three main implications. First, from an archaeological preservation standpoint, the headline action of reducing greenhouse gas emissions is not enough. It must accompany wider environmental regulation which prevents or limits activities that damage both archaeological sites and natural environments. Unfortunately, many beaches have already been pushed past their point of recovery (Cooper and Jackson 2019). Moreover, at least some of the major infrastructure responsible for coastal change will probably remain in place for the foreseeable future. For example, many large dams built in the twentieth century are coming to the theoretical lower limit of their planned lifespan (usually ~50-120 years). However, the choice of deconstruction versus repair or renewal is complex and dependant on cost, politics and whether substitutes are available for benefits, such as hydro-electric power. Also, dam building continues across the MENA region, with a new crop coming online over the coming decades (Marchetti et al. 2019). Neither will sea-level rise, and its linked destructive impacts, completely stop within the twenty first century even if carbon emissions are reduced (IPCC, 2022). Even so, we note that the main acceleration of SLR will come post–2050 if carbon emissions remain high: there is a difference of ~40cm between low and high emissions scenarios by 2100 compared to ~5cm by 2050 (IPCC 2022; Vousdoukas et al. 2018). Arguably therefore, any action which can reduce exacerbating processes should be taken before this acceleration. These could include, for example, local regulation against destructive sand mining or more active consideration of the wider impacts of coastal hardening (e.g. Bitan et al. 2020). To be fully cognisant of archaeological management requirements, this necessitates maritime heritage to be integrated within wider coastal and marine management policies, something which is not standard practice, and which has been proposed in the context of Marine Protected Areas (Breen et al. 2021).

Second, although large scale models can project with reasonable certainty general patterns of sea-level rise, the unknown impact of unpredictable human activities makes it challenging to project twenty-first century land-loss at smaller scales, such as the extent of an archaeological site or cluster of sites. Estimates are possible, particularly if they can be constrained by high spatial and temporal resolution measurement of local trends in shoreline movement (Westley et al. in press). But archaeologists, managers and other stakeholders should always be prepared to critically assess model inputs, construction and outputs, consider a range of scenarios based on the drivers of change at a given site and finally, be aware that the certainty of these projections decreases the further forward in time one looks. This requires the expansion and diversification of existing, already interdisciplinary archaeological training to include quantitative skills necessary for assessing climate-change projections and their relevance to heritage management.

Third, big archaeological databases have allowed identification of large-scale patterns of landscape alterations at times linked with the broader impact of climate change (Westley et al. 2021). These databases offer significant opportunities in identifying and conducting in-depth geological, geomorphological and palaeo-environmental research that will shed light on the frequency and intensity of phenomena attributed to climate change. Of course, identified patterns cannot be viewed outside of their unique economic and socio–political circumstances, the active consideration of which can be achieved through the incorporation of local communities (Stahl 2020), which have a daily engagement with their endangered heritage, and who will ultimately need to respond to the impact of climate change on their heritage and environment.

The challenge of untangling multiple drivers of change in order to reach confident projections for the future is as important to maritime cultural heritage management as in other sectors. To prioritize action and determine the most effective mitigation strategies in each context, archaeological practitioners and heritage managers require a clear idea of the nature, extent and intensity of future impacts. Current global-scale models go part-way to address this. They are useful from a broad-scale standpoint, mainly in terms of raising awareness of potential threat and addressing regional patterns. However, at a practical management level, more detail is needed on individual sites. This is especially relevant in the coastal zones where past, present and future impacts involve complex interactions of climate change-driven processes and human action. There are clear challenges to achieving this in the Middle East and North Africa, notably in terms of the availability of high- resolution data at a frequency which can be used track and quantify shoreline changes. This is slowly starting to change, particularly with increasing availability of satellite and UAV imagery, but in many cases, the baseline datasets are relatively recent in time, thus making it harder to determine if identified trends are anomalous, or reflective of long-term patterns.

We also note that those impacts highlighted here are but a subset of the full range of coastal complexity, which includes for example, subsidence (enhanced by hydrocarbon and groundwater extraction), salinization (enhanced by fresh- and groundwater abstraction), seawater oxygen content (affected by pollution) and seabed erosion (enhanced by seagrass loss from pollution and bottom trawling) (see also Gregory et al. 2022; ICOMOS 2019). Future changes will impact not only maritime archaeology, but the natural environment and human societies. As such, there is a strong case that maritime archaeology should be better integrated into mitigation and management efforts, which tend to focus on the natural environment and modern infrastructure. Additionally, taking a long-term view and using (geo-)archaeological evidence to extend the evidential baseline could contribute to the wider body of research that aims to disentangle the compounding processes driving change and, ultimately, assist in efforts to improve projections of future climate change impacts.

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CAPTIONS

Banner Photo: Coastal archaeological features at Tell Ruqeish, dating to the 1st millennium BCE in conjunction with human interventions on the beach (recreational infrastructure, quarring, terracing, waste). Photograph from the GAZAMAP project.

Figure 1. Archaeological sites in Gaza Strip. Map adapted from Andreou et al. (2022c).

Figure 2. Eroding archaeological features on the coast of Tell Ruqeish, Gaza Strip. Photograph from the GAZAMAP project.

Figure 3. Recreational infrastructure carved on the coast of Tell Ruqeish, Gaza Strip defining the location of the modern coastline. Photograph from the GAZAMAP project.

Figure 4. Coastal erosion impact at the Eastern Libyan sites of Apollonia (top) and Tocra (bottom). Top photograph taken by Saad Buyadem. Bottom photograph taken by Saleh Alaurfi.

Figure 5. Modern shoreline movements in/around Tocra, Apollonia and Ptolemais generated from a time series of low-resolution Landsat satellite images dating from 1985 to 2020. Image overlay shows categorized movement patterns, inset graphs show quantified movement rates (LRR in meters/year). Base satellite image courtesy of Planet Labs.

Figure 6. Comparison of recent (post-2010) and historic (pre-2010) shoreline movements at Apollonia generated from high resolution recent satellite images (Maxar, provided by the European Space Agency), declassified KH-9 images (provided by the USGS) and historic air photos. Coloured lines show shoreline movement rates (LRR) in meters/year. Bottom image shows excerpt from the historic map of Beechey and Beechey (1828:536)**.**

Figure 7. Comparison of 1974 KH-9 (provided by the USGS) and 2016 satellite images (Maxar, provided by the European Space Agency) west of Ptolemais showing extensive retreat of waterline (i.e. beach loss) and backshore cliff erosion. Scars on the beach are suggestive of sand mining.

Figure 8. Comparison of 1974 KH-9 (provided by the USGS) and 2019 satellite images (Maxar, provided by the European Space Agency) west of Apollonia showing localized zone of coastal retreat, possibly resulting from blocking or disruption of wadi flow by road construction and urbanization.

Figure 9. Map of maritime archaeological sites in Oman documented in the EAMENA database in conjunction with major cyclone tracks over the past 130 years. Adapted from Andreou et al. (2022a: 142, fig. 9.)

Figure 10. Coastal erosion on the coast of Medieval Al–Baleed, Dhofar Governorate Oman. Photograph taken by Tom Vosmer, 2013.

Banner Photo

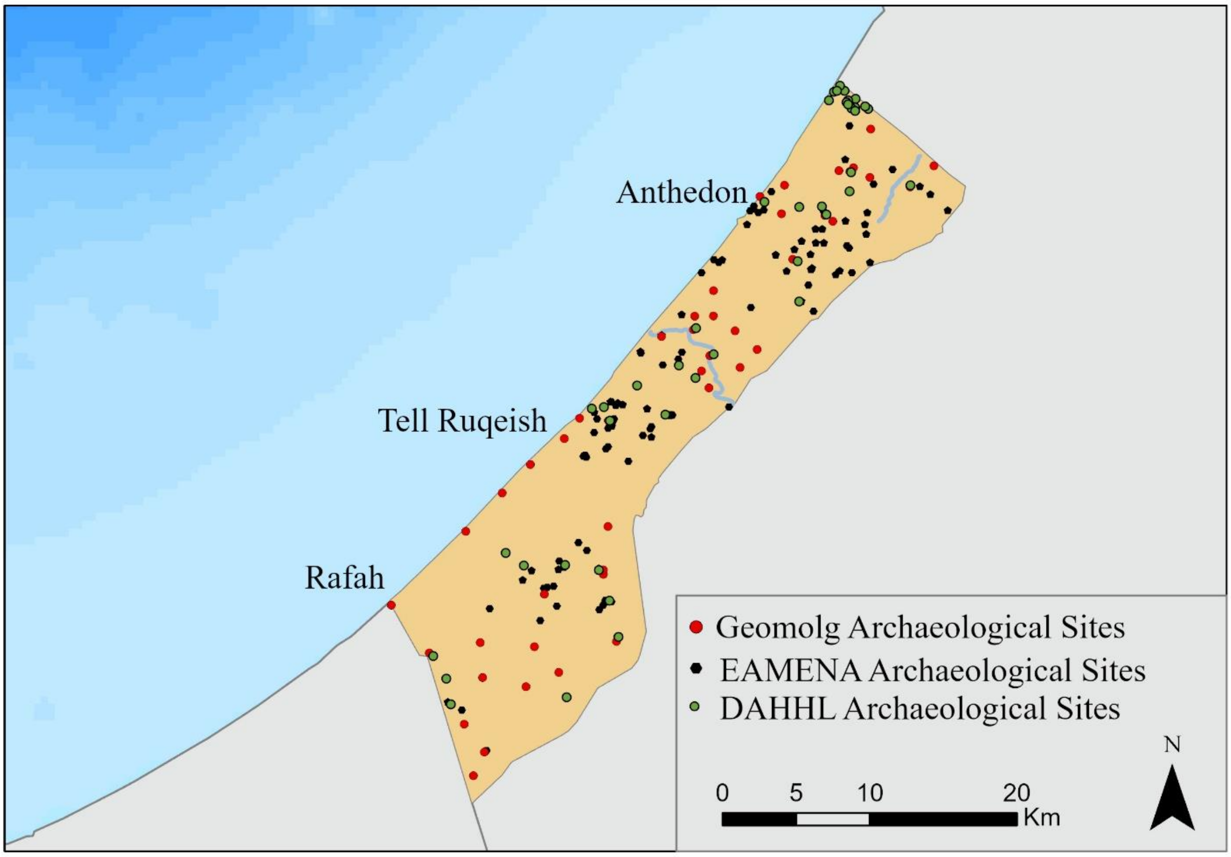
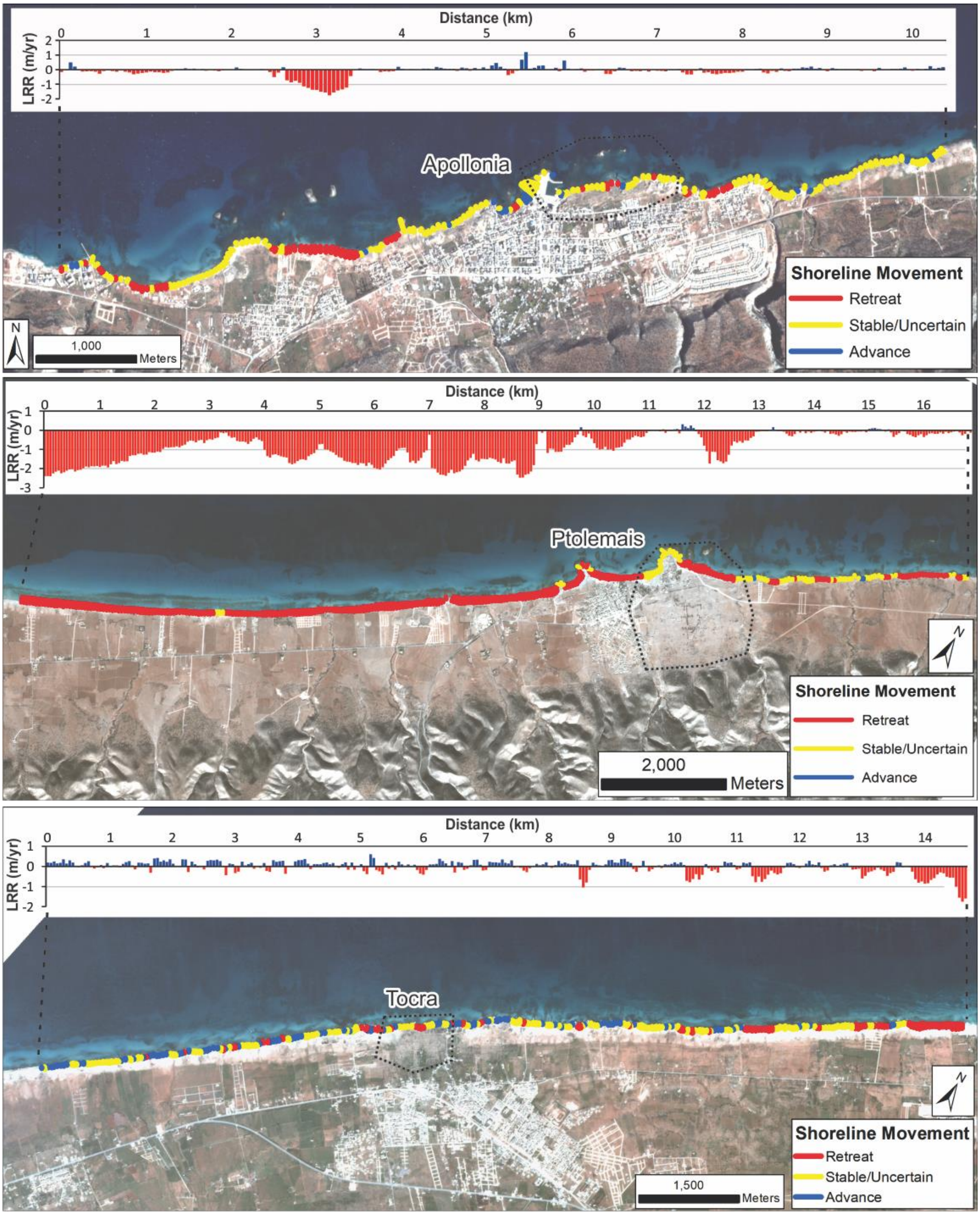


Figure 1

Figure 2

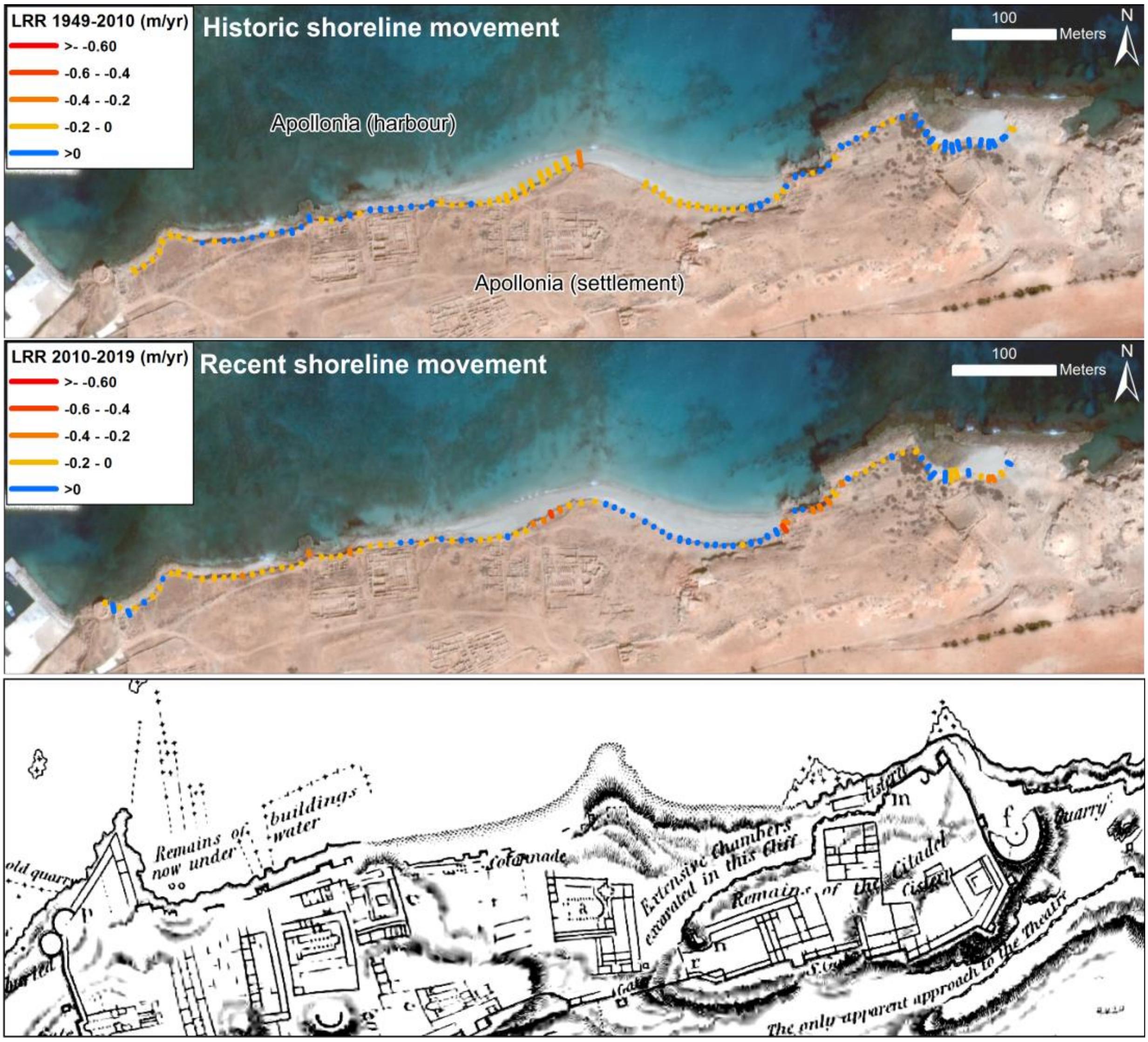
Figure 3

Figure 4



Distance (km)
LRR (m/yr)
Apollonia
Shoreline Movement
Retreat
Stable/Uncertain
Advance
N
1,000
Meters
Distance (km)
LRR (m/yr)
Ptolemais
N
Shoreline Movement
Retreat
Stable/Uncertain
Advance
2,000
Meters
Distance (km)
LRR (m/yr)
Tocra
N
Shoreline Movement
Retreat
Stable/Uncertain
Advance
1,500
Meters

Figure 5



LRR 1949-2010 (m/yr)
>- -0.60
-0.6 - -0.4
-0.4 - -0.2
-0.2 - 0
>0
Historic shoreline movement
100
Meters
N
Apollonia (harbour)
Apollonia (settlement)
LRR 2010-2019 (m/yr)
>- -0.60
-0.6 - -0.4
-0.4 - -0.2
-0.2 - 0
>0
Recent shoreline movement
100
Meters
N
Remains of buildings now under water
Colonnade
Extensive Chambers excavated in this Cliff
Remains of the Citadel
Cistern
Quarry
The only apparent approach to the Theatre

Figure 6

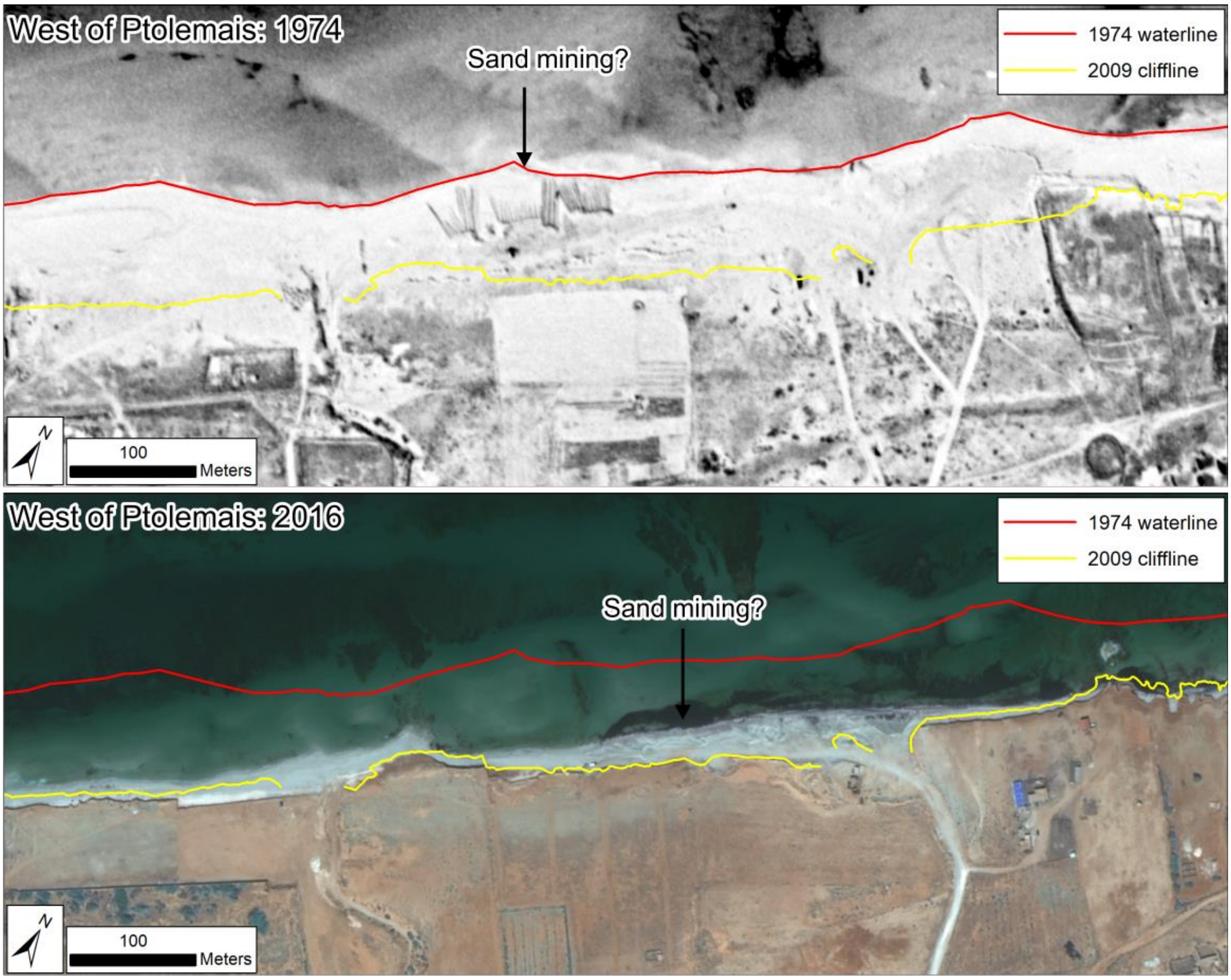
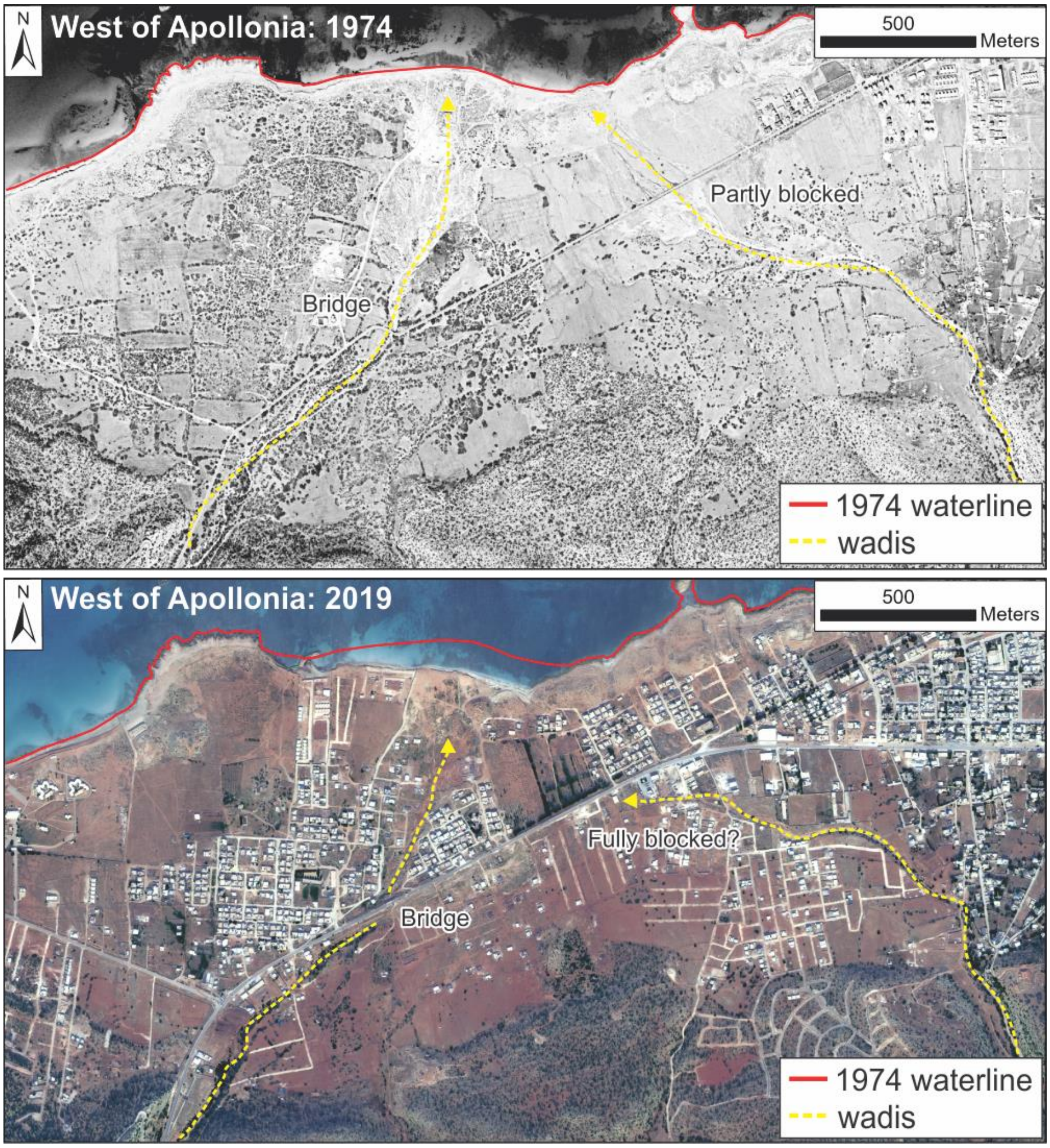

West of Ptolemais: 1974
1974 waterline
2009 cliffline
Sand mining?
100
Meters
West of Ptolemais: 2016
1974 waterline
2009 cliffline
Sand mining?
100
Meters

Figure 7



N
West of Apollonia: 1974
500
Meters
Partly blocked
Bridge
1974 waterline
wadis
N
West of Apollonia: 2019
500
Meters
Fully blocked?
Bridge
1974 waterline
wadis

Figure 8

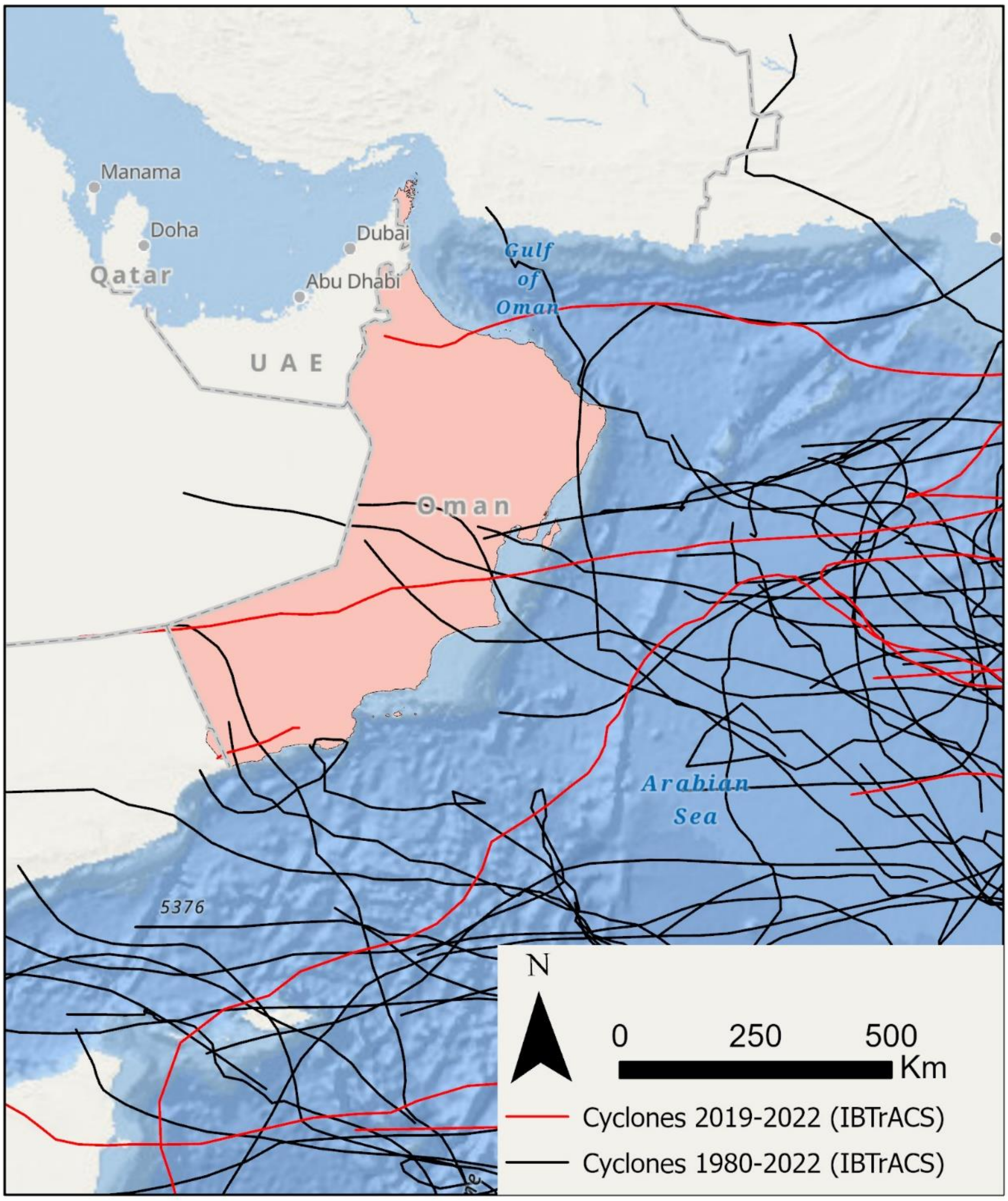

Manama
Doha
Qatar
Dubai
Abu Dhabi
U A E
Gulf
of
Oman
Oman
Arabian
Sea
5376
N
0
250
500
Km
Cyclones 2019-2022 (IBTrACS)
Cyclones 1980-2022 (IBTrACS)

Figure 9

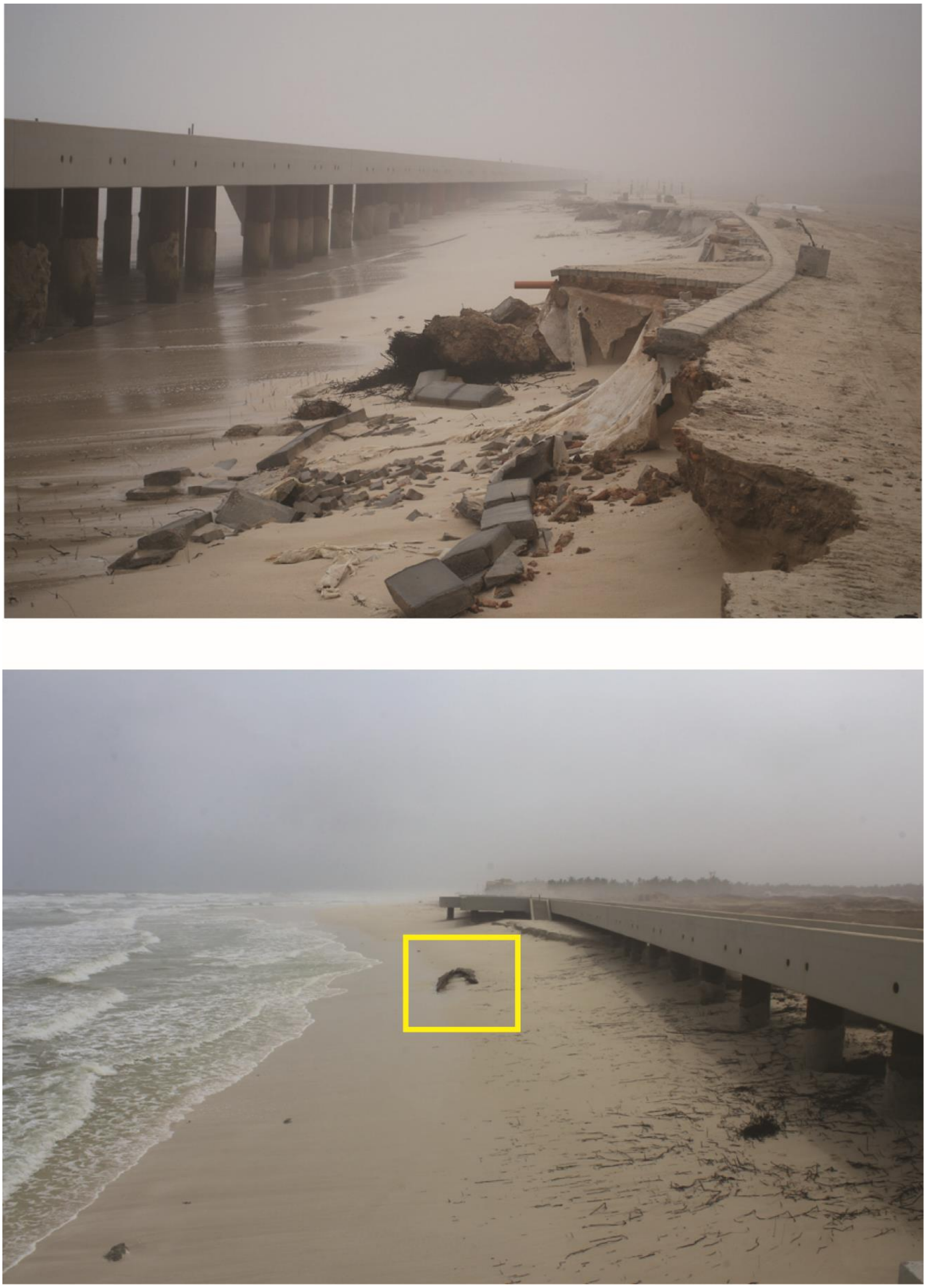


Figure 10