4-2022

ASSESSMENT OF NATURAL HAZARDS IMPACT ON HERITAGE SITES IN THE UNITED ARAB EMIRATES (UAE) USING GEOGRAPHIC INFORMATION SYSTEM (GIS)

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جامعة الإمارات العربية المتحدة
United Arab Emirates University

MASTER THESIS NO. 2022:18

College of Humanities and Social Sciences

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This thesis is submitted in partial fulfillment of the requirements for the degree of Master of Science in Remote Sensing and Geographic Information Systems

April 2022

United Arab Emirates University Master Thesis
2022: 18

Cover: Al Bidiyah Archaeological Mosque in Fujairah, Mleiha Tomb in Sharjah, Muzaira'a fort in Abu Dhabi, and Hili archaeological site in Al Ain

(Photos: By Abdulla Salem Al Yammahi)

Print: University Print Service, UAEU 2022

Declaration of Original Work

I, Abdulla Salem AlYammahi, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Assessment of Natural Hazards Impact on Heritage Sites in the United Arab Emirates (UAE) Using Geographic Information System (GIS)*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Professor Mohamed Yagoub M. Saeed, in the College of Humanities and Social Sciences at UAEU. This work has not previously formed the basis for the award of any academic degree, diploma, or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation, and/or publication of this thesis.

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Abstract

The United Arab Emirates (UAE) pays significant attention to preserving its heritage sites and archaeological finds and treats them as a vital part of its culture, history, and economy. In recent years, the field of archaeology in the UAE has witnessed tangible and significant developments, with many government initiatives being devoted to establishing archaeological departments in all emirates. The firmly stated policy of these institutions is to preserve the UAE heritage sites and educate the public about their importance. However, these sites are vulnerable to natural hazards, considered one of the most critical threats to the UAE heritage sites. In this regard, it should be noted that in the past two decades, the United Arab Emirates has witnessed a number of natural hazards, such as earthquakes and floods linked to precipitation, rising sea levels, and sand encroachment. This study aims to create a database for the UAE heritage sites, generate maps for natural hazards (earthquakes, floods, sea-level rise, and sand encroachment), and assess the proximity of heritage sites to hazard zones. The results show that heritage sites located in the north-eastern UAE are more vulnerable to floods, earthquakes, and sea-level rise and that the effects of these risks vary according to their geographical locations, i.e., whether they are close to or far from the coast and whether they are near or far from the fault line, as well as the extent of their height from ground level. The study also finds that sand encroachment threatens most archaeological sites in the western region of the Emirate of Abu Dhabi. As additional support to assess the results of the spatial analysis, the study used the Geographic Information System (GIS) and Remote Sensing (RS), as well as the Analytical Hierarchy Method (AHP). Archaeologists from the Department of Culture and Tourism in Abu Dhabi were consulted to identify the most natural hazards that may affect heritage sites in Abu

Dhabi. In a concise questionnaire, the archaeologists were explicitly asked to set a certain weight for each natural factor. It should be noted that the AHP study was limited to the Emirate of Abu Dhabi due to the lack of necessary information from other emirates of the UAE. The results of the AHP indicated that flooding due to rain is the primary threat to heritage sites in the Emirate of Abu Dhabi, followed by sand encroachment and rising sea levels. Sand encroachment is often considered a threat to heritage sites. However, apart from the areas such as castles, forts, and mosques - to which sand encroachment is one of the biggest threats - archaeologists believe that the encroachment of and burial of archaeological sites by desert sands protect them from other natural factors. This study, along with the database, methodology, and outputs, is intended to be a valuable reference for many parties interested in the cultural, historical, and tourism fields, as well as those interested in natural disaster management and urban planning. Furthermore, the GIS database of heritage sites in the UAE saves researchers in antiquities in real-time and effort regarding data collection. In a nutshell, the author of this study believes that it is essential and must be of interest to all stakeholders.

Keywords: UAE heritage sites, Natural Hazard, GIS, Remote sensing, AHP.

Title and Abstract (in Arabic)

تقييم تأثير المخاطر الطبيعية على المواقع الأثرية في الإمارات العربية المتحدة باستخدام نظم المعلومات الجغرافية (GIS)

الملخص

تولي دولة الإمارات العربية المتحدة اهتماماً كبيراً بالمحافظة على المواقع التراثية والاكتشافات الأثرية، لما لها من أهمية ثقافية وتاريخية واقتصادية. شهد علم الآثار في دولة الإمارات تطورات ملموسة في السنوات الأخيرة، فقد تم استحداث مبادرات حكومية لإنشاء أقسام تعنى بالآثار في كل إمارة. فالحفاظ على المواقع الأثرية وتثقيف الجمهور بأهمية حمايتها هي من مسؤوليات الحكومة باعتبارها ثقافة دولة بأكملها. وتعتبر المخاطر الطبيعية من اهم ما يهدد المواقع الأثرية في دولة الإمارات. فقد تعرضت دولة الإمارات العربية المتحدة في العقدين الماضيين لمجموعة متنوعة من الكوارث الطبيعية، مثل الزلازل والفيضانات الناجمة عن هطول الأمطار وارتفاع منسوب مياه البحر وكذلك الزحف الصحراوي، فجاءت هذه الدراسة لتقييم تأثير المخاطر الطبيعية التي قد تهدد المواقع الأثرية في الدولة. فتمت الاستعانة بنظم المعلومات الجغرافية (GIS) وتقنيات الاستشعار عن بعد (RS) لحصر تلك المخاطر الطبيعية في دولة الامارات ومدى قربها من المواقع الأثرية. فمن نتائج هذه الدراسة أن المواقع الأثرية الواقعة في المنطقة الشمالية الشرقية من دولة الإمارات هي أكثر عرضة للزلازل والفيضانات وارتفاع منسوب مياه البحر، وتختلف آثار تلك المخاطر باختلاف مواقعها الجغرافية بالقرب أو البعد عن خط الصدع، أو القرب والبعد عن الساحل، وكذلك مدى ارتفاعها عن مستوى سطح الأرض. كما يهدد خطر الزحف الصحراوي غالبية المواقع الأثرية في الجزء الغربي من إمارة أبوظبي. وكداعم إضافي لتأكيد نتائج التحليل المكاني باستخدام نظم المعلومات الجغرافية والاستشعار عن بعد (GIS and RS)، تم استخدام طريقة التسلسل الهرمي التحليلي (AHP) في الدراسة، حيث تم استشارة خبراء الأثار من دائرة الثقافة والسياحة في إمارة أبوظبي، لحصر أكثر المخاطر الطبيعية التي قد تؤثر على المواقع الأثرية في الإمارة، مع تحديد وزن معين لكل عامل. (اقتصرت دراسة التسلسل الهرمي (AHP) على إمارة أبوظبي على وجه الخصوص بسبب عدم توفر المعلومات الآزمة من الإمارات الاخرى. كما تشير نتائج عملية التحليل الهرمي (AHP) إلى أن الفيضانات بسبب الأمطار هي أكبر مهدد للمواقع الأثرية في إمارة أبوظبي، يليها الزحف الصحراوي وارتفاع منسوب مياه البحر. وعلى الرغم من ان الزحف الصحراوي يعتبر في كثير من الاحيان عامل تهديد للمواقع الأثرية إلاّ أن علماء الآثار يرون أن

زحف رمال الصحراء على المواقع الأثرية ودفنها هو بمثابة حماية لها من المخاطر الطبيعية الأخرى، بخلاف المباني التراثية مثل (القلاع والحصون والمساجد) التي يمثل فيها الزحف الصحراوي خطرا يهدد وجودها. في النهاية تعتبر هذه الدراسة بما تحويه من قاعدة بيانات ومنهجية ومخرجات مرجعا مفيدا لكثير من الجهات المهتمة بالمجال الثقافي والتاريخي والسياحي للدولة، وكذلك المهتمين بمجال إدارة الكوارث الطبيعية والتخطيط الحضري. كما ان وجود قاعدة بيانات نظم المعلومات الجغرافية للمواقع الأثرية في دولة الإمارات يوفر على الباحثين في مجال المواقع الأثرية الوقت والجهد في جمع المعلومات والبيانات اللازمة. وعليه فإن هذه الدراسة متاحة لجميع المهتمين.

مفاهيم البحث الرئيسية: المواقع الاثرية في دولة الامارات العربية المتحدة، المخاطر الطبيعية، عملية التسلسل الهرمي، نظم المعلومات الجغرافية والاستشعار عن بعد.

Author Profile

Abdulla Salem AlYammahi is currently the Documentation Unit Head at the Department of Culture and Tourism in the Emirate of Abu Dhabi. After graduating from college, he started his career as a land surveyor in the UAE Armed Forces' Military survey department. During his eight years in the department, he was assigned to the hydrographic survey and aerial photography sections. He also acted as a survey team leader in BAYANAT for mapping and Surveying Services Company for three years before moving to Emirates Defense Industries Company (EDIC) for two years. Besides his service awards, he was given experience certificates at each workplace. Abdulla obtained his Higher National Diploma certificate in Geographic Information Systems (GIS) and Cartography in 2006 from Luton University in the United Kingdom. In 2018, he graduated with a bachelor's degree certificate in Civil Engineering from the Higher Colleges of Technology in Abu Dhabi. Mr. AlYammahi published his first article as the co-author with his master thesis advisor Prof. Mohammed Yagoub under the name "Spatial distribution of natural hazards and their proximity to heritage sites: Case of the United Arab Emirates". Abdulla volunteered with the Emirates Red Crescent in 2007 during the Guno cyclone off the coast of Fujairah where many residents were forced to evacuate to schools, hospitals, and safe places. Abdulla is from Al Fujairah, and currently, he lives with his family in Al Ain city.

Acknowledgments

My deepest thanks go to Dr. Nazmi Saleous, coordinator of the MSc in Remote Sensing and GIS at UAEU.

I would like to thank my committee for their guidance, support, and assistance throughout my preparation of this thesis, mainly my advisor Prof. Mohamed Yagoub M. Saeed. I would like to thank the chair and all members of the Department of Geography and Urban Sustainability at the United Arab Emirates University for assisting me in my studies and research.

My special thanks are extended to the Library Research Desk for providing me with the relevant reference material.

Special thanks go to my parents and my sister Dr. Ghanimah AlYammahi (Assistant Prof. Arabic Department in UAEU), who helped me along the way. Furthermore, I would like to express my thanks to the Department of Culture and Tourism Al Ain for providing me with information about archaeology in the UAE and for helping me fill out the AHP questionnaire form.

Dedication

To my beloved parents and family

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List of Abbreviations

AHP	Analytical Hierarchy Process
BP	Before the Present
CR	Consistency Ratio
CVS	Comma Separated Values
DCT	Department of Culture and Tourism
DEM	Digital Elevation Model
GIS	Geographic Information System
IC	Cellular Automata model
IPCC	Intergovernmental Panel on Climate Change
LULC	Land Use and Land Cover
MCDM	Multi Criteria Decision Making
RS	Remote Sensing
SHP	Shape File
UAE	United Arab Emirates
UNESCO	United Nations Educational, Scientific and Cultural Organization
UTM	Universal Traverse Mercator projection

Chapter 1: Introduction

1.1 Overview

As an integral part of the built environment, cultural heritage properties play a significant role in economic development and strengthening social capital and cultural diversity (Ravankhah et al., 2019). Heritage buildings, however, have historically been exposed to a wide range of natural hazards, resulting in severe damage. Humankind's artistic works have constantly been threatened not only by the ravages of time and by our interventions but also by natural disasters (Meier, Petzet, & Will, 2007). Natural disasters are sudden events generated by natural phenomena such as storms, earthquakes, floods, and landslides that lead to significant loss of life or damage to infrastructures and economic activities (Dhanhani, Duncan, & Chester, 2010). The United Arab Emirates has experienced various natural hazards over the past two decades, including floods caused by rainfall, earthquakes, rising sea levels, sand encroachment, and tsunamis. These disasters pose a significant risk to heritage sites that provide important cultural and economic benefits (Rossello, Becken, & Santana-gallego, 2020). Despite the risk of these disasters, their management has not been established by the state of the UAE till the last few years (Kaili, Pathirage, & Amaratunga, 2014). However, recent studies stressing the impacts of past natural disasters on ancient societies have increased dramatically (Torrence & Grattan, 2003). Understanding the characteristics and effects of natural disasters that pose a risk to cultural heritage is essential to monitoring the measures that have been developed, approved, and implemented nationwide and internationally to avoid, mitigate, and deal with the effects of natural disasters. Thus, timely and accurate spatial data are required to effectively manage natural hazards on heritage sites in the UAE (Drdácký et al., 2007). Specific disaster risk management policies need to be formulated based on the particular types of cultural heritage and nature of hazards within a regional context (Jigyasu & Arora, 2014). GIS contains valuable tools for disaster prediction, identification, response, mitigation, and recovery. These tools can integrate, visualize, and analyze diverse data linked or compared with other external models (Carver, 1991; Yagoub, 2015). At the same time, the AHP decision-maker will help decide which of these criteria is the riskiest. It is a mathematical method developed (Saaty, 1980) that has been used in different situations where the decision is hard to make to finally come up with an acceptable solution (Murayama, 2012). The AHP was applied in theoretical calculation and GIS tool application. The results revealed the danger of these natural hazards on the studied historical sites; they also helped decide which criteria influence their safety more to attract the state's attention and prevent them from being lost.

1.2 The Importance of Preserving Heritage

The cultural heritage and natural history of a nation have a very high value and are unique. It is an identity that can be introduced to the world. Cultural heritage affirms our identity as a people because it creates a comprehensive framework for preserving cultural heritage, including cultural sites, old buildings, monuments, shrines, and landmarks that have cultural significance and historical value. Culture and its heritage reflect and shape values, beliefs, and aspirations, thereby defining a people’s national identity. It is essential to preserve our cultural heritage because it keeps our integrity as a people. The importance of intangible cultural heritage is not the cultural manifestation itself but rather the wealth of knowledge and skills transmitted through it from one generation to the next. The social and economic value of this transmission of knowledge is relevant for minority groups and mainstream social groups within a country. It is as important for developing States as for developed ones.

1.3 Aim and Objectives

Aim:

This study aims to assess the impact of natural hazards such as earthquakes, sand encroachment, flooding due to sea-level rise, tsunamis, and rainfall on historical buildings and archaeological sites in the UAE to provide spatial data that could be used to develop a policy that could help in mitigating the impact of such on historical buildings and archaeological sites in the UAE using GIS spatial analysis and AHP decision making.

Objectives:

- To map historical buildings and archaeological sites spread across the UAE.
- Produce land use/ Land cover map using satellite images to aid in classifying locations of historical buildings and archaeological sites.
- Produce natural hazards maps of UAE.
- Create Natural Hazards Index for the UAE historical buildings and archaeological sites using GIS-Based spatial analysis.

1.4 Research Questions

- How does each natural hazard affect historical buildings and archaeological sites in the UAE?
- Which natural hazard threatens historical buildings and archaeological sites more in the UAE?
- What historical buildings and archaeological sites are more vulnerable to the impact of all the natural hazards?

1.5 Problem Statement

Historic sites are highly exposed to the harmful effects of natural hazards, with consequences ranging from gradual decay and deterioration to outright catastrophic losses (Ravankhah et al., 2019). Various natural hazards affect historical buildings and archaeological sites differently with varying severity. Each hazard is characterized by its geographic location, area, size or magnitude, intensity, onset speed, and duration frequency (Yagoub, 2015). Despite the effects of natural hazards on historical buildings and archaeological sites in the UAE, not much has been done to assess the impact of different threats on such facilities. The effect of natural hazards on historical buildings and archaeological sites in the UAE is known. What remains vague is spatial data on the magnitude and the extent to which each and all the hazards affect those sites in the UAE.

1.6 Definitions

Natural hazards and heritage sites are the key terms used in this study. Natural hazards are defined as phenomena such as weather, hydrology, geology, and wildfires that have the potential to affect human life, structures, or activities based on their location, severity, and frequency (Oas, 2009). The definition stresses the link between social systems and nature in framing potential damage (Ravankhah et al., 2019). This study examines the spatial distribution and potential impacts of rainfall, seismic activity, rising sea level, and desert in the UAE. Monuments can be classified as cultural, natural, or mixed. Among cultural heritage are archaeological sites, historic buildings, and artworks. Sites designated as natural heritage are considered rare, unique, and exceptionally spectacular. Both genuine and culturally significant are mixed heritage (Britannica, 2021). Heritage sites in the UAE are foremost cultural, including oases and water systems (Falajs).

1.7 Study Area

The study areas concern seven states/emirates of the United Arab Emirates: Abu Dhabi, Dubai, Sharjah, Ajman, Umm Al Quwain, Ras Al Khaimah, and Al Fujairah, located between 22-26.5 °N latitude 51-56.5 °E longitude. They are bordered to the north by the Arabian Gulf, to the east by the Indian Ocean and Oman, to the south by the Kingdom of Saudi Arabia, and to the west by Qatar. The total area is 83,600 square kilometers. Most of its land is desert interspersed with oases. The UAE population was about 9,503,738 reached in 2019, according to the statistical report from the Federal Competitiveness and Statistics Center (FCSC, 2019). The United Arab Emirates has a coast extending 644 kilometers along the southern part of the Arabian Gulf. In contrast, the Fujairah coast extends 90 km along the Gulf of Oman. Most beaches are sandy, except in the northern Ras al-Khaimah, which forms the head of the Hajar mountain range. Additionally, there is a number several along the Arabian Gulf that fall under the UAE territory, including Abu Dhabi Island, the capital of the UAE, Das, Mebraz, and Arzana, which are considered the major sea petroleum fields, as well as the islands of Dalma, Saadiyat, Abul Abyad, and Ser Bani Yas. Al Sharjah emirate has two main islands, Abu Mousa and Sir Bu Naer. In Ras Al Khaimah, there are the Great Tunb and Lesser Tunb Islands (Source: Ruler's Representative Court Al Ain Region). The studied archaeological sites were 84 spread within three major geographical areas: coastlines, deserts, and mountains (Figure 1).

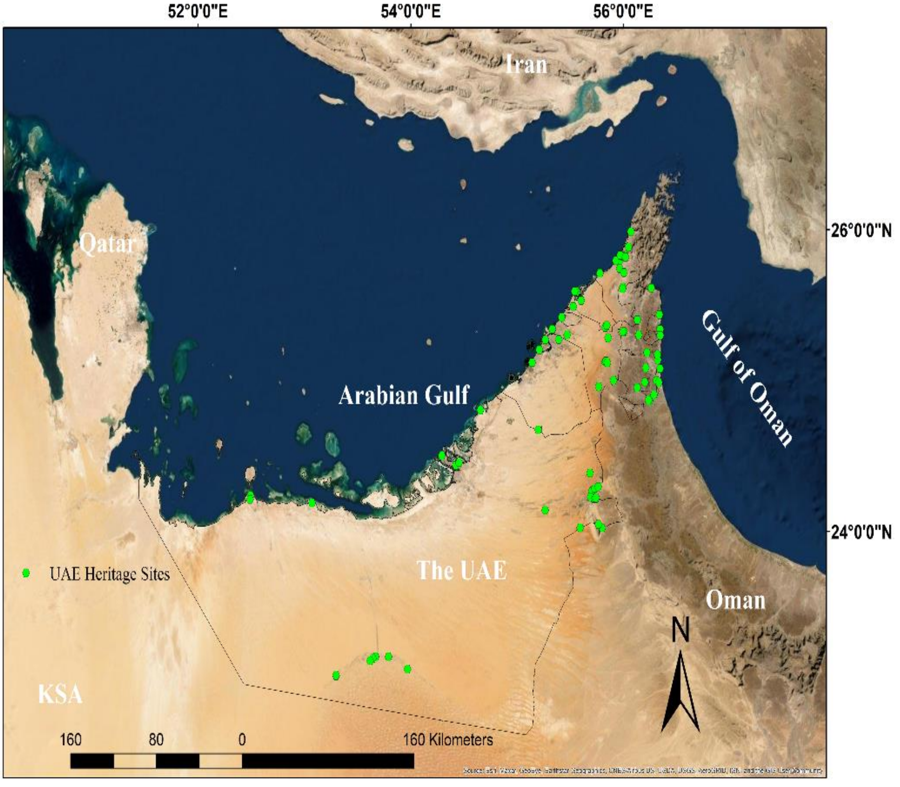


Figure 1: The study area and the UAE heritage sites

Chapter 2: Literature Review

2.1 General Outlook

As reported by the European Parliament, natural disasters are "The long-term climate impacts that cause severe damage to or destruction of whole areas of heritage sites resulting from earthquakes, storms, floods, sliding, eruptions, hurricanes, and fires (Meier et al., 2007). In a significant city with high-rise buildings and constructions, a large earthquake can cause a considerable economic loss (Barakat, Shanableh, & Malkawi, 2008). On January 12th, 2010, an earthquake of 7.3 hit Haiti, causing an unprecedented situation. Over 200,000 people died, and many significant collections of artworks, historical arches, public administration documents, and archaeological documents have been either damaged or lost. Several artworks, historical archives, public administrative manuscripts, and ancient documents have been destroyed and scattered in Port-au-Prince. It has yet to be identified what remains of the legal archives, which were hidden within the ruins of the Law Court and the National Palace (Haiti PDNA, 2010). The Gorkha earthquake in Nepal on April 25, 2015, with a magnitude of 7.8, was a severe disaster for culture and humanity. The earthquake devastated historical monuments across Nepal, including the monuments within the Kathmandu UNESCO World Heritage Property valley (Davis et al., 2020). On April 25th, 2015, UNESCO reported an earthquake that destroyed some of Nepal's cultural and natural heritage. The number of historic buildings was 691 in 16 provinces, of which 131 completely collapsed. The visual evaluation also showed that the Kathmandu Valley World Heritage site monuments had been severely affected (UNESCO World Heritage, 2015). Various historical sites have been devastated by floods worldwide. The irregular settlement of the Laudon Pavilion in the field of the Veltrusy Castle in the Czech Republic was affected by internal soil erosion. In Wachau (Austria) and Wesenstein Castle in Saxony (Germany), the walls and the terrace walls of the historic vineyards collapsed during the flood of 2002 due to the water pressure rise (Herle et al., 2010). Sand encroachment is also one of the significant natural hazards that can affect archaeological sites, as exemplified by the top 5 UNESCO World Heritage Sites: Timbuktu (Mali, Tuareg/Islam), Great Wall of China (China, Imperial China), Tulor village (Chile, Atacameño), Chinguetti mosque (Mauritania, Islam) and Dunhuang Monago caves (China, Buddhist) (MINK, 2009).

2.2 Natural Hazard Types in the UAE

The UAE is home to many historical places such as forts, museums, ancient houses, and old markets. In 1998, UNESCO named Sharjah as the 'Cultural Capital of the Arab World', one of the most popular tourist attractions in the UAE (Yagoub & Jalil, 2014). The UAE’s vulnerability to disasters increases with the ongoing massive development of industrial activities, including tectonic and weather-related disasters (Almarzooqi, 2017). The UAE is situated near the eastern margin of the Arabian tectonic plate, close to the seismically active collision zone between the Arabian and Eurasian Plates, marked by the Zagros Mountains belt of Iran (Dhanhani et al., 2010). It is exposed to several natural hazards because the environment is unique (Alsenaani, 2013). Some of the natural hazards in the UAE are climate change-induced sea-level rise (El-askary et al., 1970). earthquake (Dhanhani, 2010), flood (Yagoub et al., 2020), and sand encroachment (Mfarrej, 2019), among others. In 2007, the UAE established the National Emergency Crisis and Disaster Management Authority (NCEMA) To ensure the safety of citizens and residents as well as to preserve property. NCEMA operates under the supervision of the Supreme Council for National Security, with the aim to achieve the UAE’s policy regarding the necessary procedures for emergency, crisis, and disasters management. It's the major national standard-setting body responsible for regulating and coordinating all emergency, crisis, and disaster management efforts and developing a national plan for responding to emergencies. Therefore, its work is focused mainly on the development, consolidation, and maintenance of laws, policies, and procedures of emergency and crisis management at the national level (https://www.ncema.gov.ae/).

2.3 Earthquakes and Tsunami

According to Abdalla and Al-Homoud (2004) and Yagoub (2015), the consequences and occurrence of earthquakes can be single, continuous, or combined. The characteristics of catastrophes include their geographical site, area, magnitude, intensity, onset speed, period, and severity. The UAE is located near the most notorious seismically active zones globally (the southern shores of Iran), making it unsafe for earthquake risks (Barakat et al., 2008). This explains why several earthquakes have hit the UAE recently (Al Ruwaithi, 2019). The high seismic activities in the northern part of the UAE need attention because it is the most seismically active part of the UAE (Abdalla & Al-Homoud, 2004). A previous study by Yagoub published in 2015 showed that earthquakes occurred more frequently in 2010 and 2011. During the last 28 years, the Spatio-temporal distribution of earthquake events and their effect on the population continued. The earthquakes occurred with intensities ranging from weak to moderate, reaching a maximum severity of 5.1 recorded in the eastern part of the UAE Fujairah (Oman Thrust). Similarly, 49% of earthquakes occurred in 2011. This matches a United States Geological Survey (USGS) statement that 2011 was the year that witnessed the most frequent earthquakes in 20 years. Even though the magnitude of earthquakes in the UAE is low, the frequency has increased in recent years in the context of increasing urban development. Therefore, hazard maps must be preventive measures (Yagoub, 2015). As a result of earthquakes, the United Arab Emirates has been affected by tsunamis in the past which occurred along the eastern coastal area bordering the Arabian Sea (Indian Ocean), with small waves of 3 to 30 cm in height recorded along the Fujairah coast (Kowalik et al., 2005). Therefore, the construction of new developments near the UAE's eastern coast, including Fujairah, Khor Fakkan, Dibba, and Dadnah, needs to include tsunami mitigation planning, education, and public awareness (Dhanhani et al., 2010). Historically, records for tsunamis made available by UAE University show that tsunamis mainly occurred in the Indian Ocean countries of Indonesia, Pakistan, and Iran, with a total of 8 events. The majority of these tsunami events were due to a large magnitude of earthquakes, with one event due to a volcano eruption (Alsenaani, 2013).

2.4 Flooding and Rainfall

Flooding can occur in flood-prone areas when heavy rains occur (Yagoub et al., 2020). Heavy rainfall in the arid environment of the UAE usually results in high-level discharge and flooding (Dhanhani et al., 2010). Thus, historic sites, infrastructures, heritage landscapes, and garden areas are susceptible to damage or loss (Drdácký et al., 2007). In the UAE, flooding is a common natural disaster. Many floods in the country have led to the evacuation of residents, as in the case of Qurayyah village in 1995. The village has a population of 5026 and 414 homes located in the northern part of the Fujairah Emirate. According to Dhanhani et al. (2010), Alittihad newspapers triggered policies after the Al Qurayah flood (December 1995). Heavy rains fell for several days, leading to intense flooding, with a dam in Safad valley destroyed. The flooding caused considerable damage to infrastructure, farms, and utilities (Dhanhani et al., 2010). In addition to damaging buildings, roads, and farms, it damaged poultry and livestock and caused many people to leave their houses. The incident, however, did not result in a loss of life (Dhanhani et al., 2010). The government of the UAE allocated four million dollars for building three new breakwaters in Safad and Thayb valleys. Furthermore, Al Qurayah residents were provided with new houses and compensation (Dhanhani et al., 2010).

2.5 Sea-Level Rise

During the Flandrian Transgression from 14,000 years ago, approximately 250,000 square kilometers of land became submerged (Lambeck, 1996). The weight of this water exerted hydrostatic pressure on the eastern and northern extents of the Arabian Plate. While this caused subsidence in the north of the Arabian Gulf, it may have resulted in a slight uplift around the Emirates. As late as 10,000 years ago, most of the marine areas within Abu Dhabi Emirate are thought to have been dry land. This area flooded as sea levels rose over the following 2,500 years. The highest rates of sea-level rise began at ~11,500 and peaked between ~10,900 and 9,500 years ago, with elevations between 1.9 m and 2.5 m per century (Stanford et al., 2011). Between 8,900 and 8,100 years ago, sea-level index points suggest further rapid rises of ~14.4 m (Bird et al., 2010). Of particular importance is a ‘meltwater pulse’ (1C) at ~ 8,200 years ago, which saw a rise of 6.5 m in less than 140 years. While combined estimates suggest that global sea levels may have remained more than -13 m below current levels as late as 8,000 Before the Present (BP) (Flemming et al., 1998). Discoveries by the Department of Culture and Tourism Abu Dhabi of coastal Neolithic sites on the island of Ghagha suggest that 8,500 years ago, sea levels were lower than we see today. According to the UAE government portal (https://u.ae), the UAE is the country most vulnerable to the potential impacts of climate change, which means more warming, less rain, more drought, and a higher level of seawater, causing more storms. That leads to devastating consequences for infrastructure, human health, and natural habitat, which impact various socio-economic, health, and environmental sectors and policies. UAE coastline spans nearly 1,3kilometresers. As per the Environment Agency- Abu Dhabi report, over 90% of the UAE's infrastructure and 85% of the population are located within several meters of the sea in low-lying coastal areas (MOCCAE, 2019). Climate Change - Impacts, vulnerability, and adaptation. In the Stockholm report (Stockholm Environment Institute's US Centre), up to six percent of the UAE's developed and populated coastline could be lost due to sea levels rising by the end of the century (The official portal of the UAE Government).

2.6 Sand Encroachment

The desert is considered a hazard due to the geomorphology and landmass of the landscape. Unlike the other hazards, the desert could affect heritage sites. In the absence of proper protection, sand encroachment could result in the burying of heritage sites. Sand encroachment has been widely recognized as one of the most severe environmental problems globally, mainly in arid, semi-arid, and dry sub-humid areas (Arnous et al., 2009). It results from various factors (UNCCD United Nations Convention to combat desertification, 1994) such as winds, rain, humidity, and human factors through urban expansion. For instance, the encroachment of sand in Timbuktu completely submerged the Sankoré mosque (Mink, 2009). The Arabian Peninsula is among the five regions that generate the most dust. Over 200 tons of dust can be carried by a dust storm (De Villiers & Heerden 2007). Since the desert occupies a large part of the UAE (Kaili et al., 2014), the likelihood of sand movement is high. For example, 173 dust events and dust storms occurred between 1994 and 2003 (Alsenaani, 2013). Accidents (including fatalities) may happen upon the accumulation of sand on the road. The UAE government spends millions of dollars annually removing desert sand from the main streets to save drivers' lives. Compared to other emirates, Abu Dhabi has the largest desert area, with about 90% of its total area. Most of Abu Dhabi's archaeological sites are found in the desert, unlike the other emirates. Therefore, these archaeological sites are subject to sand encroachment due to high temperatures and strong winds throughout the year.

2.7 Applications

2.7.1 Geographic Information System (GIS) and Remote Sensing

GIS and remote sensing are gaining attention as important tools in archaeological sites studies (Nsanziyera et al., 2018) because they can provide valuable data to timely update information and documentation and set up reliable tools for systematic monitoring of cultural properties (Elfadaly et al., 2018). The ability of GIS to integrate data from a different source, such as remote sensing, has made it a preferred technology in many fields, including the archaeological field. By combining satellite remote sensing techniques with GIS, historical sites can be consistently monitored in a repetitive, unintrusive, rapid, and cost-effective manner (Alexakis et al., 2011).

2.7.2 Analytical Hierarchy Process (AHP)

Analytical Hierarchy Process AHP (Saaty, 1980) is a Multi-Criteria Decision-Making (MCDM) process that structures factors into a hierarchical framework that helps decision-makers to evaluate the relative importance of various elements using pairwise comparison tables (Papaioannou, Vasiliades, & Loukas, 2015). AHP presents a framework to manage multiple views on a complicated decision problem (Malczewski, 2006). According to Ouma and Tateishi (2014), pairwise correlations in AHP are conducted following a regulated grading system of nine classes.

Hierarchical model structures in AHP allow users to focus on measures and sub-criteria when designing weights (Saaty, 1980). Plentiful research has been achieved using AHP and GIS/remote sensing. Integration of AHP into GIS applications has been demonstrated in different scientific disciplines related to land-use suitability, assessment, classification and planning, urban development, suitability and renewal, environmental quality, landslides mapping, earthquakes, health, droughts, floods, etc. Papaioannou et al. (2015), Also, Nsanziyera et al. (2018) used an Analytic Hierarchy Process (AHP) to develop a predictive model to locate areas with high potential as archaeological sites in the Award area (southern Morocco). Agapiou, et al. (2015) assessed natural and anthropogenic hazards risk for cultural heritage sites and monuments in the Paphos district using GIS, remote sensing and AHP.

Chapter 3: Methodology

3.1 Data Collections

3.1.1 Heritage Site Data

Heritage site data was collected from diverse sources (Appendix A). In general, to obtain accurate and reliable data, official websites have been relied upon as a source of information. For instance, the Abu Dhabi Department of Culture and Tourism (https://tcaabudhabi.ae/) website covers information on Abu Dhabi, Al Dhafra area, and Al Ain heritage sites such as forts and oases. Unfortunately, some sites' statements were not available in the official sources; alternatively, other sources such as, websites, books, and scientific articles were used. An example of online resources used in this study is the Castles website, which provides a gallery of UAE castles and forts linked to their geographic locations on Google Maps. A reliable source for archaeological information is The National Atlas of the United Arab Emirates (1993), which provides valuable details about the heritage sites in the UAE. In addition, UNESCO World Heritage Convention (WHC) website, which is concerned with archaeological and heritage sites, describes some places based on their category (Cultural and Geographic Coordinates). The information on heritage sites has been compiled into an excel sheet and converted to Comma Separated Values (CSV) format in GIS applications. The database includes the name of each site, the emirate it belongs to, type, age/era, historical information, and civilization to which it belongs (Appendix B).

3.1.2 Remote Sensing Data

A UAE Land Cover/Land Use map (LULC) has been created by compiling eight scenes covering the entire UAE. The scenes were acquired from the United States Geological Survey (https://www.usgs.gov) website using Landsat 8 (OLI) satellite images. Also, Digital Elevation Model (DEM) raster images were downloaded from the same website. All the images were geometrically corrected and projected onto the Universal Traverse Mercator projection (UTM) of WGS84. The images have 11 different bands with different resolutions. Band 2 (Blue), 3 (Green), and 4 (Red) were used for the classification. The Landsat 8 Band Combinations can be arranged to bring out specific and unique information like any other image band. Spectral signatures of objects in an image can indeed be extracted. In the case of Landsat-8, some of the popular band combinations include natural color, color infrared, and various vegetation indexes. The most common band combinations and their specialties are composite bands (4, 3, 2) that give Natural Color to make the image very close to what our eyes can see. The combined bands (5, 4, 3) used for infrared color are suitable for analyzing vegetation. The composite (7, 6, 4) for short-wave infrared displays vegetation, urban areas, and soils. Bands (6, 5, 2) for agriculture are used tops and healthy vegetation. The bands (7, 6, 2) for geology include geological formations, lithology features, and faults. Bands composite (4, 3, 1) are used for bathymetric, coastal bathymetric, and aerosol studies and estimate suspended sediment (https://gisgeography.com/landsat-8-bands-combinations/).

3.1.3 Earthquake Data

The earthquake data in the UAE included in the study were obtained from the US Geological Survey (USGS). The data consist of coordinates (latitude, longitude), magnitude, and the date on which the earthquake occurred (day, month, and year). The data format is CSV. Thus, it was necessary to convert the data to shapefile format in order to be integrated into the GIS application.

3.1.4 Rainfall Data

Rainfall data were downloaded from the national center of meteorology website https://www.ncm.ae which belongs to the UAE Ministry of Presidential Affairs. The website provides the names of the meteorological stations, location data (latitude, longitude, and elevation), and the means of monthly rainfall in mm. Data were obtained from 66 stations and used to produce flood density maps (Table 1, Section 3.1.5). Through the website, average rainfall data in the UAE was available in text format. The website provides data on the location (latitude, longitude, and elevation), mean of total monthly rainfall (mm) for the period from 2003 to 2020 for each station, and the meteorological stations' names. Based on this information, a table was created in Excel, converted to CSV format, and then to Shapefile (SHP) for processing.

3.1.5 Sea Level Rise Data

In general, the present methodology seeks to devise an objective approach to identifying those parts of the UAE coast at risk of (global) sea level. Future sea-level rise is likely to increase before accelerating shoreline erosion. Moreover, the UAE coast will be much more vulnerable due to damage to coastal structures in the future. Forecasting the future of coastal changes will be helpful in coastal management and development due to its inevitability. Considering this background, this study aims to identify the degree of vulnerability of coastal segments of the UAE. The Digital elevation model DEM raster image was primarily used to obtain -level rise data. DEM data along with the coastline of the UAE were utilized to determine the changes in sea level rise.

3.1.6 DEM Data

A Digital Elevation Model (DEM) is a representation of the bare ground (bare earth) topographic surface of the Earth, excluding trees, buildings, and any other surface objects (www.earthexplorer.usgs.gov). The DEM has been categorized into five classes based on heights using The Jenks natural break classification algorithm calculated DEM ranges. The Natural breaks indicated actual classes in data (Jenks, 1967). The method allows unevenly dispersed values to be mapped, minimizing class differences, and maximizing the conflict among the classes (Same data in groups). The natural breaks (Jenks, 1967) allow the visualization of cluster/class boundaries and facilitate understanding its meaning. An overview of data used in the project is provided (Table 1), including data sources and data analysis, and data format.

Table 1: Summary of data sources

Data	Source	Analysis	Format
(ASTER DEM)	USGS	Rainfall and Sea-Level Analysis Site Elevation	Raster
Landsat 8 satellite image OLI/TIRS C2 L1 20210127	USGS	(LULC) Classification	Raster
UAE Boundary	UAE University	Clipping and Mapping	Shapefile
Earthquake dates and duration	USGS	Earthquake hazard map	Text
Mean of Monthly Total Rainfall (mm) from 2003 to 2021	National Center of Metrology	Flood Analysis	Text
Heritage sites information	Official websites in the UAE (Appendix A) (Appendix B)	Site Information	Text
Heritage sites Location	Google Earth	Site Locations	X, Y

3.1.7 AHP Data

To assess and list the hazards in order of importance, five experts from the Department of Culture and Tourism were surveyed. The questions were uniform to all experts taking part. The questionnaire was specific to the region of Abu Dhabi due to some constraints and difficulties getting access to experts from other emirates. The experts chosen were seen as the ideal candidates to take part in the survey as they are all very experienced and highly skilled archaeologists with deep knowledge and understanding of the history and landscape of Abu Dhabi. The objective of the survey is to assign weights to the factors in the hazard criteria. It was then decided to investigate how flooding was compared to other factors. The average weight was calculated, which allowed for the formation of the comparison table. A consistency ratio calculation was performed to ensure the accuracy and validity of the results found.

3.2 Data Processing

Figure 2 shows the overall methodology used in this study.

3.2.1 GIS and Remote Sensing

The section discusses the data collection process for the heritage sites (LULC) and various natural hazard maps. GIS was used to upload data collected from different sources and prepare them for further analysis in the case study. As well as visualizing these data with data projected from excel databases (archaeological site coordinates, earthquake data, rainfall stations, etc.). The manipulation feature in ArcGIS is used to determine which factor influences heritage sites for further decision-making. Based on earthquake data retrieved from the USGS, an earthquake hazard map was created using the Inverse Distance Weighted (IDW) interpolation method (Watson & Philip, 1985) (Table 2). IDW interpolation method used in our case study has a better performance (Ravankhah et al., 2019; Xie et al., 2015). Creating a digital elevation model (DEM) for the entire UAE by acquiring 21 DEM images, each of which covers a portion of the UAE. The digital elevation model was extracted from the Shuttle Radar Topography Mission (SRTM). DEM Data provides worldwide coverage and distribution of void-filled data at a resolution of 1 arc-second (30 meters).

Table 2: Earthquake hazard map classification

The magnitude of the earthquake	Weight	classification
3.91 - 5.49	5	Very High
3.27 - 3.91	4	High
2.82 - 3.27	3	Medium
2.46 - 2.82	2	Low
2 - 2.46	1	Very low

The LULC was extracted from Landsat 8 images using ENVI and ArcGIS. An image of the UAE was created using nine satellite scenes of visible bands (blue, green, and red). Each band has a spatial resolution of 30 meters. DEM raster images were projected, mosaicked, voids filled, and then clipped to the UAE boundary. A DEM dataset was used to extract elevations of each site. LULC maps were generated using supervised classification (Maximum Likelihood Algorithm). Among the seven classes, 935 training signatures were collected: 55 test samples were taken for barren land, 111 for the desert, 105 for mountains, 250 for urban areas, 155 for the sabkha, 160 for vegetation, and 93 for water bodies. The classification scheme was developed using field trips, satellite imagery by Google, and Google Maps. Supervised classification is conducted by an operator or image analyst. The operator specifies each pixel value or spectral signature associated with each class. This is done by selecting specific sample sites of a known cover type called (Training Sites) or Areas. The computer algorithm then uses the spectral signatures from these training areas to classify the whole image. Classes should ideally have minimal or no overlap with other classes. A maximum likelihood algorithm was used in this paper. The algorithm adopts the statistics for each class in which each band is typically distributed and calculates the probability of each pixel belonging to a specific category. Each pixel is assigned to the class with the highest probability - the maximum likelihood. Hazard maps for flooding and sand encroachment were generated using LULC. To ascertain the classification accuracy, additional random sampling was taken. Hazard maps of the various factors can be generated depending on the data available for each aspect. The local severity of the earthquake was rated from 1 to 5 (Ravankhah et al., 2019). Other hazards were rated similarly. The magnitude was extracted for each heritage site to determine the earthquake hazard. An interactive flood hazard map was created based on annual rainfall data, a land-use map, and a DTM raster image. A weight and scale were assigned to each subclass in each layer. The Jenks natural break classification algorithm calculated DEM and rainfall ranges. The Natural breaks indicated actual classes in data (Jenks, 1967). The method allows unevenly dispersed values to be mapped, minimizing class differences, and maximizing the conflict among the classes (Same data in groups). The natural breaks (Jenks, 1967) allow the visualization of cluster/class boundaries and facilitate the understanding of its meaning. A weighted overlay was used to reclassify and merge the layers to produce a flood hazard map (Table 3).

Table 3: Flood hazard map weights and scales

Criteria	Weights	Subclass	Scale	Qualitative Scale
(LULC)	0.3	Mountains	1	Very Low
		Waterbody	1	Very Low
		Barren-land	2	Low
		Desert	2	Low
		Sabkha	2	Low
		Vegetations	3	Medium
		Urban area	5	Very High
Rainfall (mm/year)	0.4	9-16	5	Very High
		7-9	4	High
		5-7	3	Medium
		4-5	2	Low
		1-4	1	Very low
Elevation (m)	0.3	0-79	5	Very High
		79-197	4	High
		197-398	3	Medium
		398-775	2	Low
		775-1886	1	Very low

Based on a study conducted by Ravankhah et al. (2019). In Rethymno, Crete, Greece, the coastal flooding hazard map highlighted the zones exposed to high waves or tsunamis by considering the elevation (up to 3 m) concerning the distance to the coastline (20 m inundation) within a weighted overlay model. Areas within 10 meters of the shoreline and below 10 meters above sea level are considered high, medium, or very high-risk areas, considering the variations in shoreline environments. The height of five meters was set to anticipate high tsunami waves and determine the inundation zone based on height. This study reclassified five categories based on areas below or equal to 5 meters extracted from DEM. In addition, the distance of the sites from the shoreline was calculated (Vittal Hegde & Radhakrishnan Reju, 2007). The hazard map for sea-level rise in the UAE was created mainly using the DEM data by reclassifying the DEM values based on elevation into five categories. Consequently, the lowest height in the coastal area was considered very high risk. In reverse, the higher the ground level, the lower the risk. The UAE map of sand encroachment was created by combining LULC and wind speed data (Table 4). Sand movement is the main factor of sand encroachment. A Cellular Automata model (CA) describes the movement of the sand from and to various places. CA algorithm determines the outcome of each step based on the state of the cell, its surroundings, and the cell features (Silva & Clarke, 2005). According to the CA model desert land cover takes on a larger footprint as cells close by cover the desert quicker than cells far off - a concept in which the future of a cell is predicted by observing its environment (Guan et al., 2011). A large scale is applied to areas at low elevations due to a high probability of sand accumulation. Because of the wind's role in moving sand, areas with high wind speeds have a higher scale (Table 4).

Table 4: Sand Encroachment hazard map weights and scales

Criteria	**Weight**	**Sub-class**	**Scale**	**Qualitative Scale**
Wind speed (m/s)	0.4	1.80-2.85	1	Very low
		2.85-3.42	2	Low
		3.42-3.97	3	Medium
		3.97-4.71	4	High
		4.71-5.93	5	Very High
LULC	0.6	Mountain	1	Very low
		Water Body	1	Very low
		Barren land	2	Low
		Sabkha	3	Medium
		Vegetation	4	High
		Urban	4	High
		Desert	5	Very High

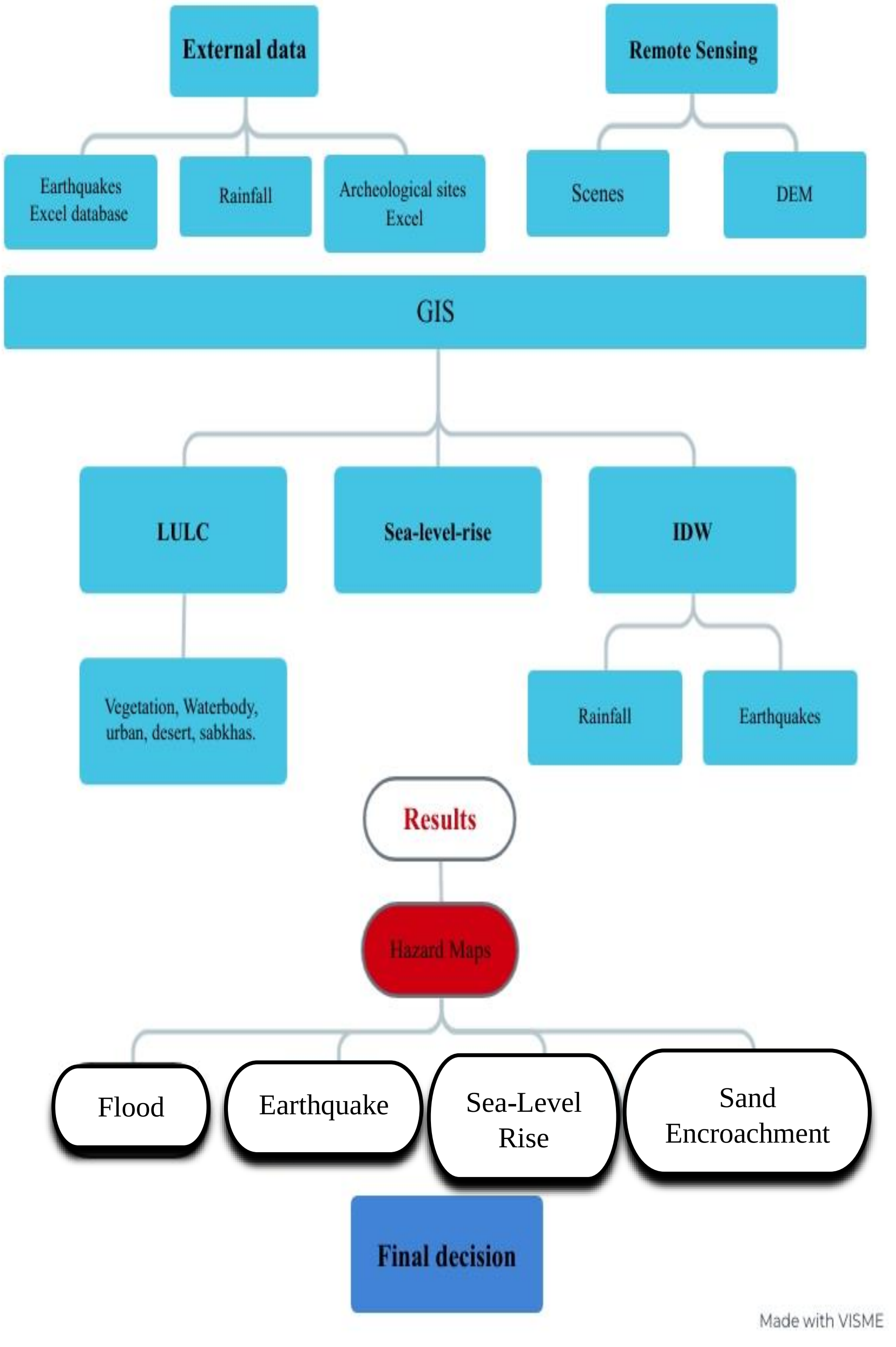


Figure 2: Flowchart of the data processing method

3.2.2 AHP Processing

To resolve an issue using AHP, we usually use a hierarchical or a network structure to represent it. We also use pairwise comparisons to build relationships within its components. These comparisons result in dominance matrices called the scale of relative importance (both positive and mutual), e.g., aij = l/aji (Saaty, R. W. 1987). In general, the hierarchical structure of a problem falls from a focus (an overarching aim or goal) down to criteria, down to sub-criteria, and lastly to the alternatives from which the choice must be made (Saaty, T. L. 1987). There is no limit concerning how many elements one should include in a hierarchy. Still, it should be small and agile enough to respond to changes and comprehensive enough to describe the situation according to a general guideline (experts, previous works, available data, etc.). The AHP is based on three significant steps that start with 0. Hierarchical structure development defining (Focus, Criteria, and sub-criteria or Alternatives). The Next step is factor weight computation, which is done based on a pairwise comparison matrix, eigenvalue, and eigenvector (priority vector), consistency index, and consistency ratio calculation. Based on the previous step, each factor (Flood, sand encroachment, sea-level rise, and Earthquake) has set weight, and each weight gives a value to the factor where the high value considered high risk. The result and decision show up after determining the weights for all factors. (Saaty, R. W. 1987). (Table 5) demonstrates the average weight of the hazards found through the experts' questionnaires.

Table 5: Weights for natural hazards

Flood									Sand encroachment							
9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9
Flood									Sea-level rise							
9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9
Flood									Earthquake							
9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Calculation steps for our case study:

Construction of hierarchy structure: In this step, we created a hierarchical structure, or network, based on our future calculation. Based on GIS processing and results, it was evident that our case study depends on four primary criteria: rainfall, earthquakes, sand encroachment, and sea-level rise.

Pairwise comparison and factor weight calculation:

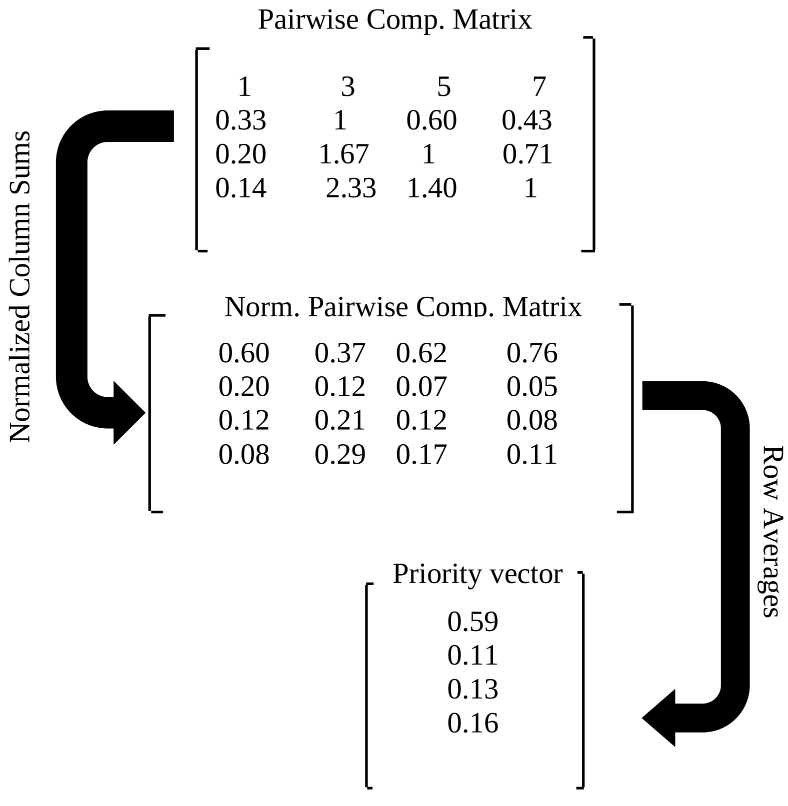
We created a pairwise comparison matrix based on the hierarchical structure in that step. The pairwise comparison gave all the criteria and compared each couple based on the Saaty comparison (Table 6), which shows the scale of relative importance, each value's meaning, and the expert's opinions. Factor weight calculation was made based on the resulting simplified pairwise comparison table. A matrix based on comparison values was completed. These considered properties were ranked based on matrix normalization based on the mathematical calculation detailed (Table 7).

Table 6: Fundamental Scale in AHP

The intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities equally to the objective
3	Moderate importance of one over other	Experience and judgment strongly favor one activity over another.
5	Essential or strong importance	Experience and judgment strongly favor one activity over another.
7	Extreme importance	Activity is strongly favored, and its dominance is demonstrated in practice.
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise needed

Table 7: Pairwise comparison

	Flood	**Sand encroachment**	**Sea-level rise**	**Earthquake**
Flood	1	3	5	7
Sand encroachment	1/3	1	3/5	3/7
Sea-level	1/5	5/3	1	5/7
Earthquake	1/7	7/3	7/5	1



Upon calculating the pairwise comparison, each criterion factor is assigned a weight, and each weight is considered its important. High values give more importance.

After the weight calculation, the next step is to compute (CR), ʎ, and (CI).

Consider (ʎx =Ax), where the Eigenvector is x and ʎ is the consistency vector.

$$\underbrace{\begin{bmatrix} 1 & 3 & 5 & 7 \\ 0.33 & 1 & 0.60 & 0.43 \\ 0.20 & 1.67 & 1 & 0.71 \\ 0.14 & 2.33 & 1.40 & 1 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} 0.59 \\ 0.11 \\ 0.13 \\ 0.16 \end{bmatrix}}_{X} = \underbrace{\begin{bmatrix} 2.69 \\ 0.45 \\ 0.54 \\ 0.68 \end{bmatrix}}_{AX}$$

$$= \lambda \underbrace{\begin{bmatrix} 0.59 \\ 0.11 \\ 0.13 \\ 0.16 \end{bmatrix}}_{X}$$

$$\text{Consistency Vector} = \begin{bmatrix} 2.69/0.59 \\ 0.45/0.11 \\ 0.54/0.13 \\ 0.68/0.16 \end{bmatrix} = \begin{bmatrix} 4.56 \\ 4.09 \\ 4.15 \\ 4.25 \end{bmatrix}$$

$\lambda = (4.56 + 4.09 + 4.15 + 4.25)/4 = 4.26$

------> $\lambda = 4.26$

Consistency Index (CI) is found by

$CI = (\lambda - n)/(n - 1) = (4.26 - 4)/(4 - 1) = 0.09$

------> CI = 0.09

Verification (Consistency Ratio)

$CR = CI/RI = 0.09/0.90 = 0.1 \leq 0.1$

Where RI is Random Index (RI) (Table 8) (Saaty, 1980).

Table 8: Tabulated by size of matrix (n):

n	*RI*
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.51

Chapter 4: Result, Discussion, and Recommendation

This chapter addresses analysis related to the UAE heritage sites, the accuracy of image classification, generation of hazard maps (earthquake, flood, sea-level rise, sand encroachment), assessment of the proximity of heritage sites to the hazard zones, and AHP results.

4.1 Results

As a basis for determining the impacts of different natural threats on the cultural heritage sites in the UAE, it is necessary to identify heritage sites within the UAE, their geographical distribution, and the type (characteristics) of each site. The nature of the natural hazard (speed and duration) should also be considered (Ravankhah et al., 2019). While genuine risk can occur suddenly and on a large magnitude, such as (seismic activities, floods, tsunamis, etc.) others occur with a slower onset (sand encroachment), or with a smaller scope (building material stress). A catastrophe such as an earthquake or flooding will have various effects on existing heritage structures (castles, forts, tombs) and the underground archaeological sites (human activity in the settlements and the ancient civilizations). As part of developing a sustainability plan (conservation strategy), it is essential to know how common and severe natural hazards are and the materials that heritage sites are composed of. An oasis is a typical example of a "heritage site" that offers food products such as dates and fruit, building materials (timber), and water supply. It also provides a habitat for birds and reduces carbon dioxide (a city's lungs). Floods are one of the natural hazards that affect an oasis. It could be possible to develop a strategy to save/conserve the oasis by knowing the frequency and magnitude of the floods. Similarly, it is also possible to cultivate vegetation around the heritage sites to protect against or mitigate sand encroachment under sustainability management. Multiple sources were used to gather data on 84 cultural heritage sites in the UAE. A map (Figure 3) depicts the distribution of heritage sites in the UAE. Several Al Ain's cultural sites have been listed on the World Heritage List (Hafit, Hili, Bidaa Bint Saud, and Oasis). The UNESCO World Heritage Center has nominated thirteen more sites (UNESCO World Heritage). Other nominations are in the pipeline. Forts and archaeological sites make up most heritage sites in the UAE (Tables 8 and 9). Ed-Dur's archaeological site, located in Umm Al Quwain near the Arabian Gulf (first century BC), Demonstrates how earlier civilizations were closely related to the aquatic environment (food, transportation, and trading). At this site, some temples serve as places of worship, "the Sun God," dating back to the first century AD (UNESCO World Heritage, 2012). In terms of geography, most of the heritage sites in the ages of Bronze and Iron were distributed in the north-eastern and south-eastern parts of the UAE. A significant factor could be the proximity to maritime activities (food, transportation, and trading) and access to fresh water (agriculture, irrigation system known as Falaj) (Cultural Resources - Abu Dhabi culture, n.d.). The distribution of sites also shows a similar pattern during the Islamic period, with a more significant number near the desert of Western Abu Dhabi. During the Islamic period, fortresses and mosques were predominant (The National Atlas of the United Arab Emirates, 1993).

Table 9: Heritage sites based on the type

Site Type	Number of sites	%
Ancient Rocks	1	1.2
Archaeological	23	27.4
Fort	41	48.8
Historic Wall	1	1.2
Mosque	1	1.2
Oases	1	1.2
Tombs	9	10.7
Tower	6	7.1
Water Structures	1	1.2
Total	84	100

Table 10: Heritage sites based on age

Age	Number of sites	%
Ancient	1	1.2
Bronze	16	19
Iron	10	11.9
Iron and Bronze	1	1.2
Islamic	53	63.1
Mixed	1	1.2
Roman	1	1.2
Nontelic and Bronze	1	1.2
Total	84	100

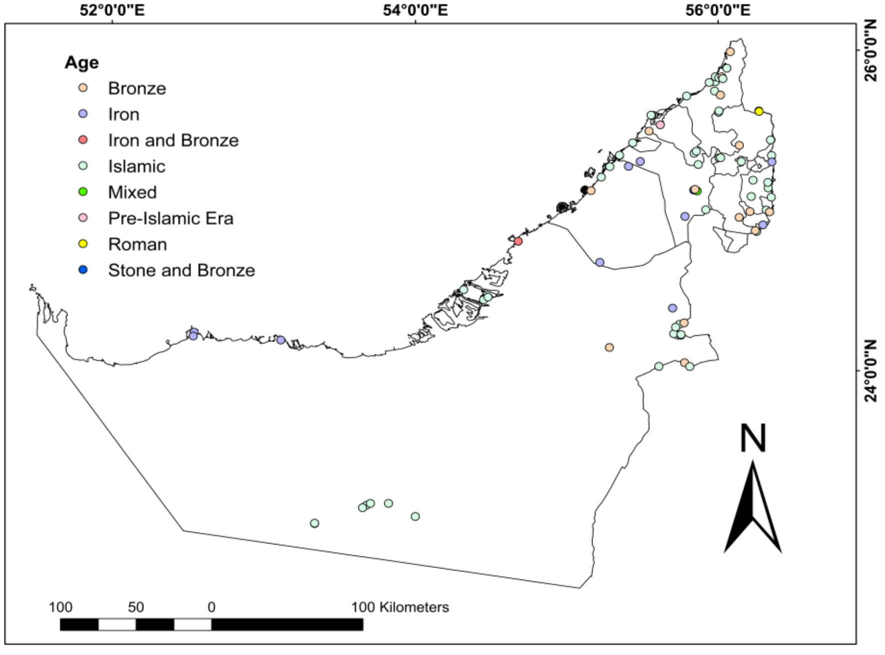


Figure 3: Spatial distribution of heritage sites based on age

4.1.1 Land Cover Map

Classification accuracy:

A confusion matrix was applied to assess the LULC map accuracy. It presents an overview of the LULC thematic map accuracy (Foody, 2002). The classification accuracy obtained is 95%, with kappa statistics of 0.95 (Table 10). The accuracy is within the range specified by Foody (2002). According to the LULC Map, deserts occupy 60% of the UAE territory. Several desert areas have been transformed into agricultural and recreational areas, built-up areas, and roads (Hussein et al., 2020). Most urban areas of the country are concentrated on the coastline of the Arabian Gulf, from Abu Dhabi to the northern part of Ras Al Khaimah. In contrast, there is a strong presence of sabkha in the western region of Abu Dhabi's coast. Water bodies within the inland area, such as reservoirs, and ponds, are included in the "water" class. There are 83,600 square kilometers of UAE land and water combined, and this study only consists of the land area. Based on information gathered from this study, the UAE land area measured here is 70603 km^2, while the World Bank was reported 71,020 km^2 in 2020 (https://www.worldbank.org/). The slight difference (around 1%) is due to factors such as shoreline changes, georeferencing, and misclassifications. The thematic map (Figure 4) illustrates the distribution of the LULC areas in the UAE.

Table 11: Confusion matrix

Class	Urban	Sabkha	Mountain	Desert	Water Body	Barren land	Vegetation	Total User	User's accuracy
Urban	216	2	2	1	1	0	6	228	0.947
Sabkha	11	153	0	1	0	1	0	166	0.922
Mountain	2	1	73	0	0	0	0	76	0.961
Desert	0	0	0	111	0	3	0	114	0.974
Water Body	4	0	2	0	110	0	0	116	0.948
Barren land	0	3	0	3	0	173	0	179	0.966
Vegetation	4	1	1	3	0	0	278	287	0.969
Total Producer	237	160	78	119	111	177	284	1166	0
Producer's accuracy	0.911	0.956	0.936	0.933	0.991	0.977	0.979	0	**0.955**
Kappa= 0.95									

The overall classification accuracy is given in Bold.

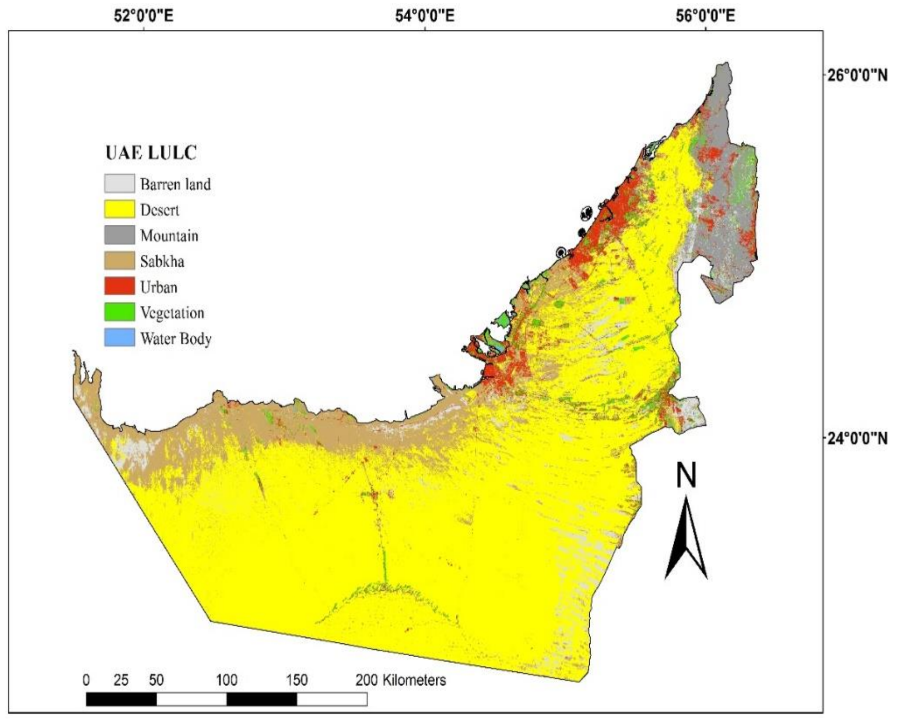


Figure 4: The UAE (LULC) map

4.1.2 Earthquake

The north-eastern region of UAE has a higher density of earthquakes and heritage sites than the southern part. The UAE's north-eastern region has the most seismically active role (Abdalla and Al-Homoud, 2004; Yagoub, 2015). Geographically, the region's location near the Arabian Plate's eastern edge, exposure to the earthquake-prone fault zone on the Eurasian plate, and the structure of its rock beneath the surface makes it susceptible to earthquakes. (Al Ruwaithi, 2019; Barakat et al., 2008; Dhanhani, 2010). According to available data, earthquakes in UAE mostly have a medium magnitude and are primarily located in north-eastern region. Several hot spots occur near the Oman Thrust and Dibba fault. The intensity of seismic waves decreases with distance away from faults (Cooke, 1997; Sarris et al., 2010). Generally, The UAE has one of the lowest earthquake activity rates worldwide (Barakat et al., 2008). In March 2002, an earthquake of 5.1 struck Masafi city in Fujairah Emirate, conceded as the highest event in UAE (Figure 5). With an average magnitude of (2.2 MW), earthquakes occurred fourteen times more frequently in 2010 than in any other year (Figure 6). The Inverse Distance Weighted (IDW) process is applied to earthquake data. A map has been created showing the impact of earthquake hazard zones based on the magnitude. The hazard map has been used to assess the risks associated with heritage sites where the map consists of 5 classes of earthquake magnitude (very high, high, medium, low, and very low). The regions with dark red color represent a very high vulnerability to the earthquake hazard (Figure 7). As mentioned previously, most of the heritage sites situated in the north-eastern part of the country are highly vulnerable to earthquakes due to active seismic activity in the region. Similarly, a thematic map showed the kernel density regardless of earthquake magnitude within the past decade, with heritage sites plotted on it (Figure 8). Despite earthquakes' infrequent occurrence and mild magnitude, this still threatens historic properties, particularly the aging and weak buildings. The term "weak structures" pertains to historic buildings like "forts, mosques, castles… " subject to cracking and material properties changes that might lead to the collapse of the buildings by ground movements including earthquakes, soil subsidence often caused by the removal of water, oil, natural gas, or mineral resources out of the ground by pumping, fracking, or mining activities or any other shaking like stone crushers in the mountains. Besides earthquakes, other natural hazards that affect the north-eastern UAE include tsunamis and floods (Alsenaani, 2013). Thus, the north-eastern part of the UAE is likely to be a high-risk area for natural hazards. Existing buildings, such as historic buildings must be retrofitted to resist earthquakes and other natural hazards.

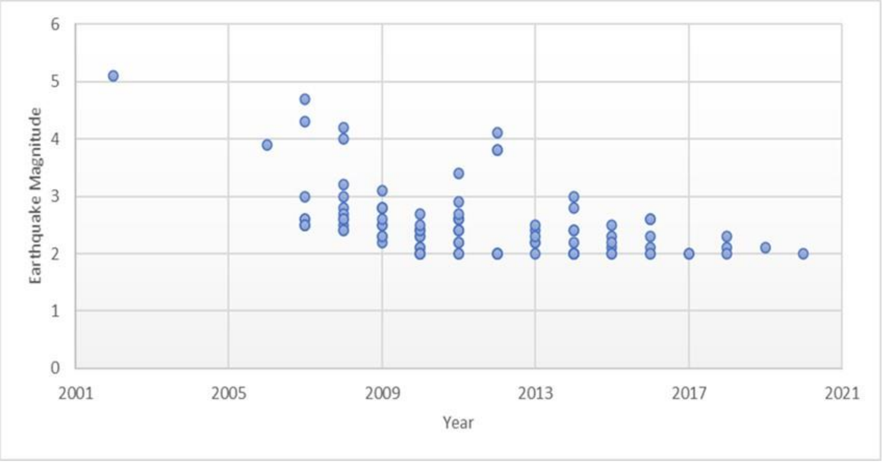


Figure 5: Earthquake magnitude in the UAE from 2002 to 2020

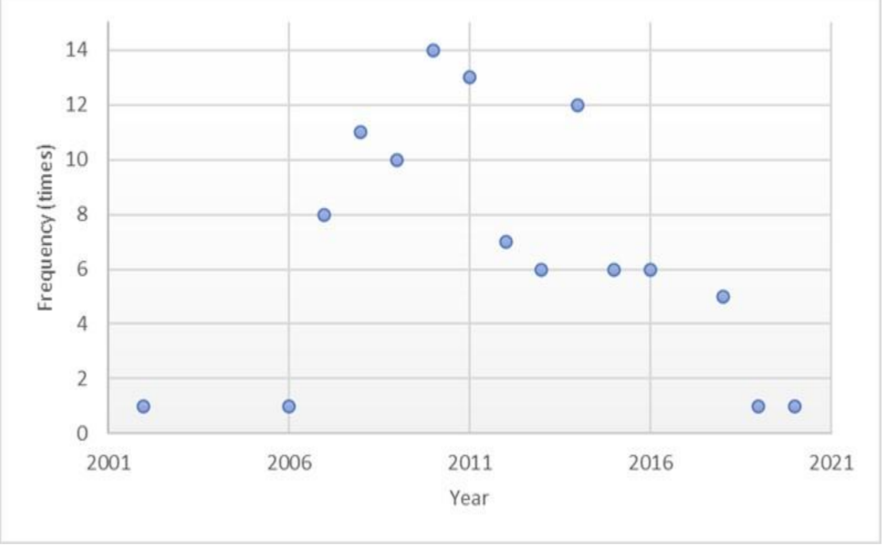


Figure 6: Earthquake frequency in the UAE from 2002 to 2020

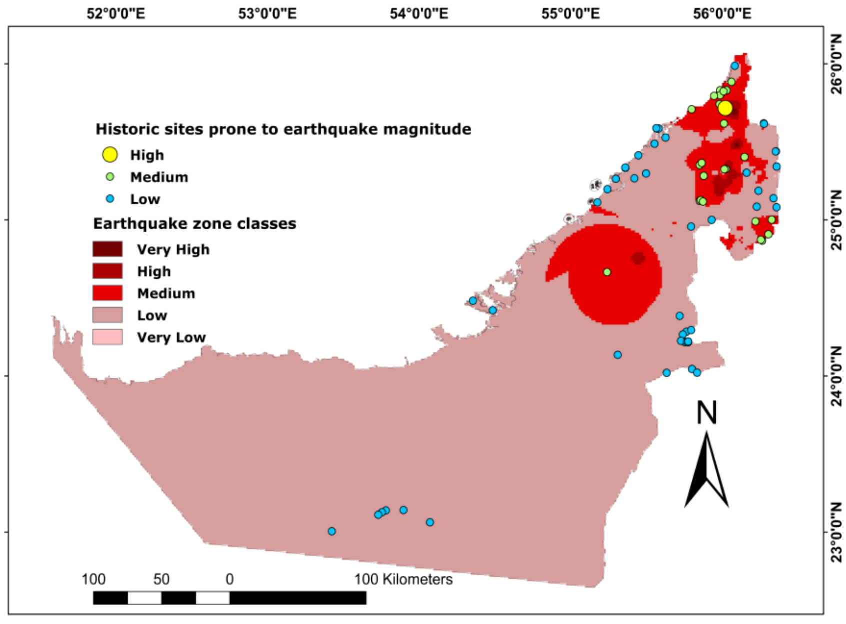


Figure 7: Heritage site within the earthquake magnitude

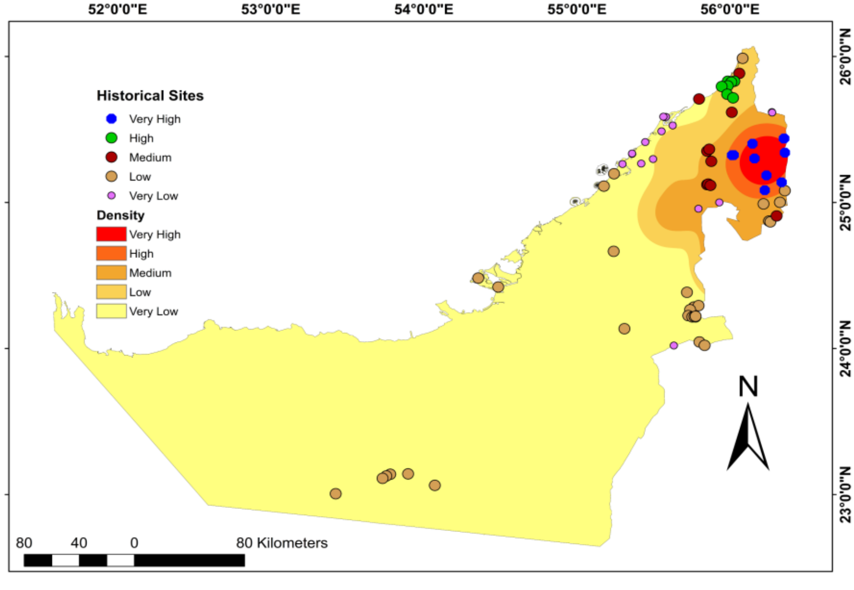


Figure 8: Heritage sites within earthquake density

4.1.3 Flood

Flooding can devastate heritage structures, infrastructure, cultural landscapes, and wildlife in many instances. A typical natural hazard in the UAE is rain-induced flooding. The country has experienced a number of such hazards in the recent past. Several buildings, structures, and properties were seriously damaged during these floods (Yagoub et al., 2020). According to the flood hazard map, the north-eastern part of the country is more prone to flooding due to high rainfall, low elevation, and the nature of the terrain (Figure 9). Analyses show that flooding poses a threat to 34 heritage sites in the UAE. The possibility of flash floods occurring in correlation with heavy rainstorms will negatively affect heritage sites. There is also the possibility of flooding caused by tsunamis. For instance, a large earthquake with a magnitude of (8.1) struck Makran in 1945 (Berninghausen, 1966), as well as the Indonesian earthquake in 2004 that impacted the coast in north-eastern UAE (Jordan, 2008), resulting in a wave height of 3 to 30 cm. The generated flood hazard map shows that the areas with high flood vulnerability are mainly located on the coastline. There are several explanations for this, including the low level of the coastal regions compared to other areas and the high levels of annual rainfall. The areas under the foot of the mountain are prone to the threat of flooding, and this is due to the flow of rainwater from the top of the mountains towards the bottom where the heritage sites are located. Despite the same rainfall rate, a moderate flood risk exists in these areas due to their high altitude compared to the first region. The third region, with a high altitude and low rainfall, is less vulnerable to flood. In order to classify them, the heritage sites were plotted on the flood vulnerability map (Figure 9). A list of Heritage sites that are in flood-prone areas has been extracted from the flood hazard map (Table 11). A common area between earthquake and flood hazard maps was found. Such a common area was not observed in other hazard factors like a desert and sea-level rise.

Consequently, a composite map combining earthquakes and floods was created utilizing the overlay method with equal weights given for both hazards. The composite hazard map for earthquakes and floods showed that heritage sites in the north-eastern region of the UAE are more vulnerable to both risks.

Table 12: Heritage sites within flood and earthquake zones

Site Name	Emirates	UNESCO	Earthquake (MW)	Rainfall (mm)
Al-Bidyah Mosque	Fujairah	Tentative	2.4	10.0
Dhayah Fort	Ras Al Khaimah	Tentative	2.6	9.0
Ras al-Khaimah Fort	Ras Al Khaimah	Tentative	3.1	9.8
Shamal Tombs	Ras Al Khaimah	Tentative	3.0	9.1
Kush Archaeological Site	Ras Al Khaimah	Tentative	3.0	9.2
Al Nudood & Al Mataf Archaeological sites	Ras Al Khaimah	Tentative	3.1	9.4

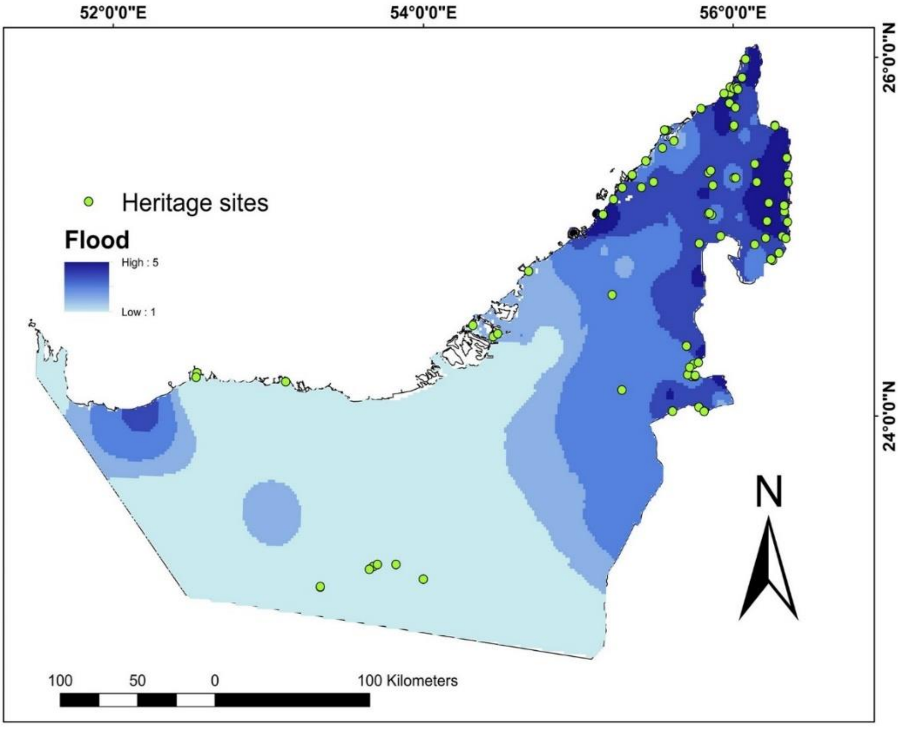


Figure 9: Flood map and heritage sites

4.1.4 Sea-Level Rise

A coastal vulnerability study found that existing shorelines are expected to move substantially inland due to sea-level rise, extensively inundating coastal areas (UAE UNFCCC, 2010). For the UAE, five scenarios have been worked out and presented. In Each scenario, the Area of land (in km^2) that the seawater would inundate had been calculated. Under a scenario of an increase of one meter in sea level, approximately 864 square kilometers of coastline will be flooded, with 15 historical sites affected. As for the second scenario, two meters of sea rise will inundate 1358 square kilometers of land and cause damage to 17 archaeological sites across the country. The third scenario assumes that if the sea level rises to three meters, 1804 square kilometers of land will be submerged. In this case, 20 archaeological sites will also be affected. According to the fourth scenario, a sea-level rise of four meters will result in a 2368 km^2 area covered by water, affecting 22 archaeological sites. Under the latter scenario, the sea level would rise by 5 meters, submerging approximately 3,422 square kilometers of land, which would lead to the destruction of 26 archaeological sites. Global warming is one of the main factors behind sea level rises, melting of ice masses, and thermal expansion of oceans caused by absorption of solar radiation. The UAE's coastline stretches along the Arabian Gulf for 644 km and along the Gulf of Oman for 90 km. The major cities of the UAE are situated along the coast. Consequently, any sea-level rise in the country will negatively impact about 85% of the population, significant ecological subsystems, and several important sites will be affected (El-Askary et al., 1970). If glacier melting is not considered, Climate change-induced sea-level rise could range from 0.37 to 0.59 meters by 2100 (IPCC, 2007). In the 21st century, experts estimate there is a 5% chance for the sea level to exceed 2 meters (Bamber et al., 2019; Kulp & Strauss, 2019). Rising sea levels can cause the UAE to lose around 6% of its coastline this century (Mfarrej, 2019). Thus, the movement of the shoreline in UAE towards the south is around 25 to 30 km, and flooding areas range from 1,155 km^2 to approximately 5,000 km^2 (El-askary et al., 1970). The study reveals that twenty-six heritage sites are at risk of flooding due to sea-level rise (Figure 10), some of which are listed on the UNESCO World Heritage tentative Lists (Table 12). The number of heritage sites, as well as the area covered by seawater, were calculated for each scenario (Table 13). Most of the sites within the risk area are below 5 m above sea level and within 800 m of the shoreline. However, Although the possibility of the Arabian Gulf region being exposed to the risk of rising sea levels is very low (Alsenaani, 2013), the heritage sites must be protected, particularly in the northern part of the Arabian Gulf near the Indian Ocean. It is essential to implement prevention measures and effective planning in order to mitigate the effects of such hazards. A combination of rigid structure and flexible actions can be taken to reduce the impact of the risk. Among the complex systems are barriers on the coast and floodwalls, setting up a sea-level rise monitoring system, better protecting the land from the sea by planting vegetation (mangroves) and constructing dunes to insulate land against the sea, developing wetlands and marshlands as buffers against sea-level rise, as well as creating barrier islands (Waqas et al., 2019). Additionally, establish and implement flood regulations and promote public knowledge and awareness about the risk of sea-level rise. The Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (IPCC 4) (IPCC, 2007) provides a sea-level rise projection suitable for use as a benchmark for assessing sea-level rise at the regional and local levels, as well as its influence on facilities like oil fields, ports, and hotels.

Table 13: List of heritage sites within sea-level rise hazard

Site Name	**Emirate**	**UNESCO**	**Elevation (Meter)**	**Sea Level Scale**
Al Nudood & Al Mataf	Ras Al Khaimah	Tentative	0	Very High
Al Jazirah Al Hamra	Ras Al Khaimah	Tentative	2	High
Ras al-Khaimah Fort	Ras Al Khaimah	Tentative	3	High
Ed-Dur Archaeological site	Umm Al Quwain	Tentative	5	Medium
Umm Al Nar	Abu Dhabi	Tentative	5	Medium

Table 14: Historic sites and inundated regions in each scenario

	1m	2m	3m	4m	5m
Historic Site	15	17	20	22	26
Area km^2	864.06	1358	1804	2368	3422

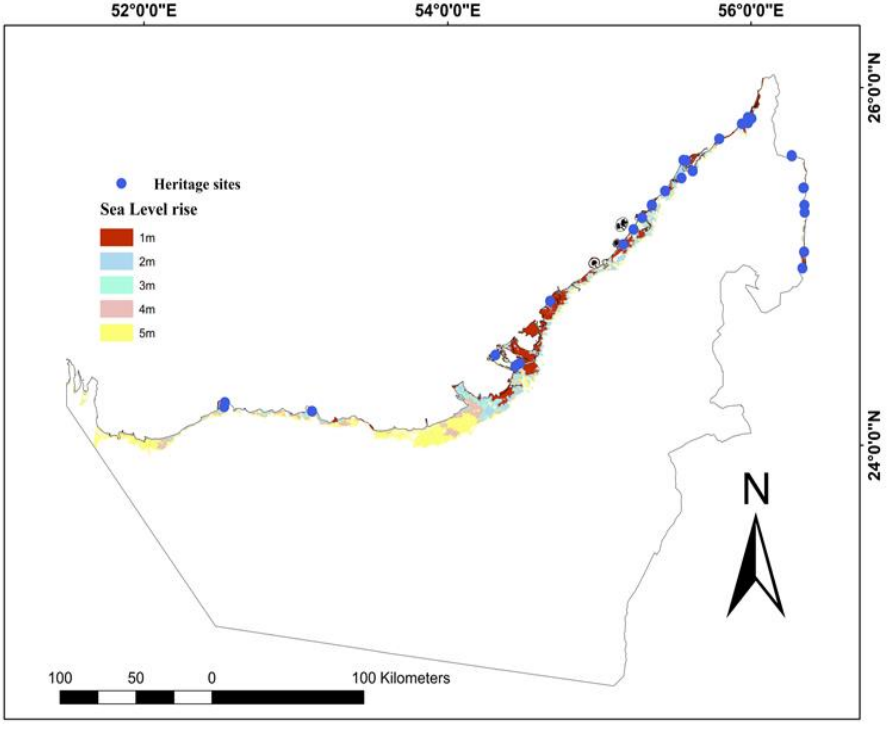


Figure 10: Inundated regions within the sea-level rise.

4.1.5 Sand Encroachment

The result shows that 15 heritage sites have been identified as being threatened by sand encroachment (Table 14). The heritage sites were identified from a sand encroachment map (Figure 11). Forts make up most of the features, followed by archaeological sites, one tomb, and one water system. Most of these features are not frequently affected by floods, earthquakes, or rainfall. It is possible in some cases to find valleys in the desert that rapidly dry up after the rain stops (Alsenaani, 2013). UAE winds average around five m/s (excluding gusts) (Yagoub, 2010). Typically, in the UAE, the wind is most robust in March and August. It usually blows from the northwest, south, and southeast due to various factors, including aridity, low precipitation rates, sandstorms, loose sand, and the wind crossing the Empty Quarter desert zone. It is possible for heritage sites to be buried, particularly those at low elevations. The sands that moved from other places can create dunes up to 150 meters high, such as the Empty Quarter in the western region of Abu Dhabi, where most heritage sites are located, like Al-Maria Al Gharbiyah Tower, Umm Hosn Fort, and others. Sand encroachment can be mitigated by increasing tree cover, cultivating the soil, and reducing soil erosion with adequate land and water management. It is necessary to mitigate sand encroachment to preserve the UNESCO archaeological site Bidaa Bint Saud in Al Ain. As a result of the geospatial analysis, flood hazards threaten heritage sites most over the UAE. Next are earthquakes in the northern and north-eastern parts of the country. Sea-level rise occurs along the coastline, especially the east coast, and the sand encroachment on the western region of Abu Dhabi. Global warming could also accelerate the increase in sea levels. Flooding effects are extensive, including landslides and the destruction of building structures.

Table 15: Heritage sites within the sand encroachment hazard

Site Name	Emirate	Site History
Bidaa Bint Saud Archaeological site	Abu Dhabi	1st Millennium BC
Al Anka Fort	Abu Dhabi	19th Century AD
Seja Fort	Abu Dhabi	19th Century AD
Al Jabbana Fort	Abu Dhabi	19th Century AD
Mezair'ah Fort	Abu Dhabi	19th Century AD
Dhafeer Fort	Abu Dhabi	19th Century AD
Qutuf Fort	Abu Dhabi	19th Century AD
Almeel Fort	Abu Dhabi	19th Century AD
Al Maria Al Gharbiyah Tower	Abu Dhabi	19th Century AD
Sarouq Al Hadeed Archaeological site	Dubai	3rd Millennium BC
Jebel Faya Archaeological site	Sharjah	Paleolithic Age
Mleiha Tombs	Sharjah	3rd Millennium BC
Mleiha Archaeological site	Sharjah	3rd Millennium BC
The Sharea of Falaj Almu'alla	Umm Al Quwain	19th Century AD
Ed-Dur Archaeological site	Umm Al Quwain	3rd Millennium BC

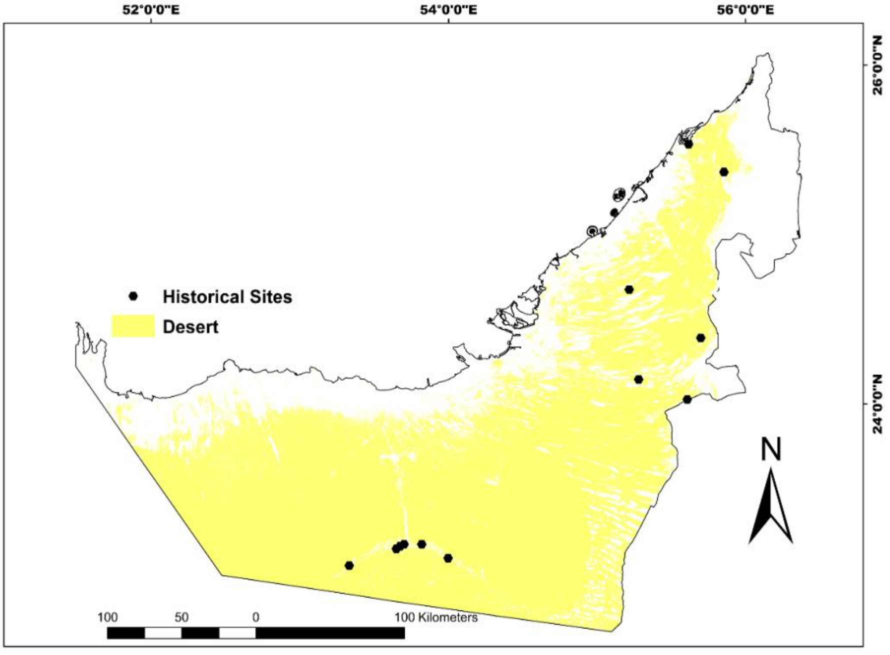


Figure 11: Heritage sites exposed to the sand encroachment

Table 15 summarizes the number of heritages sites in each natural hazard zone. Eighty-four heritage sites were added to the different factors (earthquake magnitude/density, rainfall, flood, sea-level rise, and sand encroachment). Some places were assigned in more than one factor due to their geographical location, as some areas may be exposed to more than one natural hazard. A total of 67 heritage sites in the UAE are situated in areas considered prone to high natural hazards. Ten sites in the earthquakes zone, 21 sites within high rain density and low altitude, 17 under the risk of flood, 17 in the desert, 10 on the coastline exposed to the risk of sea-level rise. Rainfall poses the most significant threat to historical sites, followed closely by floods, with seventeen sites at high risk. Sea level rise of up to 1 m poses the least risk to historical sites in the UAE. The sea-level rise could also threaten many historical sites if global warming continues, and the sea rises above 1 m. In such a situation, the economic harm to the UAE's coastal zones will be high (El-Askary et al., 1970). In addition, the desert can also have a significant impact on historical sites. The sand encroachment process can damage heritage sites by burying them through continuous sand encroachment. In Timbuktu, for example, the Sankoré mosque has been entirely buried due to constant sand encroachment (Gruber, 2008).

Table 16: Heritage sites in natural hazard zones in the UAE

Categories	Earthquake Density		Earthquake Magnitude		Rainfall		Flood vulnerable		Desert		Sea level rise		Total Score Index
	No	(%)	No	(%)	No	(%)	No	(%)	No	(%)	No	(%)	
Very high	10	14	0	0	21	30	17	24	12	17	7	10	67
High	7	10	1	1	19	27	3	4			13	18	43
Medium	10	14	24	34	15	21					6	8	55
Low	28	39	46	65	7	10	15	21			4	6	100
Very Low	16	23			9	13					41	58	66
Total	71	100	71	100	71	100	71	100	12	17	71	100	

4.1.6 AHP

The Pairwise Comparison shows experts' viewpoints regarding the used criteria and a sample of pairwise comparisons used to make the final decision matrix. For most of the comparisons, the group is homogenous. The calculated Consistency Ratio (CR) is ≤ 0.1. This is appropriate since it corresponds to 10% (Papaioannou et al., 2015; Saaty, 1990). The CR value sufficiently confirms the reliability and accuracy of the assessment results. All criteria were weighted and compared to those with the highest influence (flooding). The other hazards were compared one by one to the flooding. The resulting weights for the factors indicated that flooding had the highest importance with a value of 0.59, close to the weight criteria value found in the AHP method by Cabrera and Lee (2020). Sand encroachment was the second most important criterion, with a value of 0.16. Sea-level was the third criterion with a value of 0.13, as this criterion occurs and develops over a long period, making it less of a priority at present. Finally, earthquakes were the least important criterion with a weight of 0.11 because there has been no known seismic activity in the last decade in Abu Dhabi (Table 16).

Table 17: Weights and importance of each criterion

Criteria	**Weights**	**Importance**
Flood	0.59	First important criterion
Sand encroachment	0.16	The second most crucial criterion
Sea-level	0.13	The third important criterion
Earthquakes	0.11	The least important criterion

According to AHP analysis, flood is the highest natural hazard in the Abu Dhabi Emirate (Figure 12). The criteria used were similar to those shown in the flood hazard map.

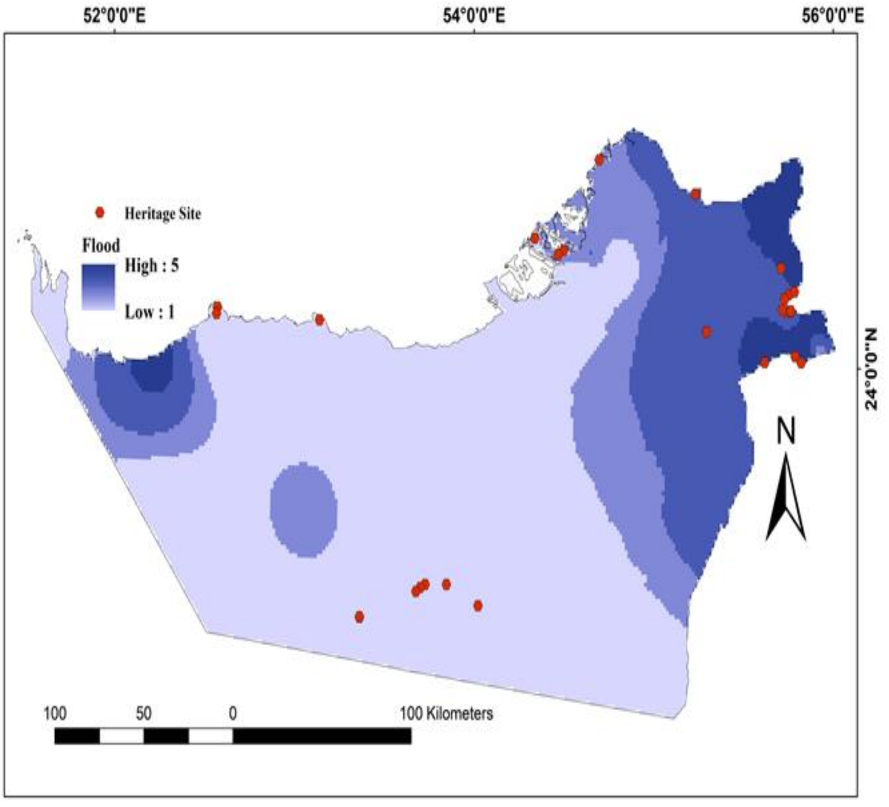


Figure 12: Abu Dhabi heritage sites within the flood area

Analytical Hierarchy Process (AHP) was made based on four criteria: rainfall, sand encroachment, sea-level rise, and earthquakes. Flood was found to be the most prevalent hazard that threatens the heritage sites in Abu Dhabi. Therefore, it is necessary to save and protect these heritage sites from floods, specifically the heritage sites in Abu Dhabi. As expected, the expert opinion was justified when calculations and tables were drawn up.

The results confirmed the expert's opinion that flooding would be the first essential criterion on our list. The second hazard after the flood was sand encroachment. However, the gap between flooding and the other three criteria was based on the expert's opinion. Experts believe that sand encroachment is not a hazardous problem unlike flooding. They think that the advantages outweigh the disadvantages. Although sand encroachment is one of the natural hazards threatening heritage sites, but experts (archaeologists) believe that sand encroachment protects heritage sites from other factors such as extreme weather conditions, theft, etc. But as stated above, when considering the advantages and disadvantages of sand encroachment, the experts believe that the benefits outweigh the disadvantages. The experts gave less weight to sea-level rise because the Arabian Gulf is a closed sea, and the probability of sea rise is low. Therefore, it is not a hazard of immediate importance but rather a risk that will hold significance in the future. According to the history of the area and the location, earthquakes are not expected as there is no historical record of an earthquake event occurring in Abu Dhabi. Therefore, the experts confidently assess that this hazard has little to no importance.

4.1.7 The UAE's UNESCO World Heritage and Tentative Sites

UNESCO world heritage sites and the Tentative Sites in UAE plotted on the high-risk natural hazards map. It was intended to bring attention to those critical sites so that precautionary measures can be taken. World Heritage sites are considered landmarks nominated by the World Heritage Committee at UNESCO to be included in the International Heritage Sites Program managed by UNESCO. World Heritage Sites are of great interest under the auspices of the international organization, so they contribute to their preservation. Table 17 shows the spatial distribution and names of UNESCO World Heritage sites in UAE within various natural hazard zones. Most of the sites are clustered in the northern and north-eastern regions of the UAE. In addition, some fall within more than one risk region. The hazards are Sea level rise (SL), Flood (FD), Earthquake (EQ), Rainfall (RF), and Desert (DS). Fifteen heritage sites are on the UNESCO World Heritage List in the UAE, out of which eleven fall within various natural hazard areas. The UNESCO Tentative Sites include Al-Bidyah mosque, as well as the archeological site of Al Nudood and Al Mataf, which are affected by three natural hazards: SL, FD & RF, and FL, EQ and RF, respectively, making them the most vulnerable sites to natural hazards. Other sites are affected by two risks, namely Al Jazirah Al Hamra (Al Zaab island) (SL and DS), the archaeological site of Kush (FL and FR), and Shamal Tombs (FL and RF). While four sites have one hazard each, four are unaffected by any risks. The Al-Bidyah Mosque seems the most vulnerable site because it also has earthquake hazards and flood and rainfall risks. See (Table 18) for a breakdown of the distribution of natural hazards among heritage sites.

Table 18: UNESCO world heritage sites in various natural hazards

Historical site	Emirate	Category	Hazard
Bidaa Bint Saud Archaeological site	Abu Dhabi	Historic Site	DS
Hafit Archaeological site	Abu Dhabi	Historic Cities	FD
Hili Archaeological site	Abu Dhabi	Historic Cities	FD, DS
Al Ain Oases	Abu Dhabi	Historic Cities	RF
Al-Bidyah Mosque	Fujairah	Mosque	FD, EQ, RF
Al Jazirah Al Hamra	Ras Al-Khaimah	Historic Site	SL, DS
Al Nudood & Al Mataf	Ras Al-Khaimah	Historic Site	SL, FD, RF
Archaeological Site of Kush	Ras Al-Khaimah	Historic Site	FD, RF
Dhayah Fort	Ras Al-Khaimah	Fort	RF
Ras al-Khaimah Fort	Ras Al-Khaimah	Fort	RF
Shamal Tombs	Ras Al-Khaimah	Tombs	FD, RF
Jebel Faya Archaeological site	Sharjah	Historic Site	DS
Mleiha Tombs	Sharjah	Tombs	DS
Mleiha Archaeological site	Sharjah	Historic Cities	FD, DS
Ed-Dur Archaeological site	Umm AL Quwain	Historic Site	DS

SL =Sea level rise, FD=Flood, EQ=Earthquake, RF=Rainfall, Desert=DS

4.2 Conclusion

GIS-based spatial analysis has been used to assess the effects of natural hazards on heritage sites. This study aims to provide spatial data that can be used to develop a policy to mitigate the impact of natural hazards on heritage sites in the UAE. Several sources are used to compile information on heritage sites across the UAE, including UNESCO sites. The sites are primarily found in the north part of the UAE. The study was undertaken to identify the different characteristics of heritage sites, their geographical location, and (Spatio-temporal). A remote sensing system effectively generates maps of the LULC on a vast land area. The (LULC) map is used to assess heritage sites. Results indicate that floods and earthquakes are the two most significant hazards, whereas desert is the primary threat in the central and western parts of the country. The length and speed of the natural hazards could cause harm to heritage sites and the north-eastern UAE communities. The conservation of heritage sites must consider all potential threats. A GIS application in this study is essential in identifying and assessing the multi-hazard impacts on heritage sites (holistic view). The techniques used in this case can be applied in many other countries worldwide. This study can determine preservation priorities and develop natural hazard mitigation strategies for heritage sites. The accuracy of the results depends on the quality and availability of the data. High-resolution satellite imagery and DEM data can play a fundamental role in the quality of the result. The integration of data on wave heights, tide timelines, geomorphological characteristics, and coastal erosion processes will help predict sea behavior in the future. The hierarchy process (AHP) finds that flooding poses the most significant threat to heritage sites in Abu Dhabi, followed by sand encroachment, sea-level rise, and earthquakes. Conserving the country’s heritage is vital since it provides character and distinctiveness to a place, region, or community, thus providing a sense of identity. Heritage is one of the sources of attracting external investment and sustaining existing businesses. Intangible and tangible heritage positively influences many aspects of how a community develops. It is vital to protect, conserve, and preserve these resources because:

1. The historic environment benefits local economies through tourism.

2. Heritage attraction can result in external investment and the preservation of existing business operations.
3. Heritage buildings' adaptive reuse plays a crucial role in creating sustainable communities.
4. Heritage protection can promote social inclusion.
5. A heritage site can be an excellent educational resource for everyone.
6. A world heritage site can also assist society in mitigating and adapting to climate change because of the ecosystem service, including water regulation.

4.3 Recommendations

Given the importance of preserving heritage sites that represent the identity of the UAE, a few recommendations have been formulated to mitigate natural hazards for heritage sites, including the creation of a separate hazard map for each heritage site in the UAE. All Sites should be plotted on the map within the different natural hazards, including (humidity, salinity, temperature, erosion factors, wind, acid rain, etc.) regardless of the risk size. Concerned entities must have accurate knowledge regarding the site's features, materials, and area to best protect it. In addition, they can develop an official website that contains a map of all heritage sites in the UAE and provides information on the archaeological sites and their locations. Users can sort Heritage sites by the emirate, type (fort, archaeological site, tower, castle, etc.), age (iron, bronze, Islamic, neolithic civilization), etc.

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List of Publications

Yagoub, M.M. and Abdulla Amed Al Yammahi, 2022. Spatial distribution of natural hazards and their proximity to heritage sites: Case of the United Arab Emirates. *International Journal of Disaster Risk Reduction. 71* (2022),102827,ISSN 2212 4209, https://doi.org/10.1016/j.ijdrr.2022.102827 . https://www.sciencedirect.com/science/article/pii/S2212420922000462.

Appendix A

Sources of information on heritage sites in the UAE

Source	No	Source
National Registry of Archaeological Sites	20	http://nras.gov.ae/en/node/88
World Heritage Convention- WHC- UNESCO	11	https://whc.unesco.org/en/list/1343/
Castles	11	https://www.castles.nl/maria-gharbiyah-fort
Department of Culture and Tourism Abu Dhabi	7	https://abudhabiculture.ae/ar/discover/pre-historic-and-palaeontology/maqta-conservation-area
The National Atlas of the United Arab Emirates (1993)	6	The National Atlas of the United Arab Emirates. (1993). United Arab Emirates University.
Department of Antiquities and Museums Ras Al Khaimah	4	https://rakheritage.rak.ae/en/Pages/Hudaybah-Tower.aspx
National Culture Encyclopedia UAE, Article 1571	4	https://nce.gov.ae/ar/article/1571/
Ras Al Khaimah Municipality	3	https://mun.rak.ae/en/pages/historical-places.aspx
Ruler's Representative Court Al Ain Region	3	https://aard.gov.ae/portal/62D659B4-3249-4324-BECD-E4E8D7322DFA.aspx
Archiqoo	2	https://archiqoo.com/locations/al_talaa_tower.php
Dubai Culture	2	https://dm.gov.ae/about-saruq-al-hadid/
Ministry of Climate changes and environment	2	https://www.moccae.gov.ae/en/open-data/ecotourism/mleiha-archaeological-centre.aspx
UAE Government portal	2	https://u.ae/en/about-the-uae/the-seven-emirates/ajman
Department of Tourism and Archaeology	2	http://tad.uaq.ae/en/about-us/museums/fort-al-ali.html

Government of Ras Al Khaimah	1	https://mun.rak.ae/en/pages/historical-places.aspx
Adventure Quest UAE	1	https://www.adventurequest.ae/
Ras Al Khaimah Government Media Office	1	https://www.rakmediaoffice.ae/en/home/
Rock Art Recording in Khatm Al Melaha (UAE)	1	https://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XLII-2-W15/85/2019/isprs-archives-XLII-2-W15-85-2019.pdf
UAE National Archives	1	https://www.na.ae/en/archives/historicalperiods/civilization.aspx
Total	84	

Appendix B

UAE heritage sites information

No	Heritage Site	Emirate	Site Type	Age	Site History	civilization
1	Qasr al-Hosn (Fort)	Abu Dhabi	Fort	Islamic	18th Century AD	Islamic Monuments
2	Al Maqta'a Tower	Abu Dhabi	Tower	Islamic	18th Century AD	Islamic Monuments
3	Bidaa Bint Saud	Abu Dhabi	Archaeological site	Iron	1st Millennium BC	Iron Age Monuments
4	Al Jahili Fort	Abu Dhabi	Fort	Islamic	19th Century AD	Islamic Monuments
5	Al sharqiya Fort	Abu Dhabi	Fort	Islamic	20th Century AD	Islamic Monuments
6	Al Anka Fort	Abu Dhabi	Fort	Islamic	19th Century AD	Islamic Monuments
7	Muraijeb Fort	Abu Dhabi	Fort	Islamic	19th Century AD	Islamic Monuments
8	Al Rumeilah Fort	Abu Dhabi	Fort	Islamic	19th Century AD	Islamic Monuments
9	Al Muwaiji Fort	Abu Dhabi	Fort	Islamic	20th Century AD	Islamic Monuments
10	Hili	Abu Dhabi	Archaeological site	Bronze	3rd Millennium BC	Bronze Age Monuments
11	Al Ain Oases	Abu Dhabi	Oases	Iron	1st Millennium BC	Iron Age & Islamic
12	Murabba Fort	Abu Dhabi	Fort	Islamic	20th Century AD	Islamic Monuments
13	Mazyad Fort	Abu Dhabi	Fort	Islamic	19th Century AD	Islamic Monuments
14	Seja Fort	Abu Dhabi	Fort	Islamic	19th Century AD	Islamic Monuments
15	Hafit	Abu Dhabi	Archaeological site	Bronze	3rd Millennium BC	Bronze Age Monuments
16	Al Jabbana Fort	Abu Dhabi	Fort	Islamic	19th Century AD	Islamic Monuments
17	Mezair'ah Fort	Abu Dhabi	Fort	Islamic	19th Century AD	Islamic Monuments
18	Dhafeer Fort	Abu Dhabi	Fort	Islamic	19th Century AD	Islamic Monuments
19	Qutuf Fort	Abu Dhabi	Fort	Islamic	19th Century AD	Islamic Monuments
20	Almeel Fort	Abu Dhabi	Fort	Islamic	19th Century AD	Islamic Monuments
21	Al Maria Al Gharbiyah Tower	Abu Dhabi	Tower	Islamic	19th Century AD	Islamic Monuments
22	Umm Al Nar	Abu Dhabi	Tombs	Bronze	3rd Millennium BC	Bronze Age Monuments
23	Umm Hosn Fort	Abu Dhabi	Fort	Islamic	19th Century AD	Islamic Monuments

UAE heritage sites information (Continued)

No	**Heritage Site**	**Emirate**	**Site Type**	**Age**	**Site History**	**civilization**
24	Qarn Al Esh	Abu Dhabi	Archaeological site	Iron	3rd Millennium BC	Iron Age
25	Jabel Az Zannah	Abu Dhabi	Archaeological site	Iron	3rd Millennium BC	Iron Age
26	Qarn Bet Ash Shaar	Abu Dhabi	Archaeological site	Iron	2nd Millennium BC	Iron Age
27	Ghanadah	Abu Dhabi	Archaeological site	Iron & Bronze	2nd &3rd Millennium BC	Iron Age & Bronze Age
28	Ajman Fort	Ajman	Fort	Islamic	18th Century AD	Islamic
29	The Red Fort	Ajman	Fort	Islamic	20th Century AD	Islamic
30	Al Mareer Fort	Ajman	Fort	Islamic	20th Century AD	Islamic
31	Al Fahidi Fort	Dubai	Fort	Islamic	18th Century AD	Islamic
32	Al Qusais	Dubai	Archaeological site	Bronze & Iron	3rd Millennium BC	Bronze & Iron Ages
33	Sarouq Al Hadeed	Dubai	Archaeological site	Iron	3rd Millennium BC	Iron Age
34	Jumeirah	Dubai	Archaeological site	Islamic	9th Century AD	Islamic
35	Al Sufouh	Dubai	Archaeological site	Bronze	3rd Millennium BC	Bronze Age
36	Al-Bidyah Mosque	Fujairah	Mosque	Islamic	15th Century AD	Islamic
37	Masafi Fort	Fujairah	Fort	Islamic	15th Century AD	Islamic
38	Al Bidya Tombs	Fujairah	Tombs	Bronze	2nd Millennium BC	Bronze Age
39	Fujairah Fort	Fujairah	Fort	Islamic	16th Century AD	Islamic

UAE heritage sites information (Continued)

No	Heritage Site	Emirate	Site Type	Age	Site History	civilization
40	Bithnah Fort	Fujairah	Fort	Islamic	18th Century AD	Islamic Monuments
41	Al-Hayl Castle	Fujairah	Fort	Islamic	19th Century AD	Islamic Monuments
42	Awhlah Fort	Fujairah	Fort	Iron and Islamic	8th Millennium BC	Iron Age & Islamic Monuments
43	Habhab Fort	Fujairah	Fort	Islamic	19th Century AD	Islamic Monuments
44	Sakamkam Fort	Fujairah	Fort	Islamic	18th Century AD	Islamic Monuments
45	Qadfa	Fujairah	Tombs	Iron	2nd Millennium BC	Iron Age Monuments
46	Dhayah Fort	Ras Al Khaimah	Fort	Islamic	16th Century AD	Islamic Monuments
47	Al Jazirah Al Hamra	Ras Al Khaimah	Archaeological	Islamic	18th Century AD	Islamic Monuments
48	Al Fulyah Fort	Ras Al Khaimah	Fort	Islamic	18th Century AD	Islamic Monuments
49	Al Hudaibah Fort	Ras Al Khaimah	Fort	Islamic	20th Century AD	Islamic Monuments
50	Ras al-Khaimah Fort	Ras Al Khaimah	Fort	Islamic	19th Century AD	Islamic Monuments
51	Khatt Fort	Ras Al Khaimah	Fort	Islamic	19th Century AD	Islamic Monuments
52	Shamal Tombs	Ras Al Khaimah	Tombs	Bronze	2nd Millennium BC	Bronze Age Monuments
53	Seih al Harf Tombs	Ras Al Khaimah	Tombs	Bronze	3rd Millennium BC	Bronze Age Monuments
54	Asimah Tombs	Ras Al Khaimah	Tombs	Bronze	3rd Millennium BC	Bronze Age Monuments
55	Ghalilah Tombs	Ras Al Khaimah	Tombs	Bronze	2nd Millennium BC	Bronze Age Monuments

UAE heritage sites information (Continued)

No	Heritage Site	Emirate	Site Type	Age	Site History	Monuments
56	Al Khan Tower	Sharjah	Tower	Islamic	20th Century AD	Islamic
57	Al Talaa Tower	Sharjah	Tower	Islamic	20th Century AD	Islamic
58	Al Rabi Tower	Sharjah	Tower	Islamic	20th Century AD	Islamic
59	Al Dhaid Fort	Sharjah	Fort	Islamic	18th Century AD	Islamic
60	Dibba Al-Hisn Fort	Sharjah	Fort	Islamic	19th Century AD	Islamic
61	Muweilah	Sharjah	Archaeological site	Iron	3rd Millennium BC	Iron Age Monuments
62	Dibba Al-Hisn Port	Sharjah	Archaeological site	Roman	2nd Millennium BC	Roman Monuments
63	Fili Fort	Sharjah	Fort	Islamic	19th Century AD	Islamic
64	Al Gheel Fort	Sharjah	Fort	Islamic	20th Century AD	Islamic
65	Kalba Fort	Sharjah	Fort	Islamic	19th Century AD	Islamic
66	Jebel Faya	Sharjah	Archaeological site	Stone & Bronze	Paleolithic Age	Stone & Bronze Ages
67	Wadi Al Helo	Sharjah	Archaeological site	Bronze	3rd Millennium BC	Bronze Age Islamic
68	Al Thaqiba	Sharjah	Archaeological site	Iron	1st Millennium BC	Iron Age Monuments
69	Mleiha Tombs	Sharjah	Tombs	Bronze	3rd Millennium BC	Bronze Age Monuments
70	Mleiha	Sharjah	Archaeological site	Stone & Bronze	3rd Millennium BC	Stone and Bronze Monuments
71	Rock engravings in Khatum Melaha	Sharjah	Ancient Rocks	Bronze	3rd Millennium BC	Neolithic & Bronze Age Monuments

UAE heritage sites information (Continued)

No	Heritage Site	Emirate	Site Type	Age	Site History	Monuments
72	Archaeological Site of Kush	Ras Al Khaimah	Archaeological site	Islamic	5th Century AD	Islamic
73	Al Nudood & Al Mataf	Ras Al Khaimah	Archaeological site	Islamic	13th Century AD	Islamic
74	Al Nasla Fort	Ras Al Khaimah	Fort	Islamic	19th Century AD	Islamic
75	Wadi Qur Tombs	Ras Al Khaimah	Tombs	Bronze	2nd Millennium BC	Bronze Age Monuments
76	Sheba’s Palace	Ras Al Khaimah	Fort	Islamic	13th Century AD	Islamic
77	Al Mine'i	Ras Al Khaimah	Archaeological site	Bronze	3rd Millennium BC	Bronze Age Monuments
78	Umm al-Quwain	Umm Al Quwain	Fort	Islamic	18th Century AD	Islamic Monuments
79	Bakhot Tower	Umm Al Quwain	Tower	Islamic	18th Century AD	Islamic Monuments
80	Falaj Almu’alla Fort	Umm Al Quwain	Fort	Islamic	19th Century AD	Islamic Monuments
81	Umm al-Quwain Wall	Umm Al Quwain	Historical Wall	Islamic	19th Century AD	Islamic Monuments
82	The Sharea of Falaj Almu’alla	Umm Al Quwain	Water Structures	Islamic	19th Century AD	Islamic Monuments
83	Ed-Dur	Umm Al Quwain	Archaeological site	Pre-Islamic Era	3rd Millennium BC	Pre-Islamic Era Monuments
84	Tell Abraq	Umm Al Quwain	Archaeological site	Bronze	3rd Millennium BC	Bronze & Iron Ages

جامعة الإمارات العربيـة المتحدة
United Arab Emirates University

UAE UNIVERSITY MASTER THESIS NO. 2022:18

This study aimed to assess the Natural hazard impacts on heritage sites in the UAE using GIS. Studies included earthquakes, flooding, sea-level rise, and sand encroachment. According to the study, heritage sites located in the north-eastern UAE are more vulnerable to floods, earthquakes, and sea-level rise, and sand encroachment threatens the sites in the western region of Abu Dhabi. The AHP was used to support the study. The results indicated that flooding is the primary threat to heritage sites in Abu Dhabi, followed by sand encroachment and rising sea levels.

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