Assessment of Sustainable World Heritage Areas in Saudi Arabia Based on Climate Change Impacts on Vulnerability Using RS and GIS

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Abstract: Heritage is considered a pillar of civilized cultural identity and an important income resource. Climate change is one of the main threats to cultural heritage as fragile buildings are highly vulnerable to its impacts, as a result, many world heritage sites, unfortunately, have been lost. This study used Remote Sensing (RS) and Geographic Information Systems (GIS) to develop risk maps that determine spatial environmental changes regarding climatic parameters. The study used satellite images to analyze changes over 20 years for three climatic factors: temperature, humidity, and precipitation patterns. The average rate of change for each indicator was developed by comparing each month over 20 years. Three sub-models classifying changes for the selected factors were created, while the climatology model integrated the three sub-models with equal weights to assess the most vulnerable World Heritage sites. The vulnerable sites were classified into five categories, from less risk to the riskier. The study showed that most of Saudi’s Heritage sites are in the moderate-risk area. The study achieved the sustainable development goals (SDGs), particularly SDG 11 and SDG 13. This paper supports decision-makers to preserve heritage sustainably and to create proactive plans for it.

Keywords: heritage site; climate change; vulnerable urban heritage; heritage climatology; SDGs; RS; GIS

1. Introduction

Climate change is so far having an impact on cultural heritage sites through changes in different condition as temperature, precipitation, atmospheric moisture, and wind intensity, as well as sea level rise and changes in the frequency of extreme events [1]. it is well known that global weather conditions are highly impacted by climate change [2]. Climate change is defined as any change in climate over time whether due to natural variability or as a result of human activity [3]. The consequences of climate changes are closely related to the environment surrounding the location, as the location is impacted by the change in the environmental climatic conditions, thus climate change reflects spatial environmental changes [4]. Cultural heritage assets can be classified into historical buildings, archaeological sites, and monuments, as well as their contents, collections, and their intangible aspects. They considered a legacy from our past that provides local populations with a sense of place, identity, and aesthetic well-being [5]. Heritage has been vulnerable to interactions with their environment because of long-term climate change [6] commonly known as chemical and physical weathering processes, as it alters the heritage buildings.
Architects and geologists realized the negative impact of climatic conditions 300 years ago as the structures were destroyed by time, smoke, and weather [7]. According to UNESCO (2022), there are 14 threats/factors affecting World Heritage properties; each of them includes a number of secondary factors such as temperature, flooding, drought, and desertification.

According to UNESCO, since July 2019, there are 53 global heritage sites at risk (17 natural sites and 36 cultural heritages). For example, 21 of the nominated cultural sites are located in Arab nations (6 in Syria and 5 in Libya), while there are 16 in Africa, 6 in Latin America and the Caribbean, 6 in Asia and the Pacific, and 4 in Europe and North America. Moreover, most of the threatened natural sites (12) are in Africa [8]. Preserving heritage needs to achieve the 17 sustainable development goals (SDGs) with their three aspects: economic, environmental, and social. This research focuses on the most affected goals, which are SDG11: sustainable cities and communities and SDG13: climate action [9].

For that, the negative impacts of climate change will consequently affect the urban planning policies of heritage areas [10] and therefore it is necessary to study and monitor climate changes and identify safe and unsafe areas for heritage areas. Thus, the possibility of developing a proactive strategy for heritage areas to explore areas exposed to the dangers of climate change from the reality of evaluating, monitoring, and following up on climate changes through satellite imagery. The primary component of the monitoring system for climate variability and change is the remote sensing (RS) time series [11].

On the other hand, climate change will have negative-impact consequences on the urban planning policies of heritage areas. Therefore, it is necessary to study and monitor climate changes and identify at risk and safe heritage sites to develop a proactive strategy for heritage sites affected by climate change. The combination of RS and Geographic Information System (GIS) techniques is an appropriate approach for evaluating, monitoring, and following up on climate change as it provides different time series, namely [11].

Moreover, it optimizes data collection and efficiently solves increasingly complex application problems. It also has the enormous potential to capture, explore, manage, and model all geographically referenced data forms [12].

Therefore, this study introduces a GIS model based on satellite images to monitor climate change factors that affect heritage site sustainability. The selected variables were: temperature, humidity, and precipitation. The risk maps of vulnerable heritage sites were produced by an analysis of selected climate variables. Thus, helping decision-makers in the appropriate selection process for the best sustainable adaptation systems to climate change.

2. Literature Review

The relation between climate change and heritage assets has an interconnected and complex relationship. Therefore, several studies have been conducted to interpret this relationship. Ref. [1] developed a systematic literature review study to investigate the climate change impacts on tangible cultural heritage by developing hazard-impact diagrams focusing on: (1) the cultural heritage exposed to the outside environment, (2) the interiors of historical buildings and their collections, and (3) a third diagram associated with climate change and the impacts due to sudden changes in the natural physical environment (e.g., storm suction). A study was conducted by [2] to calculate the impact climate change has had on the vulnerability of heritage and the significance of temperature and rainfall as threats to heritage; the increased rainfall can overburden roofs and gutters, allowing water to penetrate traditional heritage materials. Cultural sites that are part of the World Heritage are likewise at risk. Ancient structures were created for a particular local climate. Pest migration may negatively affect the preservation of the built environment. Numerous coastal sites are at danger due to rising sea levels. Additionally, as soil temperatures rise, the conditions for the preservation of archaeological material may deteriorate. In addition to these physical dangers, however, climate change will have an impact on social and cultural components, with communities possibly migrating and abandoning their built heritage as a result of altering how they live, work, worship, and socialize in buildings,
sites, and landscapes [5]. The study introduced by [13] showed that climate change directly and indirectly threatens all types of cultural heritage, including intense rainfall, prolonged heat waves, droughts, strong winds, and sea level rise, all of which are expected to become worse in the future. Furthermore, the World Heritage Committee stated the effects of climate change on such assets, but climate change is just one of several threats confronting World Heritage sites. This threat must be viewed in the context of the overall maintenance of these sites. The annual seasonal change is one of the relative temperature changes that may impact heritage [7]. Continuous global warming allows the temperature to fluctuate above and below freezing, influencing porous materials in archaeological sites and historical buildings to risk [14–17]. The resulting mechanical weathering can lead to structural damage and the disintegration of stone, brick, and ceramic materials, as in [15].

According to [16], a study has been conducted to discover the related response of heavier daily precipitation frequency to the carbon dioxide concentrations in the atmosphere [16]. Extreme precipitation is expected to worsen with global warming over much of the planet, according to the thermodynamic Clausius-Clapeyron relationship, as the concentration of water vapor in the atmosphere, which provides water for precipitation, rises in proportion to saturation concentrations at a rate of about 6–7% for every degree of temperature rise [17]. Climate change, according to recent studies on global humidity, affects not only global temperature but also the amount of water vapor in the atmosphere, which can have significant consequences. Thus, relative humidity can save our lives by regulating and balancing the temperature of our immediate surroundings. Temperatures can be hot or cold due to low or high humidity. Moisture, which makes up a large part of the atmosphere, affects fog, storms, and rain.

Assessment of climate change impacts have been addressed using many research methodologies in many fields as cultural heritage assets. Additionally, many research efforts studied climate change adaptation systems for cultural heritage and identified the specific factors for implementing these systems. A study was developed by [18] to produce risk maps for Europe and the Mediterranean Basin. The study was based on a careful selection and analysis of climatic variables and extreme weather indicators based on data from ground stations on cultural heritage, while [19] investigated how climate change would harm tangible cultural heritages and what affects they might have on the oceans. It also looks at heritage instances that have already had an impact. A study was developed by [20] to classify the threats of climate change to cultural heritage into four categories: science, mitigation, adaptation, and communication. The study included a number of examples in which communities or institutions have attempted to manage cultural heritage threatened by climate change using these four pillars. A GIS model was developed by [21] to discover the vulnerable areas in coastal zones according to climate change impacts, while [7] studied the forms of climatic changes that are expected to affect the roofs and architectural structures of cultural heritage. Additionally, the study addressed the different methods for managing heritage assets in the future. A review study was conducted by [22] that highlighted the need for periodic assessment as it included 165 research studies (2016–2020) regarding cultural heritage and climate change, mostly on Europe and USA. However, [23] mentioned that although publications on integrating cultural heritage into mitigation and adaptation are growing, they are still few in comparison to those dealing with physical impacts on building structures or sites.

The authors of [24] assert the importance of using a geographic information system (GIS) for conservation and preventing the mangling of heritage assets. They are among the most cutting-edge technologies that enable the geographic and cartographic depiction of the properties included in relational databases, allowing the visual representation of the distribution of historical monuments. For the importance of remote sensing, aerial archaeology offers up-to-date expert statements on the methodologies, successes, and potential of remote sensing with a focus on archaeological heritage management. Remote sensing is one of the primary pillars of archaeological data, supporting the knowledge and understanding of the historic environment. A study was carried out by [25] to examine
of climatic changes based on the parameters of precipitation, temperature, and relative humidity. The study focuses on the survey of climatic changes in Iran’s eastern and central regions, during a 55-year period, the monthly and yearly change trends in minimum, maximum, and mean temperatures, relative humidity, and precipitation were surveyed for 26 synoptic stations in Iran.

Many studies on climate change and adaptation assessment, questionnaire, field visits, regional and policy workshops, and physical changes in cultural heritage have been conducted. However, most of the previous research studies have concerned with the impact of climate changes on heritage, but they did not consider developing a model to address the climate change elements to identify the vulnerable areas according to climate changes using satellite imagery. This research develops an integrated model using RS and GIS techniques to evaluate the impacts of the climatic changes over twenty years with time intervals (five years). While the rate of change was determined for each month over the twenty years. The generated risk maps show Saudi heritage sites located in vulnerable areas to climatic changes. Therefore, this study supports the decision-maker to set further suitable sustainable protective plans for the adaptation process.

3. Materials and Methods

3.1. Data

The study period was set at 20 years. To track and emphasize the risk mapping of climate change parameters (temperature, precipitation, and humidity) on the heritage, it is divided into equal periods (i.e., 5 years for each period) with an average monthly beginning in 2001 and ending in 2021. For these reasons, this paper employs a variety of satellite imagery, as depicted in Table 1.

Table 1. Climate change parameters.

<table>
<thead>
<tr>
<th>Category /Parameter</th>
<th>Date /Type</th>
<th>Parameter</th>
<th>Spatial Resolution</th>
<th>Temporal Resolution</th>
<th>Level</th>
<th>Inst./Plat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Raster/Geo TIFF</td>
<td>Land surface Temperature</td>
<td>0.05 Deg.</td>
<td>Averaged Monthly</td>
<td>L3</td>
<td>MODIS/Aqua</td>
</tr>
<tr>
<td>Humidity</td>
<td>Raster/Geo TIFF</td>
<td>Relative Humidity</td>
<td>1 Deg.</td>
<td>Averaged Monthly</td>
<td>L3</td>
<td>AIRS/Aqua</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Raster/Geo TIFF</td>
<td>Precipitation</td>
<td>0.1 Deg.</td>
<td>Averaged Monthly</td>
<td>L3</td>
<td>Multi Sensors/IMERG</td>
</tr>
</tbody>
</table>

3.2. Methodology

Remote sensing is a method that is frequently used for observing, mapping, and monitoring climate change. The most popular analytical technique is estimating the rates of climate change using data from RS images over different time series regarding certain variables [22]. The Arc GIS, Snap, and ENVI 5.1 software were used for the preprocessing of different satellite images and further analysis and assessment. The heritage climate change sub-models were developed based on satellite images to determine the average rate of changes was determined for all months of the year over 20 years. Then, the climatology model was produced by considering all the sub-models (reflecting the spatial change of variables) to generate a risk map showing the vulnerable heritage sites to spatial climatic selected variables. Figure 1 depicts a conceptual flow chart diagram of the proposed model’s formation and analysis.
spatial change of variables) to generate a risk map showing the vulnerable heritage sites to spatial climatic selected variables. Figure 1 depicts a conceptual flow chart diagram of the proposed model’s formation and analysis.

Figure 1. A conceptual flowchart for the applied methodology.

4. Study Area

The Kingdom of Saudi Arabia is located in the far southwest of Asia, surrounded to the west by the Red Sea, to the east by the Arabian Gulf, to the north by the United Arab Emirates and Qatar, to the south by Iraq and Jordan, and to the north by the Sultanate of Oman [26]. The Kingdom of Saudi Arabia, with an area of over 2,000,000 km², accounts for almost four-fifths of the Arab Peninsula (see Figure 2).

There is a variety of geographic environments in Saudi Arabia due to its huge area. Therefore, each location has a different climate due to the variation in its physical environment features. Saudi Arabia experiences regular rains, freezing winters, and hot summers due to a subtropical high-pressure system. The higher temperatures are almost in the west and southwest, although it is hot and dry in the interior and moist and cool near the shore. Saudi Arabia experiences minimal rain in the winter and spring, while there are heavy rains in the summer months particularly highlands in the southwest. The western beaches and mountains have high humidity almost along all year and the humidity gets lower gradually to the south [27].

Saudi Arabia has split administratively into 13 emirates, each subdivided into a number of governorates and centers. Saudi has a distinctive and varied history in addition to recent towering buildings. Most world heritage sites are in Medinah, Hail, and Tabuk. Six heritage sites in Saudi Arabia were recorded in World Heritage Sites (WHS) between 2008 and 2021 named Al-Ahsa Oasis, Al-Hajar Archaeological Site (Madain Saleh), Al-Turaif District, Historic Jeddah, and rock art in the Hail area. Additionally, there are 10 designated World Heritage temporary sites, which are mentioned in Table 2 and depicted in Figure 3.
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Table 2. World Heritage Sites in Saudi Arabia.

<table>
<thead>
<tr>
<th>No</th>
<th>Heritage Name</th>
<th>Registration Year</th>
<th>World Heritage List</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Al-Ahsa Oasis, an Evolving Cultural Landscape</td>
<td>2018</td>
<td>Registered</td>
</tr>
<tr>
<td>2</td>
<td>At-Turaif District in ad-Dir’iyah</td>
<td>2010</td>
<td>Registered</td>
</tr>
<tr>
<td>3</td>
<td>Hegra Archaeological Site (al-Hijr/Madâ in Ṣâliḥ)</td>
<td>2008</td>
<td>Registered</td>
</tr>
<tr>
<td>4</td>
<td>Ḩimâ Cultural Area</td>
<td>2021</td>
<td>Registered</td>
</tr>
<tr>
<td>5</td>
<td>Historic Jeddah, the Gate to Makkah</td>
<td>2014</td>
<td>Registered</td>
</tr>
<tr>
<td>6</td>
<td>Rock Art in the Hail Region of Saudi Arabia</td>
<td>2015</td>
<td>Registered</td>
</tr>
<tr>
<td>7</td>
<td>Hejaz Railway</td>
<td>2015</td>
<td>Tentative</td>
</tr>
<tr>
<td>8</td>
<td>Syrian Hajj Road</td>
<td>2015</td>
<td>Tentative</td>
</tr>
<tr>
<td>9</td>
<td>Egyptian Hajj Road</td>
<td>2015</td>
<td>Tentative</td>
</tr>
<tr>
<td>10</td>
<td>Rijal Almaa Heritage Village in Assir Region</td>
<td>2015</td>
<td>Tentative</td>
</tr>
<tr>
<td>11</td>
<td>Zee Ain Heritage Village in Al-Baha Region</td>
<td>2015</td>
<td>Tentative</td>
</tr>
<tr>
<td>12</td>
<td>Uruq Bani Mu’arid Protected Area</td>
<td>2019</td>
<td>Tentative</td>
</tr>
<tr>
<td>13</td>
<td>Farasan Islands Protected Area 2019</td>
<td>2019</td>
<td>Tentative</td>
</tr>
<tr>
<td>14</td>
<td>The Cultural Landscape of Al-Faw Archaeological Area</td>
<td>2022</td>
<td>Tentative</td>
</tr>
<tr>
<td>15</td>
<td>The Ancient Walled Oases of Northern Arabia</td>
<td>2022</td>
<td>Tentative</td>
</tr>
<tr>
<td>16</td>
<td>The Hajj Pilgrimage Routes: The Darb Zubaydah</td>
<td>2022</td>
<td>Tentative</td>
</tr>
</tbody>
</table>
5. Climate Change Heritage Model

A model builder tool in ArcGIS was used to evaluate the chosen climate change parameters. Besides, it was used to develop climate change sub-models for each parameter separately (temperature, precipitation, and humidity). Then, these sub-models were combined to generate the climatology model, which determined the highly affected world cultural heritage sites by climate change. The satellite imagery was clipped over the study area in the ArcGIS 10.5 platform using the extract by mask tool. The temperature imagery was converted from Kelvin to Celsius using Equation (1) in raster calculator tools [28]:

\[
LST = T - 272.15
\] (1)

The climate change rates were computed for each month of those years independently (2001, 2006, 2011, 2016, and 2021). The average rate of climatic change for each month was then calculated using the output in conjunction with cell information. The output raster was then classified (using a geometrical interval), where 1 represents the least change and 5 represent the greatest change rate of climatic change for each month. Finally, the weighted overlay was assumed equal weight for all three sub-models. Each sub-reclassification model’s outputs are multiplied by weights based on how important the other sub-models are and all of the sub-models are then joined together to create the climatology model. The risk map of the climatology model was produced and then transformed into a vector layer in order to compute the areas of risky zones in km. The suggested model and the datasets that were used are shown in Figure 4.

Figure 3. Locations of world heritage sites in Saudi Arabia.
6. Results and Discussion

The climatology model was created with five different favorability classes, namely: low, low/moderate, moderate, moderate/high, and high impacted areas by climate change. The outcomes were thoroughly discussed and mapped in the following sub-sections.

6.1. Temperature

The most obvious parameter that will change as greenhouse warming continues is temperature. Figure 5a,b shows the results of an analysis of the monthly temperature range for each month of the year in Saudi Arabia from 2001 to 2021. The months with the highest average temperatures were June and July of 2001, which reached, 62 °C and the months with the lowest average temperatures were January of 2006 and 2011. Figure 6a,b show climate changes at the monthly level every five years, whether declining or rising. The rate of change divided into five categories, negative change and positive change ranging from less than 5% to 20%. The highest rate of change in average temperatures were recorded in April (2011–2016) and December (2006–2011 and 2011–2016) at the northeastern and southeastern parts of Saudi Arabia, while decreasing changes occurred in December (2001–2006) and April.
Figure 5. (a) Analysis results of the monthly temperature range from January to June. (b) Analysis results of the monthly temperature range from July to December.
The increasing of temperature has been affected by several natural factors, the most important of which is the location, as the Saudi is located between latitudes 16° and 33° N and longitudes 34° and 56° E. The largest part of it is within the dry tropical desert and then located in the region of tropical high pressure in winter, influenced by the hot low.
The increasing of temperature has been affected by several natural factors, the most important of which is the location, as the Saudi is located between latitudes 16° and 33° N and longitudes 34° and 56° E. The largest part of it is within the dry tropical desert and then located in the region of tropical high pressure in winter, influenced by the hot low pressure in southern Asia and dry winds in summer. Therefore, the Saudi’s climate is characterized by drought throughout the year and high temperatures, especially in the summer, due to the sun perpendicular to the Tropic of Cancer, which passes through the territory of the Saudi in an east–west direction, dividing it into almost two halves [29,30].

Figure 7 represents the average rate of change of each month over all the time ranges from 2001 to 2021. The map showed that high changes predominated throughout the majority of the Kingdom of Saudi Arabia; indicating higher temperatures during the last 20 years (see Figure 7), while Figure 8 depicts a scale from 1 to 5. The areas in Saudi Arabia ranked from 1 to 5 according to their vulnerability to temperature fluctuations in the climate, with July being the month with the largest variation throughout the whole research area.

Figure 7. Average change in temperature for the 12 months.
6.2. Precipitation

Precipitation may have potential consequences for human culture and ecosystems, thus, much research has been conducted to study responding of high precipitation to climate change [31]. Figure 9a,b depict the distribution of rainfall in Saudi Arabia from 2001 to 2021 in winter and autumn. The rainfall rates vary from 0.655 mm/h to 0.00000914655 mm/h and the heaviest precipitation was in July 2021, on the southwest parts of the country followed by July and August 2001 on the west parts, with average monthly rainfalls of 0.50655 mm/h and 0.45655 mm/h, respectively. Figure 10a,b depict the variance in the average rates of change in rainfall at the monthly level over a period of twenty years. The categories of change rates have been split and consolidated into five groups, ranging from −0.00099% to 10%. The highest rates of change occurred in February between 2001 and 2006, as it reached more than 10% in the north of Saudi Arabia. It was recognized that the rate of change was high at time interval January (2006–2011).
Figure 9. (a) Precipitation for the years 2001, 2006, 2011, 2016, and 2021 from January to June. (b) Precipitation for the years 2001, 2006, 2011, 2016, and 2021 from July to December.
Furthermore, Figure 11 depicts the average rates of change in the monthly rate over 20 years, the changes in precipitation rates varying in rate and locations according to a number of factors that may be related to land slope, temperature, wind direction, etc.

Figure 10. (a) Average precipitation change from January to June. (b) Average precipitation change from July to December.
Furthermore, Figure 11 depicts the average rates of change in the monthly rate over 20 years, the changes in precipitation rates varying in rate and locations according to a number of factors that may be related to land slope, temperature, wind direction, urban density, and economic activities. The rate of change ranged from 0.001% to 0.7%, represented in orange, considering the risky change rate.

Figure 11. Average change in precipitation for the 12 months.

Rain falls on Saudi in the winter, with the exception of the Asir region (southwest of Saudi), which rains in the summer. The falling rain is characterized by its irregular fall; it may fall in a few days then stop for a period and then fall again and in one or two days more than half of the annual rainfall falls. Rain falls either in the form of simple showers or torrential downpours, forming torrential torrents, which streams and valleys are unable to absorb and leads to floods, as happened in the obstacle of Dhala between Abha and Jazan [32,33].

Figure 12 show a standardization map ranked from 1 to 5 according to their vulnerability to rainfall change rates, as May, November, and December the largest variation in Saudi Arabia.
6.3. Humidity

Increased humidity is likely to cause heavy rains and dangerous heat waves; therefore, surface moisture should be considered and understood. Figure 13a,b show that the distribution of relative humidity in Saudi Arabia ranged from 6.1% to 58%. The rates of change in the average monthly relative humidity varied less than from −50% to 25%.

The changes of rates (5 years’ time interval) were recorded at the south, southwest, and southeast parts in January (2006–2011), April (2011–2016), and July (2016–2021) (see Figure 14a,b). Figure 15 shows the monthly change rate over 20 years, where the higher change rate values were in July and the lower were in November.

The Red Sea and the Arabian Gulf represent the main source of moisture in Saudi. As known, there is an inverse relationship between humidity and temperature, that is, the higher the temperature, the lower the relative humidity [33,34].

The standardization maps in Figure 16 show that the months of July, January, and February have the highest rates of change in relative humidity with more than 10%.
Figure 14a,b. Figure 15 shows the monthly change rate over 20 years, where the higher change rate values were in July and the lower were in November.

Figure 14. (a) Average humidity change from January to June. (b) Average humidity change from July to December.
Figure 15. Average change in humidity for the 12 months. As known, there is an inverse relationship between humidity and temperature, that is, the higher the temperature, the lower the relative humidity [33,34]. The standardization maps in Figure 16 show that the months of July, January, and February have the highest rates of change in relative humidity with more than 10%.

Figure 16. Standardized for humidity factor.
6.4. Climatology Heritage Model

6.4.1. Temperature Change

Figure 17 and Table 3 show the results of the temperature change sub-model over a twenty-year period based on the average monthly rates of change. The changes were classified into five categories, ranging from low to high risk. High-risk climatic changes appeared in north, central, and east parts of the country, with an area of 26,014.8 km², representing 1.12% of the Saudi Arabia’s total area. The northern regions are located within the arid weather areas more than the rest of the regions. Moreover, the northeastern regions were close to war zones such as the Gulf War, Iraq, and Syria during the twenty-year study period, which caused an oil spill in the coastal areas, as well as the bombing and burning, which led to an increase in air pollution in the surrounding areas [35]. The southern regions showed less climatic changes as the minimum and maximum limits of temperature values are close, besides to the highly topographic level of the southern parts.

![Temperature change modeling](image)

**Figure 17.** Temperature change modeling.

**Table 3.** Temperature change risk zones.

<table>
<thead>
<tr>
<th>Vulnerability Degree</th>
<th>Vulnerable Area</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>575.50</td>
<td>0.02</td>
</tr>
<tr>
<td>Low/Moderate</td>
<td>738,934.80</td>
<td>31.86</td>
</tr>
<tr>
<td>Moderate</td>
<td>1,554,409.40</td>
<td>67.02</td>
</tr>
<tr>
<td>Moderate/High</td>
<td>25,223.60</td>
<td>1.09</td>
</tr>
<tr>
<td>High</td>
<td>791.20</td>
<td>0.03</td>
</tr>
</tbody>
</table>

During the last twenty years, the heritage site locations were within the range of moderate risk temperature changes (Al-Ahsa Oasis, Al-Turaif District, Al-Hajar Archaeological Site, Historic Jeddah, Rock Art in Hail). The majority of Saudi Arabia, with an area of 1,554,409.40 km² and 67.02%, was within the moderate risk category. The temporary world heritage sites were in moderate to low-moderate risk changes.
6.4.2. Precipitations Change Modeling

According to the results of precipitation sub-model, the high-vulnerability climatic changes were mostly in the east to the west parts with an area of 26,014.8 km$^2$ and 1.12% of the total Saudi’s area, Table 4.

Table 4. Precipitation change risk zones.

<table>
<thead>
<tr>
<th>Vulnerability Degree</th>
<th>Vulnerable Area</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low/Moderate</td>
<td>1,486,344.6</td>
<td>64.08</td>
</tr>
<tr>
<td>Moderate</td>
<td>829,780.6</td>
<td>35.78</td>
</tr>
<tr>
<td>Moderate/High</td>
<td>3233.8</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Two of the heritage sites were in the low-moderate risk changes which are the Hima Cultural Area and Rock Art in Hail (Figure 18). Most of Saudi’s were classified as moderate risk, with an area of 1,554,409.40 km$^2$ and 67.02%, where the heritage sites: Al-Ahsa Oasis, Al-Turaif District, Al-Hajar Archaeological Site, and Historic Jeddah were located. The temporary heritage sites had moderate and low-moderate dangers.

Figure 18. Precipitation change modeling.

6.4.3. Humidity Change Modeling

Only three risk categories (moderate/high, medium, and low/moderate) for humidity change were shown in Figure 19 and Table 5. Heritage sites such as the Al-Hajar Archaeological Site and Rock Art in the Hail region of Saudi Arabia were found in the low moderate-risk category. The northern and central portions of the country were in the class of low/moderate risk of changes with an area of 657,157 km$^2$ and a rate of 28.33%.

Figure 19. Humidity change modeling.
6.4.4. Climate Change Modeling

Three sub-models for each factor and climatology model to produce risk maps were developed based on the evaluation of changes in the three selected climate factors. Over a twenty-year study time, the obtained results of the three sub-models were combined to investigate and map the risks in the study area. Then, the vulnerable world heritage sites in Saudi Arabia, whether recorded or not, were identified.

Figure 20 show that the majority of Saudi’s area was in the moderate climate change risk class map included, with a total area of 1,778,158 km$^2$ and 76.67%, as seen in Table 6.

It was recognized that all the world heritage sites (Al-Ahsa Oasis, At Turaif District in ad-Dir’iyah, Hima Cultural Area-Historic Jeddah, and the Gate to Makkah) were within the moderate risk except Rock Art, which was within the range of low-moderate climate change risk, with 479,159.1 km$^2$ and 20.66%. The moderate/high risk class was not significant as it was about 2.67% of the total Saudi’s area.
The climate change model considered equal weights for the three sub-models representing the change rate of temperature, precipitation, and humidity. Since the heritage in Saudi Arabia varies between architectural buildings, oases, rocky areas, and ancient water wells, then the climatic factors that negatively affect this heritage vary according to different building materials, and therefore it is suggested that each heritage should be studied individually to consider the most influential climatic factors and prioritize it in the model.

Therefore, this study is an approach to monitor and track the vulnerable heritage sites and most affected areas in Saudi Arabia by climate change. Hence, this study is an effective tool to achieve state policies and the 2030 strategy in accordance with the sustainability of heritage sites and adaptation for future climate changes as a proactive step towards preserving and sustainable development. It helps the government and decision-makers to develop a strategy for sustainable development and the preservation of historical areas, as well as tourism investment in accordance with the policies of Saudi Arabia to manage heritage sites.

**7. Conclusions**

This research has developed an approach to assess areas vulnerable to climatic changes (temperature, rain, relative humidity) by producing map risks of heritage sites using GIS and RS techniques. The study investigated and analyzed climatic variables on a monthly basis using satellite images over twenty years (2011–2021) with an interval of five years.
Different satellite images were used for three selected climatic factors over time ranging 20 years. The selected factors were: temperature, humidity, and precipitation rates. Three sub-models were developed and classified based on RS and GIS techniques. A climatology model was generated using an equal weight for the three sub-models. The risk maps were produced to determine the vulnerable Heritage sites, which were classified into five categories, from less risk to the riskier.

According to the obtained results of the climatology model, most of the heritage sites (Al-Ahsa Oasis, At Turaif District in ad, Dir’iyah-al-Hijr/Madain Salih-Hima Cultural Area, Historic Jeddah, the Gate to Makkah) are within the moderate risk range with the largest area of 1,778,158 km$^2$ and 76.67%.

The Rock Art in the Hail was expected as it is in the low/moderate risk range, while the majority of the temporary heritage sites were in the low/moderate risk range of climatic changes.

It is important to mention that the heritage was within the moderate risk category over the studied time (20 years), but when considering longer time changes most of the heritage sites may be located at high-risk class. This could be considered an alarm for policymakers to find appropriate and sustainable adaptation systems and rapid strategies for conservation, renewal, and adaptation plans.

Author Contributions: Conceptualization, R.H.R.; Methodology, R.H.R.; Validation, M.S.R. and N.K.; Formal analysis, M.S.R.; Resources, M.S.R. and I.Y.I.; Data curation, R.H.R. and I.Y.I.; Writing—original draft, R.H.R.; Writing—review & editing, R.H.R.; Visualization, R.H.R. and N.K.; Funding acquisition, I.I.A. and H.M.A. All authors have read and agreed to the published version of the manuscript.

Funding: Princess Nourah bint Abdulrahman University Researchers Supporting Project number (PNURSP2022R243), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Written informed consent has been obtained from the patient(s) to publish this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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