A GEOSPATIAL ASSESSMENT OF FLOOD RISK TO ARCHAEOLOGICAL SITES USING MULTICRITERIA DECISION MAKING AND ANALYTICAL HIERARCHY PROCESS

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ABSTRACT

South Asia's rich cultural heritage is prominently reflected in its archaeological sites. The Indus Civilization, also known as the Harappan Civilization, thrived in what is now India and Pakistan from the mid-third millennium BCE until around 1300 CE. In India, more than a thousand sites associated with the Indus Civilization have been discovered; however, only 15 of these sites are currently protected. Many of the remaining sites are at risk of destruction due to human activities and natural disasters. Therefore, conducting a risk assessment is crucial to understanding the current state of preservation and protection of these sites. The state of Gujarat has diverse geomorphology and faces significant threats from various natural disasters each year. While a comprehensive assessment of all risks is necessary, it is important to begin with a specific concern. This study examines the flood risk to 508 archaeological sites related to the Indus Civilization, along with regional Chalcolithic sites. To generate a flood susceptibility map for Gujarat, ten parameters were selected: clay content of the soil, distance from rivers, distance from roads, drainage density, elevation, Land Use Land Cover (LULC), Normalized Difference Vegetation Index (NDVI), rainfall deviation, slope, and Topographic Wetness Index (TWI). These parameters were assessed using Multi-Criteria Decision Making (MCDM) and the Analytical Hierarchy Process (AHP), integrated with spatial analysis. The risk assessment methodologies developed by the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) were utilized for the risk assessment of archaeological sites. The findings revealed that the districts of Bhavnagar, Botad, and southern areas of Surendranagar and Ahmedabad are more prone to flooding in Gujarat. Out of the 508 archaeological sites assessed, 188 were identified as being at high risk. Notable at-risk sites include Jaidak/Pithad, Lothal, Rangpur, Rojdi, and Valabhipur, along with many unprotected sites that are also affected. By employing various spatial techniques, this study aims to bridge the gap between natural sciences and cultural heritage management, providing a framework for conducting risk assessments in India, particularly for archaeological sites.

Key-words: *AHP, Archaeological sites, Flood risk, GIS, Gujarat, MCDM*

1. INTRODUCTION

It is undeniable that archaeological sites are increasingly threatened by natural hazards and modern urban development. As these hazards continue to rise, the need to preserve and conserve the archaeological sites becomes more important. While national protection and physical conservation after a disaster are crucial, it is also important to assess potential threats before a disaster occurs. Recently, satellite remote sensing and GIS are being used for this purpose.

Since the 1980s, GIS has been widely used in archaeology for various purposes, such as visualizing site contexts and stratigraphy, mapping monument distribution based on geomorphology, predictive modeling for site location, and modeling settlement patterns (Wescott and Brandon, 2003). The “Guidance on Heritage Impact Assessments (HIA) for Cultural World Heritage Properties,” published by ICOMOS (2011), has significantly promoted the use of GIS in preserving and archiving archaeological information. It outlines three steps for HIA: identifying heritage at risk, assessing the impact of risks by understanding the significance of heritage being lost, and providing measures to

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avoid, reduce, rehabilitate, or compensate for the impact. The guidance recommends using desk-based or historical research and field visits, as well as modern technology like GIS and 3D models, for accurate and precise evaluation in desk-based studies and employing non-intrusive geophysical surveys during field visits.

Satellite images such as Landsat, Sentinel, and IRS LISS–III (Indian Remote Sensing – Linear Imaging Self-Scanning Sensor), as well as Digital Elevation Models (DEMs) like Aster and Cartosat, are considered primary sources of remote sensing data. These sources offer a wide range of information that can be valuable in evaluating both human-made and natural hazards. Change detection can be carried out using Land Use Land Cover (LULC) analysis (Alexakis et al., 2013; Hadjimitsis et al., 2013). Furthermore, various derivatives such as slope, land cover types, stream networks, coastline, drainage density, soil type, and more are utilized to assess the likelihood of natural hazards evolving into risks (Reeder et al., 2012; Van Rensselaer, 2014). These works that fall under the heritage impact assessment category and GIS can be used in various ways, such as creating a digital archive, evaluating natural risks, and digitally conserving sites using 3D GIS (Knight and Vyner, 2006). The purpose of this paper is to contribute to this field.

Archaeological sites in Gujarat, a northwestern state of India, face threats from various natural hazards, including landslides and earthquakes, as well as rapid urbanization. Previous works have noted that landslides pose a minimal risk to archaeological sites in Gujarat (Kadapa, 2024a) and earthquakes pose a significant risk to archaeological sites in Kachchh region of Gujarat (Kadapa, 2024b). In addition to these natural hazards, according to the State Disaster Management Authority, the region is particularly vulnerable to seasonal monsoon flooding, which typically occurs from June to September (https://gsdma.org/Content/flood-4220). These floods pose a substantial risk to archaeological sites, damaging not only surface structures but also subsurface remains that hold great significance.

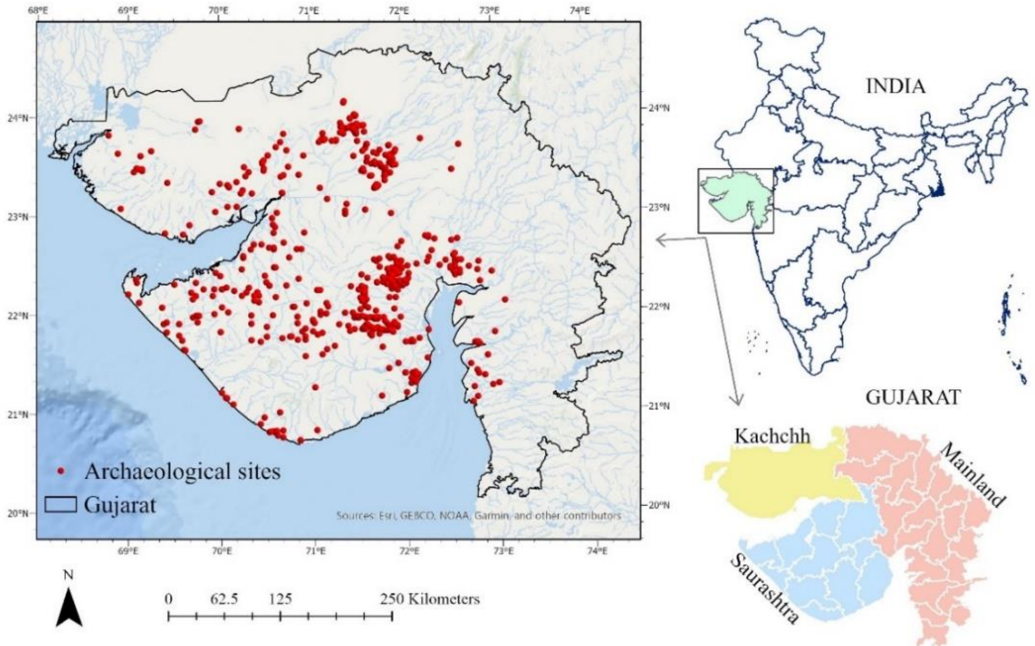

Fig. 1. Study area (Gujarat, India) and archaeological sites (Basemap source: ESRI Online).

Hence, this paper aims to assess the flood risk to archaeological sites in Gujarat (total sites = 508: Bhan, 1994; Ajithprasad and Sonawane, 2008; Rajesh, 2011) (**Fig. 1**) by integrating Geographic Information Systems (GIS), Multi-Criteria Decision Making (MCDM), and the Analytic Hierarchy Process (AHP), building on prior research from other regions. Satellite data has proven to be an effective tool for assessing flood risks and evaluating the potential impact of flooding on cultural heritage sites (Solin and Skubincan, 2013; Díez-Herrero and Garrote, 2020; Salazar, 2024). One commonly used approach involves change detection analysis of satellite imagery combined with topographic maps to identify areas of concern (Ortiz et al., 2016; Cuca, 2022; Elfadaly et al., 2022). In recent years, there has been a growing focus on predictive modeling of flood risk, which takes into account hazard exposure and the value of cultural assets (Vojinovic et al., 2016; Miranda et al., 2019; Garrote et al., 2020; Figueiredo et al., 2020; Arrighi, 2021; Vojinovic et al., 2021; Brokerhof, 2023; Davis et al., 2023; Snelling et al., 2024; Nobile et al. 2025). Notably, multi-criteria decision-making techniques, such as the Analytical Hierarchy Process (AHP) (Kandilioti and Makropoulos, 2012; Dassanayake et al., 2015; Agapiou et al., 2016; Hapciuc et al., 2016; Kittipongvises et al., 2020; Carmichael et al., 2023), are increasingly used to systematically assess and prioritize the risks that flooding poses to cultural heritage. Further, the study incorporates a quantitative risk assessment methodology proposed by UNESCO and its advisory body, the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) (Michalski and Pedersoli Jr., 2016; Kadapa, 2024a). By utilizing these advanced techniques, the research seeks to enhance our understanding of the impacts of flooding on archaeological sites and to inform effective management strategies for preservation.

2. METHOD

2.1. Cultural heritage quantitative risk assessment

Risk assessment is a systematic and quantitative process designed to evaluate the value of cultural heritage that is at risk of being lost. The value of cultural heritage can be defined using various proxies, including aesthetic, historical, spiritual, physical, religious, social, economic, political, scientific, ecological, and age-related values. Nonetheless, quantifying these abstract factors into numerical values can be challenging. To address this complexity, several quantitative methods have been developed, some of which are outlined below.

The fundamental concept of risk assessment is to proactively identify potential risks and implement preventative measures to mitigate them, with the goal of avoiding or minimizing future deterioration or loss. This approach is known as preventive conservation and encompasses all actions taken to prevent potential damage (ICOM–CC, 2008).

The process of quantitative risk assessment for preventive conservation began with the Cultural Property Risk Analysis Model (Waller, 1995). This model consists of four basic steps: (i) identify all risks, (ii) assess the magnitude of each risk, (iii) identify possible mitigation strategies, and (iv) evaluate the costs and benefits associated with each strategy (Waller, 1995). This method calculates the probability of a risk leading to a loss of value, with results expressed on a scale from 0 to 1 and plotted on a 3D graph against the agents of deterioration. Once the magnitude of the risks is identified, strategies for controlling them are explored (Waller, 2015).

Another approach uses a 3x3 matrix to assess the likelihood and impact (probability and consequence), which is categorized into small, medium, and large levels (Brokerhof, 2006). The Quick Scan method is also commonly used; it was developed from risk mapping techniques, such as earthquake risk maps, where the locations of heritage sites and potential hazards spatially overlap. This analysis considers three parameters: the value of the heritage asset, its vulnerability, and its exposure to an event (Brokerhof et al., 2017). Later, Michalski and Pedersoli Jr. (2016) developed the ABC risk management method in collaboration with the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) and the Canadian Conservation Institute (CCI–ICN). This risk assessment method involves three steps: identifying, analyzing, and evaluating hazards, which can be categorized into ten agents of deterioration. These agents are: "(i) physical forces, (ii) thieves and vandals, (iii) fire, (iv) water, (v) pests, (vi) pollutants, (vii) light, ultraviolet (UV) and infrared (IR) exposure, (viii) incorrect temperature, (ix) incorrect relative humidity, and (x) dissociation" (Michalski and Pedersoli Jr., 2016, 70). This classifies the loss of value on a 5-point scale, making it easy to comprehend.

The present study utilizes this scale to evaluate physical loss at archaeological sites. Using Geographic Information Systems (GIS), specifically ArcGIS Pro, the archaeological sites are superimposed with a flood susceptibility map of Gujarat. If the percentage of a site at risk ranges from 0.006% to 0.02%, it will be classified as a trace loss and assigned a score of 1. For areas at risk ranging from 60% to 100%, they will be considered a total value loss and assigned a score of 5.

2.2. Flood hazard assessment

To understand the loss of physical value of the archaeological sites studied in this research, a flood susceptibility map for Gujarat was created using satellite remote sensing and Geographic Information System (GIS) technology, employing a Multi-Criteria Decision Making (MCDM) approach.The MCDM procedure begins by identifying as many attributes or criteria related to the problem as possible and gathering relevant data. After that, a set of alternatives is formulated. Finally, the best alternative is selected using an appropriate decision-making method (Tzeng and Huang, 2011). To generate the flood susceptibility map for Gujarat, ten parameters were chosen: clay content of the soil, distance from rivers, and distance from roads, drainage density, elevation, Land Use Land Cover (LULC), Normalized Difference Vegetation Index (NDVI), rainfall deviation, slope, and Topographic Wetness Index (TWI).

Table 1.

Equations supporting the calculation of parameters and the generation of flood susceptibility map.

S.no	Parameter	Formula	Reference
(i)	Normalized Difference Vegetation Index (NDVI)	$\frac{(NIR-R)}{(NIR+R)}$ Where NIR is the near-Infrared band and R is the red band. These correspond to bands 5 and 4 of the Landsat 8 Operational Land Imager (OLI).	(Durigon et al., 2014)
(ii)	Rainfall deviation	$\frac{(Recorded\ rainfall - Average\ rainfall)}{Average\ rainfall} \times 100$ Where recorded rainfall is the recorded rainfall for the year 2022, and average rainfall is the average of years 2012 to 2022.	(Ali et al., 2019)
(iii)	Topographic Wetness Index (TWI)	$\ln\left(\frac{\alpha}{tan\beta}\right)$ $\alpha = (flow\ accumulation + 1) \times cell\ size$ Where α is the local upscale area and Tanβ is the slope in radians.	(Moore and Burch, 1986; Wilson, 2012)
(iv)	AHP – Consistency Index (CI)	$\frac{\lambda max - n}{n-1}$ Where n is the number of criteria.	(Saaty, 1980)
(v)	AHP – Consistency Ratio (CR)	$\frac{CI}{RI}$ where RI is the Random Index.	
(vi)	Weighted overlay	$\sum_{i=1}^{n} w_i \times R_i$ Where w is criteria weights from AHP, R is the ranks of reclassified thematic layers, and n is the number of parameters.	(Alanazi et al., 2013)
(vii)	Tolerance (TOL)	$1 - R^2$ $R^2 = \frac{Explained\ variance}{Total\ variance}$	(Oke et al., 2019)
(viii)	Variance Inflation Factor (VIF)	$\frac{1}{(1-R^2)}$	
(ix)	Normalized Difference Water Index (NDWI)	$\frac{(Green - SWIR)}{(Green + SWIR)}$ Where For Landsat 8 Operational Land Imager (OLI), Band 3 represents Green and Band 6 represents the Shortwave Infrared (SWIR)	(Xu, 2005)

2.3. Calculation of the parameters in GIS

Each of the ten parameters was individually generated in ArcGIS Pro. The input datasets used are listed in data availability.

1. *The clay content of the soil:* The clay content in an area significantly affects its flood susceptibility. Clay particles are typically less than two micrometers in diameter, which

means they are densely packed, resulting in reduced pore size. This leads to low permeability, causing water to infiltrate slowly and increasing surface runoff (Crăciun et al., 2009). As a result, areas with high clay content are generally more prone to flooding than those with lower clay content. Crăciun; Janizadeh et al., 2021) (**Fig. 2a**).

2. *Distance from rivers:* The proximity of an area to rivers increases its susceptibility to flooding. Without embankments, plains located next to rivers are prone to flooding when the river overflows. Therefore, measuring the distance from rivers is a vital factor in flood risk assessment. In this study, the Euclidean distance tool was employed for this measurement (Janizadeh et al., 2021; Dutta and Deka, 2024) (**Fig. 2b**).
3. *Distance from roads:* Urban infrastructure, particularly roads, tends to be more susceptible to flooding due to the lack of natural barriers (Faizen et al., 2023). Additionally, low-lying areas with a high concentration of roads are particularly vulnerable to flooding. Therefore, it is essential to measure the distance from roads, using the Euclidean distance tool once again for this purpose (Kittipongvises et al., 2020; Janizadeh et al., 2021) (**Fig. 2c**).
4. *Drainage density:* Drainage density is defined as “the total length of streams in a catchment area” (Bhagwat et al. 2011, 56). This measurement helps identify how water flows through an area, allowing for the identification of regions that are likely to experience high runoff. To calculate the drainage density of Gujarat, streams were delineated from Digital Elevation Models (DEMs), and the density was determined using the Euclidean distance tool (Janizadeh et al., 2021; Vignesh et al., 2021) (**Fig. 2d**).
5. *Elevation:* Elevation is a key factor in understanding an area's susceptibility to flooding. It provides insight into the topography and height of the terrain. Low-lying areas, such as river valleys and plains, can be identified through elevation analysis. From a risk assessment perspective, these low-lying areas are more prone to flooding. To assess the elevation of a region, Digital Elevation Models (DEMs) from Cartosat version 3 were utilized (Kandilioti and Makropoulos, 2012; Kittipongvises et al., 2020; Janizadeh et al., 2021; Vignesh et al., 2021; Dutta and Deka, 2024) **(Fig. 3e**).
6. *Land Use Land Cover (LULC):* Land use refers to how humans utilize an area, with examples including residential neighborhoods, agricultural farms, and more. In contrast, land cover pertains to the natural features of the land, such as water bodies and forests. Both land use and land cover play crucial roles in understanding an area's susceptibility to flooding. Areas with vegetation can absorb water and act as natural barriers against runoff, while urban areas, like those with built roads, do not absorb water and have a higher flooding potential. To analyze the LULC in Gujarat, five distinct classes were identified, including water, tree cover, croplands, built-up areas, and bare or sparse vegetation. The European Space Agency (ESA) World Cover 2021 dataset was used as a reference (Kandilioti and Makropoulos, 2012; Haidu and Ivan, 2016; Hapciuc et al., 2016; Kittipongvises et al., 2020; Vignesh et al., 2021; Dutta and Deka, 2024) (**Fig. 3f**).
7. *Normalized Difference Vegetation Index (NDVI):* The NDVI is an important measure of vegetation density in a given area. A high NDVI value indicates dense vegetation, whereas a low NDVI value signifies sparse or absent vegetation. As previously mentioned, trees absorb water and serve as natural flood barriers, so areas with low NDVI values are more susceptible to flooding. The NDVI for Gujarat was calculated using the formula by (Durigon et al., 2014) (**Table 1**) (**Fig. 3g**).
8. *Rainfall deviation:* Rainfall is the primary cause of floods, with heavy rainfall often leading to flash floods. Rainfall deviation refers to the changes in rainfall patterns in a specific area compared to the average rainfall over a given period. Data from the Indian Meteorological Department for the last ten years (2012–2022) during the monsoon season were analyzed to measure rainfall deviation in Gujarat. The deviation was calculated using the formula provided by (Ali et al., 2019; Kittipongvises et al., 2020) (**Fig. 3h**).
9. *Slope:* Slope refers to the measure of inclination or steepness of an area. Along with elevation, slope is also crucial for understanding flood susceptibility. The speed and direction

of water flow are influenced by the slope of the terrain. Water naturally flows from higher to lower elevations, so the steepness of an area affects surface runoff. Generally, steeper slopes lead to higher runoff velocities. Consequently, both elevation and slope are fundamental factors in determining an area's flood susceptibility. The slope of Gujarat was derived using the slope tool from the spatial analysis toolset applied to the Cartosat DEMs (Kandilioti and Makropoulos, 2012; Hapciuc et al., 2016; Kittipongvises et al., 2020; Janizadeh et al., 2021; Vignesh et al., 2021; Dutta and Deka, 2024) (**Fig. 4i**).

10. Topographic Wetness Index (TWI): The Topographic Wetness Index measures the wetness of an area. It "defines the effect of topography on the amount of wetness that contributes to runoff and is considered a suitable index for investigating flood potential" (Ali et al., 2019). Wetness levels can indicate soil moisture content, which in turn influences runoff potential. The TWI of Gujarat was calculated using the formula in **Table 1** (Moore and Burch, 1986; Wilson, 2012; Janizadeh et al., 2021; Vignesh et al., 2021; Dutta and Deka, 2024) (**Fig. 4j**).

Reclassifying thematic layers is an important process that facilitates data standardization. The thematic layers generated may consist of continuous or discrete raster datasets. Through reclassification, these layers are transformed to create a uniform number of classes that are suitable for comparison. Each class is assigned a score based on its likelihood of being affected by a hazard. A lower score indicates lower susceptibility, while higher scores indicate increased susceptibility. The reclassified classes of the thematic layers used for generating the flood susceptibility map along with their corresponding scores are detailed below (**Table 2**).

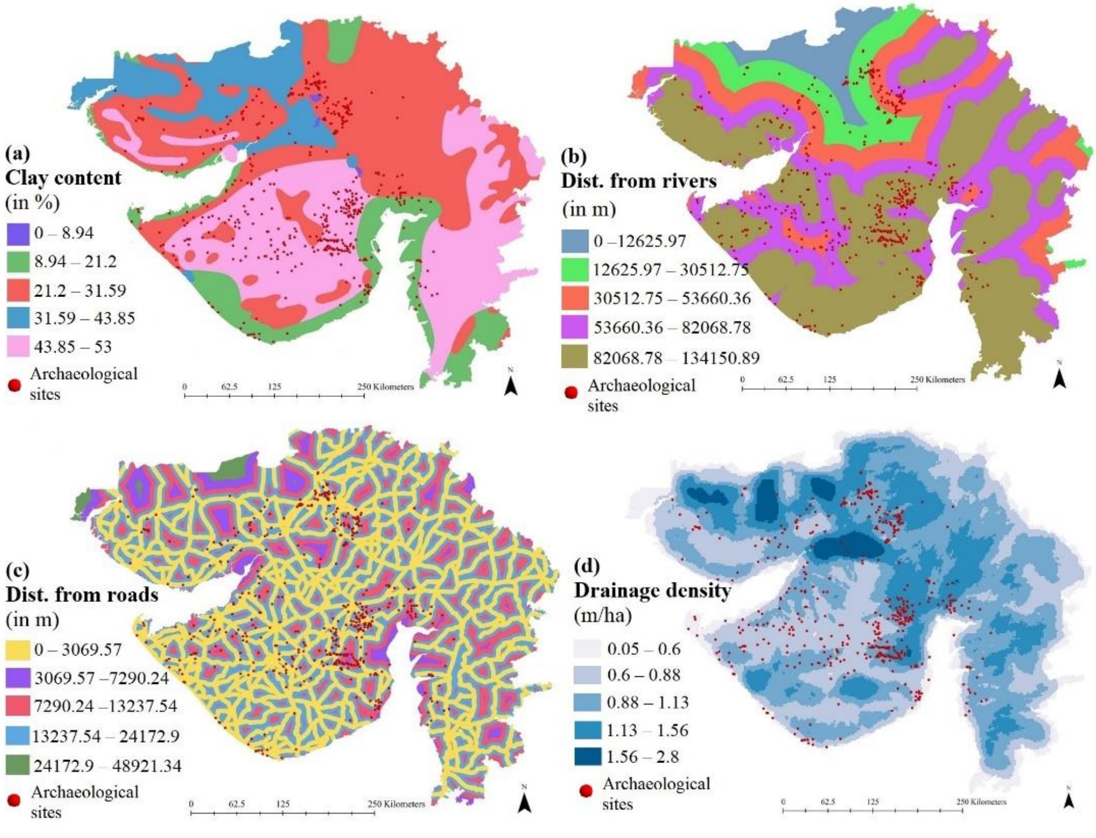

Fig. 2. susceptibility parameters (a) Clay content of the soil, (b) Distance from rivers, (c) Distance from roads and (d) Drainage density.

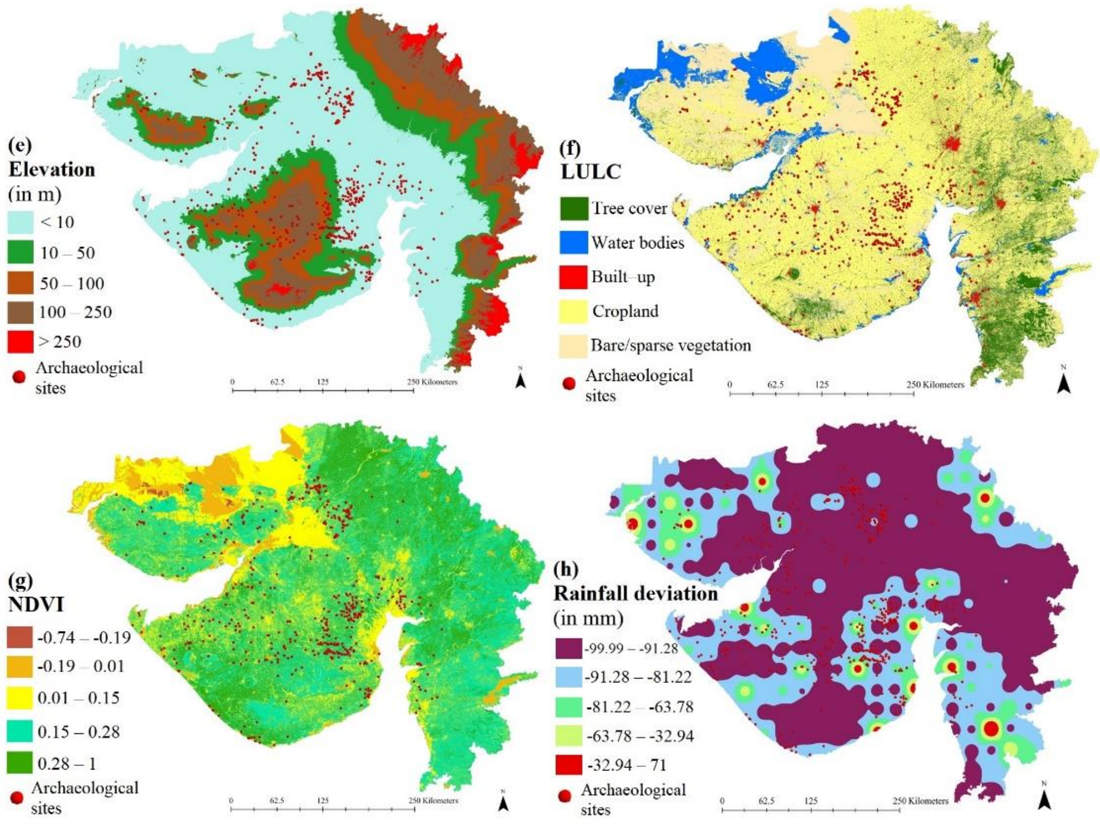

Fig. 3. susceptibility parameters (e) Elevation, (f) Land Use Land Cover (LULC), (g) Normalized Difference Vegetation Index (NDVI) and (h) Rainfall deviation.

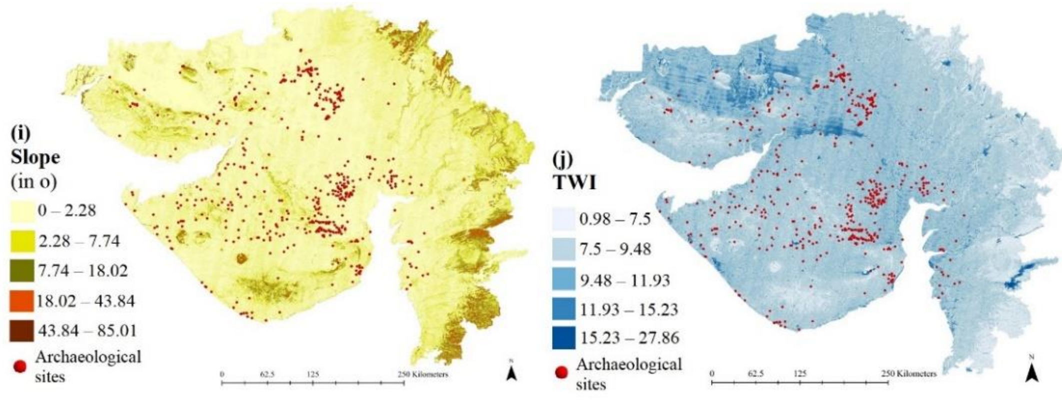

Fig. 4. susceptibility parameters (i) Slope and (j) Topographic Wetness Index (TWI).

2.4. Analytical Hierarchy process (AHP)

The Analytic Hierarchy Process (AHP), proposed by Saaty in (1980), is a widely used method for multi-criteria decision-making. AHP can effectively address various types of problems, including choice, sorting, ranking, and description. This method allows decision-makers to make subjective decisions based on weights and pairwise comparisons.

The AHP methodology involves three main steps: Define the Problem: Identify the goal of the study. Calculate Pairwise Comparisons: Establish a three-level hierarchical structure where the goal is at the top, followed by attributes or criteria, and then alternatives at the bottom. Determine the importance of each criterion relative to the goal using pairwise comparisons represented in a matrix. A scale of relative importance, usually ranging from 1 to 9, is used to assess this importance.

Check Consistency: Calculate a normalized pairwise comparison matrix by dividing all elements in a column by their sum. The criteria weights are then derived by averaging the values in each row. Consistency in the decision-making process is evaluated using the eigenvalue (λ_{max}), which is obtained by averaging the ratios of the weighted sum value to the criteria weights. For a decision to be considered acceptable, the Consistency Ratio (CR) must be less than or equal to 0.1 (**Table 1**).

Table 2.

Reclassification of the parameters used in the generation of flood susceptibility map.

Parameter	Reclassification			Parameter	Reclassification		
	Method	Classes	Score		Method	Classes	Score
Clay content (%)	Natural breaks (Jenks)	0 – 8.94	1	LULC	Supervised classification	Tree cover	1
		8.94 – 21.2	2			Water bodies	2
		21.2 – 31.59	3			Cropland	3
		31.59 – 43.85	4			Builtup	4
		43.85 – 53	5			Bare/sparse vegetation	5
Distance from rivers (m)	Natural breaks (Jenks)	0 –12625.97	5	NDVI	Natural breaks (Jenks)	-0.74 – -0.19	5
		12625.97 – 30512.75	4			-0.19 – 0.01	4
		30512.75 – 53660.36	3			0.01 – 0.15	3
		53660.36 – 82068.78	2			0.15 – 0.28	2
		82068.78 – 134150.89	1			0.2 – 1	1
Distance from roads (m)	Natural breaks (Jenks)	0 – 3069.57	5	Rainfall deviation (mm)	Natural breaks (Jenks)	-99.99 – -91.28	1
		3069.57 –7290.24	4			-91.28 – -81.22	2
		7290.24 –13237.54	3			-81.22 – -63.78	3
		13237.54 – 24172.9	2			-63.78 – -32.94	4
		24172.9 – 48921.34	1			-32.94 – 71	5
Drainage density (m/ha)	Natural breaks (Jenks)	0.05 – 0.6	1	Slope (^{O})	Natural breaks (Jenks)	43.84 – 85.01	1
		0.6 – 0.88	2			18.02 – 43.84	2
		0.88 – 1.13	3			7.74 – 18.02	3
		1.13 – 1.56	4			2.28 – 7.74	4
		1.56 – 2.8	5			0 – 2.28	5
Elevation (m)	Manual interval	< 10	5	TWI	Natural breaks (Jenks)	0.98 – 7.5	1
		10 – 50	4			7.5 – 9.48	2
		50 – 100	3			9.48 – 11.93	3
		100 – 200	2			11.93 – 15.23	4
		> 200	1			15.23 – 27.86	5

2.5. Weighted overlay

To get the final flood susceptibility map of Gujarat, a weighted overlay analysis (**Table 1**) of the reclassified layers was done by assigning the criteria weights calculated using AHP.

2.6. Multicollinearity analysis

As mentioned above, in MCDM, various attributes or criteria related to the problem are initially selected randomly, after which their independence is assessed. To evaluate this independence, a multicollinearity analysis is conducted. In this study, ten parameters were selected to create a flood susceptibility map based on the climate and geography of the area of interest. To check for independence among these parameters, multicollinearity tests were performed using Tolerance (TOL) and Variance Inflation Factor (VIF) metrics. A TOL value greater than 0.1 and a VIF value below 10 indicate that the parameters are independent (**Table 1**). Once the flood susceptibility dataset was generated, 500 random points were selected on the final susceptibility map to check the independence of parameters, and tolerance (TOL) and Variance Inflation Factor (VIF) were calculated for them.

2.7. Accuracy assessment

Post-classification accuracy assessments are essential for evaluating the precision of results. In this study, accuracy tests for flood susceptibility were conducted using various online datasets and fieldwork, employing the Receiver Operating Characteristic (ROC) curve for analysis.

To assess the flood susceptibility map, 90 random points were generated, and the ROC curve was calibrated. The true positive values, which represent known events such as floods, are plotted along the Y-axis. The Area Under the Curve (AUC) provides a measure of how well the calibrated data matches the known data. AUC values are interpreted as follows: 0.5–0.6 indicates poor prediction; 0.6–0.7 indicates average prediction; 0.7–0.8 indicates good prediction; 0.8–0.9 indicates very good prediction; and 0.9–1 indicates excellent prediction accuracy (Bhagya et al. 2023).

Additionally, flood levels were visualized through the classification of Landsat images taken before and after the monsoon season 2023. The Normalized Difference Water Index (NDWI) was calculated (Xu, 2005) to clearly illustrate changes in flood extent.

3. RESULTS

3.1. Multicollinearity results

A multicollinearity regression analysis was conducted to assess the independence of parameters. The analysis showed that the Variance Inflation Factor (VIF) values are significantly below 10, and all Tolerance (TOL) values are above 0.1. This indicates that the selected parameters are independent (**Table 3**).

Table 3.

Multicollinearity analysis results.

Parameter	R^2	VIF	TOL
Clay content	0.02	1.02	0.98
Dist. from Rivers	0.24	1.31	0.76
Dist. from Roads	0.22	1.28	0.78
Drainage Density	0.15	1.17	0.85
Elevation	0.41	1.69	0.59
LULC	0.15	1.18	0.85
NDVI	0.3	1.43	0.7
Rainfall Deviation	0.09	1.1	0.91
Slope	0.45	1.82	0.55
TWI	0.24	1.31	0.77

3.2. Weights of the parameters from AHP

A pairwise comparison matrix was established using the Analytic Hierarchy Process (AHP) to calculate the criteria weights of each parameter. From this analysis, it was found that the maximum eigenvalue (λ_{max}) was 11.26, the Consistency Index was 0.14, and the Consistency Ratio was 0.09. These values indicate the validity of the calibrated pairwise matrix and the corresponding criteria weights (**Table 4**).

Table 4.

Pairwise matrix generated from Analytical Hierarchy Process.

AHP	Clay content	Dist. from rivers	Dist. from roads	Drainage density	Elevation	LULC	NDVI	Rainfall deviation	Slope	TWI	Criteria Weights
Clay content	1	1	5	1	3	3	2	1	2	1	**0.14**
Dist. from rivers	1	1	7	2	3	5	3	2	2	1	**0.18**
Dist. from roads	0.2	0.14	1	0.33	0.33	1	0.2	0.33	0.2	0.2	**0.03**
Drainage density	1	0.5	3	1	2	3	1	2	2	1	**0.12**
Elevation	0.33	0.33	3	0.5	1	3	3	2	1	0.33	**0.09**
LULC	0.33	0.2	1	0.33	0.33	1	3	0.2	0.33	0.33	**0.04**
NDVI	0.5	0.33	5	1	0.33	0.33	1	0.2	0.2	1	**0.06**
Rainfall deviation	1	0.5	3	0.5	0.5	5	5	1	2	1	**0.12**
Slope	0.5	0.5	5	0.5	1	3	5	0.5	1	0.5	**0.09**
TWI	1	1	5	1	3	3	1	1	2	1	**0.13**

3.3. Flood hazard map of Gujarat

To determine the final flood susceptibility for Gujarat, a weighted overlay analysis was performed using the criteria weights obtained from AHP. The weighted overlay categorizes the resultant map into five classes based on their probabilities. These categories are labeled as very low, low, moderate, high, and very high, indicating varying levels of flood susceptibility.

The final susceptibility map reveals that much of the study area falls into the moderate flood susceptibility category, followed by high susceptibility. Notably, areas of very high susceptibility were identified in the southern regions of Surat and Tapi districts (**Fig. 6**). The extent of flood susceptibility for each individual class is detailed in **Table 5** below.

Table 5.

Flood hazard susceptibility zone and the corresponding percentage of area in Gujarat.

Flood susceptibility	Percentage of area (sq. km)
Very low	12179.1
Low	9331.42
Moderate	141620
High	32888.8
Very High	4.96

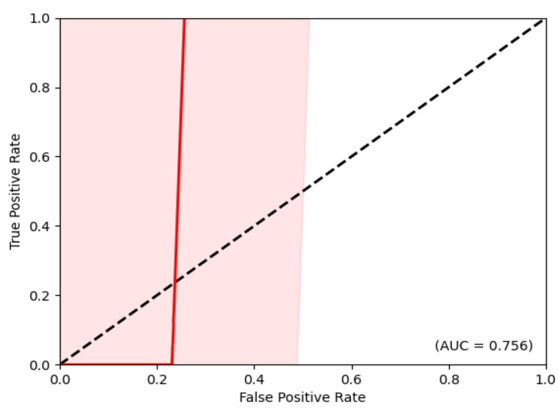

Fig. 5. Area under the Curve (AUC) value for flood susceptibility data.

3.4. Accuracy test results

To evaluate the accuracy of the final flood susceptibility parameters, the Area Under the Curve (AUC) from the Receiver Operating Characteristic (ROC) analysis was utilized. The AUC was determined to be 0.76 based on ground data, indicating that the dataset provides a good prediction of actual conditions (**Fig. 5**).

3.5. Cultural heritage quantitative risk assessment results

Using the method of superimposition described in section 2.1, the assessment of 508 studied sites revealed that 188 are of high priority, 99 are of medium priority, and 221 are of negligible priority (**Fig. 6**).

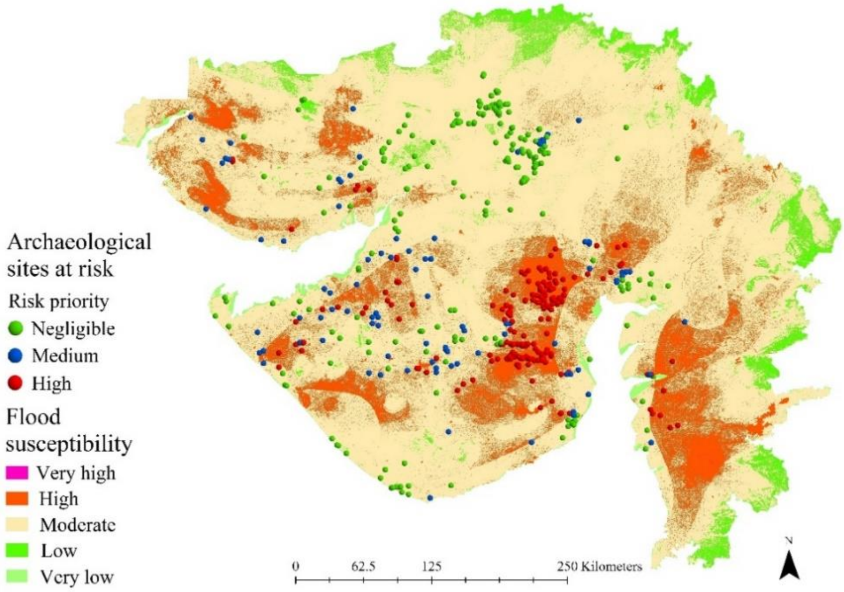

Fig. 6. Map showing flood susceptibility of Gujarat and archaeological sites at risk from floods.

4. DISCUSSION

The susceptibility to flooding was assessed by examining ten different factors and employing a multi-criteria decision-making (MCDM) method. MCDM is based on the premise that multiple factors can contribute to the occurrence of floods. Through this approach, it was determined that 188 sites are at high risk of flooding. While it can be challenging to identify the most significant factor contributing to flooding, certain general observations can be made. For instance, all high-risk sites exhibit similar characteristics.

Data analysis indicates that altitude is likely not a contributing factor to flooding in these areas. The slopes in these regions are not steep, and the topographical wetness index (TWI) is low, suggesting relatively flat terrain with limited water accumulation or rapid flow. Additionally, it was noted that the proximity of archaeological sites to rivers is significant, and the drainage density in these areas is also high. All the sites in high risk are located in regions with high clay content, which increases their susceptibility to flooding, especially when vegetation is limited.

Furthermore, rainfall data indicates a decline in precipitation levels compared to the average over the past decade. Most of the sites are situated in agricultural fields or shrublands that are in close proximity to water bodies or primary roads. These factors suggest that even with moderate rainfall, the probability of flooding at these sites remains high. The Normalized Difference Water Index (NDWI) was calculated using the specified formula for both pre- and post-monsoon seasons. According to the flood susceptibility dataset, a noteworthy increase in surface water has been observed in the Saurashtra region, particularly in Bhavnagar, Botad, and the southern areas of Surendranagar and Ahmedabad districts. Unfortunately, these areas contain a high concentration of unexcavated sites that are now at significant annual flood risk (**Fig. 7**). Additionally, prominent sites such as Jaidak/Pithad and Rojdi also show a rise in surface water following the monsoon season.

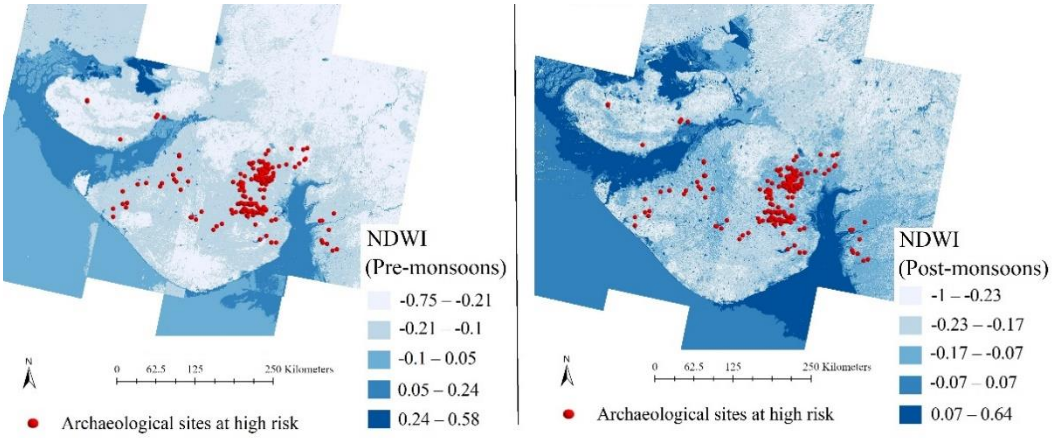

Fig. 7. Normalized Difference Water Index (NDWI) of showing pre and post monsoons period in Gujarat along with archaeological sites at risk from floods.

Further, the risk of floods at several significant archaeological sites is outlined below.

1. *Lothal:* Lothal (22°31'23.2"N, 72°14'57.6"E), located in Ahmedabad District, is a nationally protected archaeological site that offers valuable insights into the town planning of the Harappan civilization. Features such as an acropolis, lower towns, well-organized streets, advanced drainage systems, and a dockyard illustrate its maritime trade. Historically, Lothal has suffered considerable damage from floods; however, the current area is protected and is not under high risk. Conservation efforts, including improved water drainage, have mitigated flooding risks at the site. Nevertheless, the nearby buffer region remains at high risk of flooding. The high drainage density and elevated values of the Topographic Wetness Index (TWI) suggest that water accumulation is more likely in this area, potentially threatening the conservation of both the site and its surroundings (**Fig. 8a**).
2. *Rangpur:* Rangpur (22°24'14"N, 71°55'37.6"E) is another nationally protected site located in Surendranagar District. It provides evidence of a cultural trajectory from the Harappan civilization to the Lustrous Red Ware Culture, divided into four phases: RGP IIA (Harappan period, 2000-1500 BCE), RGP IIB (Late Harappan, 1500-1100 BCE), RGP IIC (Transitional Phase of Harappa Culture, 1100-1000 BCE), and RGP III (Lustrous Red Ware, 1000-800 BCE) (Rajesh, 2011). The site is at high risk of flooding, situated next to the Bhadar River, which features high drainage density and proximity to major roads, making it particularly susceptible. Additionally, the area's high clay content inhibits water absorption, heightening the flood risk. Despite experiencing less rainfall than average in the last decade, it remains vulnerable due to elevated water levels in surrounding rivers (**Fig. 8b**). Unfortunately, the Rangpur archaeological site is currently buried under a village, and after heavy rainfall, valuable artifacts like pottery and bones are washed out, exposed, and often discarded by villagers during cleanup efforts, leading to a significant loss of important archaeological information.
3. *Valabhipur:* Valabhipur (21°53'39.5"N, 71°52'25.3"E), a significant site in Bhavnagar District, is also nationally protected. Excavated by Father Heras in 1930, it was the first Harappan site discovered in Gujarat (Shirvalkar, 2013). Despite its protected status, Valabhipur faces risk from floods. Positioned between urban areas and adjacent to a water body, it experiences significant drainage density and lacks adequate conservation measures

and vegetation cover as indicated by low NDVI values. As a result, even with minimal rainfall, Valabhipur is vulnerable to flooding (**Fig. 8c**).

4. *Jaidak / Pithad:* The site (22°40'N, 70°35'E) is located in Pithad Village, Jamnagar District. Excavations classify it within the Late Harappan phase, based on the similarity of its pottery assemblage to Rangpur IIB and IIC (Ajithprasad, 2003; 2008). Jaidak is at high risk of flooding, primarily due to its location on the right bank of the Aji River and its streams, exacerbated by the construction of a check dam nearby, which has led to increased drainage density. The area's high clay content further hampers water absorption, increasing flooding likelihood. Despite experiencing less rainfall than average over the past decade, Jaidak remains at high risk due to elevated water levels in surrounding water bodies (**Fig. 8d**).
5. *Rojdi:* Rojdi (21°51'45.8"N, 70°55'15.7"E), located in Rajkot District, was excavated by Possehl et al. (1989), leading to the identification of a new culture termed the 'Sorath Harappan culture.' The pottery from this site deviates substantially from the mature Harappan style, lacking typical forms and decorations, and does not feature classical Harappan seals or elaborate architecture. Artifacts such as copper tools, stone beads, and shell bangles were either absent or found in very limited quantities. The excavation confirmed three periods of occupation: Rojdi A (2500–2200 BCE), B (2200–1900 BCE), and C (1900–1700 BCE). Similar radiocarbon dating helps date numerous other Chalcolithic sites in Gujarat. Rojdi is also at high risk of flooding due to its proximity to the Bhadar River and a stream that flows through the site, resulting in high drainage density. The high clay content of the soil further complicates water absorption, increasing the chances of flooding (**Fig. 8e**).
6. Khanpur: Khanpur (22°29'N, 72°23'E) is situated in the Ahmedabad district and is classified as belonging to the mature Harappan and Sorath Harappan cultures (IAR, 1972–73). The site faces a high risk of flooding for several reasons. Firstly, the area has a high Topographic Wetness Index (TWI), indicating a greater likelihood of water accumulation. Additionally, there are two channels in the vicinity that transport water, and the drainage density is also high. However, unlike other sites with significant clay content, Khanpur has low clay levels. This characteristic should make the area less prone to flooding, as the lower clay content allows water to percolate into the ground more easily, thereby reducing surface runoff. But the proximity of the site to a major highway increases its vulnerability to flooding (Parveen and Kumar, 2012). The combination of high drainage density and the presence of water channels further contributes to the flooding risk in this low-lying area. Currently, the site remains unprotected and is being utilized by the local population for brick manufacturing (**Fig. 8f**).

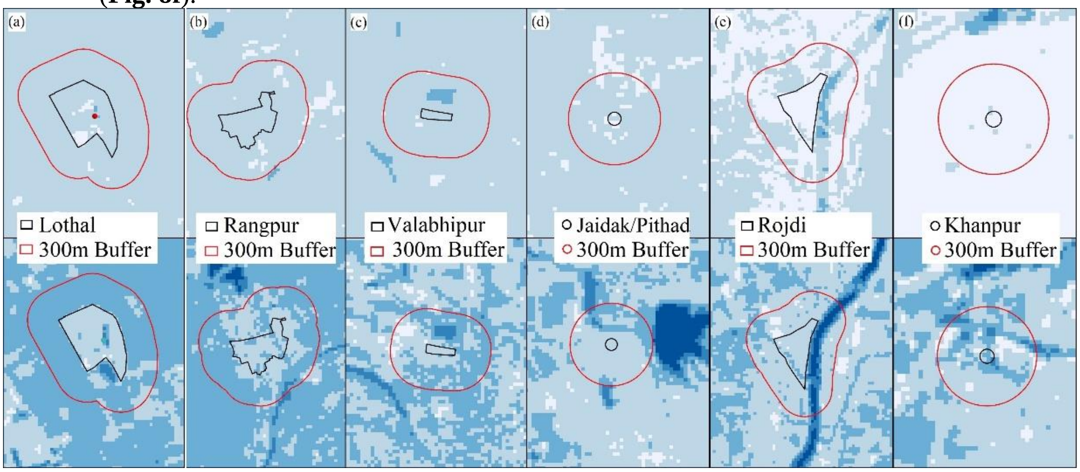

Fig. 8. Normalized Difference Water Index (NDWI) during pre-monsoon (top) and post-monsoon (bottom) periods at prominent high-risk sites.

5. CONCLUSION

The results indicate that many archaeological sites in Gujarat are at risk from natural hazards, with 188 sites specifically noted as vulnerable to floods. It is evident that risk can be managed with appropriate protective measures, as illustrated by the case of Lothal. Therefore, this study recommends prioritizing the protection of prominent sites such as Jaidak and Rojdi. These sites' easy accessibility and their significant contributions to scientific knowledge make them ideal candidates for preservation. Unlike sites located in agricultural fields, these locations do not fall under private ownership, making conservation efforts more feasible.

In addition to protection, it is crucial to share the information gained from archaeological excavations, including results and interpretations (ICOMOS, 1990; 1996; 2011), especially for sites situated in agricultural fields and on private properties. Failure to do so increases the risk of obscurity due to inaccessibility.

Moreover, archiving archaeological information and interpreting excavation findings is essential. Therefore, a GIS-based inventory is recommended, which should include site locations, excavation statuses, ownership information, identified risks, and potential conservation measures. This inventory should be periodically updated.

Finally, by employing diverse geological, statistical, and spatial techniques, this study aimed to bridge the gap between natural sciences and cultural heritage management. It presented a method for conducting risk assessments, particularly concerning archaeological sites. While this study only evaluated one risk, flooding, many other risks, such as erosion and urban encroachment, also need to be assessed.

Data Availability

The input data used in the study is openly available from the following sources.

1. The Digital Soil Map of the World (DSMW) is available at the Food and Agriculture Organization (FAO) website: https://www.fao.org/home/en/
2. The Geomorphology and roads of India shapefiles are available at the Geological Survey of India (GSI) website: https://bhukosh.gsi.gov.in/Bhukosh/Public
3. The Cartosat Digital Elevation Models (DEM) are available at the Indian Space Research Organization (ISRO) website: https://bhuvan.nrsc.gov.in/home/index.php
4. The WorldCover dataset is available at the European Space Agency (ESA) website: https://worldcover2021.esa.int/
5. The landsat 8 dataset is available at the United States Geological Survey (USGS) website: https://earthexplorer.usgs.gov
6. The rainfall data of India is available at the Indian Meteorological Department (IMD) website: https://mausam.imd.gov.in/

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