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Spatialization of soil erosion and flood hazards using analytic hierarchy process modeling in Northern Morocco

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ABSTRACT

Soil erosion is considered one of the major problems in the Mediterranean regions that experience sudden floods and poor water flow control policies. Risk mapping is an essential tool for understanding natural processes affecting the ecology, economy, and citizens of these regions. The present research focuses on finding the flood and erosion-prone zones in a district of Morocco called Fahs-Anjra. By applying a specific method, namely the analytical hierarchy process (AHP), it was possible to achieve an accuracy of 76% regarding erosion probability and 89% with respect to flooding. The produced maps showed that more than 50% of the area had a medium risk for flooding and erosion, while 16% to 37% had a high risk. This would mean their evaluation method is significantly reliable. These results are important to understand in terms of devising flood and erosion mitigation strategies for the future, which is highly relevant to regional planning in these areas.

Keywords: erosion, flood, Fahs-Anjra, vulnerability, AHP, ROC.

INTRODUCTION

Soils erosion depends on many factors, which include heavy rainfall, irregular topography, and the disturbance of vegetation cover (Diodato et al., 2022). Such a process results in the decrease of sediment conveyance in aquatic systems and reduces the productivity capacity of land while increasing its vulnerability to flooding (Kayet et al., 2018). The various types of risks associated with river valley systems, such as soil degradation and flooding, make the challenges very serious for the Northern Morocco region (Loudyi et al., 2022). Such a threat is increased due to the interaction of geographical factors, climate change, and human activities (Hssaisoune et al., 2020), thus putting already fragile ecosystems and the social well-being of the region at risk (Sired, 2024). Climate change has made an already vulnerable region experience increasing soil erosion and increased predisposition to flood impacts; that is the scenario more especially in Northern Morocco. Soils are rapidly weathering as a result of rainfall's changing patterns towards intensified downpours, making flash floods common during upbeats (Kebede et al., 2021). On an ecosystem and community scale, these changes interfere with a proper hydrological equilibrium of the environment. Studies have shown that areas with less vegetation cover are more vulnerable, especially because vegetation is necessary for soil stabilization and excess water absorption during heavy rainfall (Rojas et al., 2023). Unless proactive steps are taken, these cumulative factors are most likely to continue in worsening land quality and threatening agricultural productivity, which is central to the livelihood of the local communities. Unstained agricultural practices and degradation of vegetation, in general, result in soil erosion rates enhanced over recent decades (Farhan et al., 2018; Benzougagh et al., 2021). The northern regions of Morocco present a unique geographical position at the level of the intersection between Pre-Rif, South-Rif corridor, and Middle Atlas (Benzougagh et al., 2021). This complex situation, added to socioeconomic vulnerabilities, enhances the negative consequences of flooding upon the local populations of this area (Bouaakkaz et al., 2023). According to Olorunfemi et al. (2020), sustainable land management practices must be applied for long-term sustainability of the ecosystem. Natural risk mapping shows the area most prone to the risk; it also supports the designing and promoting protective policies to mitigate the hazards and, hence, protecting the vulnerable populations, since it decreases the probability of disaster occurrences (Li et al., 2014). These practices can mitigate environmental degradation, thereby making the land secure (Neeraj et al., 2020). On top of natural processes, most land alterations caused by humans tend to make soil erosion and flooding more probable. Human activities of building cities, deforestation, and poor farming techniques ruin the soil, increase water runoff, and alter how water drains, thereby increasing the chances of both soil erosion and flooding (Hossain et al., 2022). Accelerated urbanization and inept land-use policies in northern Morocco have given rise to several vulnerability hotspots where areas with greater population density are exposed to higher risks from natural disasters (Boukherroub et al., 2023). In order to limit the negative impacts of these phenomena, certain adaptive land-use practices, notably reforestation and soil conservation, must be integrated into the development plans of the region. Analytic Hierarchy Process is one of the most frequent methods of multi-criteria decision analysis based on evaluating the relative importance of various parameters (Saaty, 1987). It uses a hierarchic structure for the simultaneous consideration of several criteria that influence an extreme phenomenon (Saaty, 1980). With its integration in GIS, the AHP methodology enables correct estimation for arid regions where such phenomena are more frequent (Nasir et al., 2024). This method, combined with several other modeling approaches, is often used in making maps that classify regions into risk zones based on specific levels (Tariq et al., 2022; Tairi et al., 2019). Indeed, such maps are considered very crucial tools for the implementation of land management practices to reduce the impacts of sudden and intense natural disasters (Aichi et al., 2024). Correspondingly, the analytic hierarchy process (AHP) integrates the major causes of erosion and flood, such as "precipitation distribution, vegetation cover, soil composition, slope, drainage systems, and density" (Ouma and Tateishi, 2014). Brito and Evers, (2016) established that the most essential driving forces for flood risk assessment are precipitation by 42%, slope by 23%, and altitude by 15% (Pasaribu et al., 2023). Similarly, Bousaleh et al. (2014) showed that the AHP can combine different sets of data to create a comprehensive and dependable erosion and flood risk maps in order to aid decision-making. Advancements in geospatial technologies have provided researchers and practitioners with critical tools for assessing and managing numerous hazards. The combination of the Analytic Hierarchy Process and Geographic Information Systems has thus empowered academics and policymakers to create elaborate maps showing risk zoning based on the susceptibility of regions to erosion and flooding (Rahmati et al., 2022). It, therefore, means that such maps provide very critical information to facilitate informed decision-making in terms of pointing out high-risk areas so that resources intended for mitigation initiatives can be placed in a strategic manner. Furthermore, it is important to note that the integration of the Analytic Hierarchy Process with machine learning methodologies will improve the precision level of the risk assessment significantly in a complex landscape such as Northern Morocco (Chen et al., 2024). The aim of the present research is to utilize the analytical hierarchy process methodology in evaluating and explaining the likely dangers of flooding and soil erosion in the Fahs-Anjra area in the north of Morocco. The present research combines the key environmental and topographic determinants with a significant impact on the vulnerability to erosion and flooding, such as slope gradient, soil type, vegetation cover, land use types, and rainfall intensity. For reliability and accuracy, the resulting risk maps are verified through the integration of satellite image analysis and field surveys. This enables testing the performance of the model in identifying zones of potential erosion and flood risk stringently. In addition to the technical mapping techniques, the study also purports to establish a foundational database that will become an essential aspect in formulating sophisticated risk management strategies. Such strategies are poised to benefit the local governments, policymakers, as well as other stakeholders in facilitating the implementation of sustainable land use policies and the proactive approach of mitigation. This research aids in the long-term preservation of natural ecosystems and indigenous communities through increasing the region's resilience to environmental adversity, enabled by the implementation of a more climate-resilient and sustainable land management system.

MATERIALS AND METHODS

Study area

Fahs-Anjra is a province in the western coast of the Mediterranean Sea in Morocco, forming part of the region of Tanger-Tétouan-Al Hoceima. It is placed geographically between latitudes 35° 38' N and 35° 23' N and between longitudes 5° 43' W and 5° 23' W; it has an area of 693.4 km² (Figure 1). This province is composed mostly of rural communes and harbors a population of about 76,447 inhabitants living along the Strait of Gibraltar, including important cities such as the port of Tanger-Med. The province has a Mediterranean climate; it is relatively humid in winter and dry in summer. The average annual temperature is 17.8 °C, and the annual rainfall is about 667 mm.

The region is being modernized through a process of urbanization with the new city of Cherrafat and with business and activity centers in Mellousa. FAhs-Anjra is faced with some environmental and developmental issues in social, just, and human aspects (Sired, 2024).

Data sources

The analytic hierarchy process is able to offer a systematic approach for the determination of the relative importance of different factors, contributing to soil erosion and flood susceptibility.

Integration of such ranked variables in a GIS allows detail in creating risk maps and classifying the area into classes with high, moderate, and low risks The first step in this study starts with the identification of major controlling factors for erosion and flood vulnerability, which comprise topographic data as well as the hydrologic network to be extracted from digital elevation models (DEM) based on SRTM satellite imagery. The geologic data were derived from the 1:50,000 geological map of Fahs-Anjra (Table 1). The methodological flowchart shown in Figure 2 is designed to derive systematically the vulnerability to erosion as well as flooding. A decision hierarchy was followed to establish a methodology that would achieve the objectives of research. This is because each criterion had a relative importance evaluated using pairwise comparisons to derive the weights, which were assigned to their contribution to erosion and flood risks.

Such weighted criteria were then used to classify areas into different risk categories, which results were integrated into a GIS that gives a visual presentation of the risk distribution. This integrated approach using AHP and GIS together enables the identification of high-risk areas,

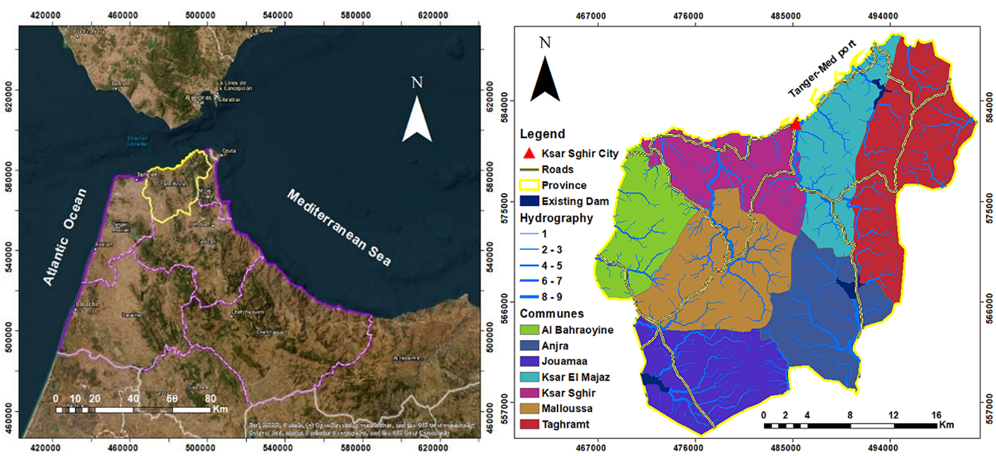

Figure 1. Maps of the geographical position of Fahs-Anjra province in northern Morocco

Table 1. Methods used to set parameter values for the AHP modeling

Data	Description	Source
SRTM[1]	Downloaded (Resolution 30 m)	https://earthexplorer.usgs.gov
TWI[2]	Derived from DEM 30 m	DEM 30 m
Landsat 8 OLI[3]	Downloaded (2021)	https://earthexplorer.usgs.gov
Slope	Derived from DEM 30 m	DEM 30 m
Elevation (m)	Derived from DEM 30 m	DEM 30 m
NDVI[4]	Derived from Landsat 8 OLI	Landsat 8 oli image
Rainfall	Downloaded (2018–2023)	http://power.larc.nasa.gov/data
Land use	Derived and field observation	Landsat 8 oli image
Roads	Extracted	Google Earth
Rivers	Extracted	DEM5 30 m
Erosion and flood location	Evidence within the study area	Field data

Note: [1]The shuttle radar topography mission, [2]Topographic wetness index, [3]Operational land imager, [4]Normalized difference vegetation index, [5]Digital elevation model

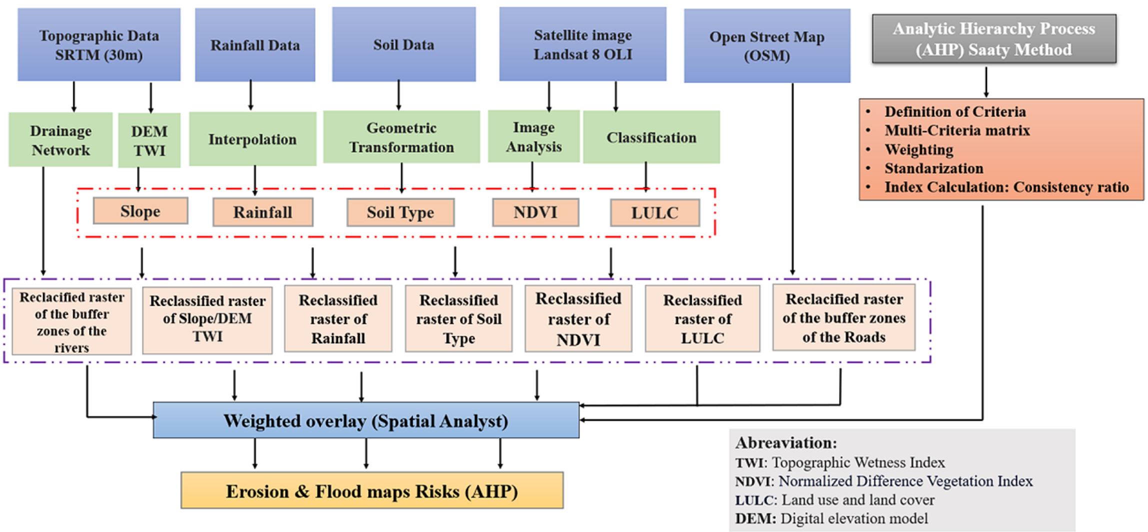

Figure 2. Flowchart methodology followed in the study

which further helps in making informed resource management decisions within the study area. All this requires careful data preparation within AHP modeling, going through GIS preprocessing, determination of the evaluation hierarchy, weight quantification of factors, consistency, and integration of weighted factors to produce final maps. Another crucial step at the end results in validation. The methodological course of action followed in this study from data acquisition through the creation of the erosion and flood risks final map is hereby presented.

Data preparation

Upland surfaces increase the speed of water flow, hence increasing soil erosion and the risk of flooding. The type and nature of soil also highly determine its water absorption potential, sediment transport, and level of surface runoff. Also, important to reducing soil erosion and slowing down the runoff of water are land use practices and the level of vegetation cover. The most driving factor of risks affecting both soil detachment and water accumulation is precipitation. On one side, floods increase erosion by dislodging soil particles and transporting sediments; on the other side, erosion enhances flood risk because it reduces the capacity of rivers and drainage channels, hence increasing the potential for flooding. Holistic modeling approaches, such as AHP, are therefore well suited to capture these complex interactions between soil erosion and flood risks. The current methodological framework allows developing strategies for risk management, including the strengthening of vegetative cover and effective execution of runoff management methods. This integral approach will provide practical tools to use for the attenuation of the effects of erosion and flood impact on regions at high risk (Fig 3).

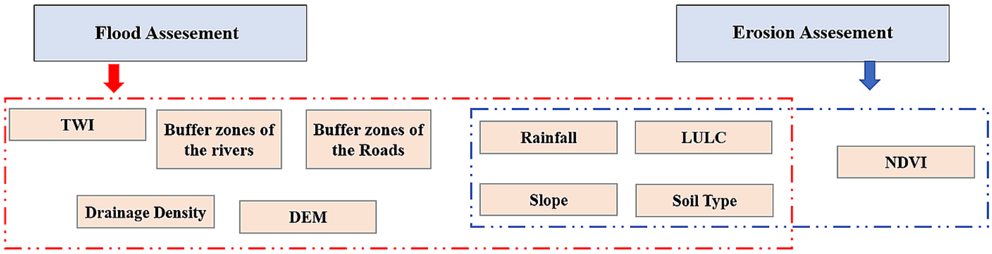

Figure 3. Suitability hierarchy input data for erosion and flood risks

AHP modeling approaches

The AHP is based on three basic principles: identification of the components, decomposition, comparative analysis, and prioritization Table 3. AHP is an extensively practiced process that has been recognized through its logical and detailed approach to helping find solutions to complex multi-criteria problems. Decomposition theory forms part of the AHP when a problem is decomposed from its highest level down into smaller components in which case their solution becomes much easier. This methodology enables decision-makers to solve complex problems efficiently and effectively (Saaty, 1983).

The analytical hierarchy process (AHP) is the technique used in evaluating the importance of different parameters and comparing their relative importance. Ait Kacem et al. (2019) and Saaty (1989) assert that the chosen parameters must exhibit logical consistency, which can be obtained by calculating the consistency ratio, whose value is between 0 and 1; it helps in validating the existing values in the matrix. The above ratio, which is denoted by CR, is computed as in Equation 1; the inclusion of CR, therefore, is very necessary if the integrity of the decision-making process is to be upheld.

$$CR = CI/RI \tag{1}$$

The consistency index is obtained by using the following equation (Eq. 2). While the Random Index depends on the Random Index (Table 4) depends on the number of criteria, n (Echogdali et al., 2018).

$$CI = (\gamma max - n)/(n-1) \tag{2}$$

The maximum eigenvalue (λmax) is obtained through this equation (Eq. 3), ws is the eigenvector which the priorities of the criteria or alternatives, wc is normalized weight (priorities) of criteria or alternatives.

$$\gamma max = Average\ (ws/wc) \tag{3}$$

Validation procedures

The erosion hazard is defined as land areas' susceptibility to erosion, and scoring should provide

Table 3. Saaty's scale of preference (Saaty, 2008)

Intensity importance	Definition
1	Equal importance
2	Moderate importance
3	Importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong
8	Verry, very importance
9	Extreme importance

Table 4. RI used to compute CR (Saaty, 1980)

N	1	2	3	4	5	6	7	8	9	10
R	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

the levels of erosion risks. In that direction, 70 points will represent erosion, while 26 stands for flood risks. In addition, restoration in cases of erosion can be considered merely in a simulation way. Given this scenario, recorded actual erosion should be integrated with simulated data in the research to determine the percentage of deviation using the method proposed by Mihi et al. (2019). The formula for accuracy, intended to ensure the reliability of the predictive system, shall now be used:

$$\text{Accuracy} = \frac{\text{Number of correctly assesed sample}}{\text{Total number of samples}} \times 100 \quad (4)$$

The delineation of flood and erosion hazard areas is based on field sample points and satellite data; this initial data is critically reviewed for better accuracy in risk delineation. As stated by Rahmati et al. (2019) and Arabameri et al. (2020), the accuracy of the risk model is appraised by using the receiver operating characteristics (ROC) curve. Using ArcSDM tool in ArcGIS 10.8 version, geospatial layers of contextual variables of erosion and flood susceptibility are developed. The effectiveness of this prediction model has been evaluated by the Area Under the Curve (AUC) metric. It is expressed that AUC values ranging between 0.8 and 0.9 indicate a good fit of the models, while for values ranging between 0.9 and 1, the model has an excellent performance according to Razavi-Termeha et al., 2020. The AUC is derived from the rate curves plotted during the analysis, hence giving an assessment on the system's ability to model the risk areas effectively. The integration of AUC values into the process of evaluation allows validation of the reliability of the developed predictive model in producing risk maps, hence ensuring that the results are robust and feasible for erosion and flood hazard management.

RESULTS AND DISCUSSIONS

Maps factors

Soil erosion and flood risks should be assessed in the general management of land use, more so in ecologically fragile countries like Morocco. According to Boufala et al. (2020), morphometric analysis may describe the source of these dangers by considering geographical and topographical characteristics, including drainage systems and land use patterns. Mostakim et al., 2021. The most relevant factors controlling soil erosion risk are vegetation cover, slope, land use/land cover, rainfall erosivity, and soil erodibility, which are painstakingly collected, classified, and standardized for analysis. These are the topographic wetness index, rainfall, drainage density, proximity to rivers and roads, LULC, altitude, and slope, among others, which give insight into flood susceptibility when integrated with past research (Bannari et al., 2016; Darabi et al., 2019; Yang et al., 2018). Precise pre-processing and analysis have been made using advanced ArcGIS 10.8 and Envi 3.4 software. More specifically, the Line Density tool in ArcGIS will help in calculating drainage densities, as it divides the total stream length by an area of a selected grid—information that is always important for water management and prevention of floods (Fig. 4).

NDVI

First, the dataset from the Landsat-8 OLI sensor: the satellite images of Landsat are then processed to answer the research question and create a map showing the NDVI; the images from Landsat are acquired in 2021 and downloaded from the United States Geological Survey (USGS); the satellite has great characteristics in the study area, such as a 30 meters spatial resolution, covering the infrared spectrum in the later bands, a large coverage area, and many acquisition dates available online.

Soil map

The prime cause of offloading genesis is insufficient water absorption by the soils O'Mara et al. 2019. Hence, determination of the soil types of the area of study and a corresponding soil map needs to be done and can be carried out using FAO soil data at a scale of 1:3,000,000. The three major classes of soil that have been extracted divide the area into loamy soil in the northeast, sandy loam, which predominates most of the study area, and clay soil in the southern region near the Ibn Batouta Dam (FAO/UNESCO, 2003).

Land use land cover

Land use information in the study area was obtained based on high spatial resolution data with 20 meters of granularity in the Sentinel-2A dataset (ESACCI, 2016). The study area was classified into nine major classes of land use/cover: tree-covered areas, shrub-covered areas, grasslands, croplands, lichen mosses/sparse vegetation, barren lands, developed lands, and open water bodies. Monthly and annual precipitation information for the research exercise was extracted as source material from the NASA Power Projects DAV – Time Series Data Set.

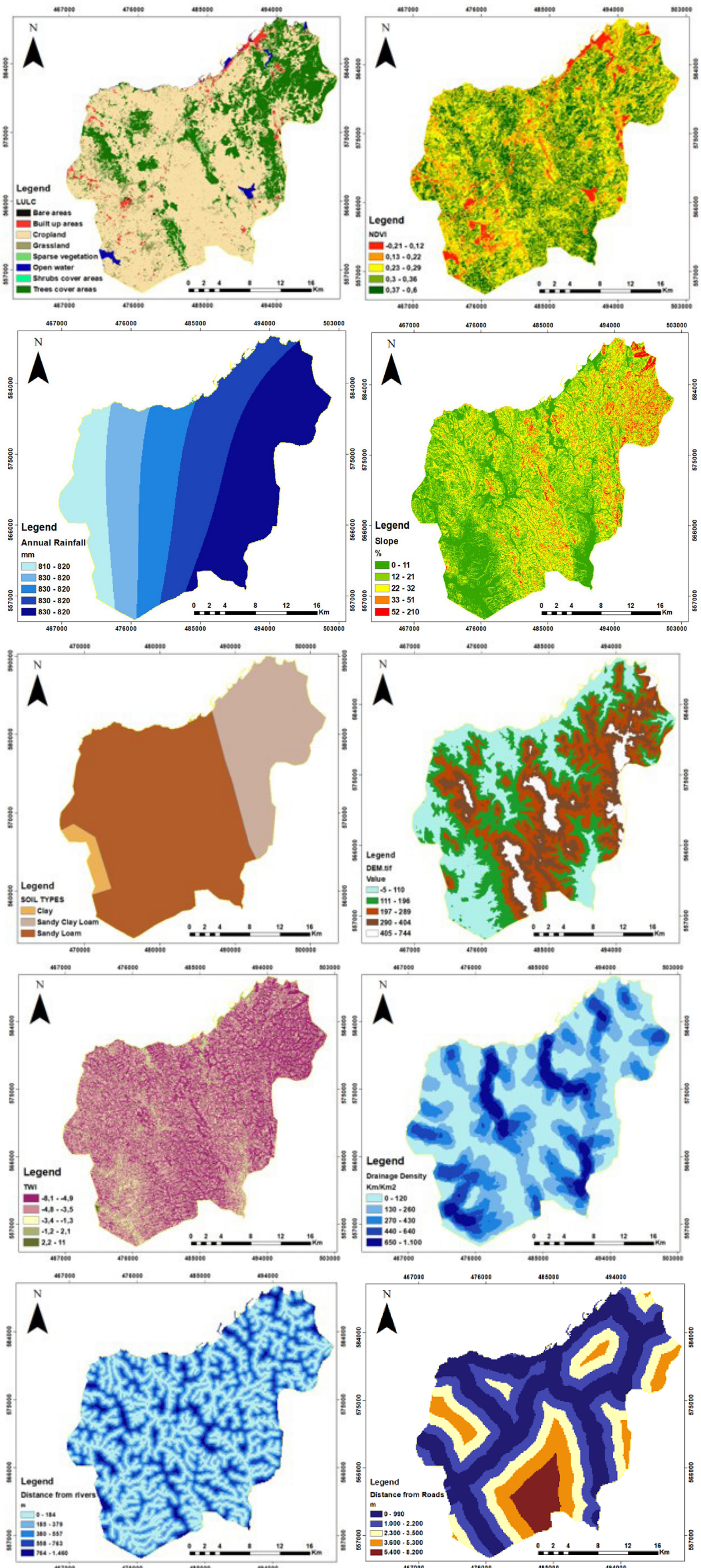

Figure 4. Input data for erosion and flood risk maps showing: LULC (a), NDVI (b), rainfall (c), slope (d), soil texture (e), and elevation (f), TWI (g), drainage density (h), distance from rivers (i), and distance from roads (j)

Rainfall data

Precipitation data was interpolated over the study area using the inverse distance weighting (IDW) interpolation technique implemented in ArcGIS 10 software. The IDW method is known to be one of the most common methods used to estimate spatial variations of rainfall over topographic features and also shows good integration with geographic information systems (GIS). Hence, the precipitation map was classified into five individual classes showing aspects of the distribution of rainfall.

Slope

The DEM map indicates the inclination of the study area in creating a slope map that will help in the identification of topographical and landscape features. Slope is closely associated with flood risks since it plays a major role in water runoff. Land surface inclination is one of the important runoff rate determinants, hence affecting the likelihood of flash floods (Fenton, 2019). A study of slope and topographical features, therefore, becomes necessary in determining susceptibility to flooding within an area, hence their importance within the management of flood risks.

Drainage density

Mohamed and El-Raey, in their 2019 study, highlighted the relationship between water circulation and rainfall as a very critical one. In this respect, drainage density is one of the important factors governing the drainage network and hence flash flood risk. This usually means that low drainage density is not effective in water drainage in watersheds; hence, it contributes to water accumulation and exposes the affected areas to frequent flooding. There is a special place reserved for drainage density within an assessment of flood risk.

DEM

The SRTM data at a 30 m spatial resolution was used under the Arc Toolbox of ArcGIS 10.8. The quality DEMs created represent the topography of the Earth's surface using this data. The DEMs are essential in flood modeling and natural resource management, as they provide exact topographical information that is necessary for assessing the risks of floods and planning effective resource management strategies.

TWI

One of the main reasons to combine remote sensing data and the topographic wetness index is for analyzing the risk of flooding. The method makes it easy to identify areas prone to overland flow due to saturation, therefore showing the areas that will most likely face flooding. In the calculation of the topographic wetness index, surface topography is derived from shuttle radar topography mission digital elevation model, which supports the integrity of flood risk mapping. Unlike traditional hydrodynamic models, TWI calculations are both precise and cost-effective, offering an efficient alternative for flood risk modeling (Pourali et al., 2016).

Distance from road

The proximity of transportation ways to water bodies is an important determinant of the susceptibility of flooding. When flooding occurs, the water levels build up in the rivers and overflow to low-lying areas adjacent to the rivers and further overflow to roadways and waterways result in damages to public facilities, homes, and infrastructural elements. The closer a road is to a river, the higher the vulnerability. With increased distance from the main road to the river, there is an increased sense of safety. In the context of flood risk assessment and in the delineation of areas prone to flooding, therefore, distance to rivers becomes very useful in this regard.

Distance from river

Areas that are situated at greater distances from the river have fewer chances of flooding compared to the ones nearer the river. During flooding, the river erodes the banks, depositing sediments on the floodplain, the dry land beside the river. The closer to the river, the greater the susceptibility due to flooding; thus, the farther away one goes, the lesser the risk. These are the factors chosen to represent each criterion, selected very carefully to best describe the peculiar characteristics of the hazards and vulnerabilities relevant to the study. A review of literature and established definitions of hazards and vulnerabilities Derive the major indicators considered necessary for an adequate description of the risks facing the communities. This helped develop a robust framework to assess and analyze potential impacts of such natural and artificial hazards.

Analytical hierarchy process

It basically involves the identification of key factors, developing a pair-wise comparison matrix – see Tables 5 and 7, normalization of the matrix – see Tables 6 and 8, computation of factor priority vectors, and checking consistency of comparison made by the decision maker. Once thematic maps are drawn and categories developed, AHP assigns weights to factors and ranking of sub-watersheds in order of their vulnerability to erosion could be performed. The results of the survey are integrated into a typology of erosion sensitivity by combining data with different weights attributed to each criterion. This thus allows the realization of a general map of sensitivity to water erosion in the region studied. A risk map showing areas prone to soil erosion in Fahs-Anjra was therefore developed by combining the various factors that determine the susceptibility of the area to erosion through ArcGIS 10.8 as illustrated in Figures 5 and 6. This was done following the sensitivity categories of these factors. Also, integration of the parameters using weighted overlay will result in a map depicting hazard as illustrated with Tables 5, 7, 9, and 10. Standardization of the matrix value allows comparison to be reliable as per erosion risk. This step usually makes the values of the matrix normalized to a common scale, usually from 0 to 1. In this case, the CR of the matrix representing influential factors (see Tables 6 and 8) is less than 0.1, which reflects a high degree of consistency. The ratio shows very good concordance, thus proving the reliability and validity of the comparison matrix.

Table 5. Erosion hazard matrix

Parameters	NDVI	Rainfall	Slope	Soil type	LULC	Weight %
NDVI	1	4	3	3	5	33.31
Rainfall	1/4	1	2	1	5	20.71
Slope	1/3	1/2	1	2	3	18.71
Soil type	1/3	1	1/2	1	2	16.56
LULC	1/5	1/5	1/3	1/2	1	10.72
SUM	2.12	6.70	6.83	7.50	16.00	100.0

Table 6. Normalization of erosion hazard matrix

Parameters	NDVI	Rainfall	Slope	Soil Type	LULC	Average	λ	CI	RI	CR	λ max
NDVI	0.47	0.60	9.00	6.00	0.31	3.276	5.84	0.10	1.12	0.09	5.40
Rainfall	0.12	0.15	6.00	2.00	0.31	1.716	4.94				
Slope	0.16	0.07	3.00	4.00	0.19	1.484	4.26				
Soil type	0.16	0.15	1.50	2.00	0.13	0.786	6.63				
LULC	0.09	0.03	1.00	1.00	0.06	0.437	5.31				
SUM	1.00	1.00	20.50	15.00	1.00		5.40				

Table 7. Flood hazard matrix

Parameters	DEM	Rainfall	DD	D_RI	TWI	LULC	Slope	D_RO	ST	Average	λ	CI	RI	CR	λ max
DEM	0.35	0.44	0.33	0.40	0.29	0.25	0.22	0.20	0.20	0.297	10.14	0.09	1.45	0.064	9.75
Rainfall	0.18	0.22	0.33	0.30	0.24	0.21	0.19	0.17	0.17	0.222	10.33				
DD	0.12	0.07	0.11	0.10	0.18	0.17	0.16	0.15	0.15	0.133	10.19				
D_RI	0.09	0.07	0.11	0.10	0.18	0.17	0.16	0.15	0.15	0.129	10.25				
TWI	0.07	0.05	0.04	0.03	0.06	0.13	0.13	0.12	0.12	0.083	9.80				
LULC	0.06	0.04	0.03	0.02	0.02	0.04	0.09	0.10	0.10	0.056	9.34				
Slope	0.05	0.04	0.02	0.02	0.01	0.01	0.03	0.07	0.07	0.037	9.03				
D_RO	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.021	9.31				
Soil type	0.04	0.03	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.021	9.31				
SUM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		9.75				

Table 8. Normalization of flood hazard matrix

Parameters	DEM	Rainfall	DD	D_RI	TWI	LULC	Slope	D_RO	ST	Weight %
DEM	1	2	3	4	5	6	7	8	8	30.21
Rainfall	1/2	1	3	3	4	5	6	7	7	22.88
Drainage density	1/3	1/3	1	1	3	4	5	6	6	13.57
Distance to rivers	1/4	1/3	1	1	3	4	5	6	6	13.14
TWI	1/5	1/4	1/3	1/3	1	3	4	5	5	7.81
LULC	1/6	1/5	1/4	1/4	1/3	1	3	4	4	5.06
Slope	1/7	1/6	1/5	1/5	1/4	1/3	1	3	3	3.30
Distance to roads	1/8	1/7	1/6	1/6	1/5	1/4	1/3	1	1	2.01
Soil type	1/8	1/7	1/6	1/6	1/5	1/4	1/3	1	1	2.01
SUM	2.84	4.57	9.12	10.12	16.98	23.83	31.67	41	41	100

Note: Drainage density: DD; Distance to rivers: D_RI; Distance to roads: D_RO; Soil type: ST.

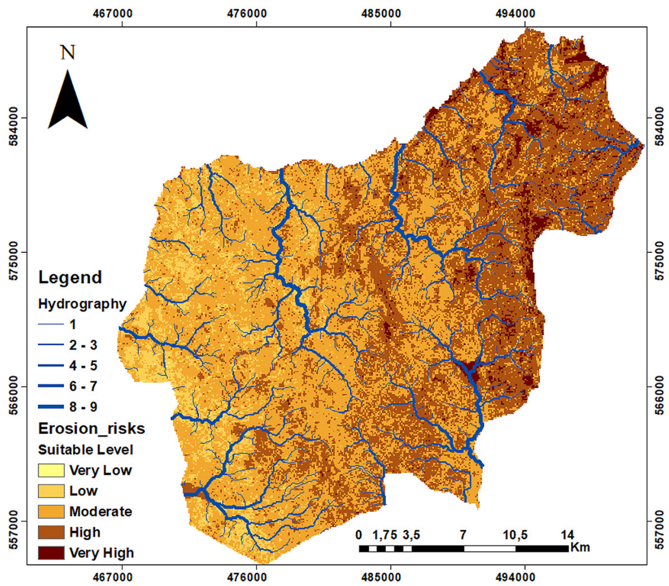

Figure 5. Vulnerability zone map showing erosion suitable level

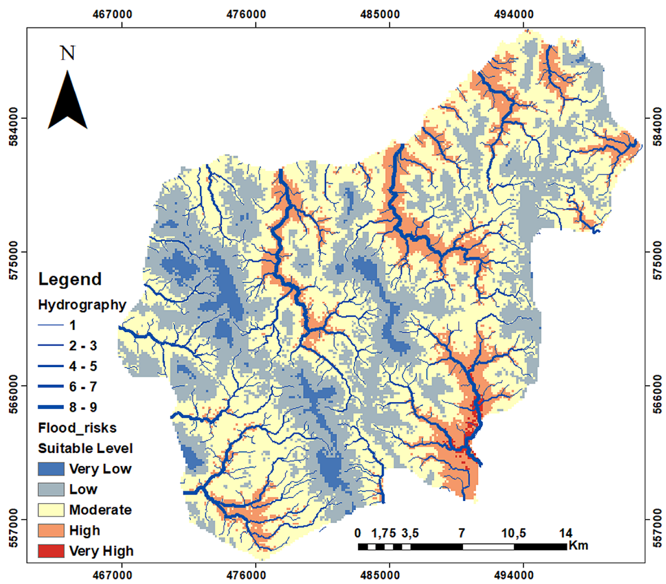

Figure 6. Vulnerability zone map showing flood suitable level

Table 9. Weights of sub-classes using (AHP) comparison erosion matrix

Flood criterion	Units	Class	Susceptibility class ranges and ratings	Susceptibility class ratings
NDVI	level	-0.21–0.12	Very high	5
		0.13–0.22	High	4
		0.23–0.29	Moderate	3
		0.3–0.36	Low	2
		0.37–0.6	Very low	1
Land use	level	Water bodies	Very high	5
		Agriculture	High	4
		Urban	Moderate	3
		Bare land	Low	2
		Forest	Very low	1
Slope	%	0–11	Very low	1
		12–21	Low	2
		22–32	Moderate	3
		33–51	High	4
		52–210	Very high	5
Rainfall	mm/year	814.33–816.47	Very low	1
		816.48–817.87	Low	2
		817.88–819.23	Moderate	3
		819.24–820.41	High	4
		820.42–822.62	Very high	5
Soil type	level	Clay	Very high	5
		Sandy clay loam	High	4
		Sandy loam	Moderate	3

The flood hazard map was produced based on nine key parameters that are classified and prioritized using their relative importance for assessing the flood risk. Using these in a systematic and quite rigorous approach, a final map of potential flood zones was drawn with precision. This exhaustive exercise enhances the quality and reliability of the results and contributes to the formulation of suitable mitigation strategies for the vulnerable areas (Table 7). For instance, concave areas had a high probability of flooding; the areas with negative NDVI values were vulnerable because of the lack of vegetation; areas that showed high values for TWI had a high potential for retaining water. In terms of land cover, water and vegetation along the river were more prone to flooding conditions than other land use types.

The most influential factors causing flooding in the area were identified as elevation, slope, precipitation, drainage density, and distance from the river. Areas with low elevation are more prone to flooding since water always moves towards low-lying areas, which eventually floods during heavy rainfall. Statistics show that steeper slopes are more prone to flash flooding.

Precipitation was high in the study area during the winter season, which also contributed to flooding. Moreover, the proximity to the river made the area more prone to flooding. Other factors like curvature, NDVI, TWI, LULC, and soil type contributed less to flooding. In AHP, the pairwise comparison of subclasses is performed regarding their relative importance, in which numerical values are given to each comparison to manifest the preference of one subclass over another. These values are then summed up in weighted rankings, showing the hierarchy and relative importance of each subclass with respect to others. After the analysis, an interpretation of the results is performed in order to enable informed decision-making based on the priorities assigned to each factor. This helps understand the relative importance of various factors with respect to the overall performance or outcome by systematically assessing and evaluating their weight. Each factor will be weighted according to the level of importance, while AHP breaks down complex decisions into simpler pairwise comparisons for a final ranking of factors by their relative importance.

The results of this research clearly distinguish different levels of vulnerability to geo-environmental phenomena, thus leading to an overall

Table 10. Weights of sub-classes using (AHP) comparison flood matrix

Flood criterion	Units	Class	Susceptibility class ranges and ratings	Susceptibility class ratings
TWI	Level	-8.1– -4.9	Very low	1
		-4.8– -3.5	Low	2
		-3.4– -1.3	Moderate	3
		-1.2–2.1	High	4
		2.2–11	Very high	5
Elevation	m	-5–110	Very high	5
		111–196	High	4
		197–289	Moderate	3
		290–404	Low	2
		405–744	Very low	1
Slope	(Percent) %	0–11	Very high	5
		12–21	High	4
		22–32	Moderate	3
		33–51	Low	2
		52–210	Very low	1
Rainfall	mm/year	814.33–816.47	Very low	1
		816.48–817.87	Low	2
		817.88–819.23	Moderate	3
		819.24–820.41	High	4
		820.42–822.62	Very high	5
LULC	Level	Water bodies	Very high	5
		Agriculture	High	4
		Urban	Moderate	3
		Bare land	Low	2
		Forest	Very low	1
NDVI	Level	-0.21–0.12	Very high	5
		0.13–0.22	High	4
		0.23–0.29	Moderate	3
		0.3–0.36	Low	2
		0.37–0.6	Very low	1
Distance from river	m	0–184	Very high	5
		185–379	High	4
		380–557	Moderate	3
		558–763	Low	2
		764–1.460	Very low	1
Distance from road	m	0–990	Very high	5
		1.000–2.200	High	4
		2.300–3.500	Moderate	3
		3.600–5.300	Low	2
		5.400–8.200	Very low	1
Drainage density	km/km^2	0–120	Very low	1
		130–260	Low	2
		270–430	Moderate	3
		440–640	High	4
		650–1.100	Very high	5
Soil type	Level	Clay	Very high	5
		Sandy clay loam	High	4
		Sandy loam	Moderate	3

understanding of the complex interrelationships arising among the criteria being used. These criteria, through the combination of standardized and unbiased weights, uncover the subtle dynamics of the region. The weighting technique used the benefit ratio for comparative analysis of paired elements, in order to emphasize the factors that have a positive influence on environmental conditions compared to those causing degradation. Consequently, the environmental vulnerability map produced by this method offers much insight into complex dynamics surrounding the environmental condition of the area under study.

Analytical hierarchy maps

The classification of flood risk areas involves four classes: "very high", "high", "moderate", and "low", which were attained by the standard deviation approach, as illustrated in Tables 9 and 10. Such hazard maps present a concise and readily accessible summary of the related flooding and erosion risks and are very useful where primary data is poor. Figures 5 and 6 present the erosion and flood risk zones with their different high and low risk classes. The application of the AHP technique allows the ranking of contributing factors to risk susceptibility, identifying which of these factors provide more importance to increasing vulnerability. Of these five factors causing water erosion, NDVI and rainfall had the highest impact. Thus, NDVI explained more than 25% of the erosion risk, while rainfall explained about 21%. Then came soil type and slope, each accounting for more than 16%, while the smallest effect was exerted by LULC with about 11%. The high-weight NDVI factor plays a very important role in deciding erosion risk in the area.

This makes the estimation and monitoring of vegetation vitality and density very critical for efficient erosion risk assessment and mitigation. The high impact of precipitation and topography points out the need for practices in sustainable land management aimed at controlling erosion. While soil classification and land use/land cover are of importance, their relatively lower weights suggest that they exert lesser influences on erosion risk compared to the factors that have a more pronounced effect. DEM has the highest weight percentage, contributing 30% in frequency among the flood incidents of the research area. According to this map, starting from the most effective, the order of priority goes like DEM 33%, rainfall 23%, drainage density 14%, distance to river 13%, TWI 8%, LULC 5%, slope 3%, and distance to road and soil type 2%. This ranking reflects the critical role that topography and rainfall play in terms of occurrence of flooding events within the study area. The DEM factor shows that the lower the elevation and higher the slope, the more flood occurrence will be experienced. The factor of rainfall comes close after, further reflecting the predisposing rate of precipitation to initiating flood events. Hence, both the flood frequency and the DD are found out to have an influential role concerning the significance of the latter in view of the flooding possibility, while on the other hand, TWI predicts high values of this index at locations predestined to flooding occurrence; LULC and soil type also contribute relatively smaller influences, though still account for flooding. Land-use and soil-character changes, infiltration and runoff rates of water, and hence flood risk.

About 54% of the studied area shows a moderate level of vulnerability to erosion, while 31% is susceptible to flooding. The most exposed areas are mainly agricultural lands and are situated along the coast and rivers. In the south of the study area, the geomorphological features make flooding more frequent because heavy storm events allow water to flow easily from high to low-lying areas.

With its mainly flat topography, the south experiences slow drainage of water; thus, waterlogging stays for a long period of time, resulting

Table 11. Vulnerable zones area in (ha), and in percentage (%)

Vulnerable zone	Erosion area (ha)	Flood area (ha)	Erosion area (%)	Flood area (%)
Very low	10	2750	0.01	3.97
Low	6171	19948	9	29
Moderate	35268	35068	51	51
High	25321	11207	37	16
Very high	2576	372	4	1
Total sum	69345	69345	100	100

in a high likelihood of flooding. Consequently, both the population and infrastructure in this area are far more susceptible to flood risks compared with areas of higher altitudes and steeper slopes. It is important that both the local government and people within these regions be made aware of these dangers in order to implement the necessary plans aimed at reducing the possibility of flooding. From Table 11, 37% of the region falls under the category of high erosion risk while 16% is high on the flood risk index. On the contrary, 51% of the land is moderately affected by both erosion and flooding. A low percentage belongs to the high-risk categories: less than 4% are affected by erosion processes, whereas only 1% is exposed to flooding risks. In view of the negative effects of floods, proper countermeasures ensuring the right and sustainable development of such flood-prone areas are to be performed. Moreover, the northeastern part of the research area represents a zone with high values for elevation as well as slope parameters. It is, therefore, more susceptible to erosion, particularly in coastal areas as illustrated in Figure 6.

Validation and comparison

The validation of models is important for the establishment of its precision and reliability, in comparison to the empirical observations from the field. A model analyzing erosion and flood susceptibility is imperative to be validated using data observed in practice. The validation confirms that a model represents reality well; consequently, the model is trusted for risk assessments with confidence in their results for the future. Based on field observations, the results firstly validated the AHP model used in this study; it proved that the model effectively assessed erosion risk scoring 70 points and flood risk which scored 26 points, as shown in Figure 7.

Field surveys, production of flood maps using the outputs of the AHP model, validation using Siredd data maps (Siredd, 2024) and performance assessment through receiver operating characteristics curves are carried out to establish its validity. Figure 8 shows the ROC curve, which indicates that predictions of erosion risk are pretty good, as can be seen from an AUC of 0.756, which corresponds to a prediction accuracy of 76%. On the other hand, flood risk prediction was even better, with an AUC of 0.890 corresponding to an accuracy of 89% in prediction. These empirical observations provided practical data that was useful in substantiating the model's predictions and the corresponding data maps that aided further analysis and comparison (Siredd, 2024). In this respect, ROC curves were useful in assessing the models regarding sensitivity and specificity. Conclusively, the validation showed that the AHP models were adequate in predicting and delineating erosion and flooding-prone areas. Moreover, the current trend of global warming is linked to an increased rate of erosion and increased risk of flooding on Morocco's northern coast in consequence of sea level rise and increased weather instability. This is further accelerated by coastal development near shorelines as it interrupts natural dynamic coastal processes and weakens natural inherent mechanisms that operate to reduce water absorption thus increasing vulnerability to erosion.

Local awareness of erosion and flooding risks is crucial for assessing community vulnerability.

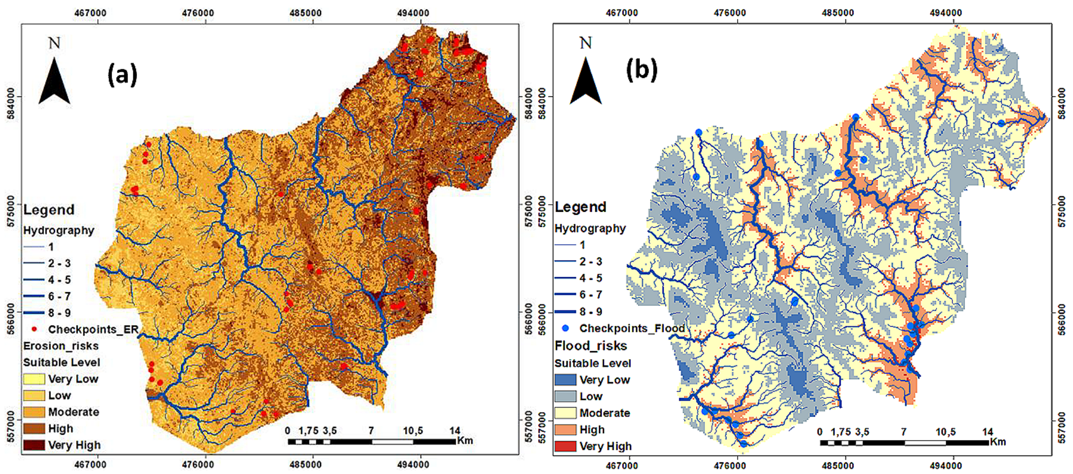

Figure 7. Classified erosion (a), and floods (b) suitable maps with existing vulnerable areas

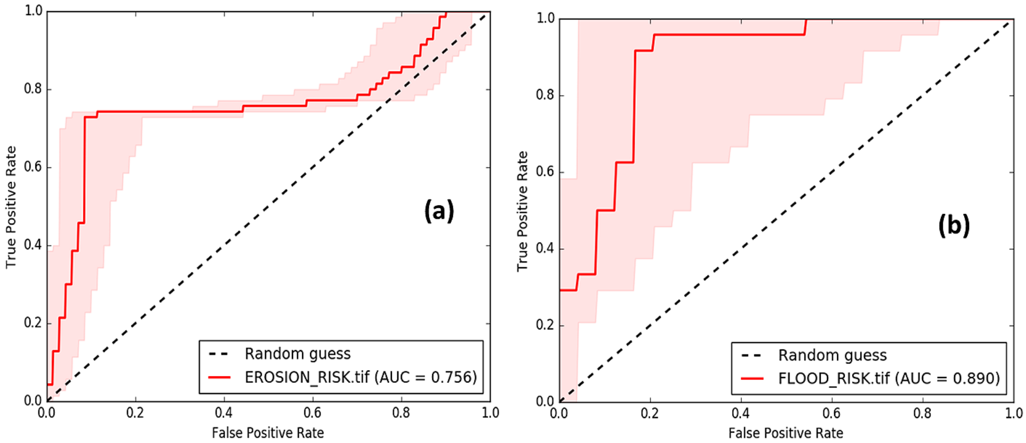

Figure 8. ROC curves for erosion (a), and flood (b) susceptibility

In many cases, residents may not fully understand the risks they face or lack the resources to implement effective risk management strategies. Increasing education and outreach initiatives can enhance local comprehension of these risks, empowering communities to take proactive measures for self-protection. The adoption of suitable risk management strategies – such as coastal protection structures, land-use planning regulations, and early warning systems – can help mitigate the impacts of erosion and flooding in North Morocco. By acknowledging the interconnected nature of these risks and addressing both their causes and immediate effects, policymakers can better safeguard communities. While the current study provides valuable insights, it also has limitations, such as subjectivity in assigning ratings to certain parameters. However, the susceptibility maps derived from the study area will be useful for development, planning, and decision-making by local authorities and decentralized communities. It is important to recognize these limitations and incorporate them into future research to improve model accuracy. Additionally, integrating additional data sources and variables into the AHP models could enhance the precision of the generated maps. This study lays the foundation for creating effective strategies to mitigate erosion and flooding risks, offering valuable information for policymakers and stakeholders. By understanding the area's susceptibility to these natural hazards, decision-makers can prioritize resources and investments to strengthen resilience and reduce vulnerability. Ultimately, this research contributes to sustainable development efforts in Fahs-Anjra, ensuring the safety and well-being of its residents.

DISCUSSION

This research investigates some of the interrelated complex factors that determine the level of soil erosion and flood risks in the Fahs-Anjra region by showing how the combined roles of NDVI, rainfall, DEM, and topography shape vulnerability. These findings build on the existing literature, such as the one by Mostakim et al. (2021), where vegetation cover and rainfall erosivity were the leading factors of soil erosion, and Darabi et al. (2019), who outlined the influence of elevation and slope in flood risk. This might include some of the key strengths of the study, considering the AHP method in association with the tools of GIS for prioritizing these variables effectively. This ROC analysis confirmed validity, with predictive accuracy at 75.6% for erosion and 89% for flood risk, hence proving evidence to support the studies carried out by Alam et al. (2021) and Bui et al. (2022), putting more faith into using a GIS-based multi-criteria decision-making framework to assess hazards within variable environmental regions. From these, in fact, developed vulnerability maps; some trends outline an area of about 37% that is highly prone to erosion conditions, while on the other side, about 16% faces risks from floods, especially those areas either with intensive agricultural development or within the coastal zone locations. These findings run parallel to observations in similar contexts, like the coastal plains of Tunisia, for instance, where human activities accelerate erosion (Kefi et al., 2020), and the Mekong Delta, where shifts in rainfall and land use exacerbate flooding (Nguyen et al., 2021). Not only does this enhance the findings by linking them with broader regional and global trends, but it also underlines the pervasiveness of such problems across environmentally sensitive areas. The present study thus brought into light the requirement for focused land-use planning and an adaptive management strategy which would contribute to addressing these risks and enhance resilience to support sustainable development in the most vulnerable sections.

Moreover, the weighted overlay method followed in this study underlined that NDVI and rainfall are the most contributing factors to soil erosion risk, each contributing more than 46% to the total risk. This agrees with Yang et al. (2018), who indicated a critical role of vegetation in stabilizing soils in erosion-prone areas. Moreover, the high influence of Digital Elevation Models (DEM) on flood risk 33% outlines the critical role that elevation gradients can play in the modeling of flood hazards, as observed by Bannari et al. (2016). It further conducted field surveys that intended to validate the model by comparing it to empirical data, which indeed substantiated its reliability and robustness. It to an extent follows the methodology proposed in Bui et al., 2019, that underpins model validation to be of utmost importance toward obtaining credible hazard assessments. However, there are a few limitations in this study: for example, subjectivity of AHP weight assignments and exclusion of effects from urbanization on erosion and flood susceptibility. In fact, these are open promising directions for future research in such aspects by adopting integrated techniques, for instance, machine learning models or dynamic simulations of flood susceptibility. This can also be further exemplified on how Fathabadi et al. (2022) had used an AHP model and fused it with neural networks, giving much better mapping with higher-order precision and reducing both risk and error to an unprecedented level of giving accurate predictions for hazard assessment within a dynamically changing environment. This research can help to improve the understanding of future hazard mapping, which will provide more effective risk management by including the full dynamism of environmental and anthropogenic factors within the framework of regional planning and mitigation measures.

These results have very broad implications and underline the need for focused interventions, including reforestation programs and improvements in drainage infrastructure in at-risk areas, coupled with public education and promotion of sustainable land-use practices. These results are in line with similar measures recommended by Zorn et al. (2021) in Slovenia and those proposed by Hossain et al. (2022) for Bangladesh, where community-based approaches have significantly reduced the impacts of erosion and flooding. These measures are being considered more and more essential with respect to the enhanced impacts as a consequence of climate change, like the increase in precipitation along with rising sea levels—referring to Boufala et al. (2020), which explained that the coastal areas in Morocco are vulnerable to such an impact. Considered within the context of global patterns, these findings make a compelling case for the integration of scientific research with the enactment of stringent policies that reduce risks, safeguard vulnerable populations, and strengthen resilience against future environmental changes. In this sense, the manuscript provides a framework for hazard assessment with foundational insights toward more nuanced, evidence-based, and adaptive management strategies. This approach will be important in addressing complex and dynamic environmental risks, taking preventive measures to protect the ecosystems and human livelihoods, more so in areas that have been facing increased vulnerability due to climatic and anthropogenic stresses.

CONCLUSIONS

This study uses the Analytical Hierarchy Process (AHP) method in the Fahs-Anjra province. Its presents a standard and effective way of ascertaining environmental risks. The method is integrated with the ArcGIS software to produce maps that show areas' vulnerability to floods and erosion. The study gives accurate, high-resolution maps of sub-regions to enable easier identification of risks. In addition, incorporating more environmental and landscape factors into the AHP model adds equity and consistency to the analysis. These maps suggest that a total of about 4% of the study area falls within the very high vulnerability class, more than 37% fall under the high vulnerability, about 51% in moderate vulnerability, between 9–29% in low, and about 3.97% in very low vulnerability class. The highest classes of vulnerability are mainly located in the northern part of the study area near the coastal regions. In turn, such factors were integrated using the methodology of ArcGIS to depict integral spatial analysis of the given area. Obtained AHP-modelled vulnerability maps required their verification using ROC curves: it has been established that the assessment of erosion risks colitis performed with accuracy of 76%, flood risks -89%, based on 70 and 26 validation points respectively. This will help researchers and planners to integrate various data layers to better understand the current environmental situation and the potential hazards of the area. This information shall then be useful for decision-makers in terms of land use planning, natural resources management, and disaster risk management. The ability to view and analyze these variables in a geographic information system allows decisions to be made more rapidly and promotes the development of sustainable practices.

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