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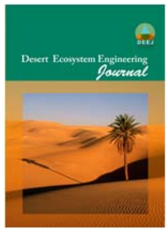

Modeling Fire in Arid Rangelands of Northeastern Iran: A Case Study of Namakzar Watershed, Khaf, Iran

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Abstract

Arid regions' ecosystems are known as delicate responsive environments, where the effective management and regulation of natural events are essential for maintaining their suitability and promoting sustainable practices. Therefore, this study sought to investigate the extent of fire propagation in the arid rangelands of the Namakzar watershed in terms of topographical (altitude, aspect, slope), climatic (precipitation, temperature), ecological (NDVI), and human factors (distance from the roadway and residential areas) using the geographical information system (GIS) and the Analytic Hierarchy Process (AHP) method. The findings revealed that southwestern and northeastern regions had a great potential for fire occurrences (8%). Moreover, it was found that the middle class (17%) was dispersed in patches, tending to move from the central region towards the eastern and southwestern areas. Moreover, the regions with low or very low-risk status were identified to have made up nearly 75% of the total area of the region. On the other hand, the results of the AHP indicated that temperature (0.20) contributed the most to the fire incidence, followed by aspect (0.17), vegetation (0.17), and distance from residential areas (0.16). Furthermore, the results suggested that modifications in the slope (0.017) and elevation (0.02) of the region exerted negligible influence on the incidence of fire. Therefore, to minimize the chances of the occurrence of such incidents, managers are recommended to employ nearby communities' local knowledge and cooperation in implementing new techniques to control fire incidence in pastures.

Keywords: Arid Ecosystem, Natural Hazards, Spatial Patterns, GIS, Khorasan Razavi.

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1. Introduction

Known as unforeseen phenomena that can cause significant damage to human settlements, infrastructure, and the environment (Harrison & Williams, 2016; Sharma et al, 2023), natural disasters are often characterized by their sudden strike and uncontrollable nature, making them difficult to predict and control (Cui, 2020; Barmpoutis et al, 2020). On the other hand, the consequences of natural disasters can be severe, ranging from loss of life and injury to property damage and disruption of essential services (Rahdari et al, 2021). Wildfire incidents cause extensive damage and devastation annually, thus being recognized as one of the most destructive disasters known to man (Kalogiannidis et al, 2023). In this regard, the increasing number of forest and rangeland fire incidences over the past few decades has turned the fire into a pressing crisis of global significance (Leal et al, 2021; Kalogiannidis et al, 2023), gaining particular attention due to its technical complexities and the need to understand its underlying causes.

As a significant ecological disturbance, fire plays a crucial role in the development of plant communities (He et al 2019; Hinojosa et al 2021). However, unregulated fire incidences may cause substantial vegetation loss, leading to the reduction of plant and animal biomass, the emission of carbon into the atmosphere (Kelly et al, 2020; Pivello et al, 2021), soil erosion, reduced species diversity, and the growth of invasive non-native species (Rahdari et al, 2013; Gajendiran et al, 2023). On the other hand, changes in fire patterns may bring about far-reaching consequences for vegetation dynamics, posing a severe threat to pasture productivity, ecosystem resilience, and conservation initiatives (Dias et al, 2023).

Rangelands provide valuable services such as soil erosion control, water regulation, and grazing land for livestock, and thus they are essential to ecosystem health and function (Mohammadzadeh-Chenar et al, 2022). In other words, rangelands serve as habitats for diverse plant and animal species, whose proper management is crucial to maintaining ecological integrity (Esbati et al, 2021). On the other hand, in addition to their environmental importance, rangelands play a vital role in producing medicinal and industrial compounds (Aghajanlou et al, 2021), maintaining genetic diversity (Scherf et al 2008), and regulating atmospheric composition (Polley et al, 2010).

Occupying more than 52% of Iran’s land area, rangelands are essential to the country’s natural ecosystem due to their location in arid and semi-arid regions (Esbati et al, 2021; Mohammadzadeh-Chenar et al, 2022). Such regions are characterized by vast grasslands and shrublands that are crucial to grazing, wildlife habitats, and biodiversity conservation (Karkon-Varnosfaderani et al, 2017). Therefore, the unique ecological and environmental conditions of rangelands make them a valuable subject of study and innovation in terms of land management, livestock production, and ecosystem services (Briske et al, 2023).

Located in the earth's arid zone, Iran lies in the subtropical region's high-pressure belt in a geographically significant area (Rahdari et al, 2023), being exposed to natural calamities such as floods, earthquakes, and fires. In this regard, fire incidence is a critical crisis that demands constant monitoring and management, taking into account its location and associated technical intricacies (Eskandari et al, 2020). Characterized by varying climates and vegetation (Rahdari & Rodríguez-Seijo, 2021), Iran is subjected to recurring wildfire incidents annually due to its diverse ecosystems, causing considerable forest damage (Eskandari et al, 2021). According to the report published by the Iranian Food and Agriculture Organization, such uncontrolled fire incidents destroy nearly 9% of Iran's forest cover annually (Javaheri & Tarahi, 2021). In this regard, the most recent statistical analysis suggested that Iran ranked fourth in the Middle Eastern and North African region in terms of the incidence of forest fires (Naghipoor-Borj, 2019). On the other hand, wildfire is now recognized as one of the most widespread and devastating threats to natural ecosystems in arid areas, where urbanization, land use change, and intensive agriculture have become prevalent (Pausas & Keeley, 2021).

In forest and rangeland management, effective fire control and prediction require a detailed analysis of multiple factors, including topographical features, biophysical conditions, and socio-economic variables (Xiong et al, 2020). Therefore, experts can better understand the complex interactions influencing the occurrence of fire and its behavior in such environments by carefully examining the aforementioned factors (Thompson & Calkin, 2011). Thus, identifying the critical areas that are subjected to fire incidence can help determine the most effective strategies involved in preventing and controlling the spread of fire (Jahdi et al, 2020).

To predict the occurrence of fire and prevent the destruction of rangelands, it is essential to create a risk potential map that involves all relevant influencing factors (Nasiri et al, 2022). In this regard, Geographic Information Systems (GIS) and weighted indicators are widely used as fundamental methods for accurately identifying critical areas that are subjected to fire incidence in natural settings. Therefore, managers can use such an approach to take necessary precautions and mitigate potential fire outbreaks, as the approach has widely been welcomed in recent years and has proven to be a valuable tool in the field.

The current study used digital spatial data and the analytic hierarchy process to develop an innovative spatial fire model for the Namakzar watershed region in northeastern Iran, where numerous reports have been delivered by local people within the past few years regarding fire incidents (Shoja, 2023). Therefore, the study attempted to provide an in-depth analysis of the factors involved in the outbreak and spread of fire in the area, seeking to identify and prioritize the most vulnerable zones that are prone to catch fire in the future. The findings of the study can be used in developing effective fire management strategies so that the risk of wildfire is decreased in the Namakzar watershed and its surrounding areas.

2. Materials and Method

2.1. Study Area

As a closed basin in the eastern parts of Khorasan Razavi and South Khorasan South provinces, Khaf is adjacent to the Iran-Afghanistan border. Comprised of three main sub-basins, including Qara Qom, Kavir Merkazari, Kavir Lut, and Hirmand (Taabe et al, 2017), the Khaf basin is surrounded by moderately elevated mountain ranges to the north, west, and south which effectively separate it from adjacent basins. On the other hand, the Namakzar watershed is located in the northern region at coordinates ranging from 58°35′ to 60°56′ east longitude and 32°05′ to 35°00′ north latitude, serving as a basin for the drainage originating from the southeastern part of Razavi Khorasan and the northeastern part of South Khorasan province. Moreover, the basin encompasses a total area of 33000 km^2, out of which 15000 km^2 is characterized by mountainous terrain, and the remaining 18000 km^2 area consists of plains, foothills, and salt marshes.

In terms of botanical vegetation, Khorasan Razavi province and Khaf City are commonly classified under Iran's Turani region. Moreover, Khaf City hosts various forest species, predominantly found in the mountainous and valley areas of the region. In this regard, as essential and strategic species, *Wild pistachio* and *Amygdalus scoparia* are sparsely covered in these areas (Shoja, 2023).

2.2. Methodology

2.2.1. Data set

Topography (altitude, aspect, and slope)

The topography of a region plays a crucial role in determining the type and distribution of vegetation, which in turn affects the flammability of the region (Alexandre et al, 2016). Some parameters such as altitude, slope, and direction influence topography, and the relationship between altitude, temperature, and humidity significantly affects the fire risk (Sharples, 2009). On the other hand, the risk of fire occurrence is lowered when the temperature decreases and humidity rises (as altitude increases) (Jain et al, 2022). Moreover, modifying the slope angle significantly affects soil moisture and its dynamics, which in turn increases the risk of fire occurrence.

Steep terrains are especially vulnerable to wildfire due to the proximity of the flame front to the ground surface, which further exacerbates the fire risk (Bradstock et al, 2010). Furthermore, the areas exposed to more excellent solar irradiation may witness a surge in the magnitude of the blaze (Eskandari et al 2020). In this regard, the spatial information of topographical layers was needed to conduct the study, which was collected using a 30-meter digital elevation model (DEM) created by the ASTER satellite. The data was downloaded from the United States Geology website (earthexplorer.usgs.gov).

Climate (temperature and precipitation)

The temperature of the fuel plays a crucial role in determining the risk of fire (Arroyo et al, 2008). Therefore, the ambient temperature directly influences the likelihood of fire occurrence. Accordingly, when the ambient temperature rises, the fuel materials approach their ignition point, increasing the fire propagation rate (Irvine et al, 2000; Warren et al, 2022). Thus, regions that experience higher temperature rates are particularly prone to rapid fire spread.

Precipitation can play a crucial role in reducing the likelihood of fire outbreaks in a particular area (Raoelison et al, 2022). In other words, the moisture content of the soil surface and fuel materials can significantly be increased by rain, reducing the risk of ignition and fire spread. Therefore, this study used spatial information from the climatic layers of the executive projects in the Namakzar watershed to prepare climatic layers. It should be noted that these spatial layers were generated through the application of climatic data obtained from the synoptic stations located around the basin and the subsequent interpolation process carried out in GIS.

Distance from the road and residential areas

The anthropogenic activities carried out by humans significantly contribute to the ignition of fire in natural resource areas (Costafreda-Aumedes et al, 2017). Residential areas tend to experience more fire incidents due to the high concentration of buildings and human activities. However, the quick response of humans in these areas often leads to a faster extinguishing of the fire (Smith & Trenholme, 2009). However, in remote areas, a lack of human presence and accessibility often leads to a delayed response time and a more severe fire outbreak. As for wildfire, the distance from the roads is a vital factor (Leone et al 2009). In other words, as we move further away from primary and secondary roads, the fire spreads rapidly over a larger area, making it much more difficult to contain (Bentekhici et al, 2020). Furthermore, the considerable distance between the fire and the roads can present a significant challenge to firefighters and complicate the extinguishing process (Chen et al, 2020). Therefore, this study prepared the spatial layers that show the proximity of residential areas and roads using the maps collected from the Iranian National Cartography Center n (NCC) with a scale of 1:25000.

Vegetation

NDVI (Normalized Difference Vegetation Index) is the most renowned and extensively used remote sensing index for vegetation identification. The analysis of the index is crucial in evaluating ecosystem dynamics as it is commonly used to monitor changes in vegetation and investigate vegetation responses. Moreover, it is a critical indicator in comprehending the complex interactions between the ecosystem and the environment.

Vegetation can act as a significant fuel source in rangelands, completing the fire triangle which consists of oxygen, temperature, and fuel (Chinthala et al, 2023).

The current study used NDVI to generate a vegetation density map from the Landsat satellite images. In other words, the study used Landsat satellite imagery (earthexplorer.usgs.gov) to produce a comprehensive vegetation map of the rangelands. To this end, the required data were collected through a spectral analysis of the normalized difference vegetation index, a dependable metric for assessing vegetation health and density.

2.2.2. Analytic Hierarchy Process

Today's multifaceted issues demand a comprehensive evaluation of various aspects and criteria to make informed decisions (Sahoo et al, 2023). Developed by Tomas L. Saaty in the 1970s, the Hierarchical Analysis Process is a well-known multi-objective decision-making method (Neves et al, 2022) that involves a series of pairwise comparisons between the various decision criteria, enabling a structured approach to decision-making processes. The method provides a framework for quantifying the relative importance of each criterion, which is then used to calculate the overall priority score for each option (Morandi et al, 2020).

This study evaluated the selected indicators through a researcher-developed questionnaire designed based on the opinions of qualified regional experts. Subsequently, the collected data were entered into the Expert Choice v.11 software, where pairwise comparisons were averaged for each indicator, and other quantitative calculators were assessed.

3. Results and Discussion

The altitude classes showed that the southern and southwestern regions had higher altitudes, with most of the area falling under 600 to 1000 meters (Figure 1). According to the studies carried out in this regard, altitude plays a crucial role in determining the abundance and quantity of vegetation as a factor that fuels fires in natural environments (Korb et al, 2019; Al-Shabeeb et al, 2023). In other words, vegetation does so by influencing the biological processes of plants and indirectly affecting climatic factors. Moreover, vegetation notably impacts wind speed at higher elevations, a phenomenon identified in multiple studies (Daşdemir et al 2021). On the other hand, the studies conducted on slope percentage revealed that only specific regions in the central, northeastern, southeastern, and southwestern areas exhibited a slope greater than 15% (Figure 1). In this regard, a detailed analysis was performed on such regions to gauge the severity of the hill and its impact on the surrounding environment. Conversely, other areas were found to have been located at less than 5% slopes, which may not be similarly conducive to rangeland fire processes (Figure 1), implying that these areas may have a lower fuel accumulation potential than their counterparts on steeper slopes.

Numerous studies have demonstrated that the slope significantly contributes to determining the fire's velocity and direction (Abouali et al, 2021). Moreover, studies have found that due to the density of vegetation, fires advance more rapidly uphill than downhill (Vadrevu et al, 2010). Based on the analysis, Figure 1 shows a comprehensive overview of the most relevant topographic indicators contributing to the aspect index.

Over the past five years, an extensive examination of the climatological patterns has been carried out in the region, with a specific focus on the precipitation level. In this regard, the collected data revealed that the minimum and maximum recorded precipitation rates in the study area were 70 millimeters and 260 millimeters throughout the study period, respectively (Table 1). The findings provide valuable insights into the local weather patterns, which can be used to make informed decisions concerning agricultural practices, water management, and other relevant activities. Moreover, the data indicates that the high-altitude and low-altitude regions in the study area experience the most and the least precipitation, respectively. Furthermore, most precipitation events were found to have occurred during the spring and winter. Also, it was found that the increase in precipitation was concomitant with increased moisture content within vegetation (Van Ginkel & Biradar, 2021), which was regarded as a negative factor in creating and disseminating fire in rangeland (Li et al 2019; Romanov et al 2022).

Temperature is a crucial climatic factor that significantly affects the outbreak and spread of fire in rangelands (Tian et al, 2022). In this regard, a comprehensive analysis of temperature revealed that the southwestern region of the study area experienced the highest temperature rates. According to the results of most case studies, average temperature rates vary from 20 to 28 degrees Celsius (Table 1). Such temperature ranges play a vital role in the ignition, fuel moisture, and fire behavior, thus making it critical to monitor the temperature trends in rangeland areas so that potential wildfire outbreaks can be predicted and prevented.

On the other hand, temperature plays a crucial role in rangeland management, as it can significantly affect the water content of plants and the surface soil (Ban et al, 2023; Kharazmi et al, 2023). Therefore, being able to reduce water availability for essential processes, and temperature may bring about negative consequences for the ecosystem and its inhabitants (Yin et al, 2021; Wani et al, 2023). Furthermore, monitoring and managing temperature rates in rangeland is essential for maintaining a healthy sustainable environment (Efremova et al, 2023).

Table (1): Temporal variations of precipitation (mm) and temperature (℃) at the synoptic station of Khaf

Year	2016		2017		2018		2019		2020	
Month	Pre	Tem	Pre	Tem	Pre	Tem	Pre	Tem	Pre	Tem
Jan	32.6	6.1	25.8	5.9	0.0	6.6	42.4	7.1	62.2	4.9
Feb	24.8	6.2	4.6	6.0	0.2	6.7	81.2	6.3	13.4	6.1
Mar	24.9	11.2	7.3	9.8	43.8	14.2	39.8	9.6	8.9	11.5
Apr	8.8	16.8	55.7	17.3	17.0	17.2	50.1	17.3	117.9	13.2
May	3.2	24.8	1.3	23.5	6.8	22.0	2.1	21.4	7.2	21.9
Jun	0.0	29.2	0.0	30.2	0.0	28.0	0.0	26.8	0.0	29.1
Jul	0.0	30.8	0.0	30.6	0.0	32.9	0.0	32.7	0.0	30.7
Aug	0.0	30.2	0.0	30.4	0.0	31.1	0.0	31.1	0.0	30.9
Sep	0.0	27.3	0.0	27.0	0.0	25.5	0.0	26.2	0.0	25.2
Oct	0.8	20.5	0.0	19.6	0.0	18.4	0.0	21.4	0.0	16.8
Nov	13.5	13.9	0.1	16.0	1.8	12.1	29.5	12.1	7.5	12.4
Dec	24.2	6.3	2.5	6.6	12.2	9.4	14.1	7.6	23.7	5.8

The presence of vegetation in a particular area and its characteristics play a crucial role in the rangeland fire process (Jafari et al, 2004; Ghasempour et al, 2022). Considering the fact vegetation is a primary fire fuel source, its density and distribution determine a wildfire's potential intensity and extent (Wills et al, 2020; Yousefi et al, 2022). Therefore, an in-depth understanding of vegetation composition, distribution, and density in a specific region is required for effective fire management and conservation efforts (Gholami et al, 2020; Or et al, 2023). Such knowledge can inform strategies for fuel reduction, prescribed burning, and fire suppression, contributing to developing policies and practices to promote healthy ecosystems and reduce the risk of catastrophic wildfires.

The index analysis revealed that was vegetation sparsely distributed in most areas, indicating that vegetation density falls within the range of 10 to 30 percent (Figure 1). Therefore, the finding implies that significant portions of the landscape exhibit low levels of plant cover, which may have implications for the ecological health and biodiversity of the region.

Numerous studies have proved that vegetation is the primary ignition source for rangeland fire incidences (Li et al, 2022; Akhzari et al, 2022). In this regard, the current study found that the southwestern parts of the study area had a higher potential for such occurrences. Therefore, it is essential to develop and implement effective fire management strategies to mitigate the risk of fire events in those parts. However, it should be noted the region is highly susceptible to wildfire due to prolonged drought periods and the adverse impacts of climate change (Tervonen et al, 2015; Babaeian et al, 2021), posing a significant challenge to the region's inhabitants, with the potential for devastating consequences. It is, therefore, imperative to adopt appropriate measures such as regular vegetation management, proper disposal of flammable materials, and education on fire safety practices to mitigate the risks associated with wildfire. Nonetheless, it should be acknowledged that the probability percentage of such occurrences is higher in southwestern parts of the region than in other parts.

Over the past few decades, human activities have exerted a significant and widespread influence on rangeland (Liu et al, 2019). In other words, human actions such as deforestation, agriculture, and urbanization have led to changes in plant communities' composition, structure, and distribution (Barbosa et al, 2020; Ortiz et al, 2021), affecting not only the natural habitats of many plant species but also the ecosystem services provided by vegetation, including air purification, water regulation, and carbon sequestration. Therefore, it can be argued that the destruction of vegetation and its deposition on the earth's surface as non-living matter can significantly contribute to the creation and spread of raw materials, which may later serve as fuel for fire occurrences in rangelands.

Accumulation of vegetation on the earth's surface can act as a readily available source of fuel that is subject to ignition and rapid spread, thereby causing significant damage to the environment and biodiversity. This study identifies the impact of human activities' distance from the road and residential areas as an important factor in mitigating and regulating pasture fires (Figure 1). In this regard, similar studies conducted in other geographical locations have also reported such an observation (Al-Fugara et al, 2021; Eskandari et al, 2023).

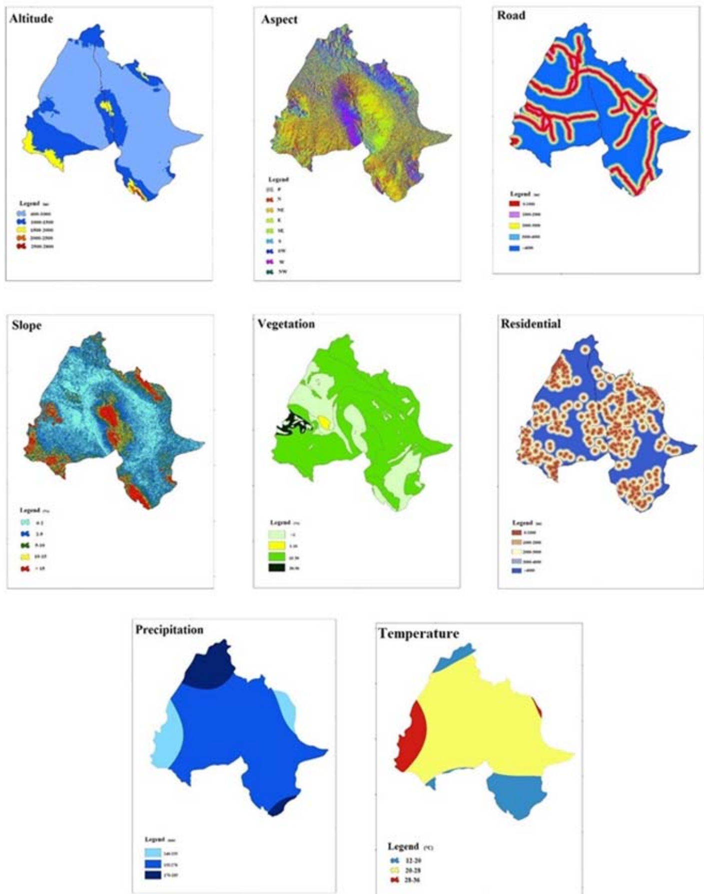

Figure (1): Spatial pattern of changes in indicators

The evaluation of the AHP method by experts who are well-informed on the subject of this study revealed that temperature played the most crucial role in the firing process. Specifically, the results of the study suggested that the chances of fire occurrence increased with an increase in temperature. However, the slope percentage was found to have a negligible impact on the fire process in the area (Figure 2).

Forest fires comprise various complex components that require careful individual examination. Therefore, understanding the intricate dynamics of such factors is critical for comprehending the causes and consequences of rangeland fires. The factors can also be used for devising effective strategies to mitigate their adverse effects (Humphrey et al, 2021; Gupta et al, 2023).

Notably, the occurrence of fire is not significantly influenced even when the slope is steep. Rangeland fire is a multifaceted phenomenon caused by various interdependent factors that can be classified under two main categories: natural and anthropogenic factors (Biermann et al, 2016; Khan et al, 2020). The latter pertains to human-induced activities, including land-use modifications and unintentional ignition (Dietze et al 2019). Conversely, the former encompasses natural factors such as vegetation type and density, precipitation patterns, slope direction, and proximity to residential areas (Li et al, 2020). Thus, a careful evaluation of both components is required for efficient prediction and management of forest fires. For instance, dry and highly combustible vegetation can significantly increase the chances of fires, while wet and less flammable vegetation can mitigate such a risk (Pausas & Keeley, 2021).

Similarly, topographical features such as slope direction can dramatically affect the speed and direction of fire propagation (Eftekharian et al, 2019). At the same time, distance from residential areas can influence the availability of firefighting resources and the response rate in case of a fire outbreak (Eskandari et al 2021). Therefore, understanding and effective management of such factors are essential in mitigating the impact of pasture fires.

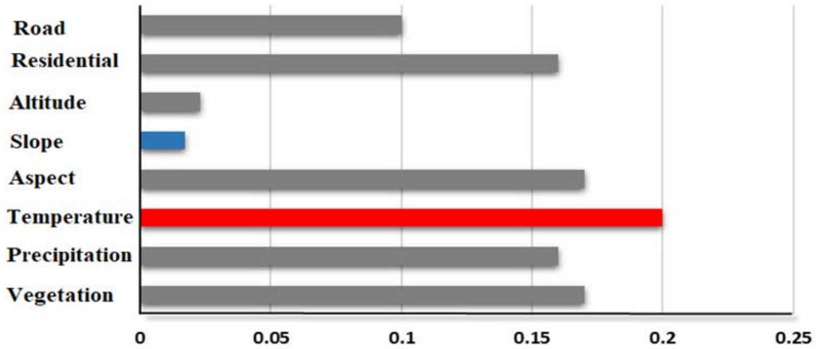

Figure (2): Evaluation of the AHP method to assess and prioritize indicators

Following an exhaustive evaluation of the spatial patterns of all the indicators and the identification of the significance of relevant layers in the rangeland of the Namakzar watershed, the study completed a map that shows the occurrence of fire. The map is presented in Figure 3, displaying the distribution of fire incidents in the region. Moreover, the map provides essential insights for understanding the area's fire occurrence patterns, serving as a valuable reference for planning and managing regional fire-related risks. According to the map, the southwestern and northeastern parts of the area show a more significant potential for fire incidents than other regions. Therefore, it is recommended that appropriate management solutions be developed to control and mitigate the incident. In this regard, it is necessary to focus on reducing the chances of the occurrence of such a phenomenon through effective management strategies.

As found by the current study, approximately 75% of the study area is classified as very low and low fire classes, suggesting that pasture lands have been controlled and managed properly with due attention. The finding also indicates that the measures taken to mitigate fire hazards have been effective and executed appropriately. Moreover, using plant cover as a primary material in the rangeland for starting a fire faces considerable limitations.

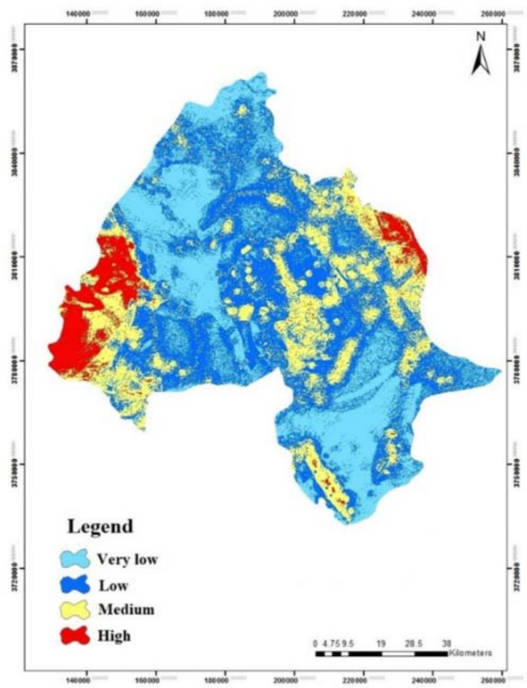

Figure (3): The spatial pattern of fire changes in the rangeland of the Namakzar watershed

4. Conclusion

Fire has long been considered an ecological and anthropogenic phenomenon in arid rangelands; a fact that has been proven in various regions through different mechanisms. Therefore, considering the varying effects of fire on other ecological indicators, it is necessary to understand the dynamics of fire occurrence in rangelands. On the other hand, investigating the fire process in rangelands is required for the sustainable management of such ecosystems. Therefore, identifying the key factors involved in the occurrence of fire and determining the areas dominated by such factors is crucial for preventing fire in rangelands.

The occurrence of fire in rangelands can be predicted by modeling spatial data's influence on fire events within a geographical information system environment. This approach offers a viable solution for assessing the chances of fire outbreaks. This study sought to develop a model for predicting fire incidences in arid rangeland by evaluating a range of natural and human-induced indicators, whose appropriate weights were determined using the AHP method to ensure accuracy.

The present study found that non-vegetation-related factors, including temperature, precipitation, and slope play a crucial role in arid rangelands such as the Namakzar watershed. Acting independently from the vegetation, the aforementioned factors are essential in understanding the overall dynamics of the ecosystem. Furthermore, effective management of fire incidences in rangeland is heavily influenced by various human factors, particularly those related to the proximity of residential settlements to the rangelands, highlighting the critical role of human societies in controlling natural events in such areas. Therefore, recognizing the importance of human intervention in managing such environmental hazards is necessary to ensure the safety of the public and the preservation of natural resources. Finally, executive managers should attempt to control such an event by using their local knowledge and fostering cooperation with local communities while taking the required measures to prevent fire outbreaks in rangeland.

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