

ORIGINAL ARTICLE

Assessment of livability trends and ecological zoning in arid and semi-arid regions: Evidence from Chabahar, Konarak, and Zarabad, Iran

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Abstract

Ecological livability is a key concept in environmental and ecology studies, playing a critical role in maintaining ecological balance and promoting sustainability. Given its importance, numerous studies in Chinese cities have assessed and ranked ecological livability based on various ecological indicators. However, the ecological potential of other regions has received comparatively less attention. A major research gap in existing studies is the lack of zoning frameworks for livable settlements based on ecological indicators. This study addresses this gap by investigating whether the spatial distribution of human settlements in the Chabahar, Konarak, and Zarabad counties of southeastern Iran aligns with the area's ecological capacities and potentials. To this end, the study first examines livability trends over the period 2010 – 2022. It then identifies optimal zones for livable settlement development using 27 ecological indicators. For this purpose, regions in southern and southeastern Iran were selected, and the evaluation was conducted using multi-source data and geographic information system tools. The results indicate that ecological indicators in the region are in a sensitive and fragile state, and livability trends exhibit a sinusoidal pattern over time. In addition, the zoning analysis indicates that many current settlements are not located in ecologically suitable areas according to livability standards. The findings provide a basis for informed decision-making in human settlement development. They also enable planners to better understand the existing conditions and to formulate strategies that enhance resilience and improve livability in urban communities in the face of natural and anthropogenic challenges.

Keywords: Ecological livability; Sustainability; Livability trend; Spatial analysis; Spatial zoning; Iran

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1. Introduction

In recent years, the concept of ecologically livable cities has gained attention among researchers aiming to preserve the environment and promote sustainable use of

natural resources (Pan *et al.*, 2023). Introduced in the early 21st century (Wang *et al.*, 2024), ecological livability emphasizes the long-term survival and resilience of ecosystems (Baumgärtner & Quaas, 2009; Berardi *et al.*, 2015). As urbanization accelerates – accompanied by the degradation of natural resources, increased air pollution, and growing urban challenges – ecological livability has emerged as a new paradigm for sustainable urban development (Hashemkhani Zolfani *et al.*, 2022).

Ecological livability underscores a sustainable relationship between humans and the environment, emphasizing the maintenance of ecological balance (Pan *et al.*, 2023). Fu & Zhang (2023) believe that ecologically livable cities are grounded in human-centric principles and provide a suitable living environment for residents. Wang *et al.* (2024) describe ecological livability as an integrated system that encompasses a harmonious natural environment, comfortable living conditions, and a civilized social context. Similarly, Hashemkhani Zolfani *et al.* (2022) define it as an approach aimed at optimizing the balance between urban development and eco-environmental processes. Shi *et al.* (2022) emphasize the integration of natural and human environments, where social systems and ecosystems coexist harmoniously. Despite the diversity of definitions, researchers share a broadly consistent understanding of ecologically livable cities (Fu & Zhang, 2023). Many agree that ecological livability serves as a measure of environmental sustainability and the long-term capacity to maintain biodiversity. In essence, the concept reflects a region's potential for sustainable development (Fan *et al.*, 2021; McGreevy *et al.*, 2019).

The evolution of research over time reveals the emergence of varying perspectives. Initially, ecological livability was primarily concerned with natural and environmental factors such as climate indicators, air quality, and green spaces. Lu *et al.* (2012), however, highlighted the significance of human factors in ecological assessments, developing an evaluation system that integrates both natural and human dimensions. Since then, the concept has expanded to encompass infrastructural and physical criteria, economic development, and social factors (Fan *et al.*, 2021; Fu & Zhang, 2023).

Since 2020, ecological livability has gained increasing scholarly attention, though the volume of research remains relatively limited and concentrated largely in Chinese regions. A review of recent studies (e.g., Cui *et al.*, 2022; Fu & Zhang, 2023; Gong & Chen, 2020; Li *et al.*, 2021; Pan *et al.*, 2023; Wang *et al.*, 2024; Yu *et al.*, 2024) indicates that most research has been carried out at the urban regional scale, focusing on three main aspects: ranking, evaluation index systems, and spatial autocorrelation. These studies

often assess levels of economic, social, and environmental development, employing methods such as the analytic hierarchy process (AHP), entropy, and TOPSIS for indicator weighting and city ranking. In addition, many studies have aimed to establish evaluation index systems or composite models for livability. However, Fu & Zhang (2023) and Pan *et al.* (2023) have concluded that such systems may yield biased results due to a limited number of indicators and insufficient data. They argue that a more accurate assessment of ecological livability requires the use of long-term time series for climatic and green space indicators, broader spatial coverage, and the integration of remote sensing and multi-source data. Supporting this, studies by Yu *et al.* (2024) and Hashemkhani Zolfani *et al.* (2022) demonstrate that remote sensing-based evaluations can effectively monitor spatiotemporal changes in urban environments and provide valuable insights for informed decision-making.

Despite these advancements, a significant research gap remains: the absence of ecological zoning and site selection strategies for livable settlements. Identifying ecologically suitable locations is a fundamental prerequisite for the development of livable cities. As such, zoning and site selection play an important role in shaping livable, sustainable, and resilient urban environments. Proper zoning can mitigate environmental impacts (Flämig *et al.*, 2020), improve resilience (Poom *et al.*, 2014), ensure social justice (Xiao *et al.*, 2022), and enhance economic efficiency (Qian, 2010).

In this study, ecological livability is operationally defined as the relative capacity of a region to support sustainable human settlement, based on a multi-dimensional evaluation framework. Specifically, 27 indicators across six dimensions are considered: infrastructure, public safety and services, living environment, climatic conditions, topographic features, and geological factors. An ecologically livable area, therefore, is one that provides tolerable climatic conditions, sufficient access to public services, low risk of natural hazards (e.g., earthquakes and soil erosion), and adequate infrastructure to support human development. This definition underpins the subsequent trend analysis and spatial zoning of livable settlements. The central focus and innovation of the present research lies in analyzing livability trends and conducting spatial zoning of livable settlements. To ensure a comprehensive, accurate, and dynamic evaluation of indicators, remote sensing and multi-source data were used. A further notable contribution of the present research is its focus on a region characterized by specific climatic challenges.

Attention to ecological livability principles is especially critical for regions with fragile climatic and geographical

conditions. Accordingly, the present study aims to analyze spatial patterns and identify ecologically livable areas based on ecological characteristics in the southern and southeastern regions of Iran. The study area includes the Chabahar, Konarak, and Zarabad counties, which together cover over 21,162 sq km along the coastal strip of the Sea of Oman (Figure 1). These regions exhibit unique ecological features due to their proximity to the Sea of Oman and the Persian Gulf, their location near the Tropic of Cancer, and their exposure to both Indian monsoon winds and Mediterranean air currents. The climate is dry with low annual rainfall and minimal seasonal variation in average temperature. During the hot months, relative humidity in parts of the region exceeds 70% due to maritime influences (Sistan and Baluchestan Meteorological Organization, 2020). Moreover, the area faces acute water scarcity, recurrent floods and droughts, and transboundary water stress along its border with Pakistan (Yazdandoost *et al.*, 2020). Given these challenging geographic and climatic conditions, investigating ecological livability in this study area is both timely and essential.

2. Research method

The present research consists of two main parts carried out in five steps.

- Part 1: Analysis of livability trends from 2010 to 2022

- Part 2: Spatial zoning and identification of livable settlements.

The overall methodology is presented in Figure 2, and the indicators, data extraction sources, and step-by-step procedures are described below.

2.1. Step 1: Selection of livability indicators

Ecological livability indicators were selected based on two criteria: the characteristics of the study region and data availability. Through a review of relevant literature and the characteristics of the Chabahar, Konarak, and Zarabad regions, 27 ecological livability indicators were identified and categorized into six main groups (Table 1): infrastructure, public safety and services, living environment, climatic conditions, topographic features, and geological factors.

2.2. Step 2: Data extraction

Data were collected from diverse sources: statistical yearbooks of the Statistical Center of Iran (for infrastructure and public safety and services indicators), synoptic stations (for climatic indicators), ASTER sensor (for topographic indicators), Landsat 8 satellite imagery (for vegetation density), the NASA website (for earthquake data), and the website of the National Cartographic Center and Geological Survey of Iran (for geological indicators). These sources are referenced in Table 1.

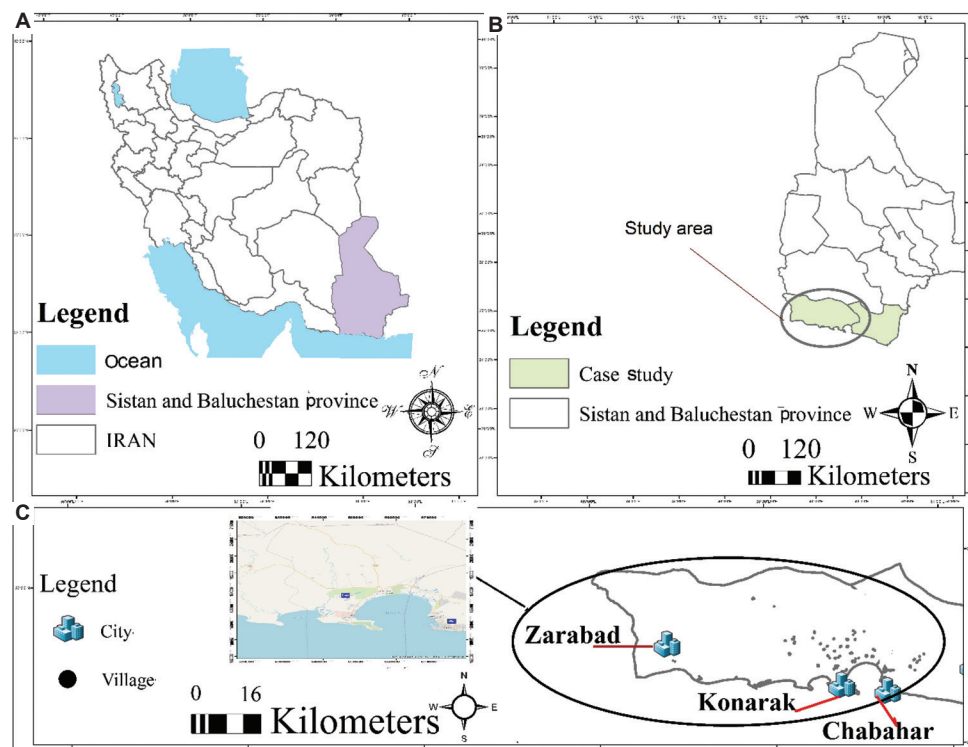


Figure 1. (A-C) Spatial location of Zarabad, Chabahar, and Konarak counties
Source: Maps by the authors.

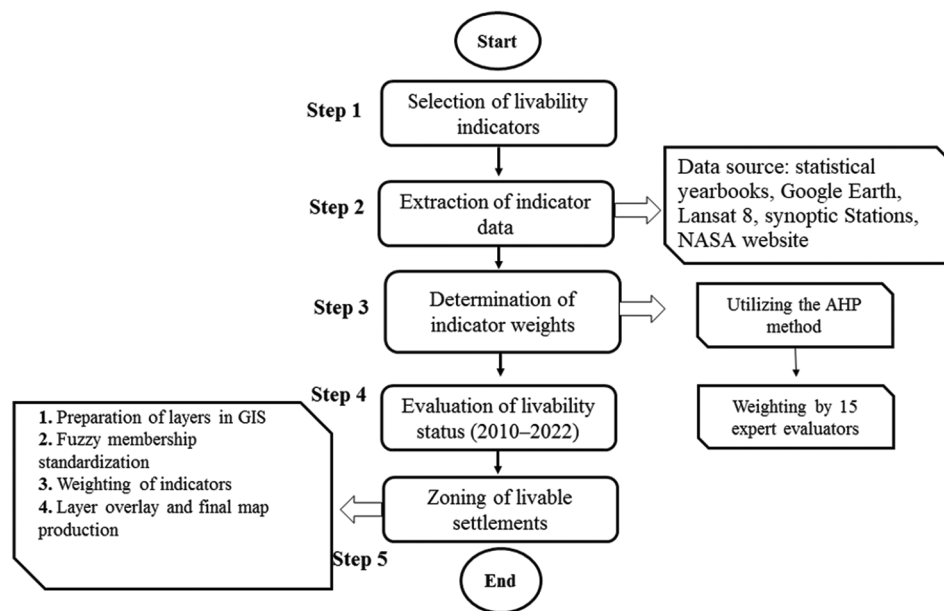


Figure 2. Research methodology steps

Source: Diagram by the authors.

Abbreviations: AHP: Analytic hierarchy process; GIS: Geographic information system.

2.3. Step 3: Weighting

This stage involved assigning weights to the indicators. The weighting process combined the Delphi method (expert opinion) and the AHP to ensure both expert consensus and methodological rigor. The Delphi method is a structured technique for gathering expert opinions and achieving consensus on complex issues through multiple rounds of anonymous questionnaires (Lorusso *et al.*, 2021; McMillan *et al.*, 2016). In this study, the expert panel comprised specialists in environmental science, urban planning, ecology, geology, flood management, and geography. Using purposive sampling, 15 experts were selected.

After gathering expert input through three iterative rounds, the AHP method was used to perform systematic pairwise comparisons of the indicators. Experts rated the relative importance of indicators using Saaty's nine-point scale, which includes values such as 1 (equal importance), 3 (moderate), 5 (strong), 7 (very strong), 9 (extremely strong), and intermediate values (2, 4, 6, 8). These comparisons were organized into a matrix, from which indicator weights were calculated. The final step in this process was the evaluation of the inconsistency ratio to verify the internal consistency of the expert responses. An inconsistency ratio below 0.1 was considered acceptable. In the present study, the inconsistency ratio of the livability indicator matrix met this threshold, confirming the reliability of the weighting results.

2.4. Step 4: Evaluation of livability status (2010 – 2022)

This stage involved assessing the livability status over a 13-year period (2010 – 2022). Two key factors supported the selection of this time frame: (i) it is sufficiently long to capture meaningful trends and gradual changes in livability indicators and (ii) it aligns with the availability of reliable and comparable indicator data, enhancing the validity and comprehensiveness of the analysis.

A crucial consideration in this stage was indicator variability. Indicators that show little or no change during the study period – or typically evolve over decades – were excluded from this analysis. Consequently, indicators within the topographic features and geological factors dimensions were not considered. For example, soil erosion is a gradual process that may take years or decades to produce noticeable environmental effects. Therefore, it may not accurately reflect current or short-term changes in community livability (Gomiero, 2016; Luo *et al.*, 2022). Livability assessments benefit from using variability indicators can reduce responsiveness and potentially lead to misinterpretations of emerging trends (Liang *et al.*, 2020).

It is worth noting that due to the diversity of indicators and variations in their numerical ranges, the data needed to be standardized to a common scale to enable meaningful comparison. To address this, normalization was performed in Microsoft Excel (Microsoft, USA), which rescaled all values to

Table 1. Weights of livability indicators

Category	Indicators	Weights of indicators	References	Data source
Infrastructure	Number of postal units	0.254	Hedayatnezhad Kashi <i>et al.</i> , 2024	Statistical yearbooks
	Number of city P.O. boxes	0.151		
	Number of government counter offices	0.158		
	Number of kindergartens	0.086	Baig <i>et al.</i> , 2019; Hedayatnezhad Kashi <i>et al.</i> , 2024; Liang <i>et al.</i> , 2020	
	Number of primary schools	0.122		
	Number of secondary schools	0.118		
	Number of tertiary institutions	0.078		
	Number of rural information and communication technology service centers	0.033	Hedayatnezhad Kashi <i>et al.</i> , 2024	
Public safety and services	Number of emergency centers	0.151	Lowe <i>et al.</i> , 2015	
	Number of medical centers	0.214	Baig <i>et al.</i> , 2019; Xiao <i>et al.</i> , 2022	Statistical yearbooks of the provincial health center
	Number of public parks	0.188	Cleland <i>et al.</i> , 2021	Statistical yearbooks
	Road; built-up area per year (sq km)	0.238	Liang <i>et al.</i> , 2020	OpenStreetMap
	Number of transportation stations	0.209	Jun <i>et al.</i> , 2022; Zolfani <i>et al.</i> , 2023	Google Earth: The municipalities of the counties of Chabahar, Konarak, and Zarabad.
Living environment	Area of agricultural lands (ha)	0.4	Hedayatnezhad Kashi <i>et al.</i> , 2024	Statistical yearbooks; Landsat 8
	Area of green space (ha)	0.6	Alderton <i>et al.</i> , 2019; Xiao <i>et al.</i> , 2022	
Climatic conditions	Temperature (°C)	0.312	Wang <i>et al.</i> , 2021; Yu <i>et al.</i> , 2024	Synoptic stations
	Humidity (%)	0.287	Hedayatnezhad Kashi <i>et al.</i> , 2024; Yu <i>et al.</i> , 2024	
	Wind (km/h)	0.133	Wang <i>et al.</i> , 2021; Yu <i>et al.</i> , 2024	
	Drought severity	0.268		
Topographic features	Elevation (m)	0.294	Chen <i>et al.</i> , 2024; Hashemkhani Zolfani <i>et al.</i> , 2022	Aster
	Slope (%)	0.447		
	Aspect (°)	0.259		
Geological factors	Distance to rivers	0.281	Olthuis, 2021	Iran National Cartographic Center
	Distance to fault lines	0.278		
	Land uses	0.139	Fu <i>et al.</i> , 2019; Zolfani <i>et al.</i> , 2023	
	Soil erosion	0.164	Chen <i>et al.</i> , 2024	
	Earthquake epicenters	0.138		NASA

a uniform range between 0 and 1. This process enhances data coherence and allows for comparability and interpretability across indicators. Various normalization techniques exist; in the present study, the following formula was used:

$$\text{Normalizes value} = 2 \times \frac{x - \min(x)}{\max(x) - \min(x)} - 1 \quad (\text{I})$$

2.5. Step 5: Zoning of livable settlements

Zoning facilitates the identification of areas deemed suitable in terms of livability. The zoning process consisted of four stages:

- (i) The layers corresponding to the 27 research indicators were prepared in a geographic information system (GIS) and visualized based on standard intervals (Here, “layer” refers to the spatial representation of an indicator’s data in GIS). Table 2 presents the characteristics of these indicators used for zoning.
- (ii) In the second stage, the indicators were standardized using the fuzzy membership function method. The Fuzzy Membership tool reclassifies input data onto a continuous scale from 0 to 1, reflecting the degree to which a value belongs to a specified set. A value of 0 represents complete non-membership, while a value of 1 indicates full membership. Intermediate

values reflect partial membership, with higher values indicating greater likelihood of inclusion. The tool supports various fuzzy membership functions such as triangular, trapezoidal, Gaussian, and sigmoid (Fan *et al.*, 2019). In this study, the Gaussian membership function was adopted. The fuzzy Gaussian function transforms original values to follow a normal distribution. The central value of this distribution is considered the ideal representative of the set and is assigned a membership value of 1. Membership values decrease as input values deviate from this center, eventually reaching 0 once they fall outside the acceptable threshold. Figure 3 displays different shapes of Gaussian membership functions.

The Gaussian membership function is expressed as Gaussian ($x: c, s$) (Equation II), where c denotes the mean (center), s is the standard deviation (width), and m signifies the fuzzification factor:

$$\mu_A = (x, c, s, m) = \exp \left[-\frac{1}{2} \left| \frac{x - c}{s} \right|^m \right] \quad (\text{II})$$

Table 2. Livability scores of Chabahar, Konarak, and Zarabad counties, Iran (2010 – 2022)

Years	Chabahar	Konarak	Zarabad
2010	0.271054886	0.114405	0.094405
2011	0.311273116	0.083806	0.063806
2012	0.31161065	0.082623	0.062623
2013	0.33161065	0.078928	0.058928
2014	0.349774736	0.092289	0.072289
2015	0.367665169	0.085696	0.073641
2016	0.396301155	0.078804	0.063804
2017	0.414518387	0.09492	0.07992
2018	0.42561842	0.090735	0.075735
2019	0.40561842	0.081735	0.066735
2020	0.396616637	0.070735	0.030735
2021	0.385716637	0.060735	0.020735
2022	0.395716637	0.064735	0.035735

- (iii) In the third stage, the weight of each indicator was calculated using the AHP method.
- (iv) In the fourth and final stage, the standardized indicators were overlaid using the simple additive weighting (SAW) method, with the calculated weights applied to perform the livability zoning. Table 3 provides an overview of the indicators.

3. Results

3.1. Livability trends

Table 2 presents the livability scores of Chabahar, Konarak, and Zarabad counties from 2010 to 2022, while Figure 4 illustrates the corresponding trends over this period. According to Table 2, Chabahar county had its lowest livability score in 2010 (0.27), which steadily increased to its peak in 2018 (0.42). This observation indicates an overall upward trend in livability for Chabahar from 2010 to 2018. However, from 2019 to 2022, a decline in livability was observed.

Zarabad and Konarak counties exhibited persistently low livability scores throughout the study period (Table 2), with both showing a general downward trend. These two counties recorded their highest livability scores in the base year (2010) but followed a fluctuating, sinusoidal decline in subsequent years, reaching their lowest levels in 2021. This downward trend persisted through the years 2019, 2020, and even 2022 (Figure 4).

Among these three counties, Zarabad consistently had the lowest livability scores. The highest recorded score for this county was 0.09, which is significantly lower than Chabahar's peak value of 0.42. This stark contrast indicates the significant disparity in livability levels among the counties.

3.2. Characteristics of indicators for zoning

A range of economic, social, physical, and environmental factors is essential for ensuring livable urban environments. However, there are differing views on which dimensions are most critical to livability. For example, Yi *et al.* (2021) and Wang *et al.* (2023) emphasized the role of economic

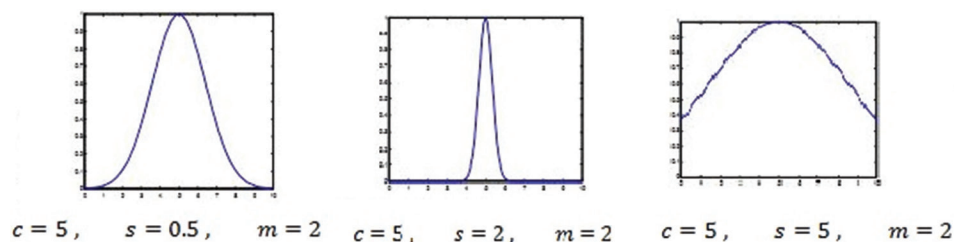


Figure 3. Various shapes of Gaussian membership functions with varying values of s and m
Source: Diagram adopted from Fan *et al.* (2019).

Table 3. Preparation of indicators for zoning

Indicators	Explanations
Distance to postal units	The Euclidean Distance tool in ArcGIS was used to calculate proximity to infrastructure and services. This method was based on the assumption that areas closer to infrastructure and services possess higher ecological capacity and livability potential. The output was a raster map, where each pixel value represents the distance to the nearest infrastructure or service. Following the distance calculation, fuzzy logic was applied to score the areas. In this stage, areas in close proximity to infrastructure and services were assigned the highest scores, while areas farther away received lower scores.
Distance to city P.O. boxes	
Distance to the government counter office	
Distance to Kindergarten schools	
Distance to primary schools	
Distance to secondary schools	
Distance to tertiary institutes	
Distance to rural information and communication technology service centers	
Distance to emergency centers	
Distance to medical centers	
Distance to public parks	
Distance to road	
Distance to transportation stations	
Distance to agricultural lands	The NDVI was used to generate the vegetation density layer. NDVI values range between −1 and +1, with higher values indicating greater vegetation density. Areas with NDVI values between −1 and 0 were excluded due to the absence of vegetation cover. The NDVI layer was generated using IDRISI software, based on the following formula: $NDVI = \frac{(NIR - RED)}{(NIR + RED)} \quad (III)$ where <i>NIR</i> represents near-infrared reflectance and <i>RED</i> represents red-band reflectance (Yu <i>et al.</i> , 2024). It was assumed that areas farther from dense vegetation and agricultural lands are more suitable for construction. Maintaining distance from these areas helps preserve biodiversity and natural ecosystems. In addition, avoiding proximity to agricultural areas can reduce residential exposure to pollutants from farming activities, such as pesticides and dust, in residential areas. In the fuzzy analysis, areas near these layers were assigned a score of 0, while those farther away received progressively higher scores, with the most distant zones assigned a value of 1. The greater the distance, the better the preservation of biodiversity and the prevention of environmental degradation.
Distance to green space	
Temperature (°C)	
Humidity (%)	
Wind (km/h)	Zoning was performed using the Kriging method in GIS, which classifies areas based on the intensity of environmental parameters. According to the fuzzy logic model, areas with lower temperature, humidity, wind speed, and drought severity were assigned the highest score (1), while increasing values of these factors resulted in lower scores, down to a minimum of 0.
Drought	
Elevation (m)	
Slope (%)	
Aspect (°)	DEM data from ASTER satellite imagery were used to develop topographic indicators. Each ASTER image pixel covers an area of 12 sqm and represents elevation above sea level. From the DEM, two additional layers were derived: Slope and aspect. • Slope classification in the fuzzy stage, using the Gaussian membership function, was as follows: • Slopes between 0% and 3% were assigned the lowest score • Slopes between 3% and 7% received the highest scores (0.9 – 1.0) • Slopes above 7% were assigned lower scores. Therefore, slopes ranging from 3% to 7% were considered optimal for livable habitat development. For the aspect, it was assumed that south-facing slopes offer the most favorable conditions for construction. In the fuzzy classification, south-facing aspects were assigned a score of 1. Scores decreased as the aspect shifted toward the west or east, while north-facing slopes were given a score of 0 due to their generally undesirable conditions.

(Contd's...)

Table 3. (Continued)

Indicators	Explanations
Distance to rivers	The Euclidean Distance tool in ArcGIS was used to calculate distances from rivers and fault lines. According to the fuzzy logic framework, greater distance from these features corresponds to higher ecological suitability for settlement. This approach protects sensitive riverine ecosystems and reduces the risk of flooding and earthquakes. Areas closest to these layers were assigned a score of 0, while the most distant zones received a score of 1.
Distance from fault	
Land uses	After extraction at a 1:20,000 scale, land use data were classified in GIS. For the land use indicator, zoning was based on the suitability of land uses. It was assumed that the land most suitable for the development of settlements and buildings should receive the highest score. Accordingly, barren lands were prioritized. The lowest scores were assigned to agricultural lands, gardens, and forests due to their ecological values. Regarding soil erosion, the fuzzy model assumed that proximity to these layers received a value of 0, while those farther away received higher scores, with the most distant zones assigned a value of 1. This reflects a lower risk of landslides and structural damage.
Soil erosion	
Distance to earthquake epicenters	This layer was zoned based on the intensity of earthquakes at each epicenter, using the Kriging method in GIS. It was assumed that areas farther from earthquake epicenters offer greater ecological potential for livability. In the fuzzy logic approach, areas near epicenters were assigned a score of 0, while most distant areas received progressively higher scores, with the farthest zone assigned a value of 1.

Abbreviations: NDVI: Normalized difference vegetation index; GIS: Geographic information system; DEM: Digital elevation model.

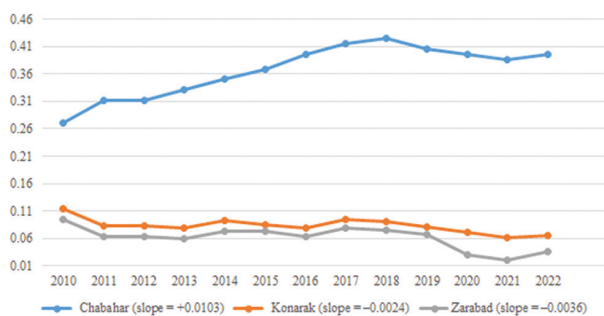


Figure 4. Livability trends in Chabahar, Konarak, and Zarabad counties (2010 – 2022)

Source: Graph by the authors.

development; Liang *et al.* (2020) and Hedayatnezhad Kashi *et al.* (2024) focused on climatic indicators; Ruszczyk *et al.* (2023) and Lloyd *et al.* (2016) underscored social indicators; and Zolfani *et al.* (2023) and Anderson *et al.* (2024) highlighted physical factors. However, in identifying livable locations, topographic and geological factors, along with physical, environmental, and climatic dimensions, should also be considered. In the result section, we present the zoning of livable settlements in the Chabahar, Konarak, and Zarabad counties based on 27 indicators spanning six dimensions: infrastructure, public safety and services, living environment, climatic conditions, topographic features, and geological factors. To perform the zoning, the layers (indicators) were prepared through a multi-stage process, as mentioned in the methodology section. The results of the zoning analysis are presented in the following sections.

3.3. Infrastructure and public safety and service indicators

It was assumed that areas in closer proximity to infrastructure and services possess greater ecological capacity and potential for livability. Based on this assumption, a fuzzy analysis was conducted. Accordingly, the highest scores were assigned to zones nearest to infrastructure and services, while the lowest scores were allocated to more distant areas. Given the consistent hypothesis applied across all Infrastructure and public safety and services indicators, presenting the spatial distribution of a single representative indicator is sufficient. For example, Figure 5 illustrates access to the communication network. As shown in the figure, human settlements such as villages and cities exhibit more favorable conditions due to their ready access to infrastructure and facilities.

Figure 5 further indicates that the southern and southwestern parts of the study region, particularly around the central Chabahar and its main transportation corridors, have relatively good access to the transportation network. In contrast, the northeastern zones and parts of Zarabad exhibit weaker transportation infrastructure and are in a less favorable position regarding access to service centers. This spatial distribution suggests that the lack of an effective transportation network in these areas could pose a significant obstacle to the sustainable development of human settlements.

3.4. Living environment indicators

The living environment indicators in the present study include distance from agricultural lands and vegetation

cover density (Figure 6). The underlying assumption is that the human settlements located farther from agricultural lands and areas with dense vegetation cover are more suitable for construction. In the fuzzy analysis, areas in close proximity to these layers were assigned a score of 0, while more distant areas received higher scores, with the farthest zones assigned a value of 1. A greater distance from these ecologically sensitive areas helps preserve biodiversity and reduces the risk of environmental degradation. Proximity to agricultural lands may lead to the destruction of natural habitats and a decline in biodiversity. Our findings indicate that both vegetation cover density and the extent of agricultural land are generally low across the study area (Figure 6). Spatial analysis also revealed that zones along river corridors tend to have more suitable vegetation cover. As shown in Figure 6A, the western areas exhibit relatively higher vegetation cover density. However, factors such as low average rainfall, water scarcity, rising temperatures,

soil erosion, and recurrent droughts have contributed to a decline in vegetation cover over time.

3.5. Topographic indicators

Figure 7 presents the elevation data in three dimensions, showing minimum and maximum elevation levels across the study area. Low-elevation zones – depicted in blue – correspond to coastal and marine areas, while red areas represent the highest elevations. The fuzzy analysis was based on the assumption that lower elevations (excluding water surfaces) are more suitable for construction. Therefore, areas at the lowest elevation (elevation = 0) were assigned a value of 1, with scores decreasing toward 0 as elevation increases. Based on this criterion, the northern and northeastern parts exhibit low ecological potential for human settlement due to their higher elevation and slope. It can be inferred that as one moves from the west or east toward the northern highlands, the slope and elevation

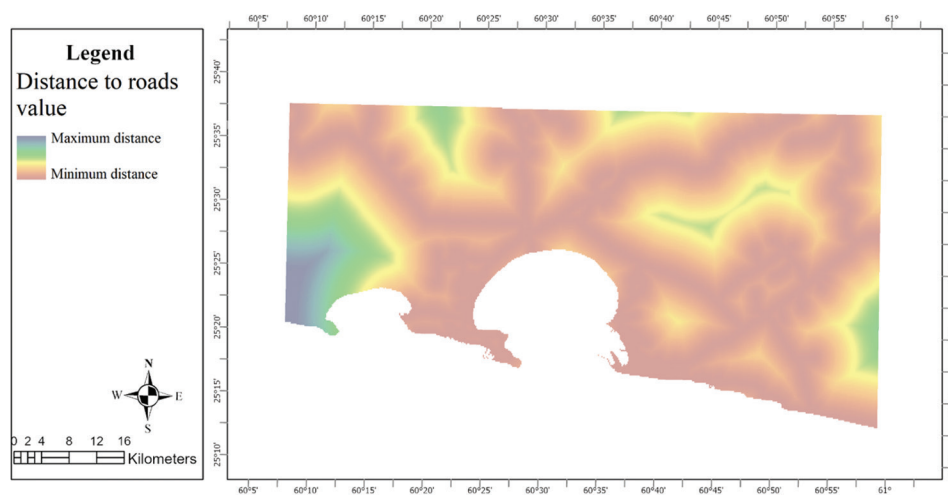


Figure 5. Spatial zoning based on access to the communication network
Source: Map by the authors.

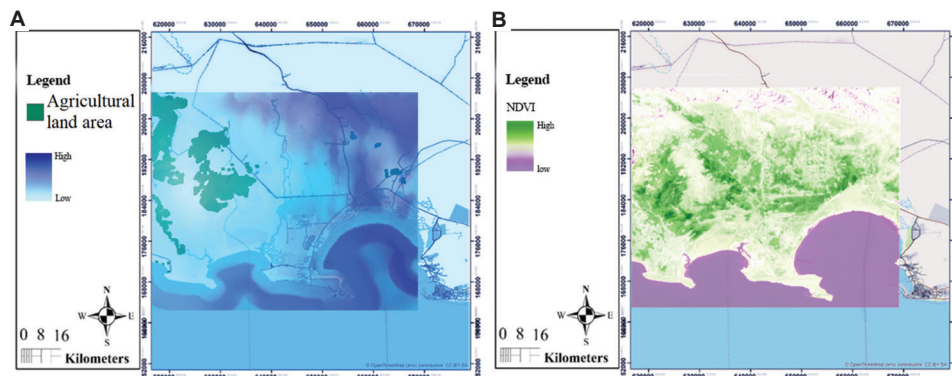


Figure 6. (A and B) Vegetation cover index, represented by the normalized difference vegetation index, and agricultural land area
Source: Maps by the authors.

become increasingly unsuitable for human habitation and construction. In contrast, the southern (excluding water surfaces), western, and central parts of the region demonstrate more favorable conditions for development.

3.6. Climatic indicators

In the zoning process, it was assumed that lower values of temperature, humidity, wind speed, and drought severity are more favorable for livability. Accordingly, areas with lower values were assigned higher scores (closer to 1), while areas with higher values received lower scores (closer to 0) (Figure 8).

Figure 8 illustrates the spatial distribution of key climatic indicators, including temperature, humidity, wind speed, and drought severity, across the study area. These climatic conditions exhibit complex spatial patterns that directly influence ecological livability.

According to the temperature map (Figure 8A), air temperature generally increases from south to north and from west to east, likely due to variations in topography, distance from the coastline, and land cover types. Elevated temperatures impose thermal stress on settlements, particularly in urban areas with limited access to green spaces and cooling infrastructure. The

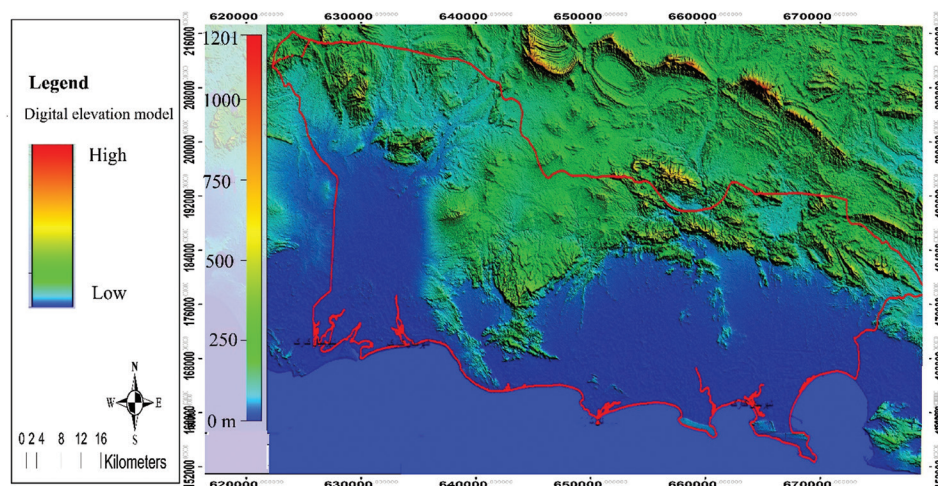


Figure 7. Elevation classification using a digital elevation model
Source: Map by the authors.

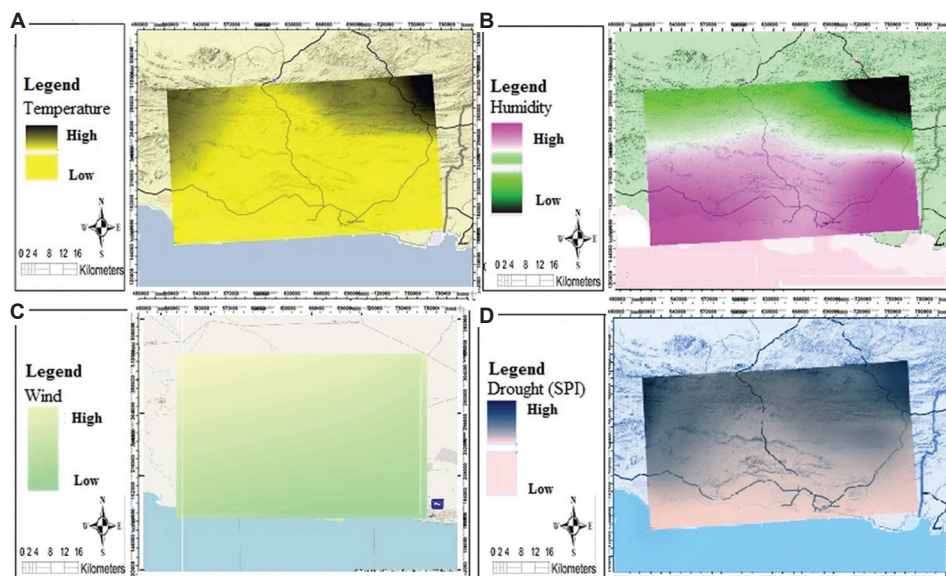


Figure 8. Spatial zoning based on climatic indicators: (A) Temperature, (B) humidity, (C) wind speed, and (D) drought severity
Source: Maps by the authors.

humidity map (Figure 8B) shows that the southern part of the region exhibits the highest relative humidity, while the northwestern and northeastern parts exhibit the lowest levels. Reduced humidity in these areas increases evapotranspiration, which in turn lowers soil moisture and intensifies erosion.

The wind speed map (Figure 8C) indicates that the southern and central zones experience higher wind velocities, primarily due to their proximity to the sea. The temperature differential between land and sea, especially during hot seasons, generates strong monsoonal flows inland. These winds transport dust and soil particles, which can lead to respiratory issues for residents and contribute to soil degradation and reduced vegetation cover.

Finally, the drought map (Figure 8D) reveals that central and northern areas, as well as parts of Konarak and Zarabad, are subject to the most severe dryness and climatic stress. These conditions reflect acute water scarcity, low rainfall, and rising temperatures.

In summary, climatic indicators not only play a crucial role in the spatial zoning of livable settlements but also serve as key limiting factors in the sustainable development of these regions.

3.7. Geological indicators

Figure 9 displays the geological indicators in the case study. In the present study, it was assumed that the farther human settlements are from the sea, fault lines, soil erosion zones, and earthquake epicenters, the greater their ecological

potential. However, the assumption differed for the river indicator. Proximity to rivers offers both advantages – such as aesthetic value, recreational opportunities, and potential economic benefits – and disadvantages, particularly the risk of flooding. Therefore, the benefits of proximity must be balanced with flood risk (Åberg & Tapsell, 2013; Vollmer *et al.*, 2015). Accordingly, in the fuzzy analysis for river proximity, areas located very close to rivers were assigned a score of 0, while intermediate distances received the highest scores. As the distance increased beyond its optimal range, the scores gradually decreased (Figure 9A). Our findings indicate that most rivers and watersheds in these regions are primarily seasonal and prone to flooding due to heavy and torrential rainfall. Given the geographical conditions and the proximity of many settlements to water resources, a substantial number of residents are exposed to flood risks.

Earthquake risk is another significant concern. Indicators such as distance from fault lines (Figure 9B) indicate that Chabahar, Konarak, and Zarabad have been exposed to significant seismic risks from 1980 to 2022. Tectonic activity in these regions has created numerous faults and fractures, some extending several kilometers.

Soil erosion analysis Figure 9C indicates that erosion intensity is predominantly high in the southern and central zones of the study area, particularly in southern Zarabad and southwestern Konarak. These regions are characterized by moderate to steep slopes, sparse vegetation cover, and scattered human activity – all of which contribute to

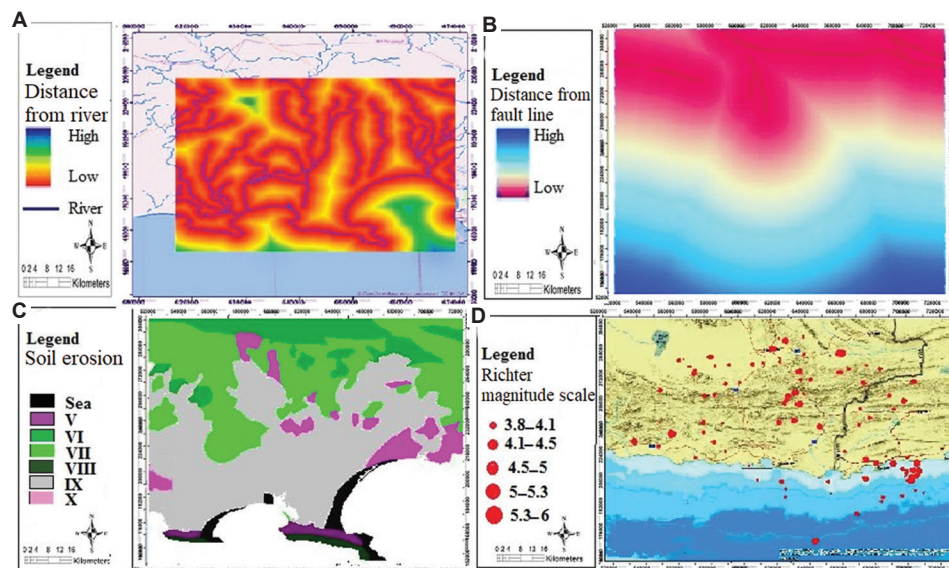


Figure 9. Spatial zoning of geological indicators. (A) River proximity, (B) fault lines, (C) soil erosion, and (D) earthquake epicenters. Source: Maps by the authors.

Note: In Panel C, Roman numerals indicate the intensity of erosion (e.g., V: Low erosion; X: Very high erosion).

increased water and wind erosion. In contrast, the northern and northeastern areas exhibit more favorable conditions, with lower levels of erosion. This spatial pattern highlights the need to address soil erosion as a key ecological risk in development planning and site selection, especially in the southern parts of the region. As shown in Figure 9D, earthquake epicenters are distributed throughout the central and southeast zones. However, the western area is relatively safe compared to the east regarding this natural hazard.

The final indicator in this category was land use, which plays a critical role in shaping the development of livable spaces and human settlements. The ecological value and functional characteristics of different land uses – as well as the compatibility of adjacent land uses – significantly influence livability (Hashemkhani Zolfani *et al.*, 2022). In the present study, land parcels were classified according to their suitability for settlement development based on their land-use characteristics (Figure 10). The lowest zoning scores were assigned to agricultural, orchard, and forested lands due to their ecological value. In contrast, barren lands were prioritized for development. The results reveal that barren lands are predominantly concentrated in the southern zones, particularly due to the presence of the counties of Chabahar and Konarak.

3.8. Zoning of livable settlements

After zoning all individual indicators, the next stage involved integrating the weighted indicators to determine priority zones for livable settlement development. Using the SAW method, the indicator layers were overlaid based on their assigned weights. Figure 11 presents the final zoning map, which identifies suitable areas for the

development and location of livable settlements based on the combination of 27 indicators.

As shown in Figure 11, the eastern and southeastern parts of the study area exhibit the highest suitability for human settlement in terms of ecological livability. However, the current distribution of human settlements does not align well with these ecological standards. Most existing villages are concentrated in the central, northern, and northwestern regions, which are classified as less suitable. Notably, the county of Zarabad is located in an ecologically unsuitable zone, indicating a mismatch between settlement location and livability potential. In contrast, the counties of Chabahar and Konarak are located in zones that are relatively more favorable, although their locations are not entirely in line with ecological livability principles either. Furthermore, the eastern zones – despite having high ecological potential – remain largely uninhabited. This suggests a missed opportunity for sustainable urban development. The primary reasons why the eastern and southeastern zones have been evaluated as highly suitable for the development of livable human settlements include the more favorable conditions of several key indicators – especially climatic factors (e.g., temperature and precipitation) and topographic features.

4. Discussion

The findings from the present study reveal significant variations in livability conditions among the three studied counties. All three exhibited a sinusoidal trend over the study period; however, the livability trends for Zarabad and Konarak were generally unfavorable. Notably, all counties experienced a marked decline in livability from 2019 to

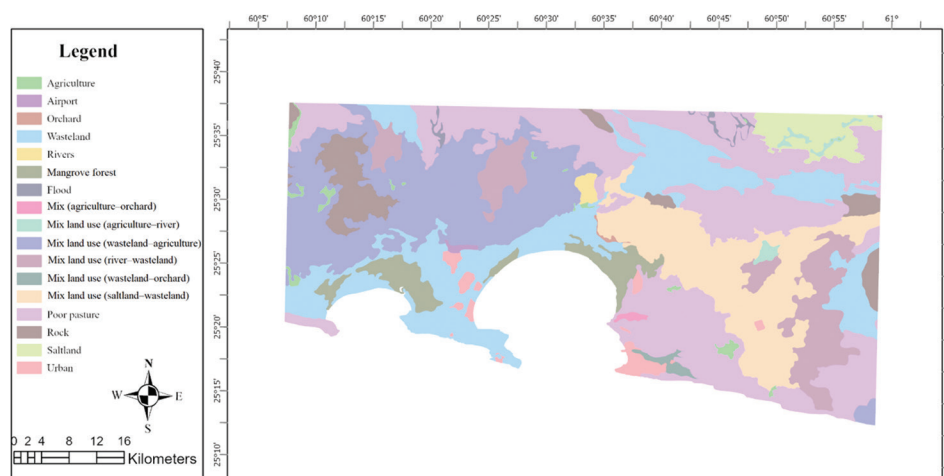


Figure 10. Land use status of the study region.

Source: Maps by the authors.

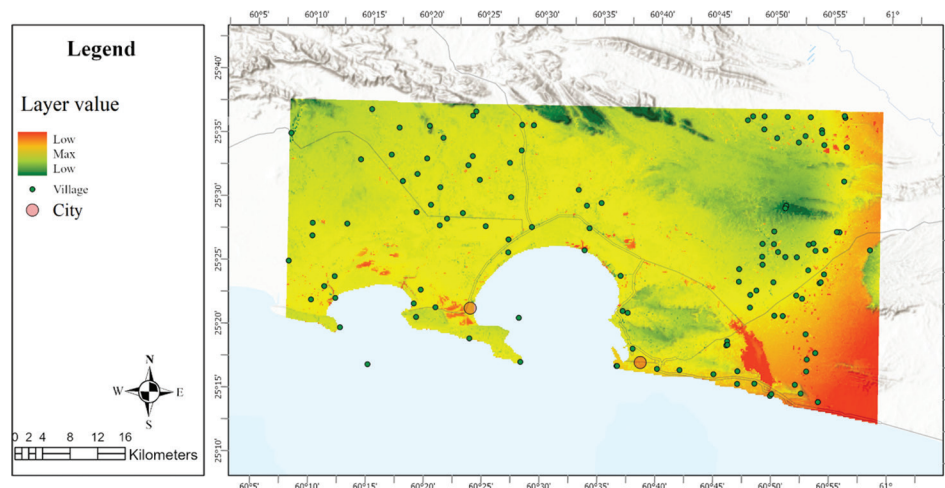


Figure 11. Final valuation map for determining suitable livability zones

Source: Maps by the authors.

2022. One of the primary contributing factors was the COVID-19 pandemic, which had a widespread negative impact on multiple dimensions of livability. Globally, COVID-19 adversely impacted the quality of urban life (Mouratidis, 2021), and its economic repercussions were substantial. For example, global economic growth in 2021 decreased by 3.6% compared to 2020, largely due to the COVID-19 pandemic (Zhao *et al.*, 2022). The study area was no exception. The counties experienced a decline in agricultural production, a slowdown in construction activities, a reduction in information and communication technology-related services and urban development funds, and a decrease in the number of educational facilities during the 2020 to 2022 period.

Another major factor contributing to the unfavorable and fluctuating livability conditions in the counties was the impact of international sanctions. Since 2012, Iran has faced economic sanctions imposed by the United States, the European Union, and the United Nations, particularly targeting oil exports and foreign investment (Farzanegan *et al.*, 2015; Karimi & Turkamani, 2021). These sanctions have led to reduced liquidity, larger budget deficits, currency instability, and rising inflation, all of which have negatively affected livability. In addition, these conditions disrupted trade relations in the studied counties, especially Konarak and Zarabad. Due to their geographical proximity to Pakistan, Afghanistan, Oman, and the United Arab Emirates, the counties of Konarak and Zarabad historically maintained strong cross-border economic relations. However, sanctions severely constrained these trade relations.

In contrast, Chabahar county demonstrated a more favorable and steadily improving livability trend, with

a positive slope of approximately 0.01. Several factors contributed to this upward trend, including increased agricultural land area, improved postal services, a higher number of schools and hospital beds, and expanded public amenities such as parks, relative to the baseline year of 2010. Chabahar's improved livability can be largely attributed to its strategic political and commercial significance. Bordered by the Oman Sea to the south and Pakistan to the east, Chabahar functions as both a port and tourist hub, attracting the interest of policymakers, investors, and regional planners. With the second-highest population density in the province after Zahedan city, Chabahar has received more attention from investors compared to Konarak and Zarabad. In addition, targeted investments by the central government in recent years have supported its development. Its favorable geographical location, investment-ready infrastructure, natural beauty, and prioritization by the Iranian government have contributed to its rapid economic development. As a result, Chabahar has enjoyed more favorable livability outcomes compared to Konarak and Zarabad counties.

Another notable factor negatively affecting livability in the counties is the unfavorable trend in climatic indicators. The study regions face extremely severe climatic stresses that present significant challenges to maintaining livability. Among all evaluated indicators, climatic drivers had the most pronounced adverse impact. A detailed analysis of these climatic indicators is presented in the Appendix. The humidity and temperature indicators have shown increasing trends, while the precipitation indicator has declined over time (Table A1). In addition, the wind indicator is noteworthy. The findings indicate that average daily humidity often exceeds 70% (Figure A1A), and

temperatures frequently surpass 35°C (Figure A1B). Precipitation trends show a consistent decline over the years (Table A1), with annual rainfall never exceeding 180 mm, and the majority of days remaining dry (Figure A1C). In contrast, wind speeds have reached over 9 m/s on some days, with many days recording wind speeds above 5.5 m/s (Figure A1D).

These observations align with previous studies. Hedayatnezhad Kashi *et al.* (2024) and Liang *et al.* (2020) identified a correlation between reduced livability and various types of severe climatic events. Hedayatnezhad Kashi *et al.* (2024) noted that days with relative humidity exceeding 53% negatively impact residents' well-being. Similarly, Brode *et al.* (2012) suggested that temperatures above 26°C can disrupt comfort and quality of life. In the present study, such thresholds are frequently exceeded (Figure A1A).

Persistent droughts in the study area are largely attributable to its geographical context – specifically, its distance from rain-generating systems, low elevation, and proximity to expansive desert regions. These climatic conditions – characterized by high temperatures and critically limited precipitation – have contributed to severe droughts over the years. The study regions are particularly vulnerable to climatic change due to their fragile ecosystems and their location within arid and semi-arid climatic zones. Rising temperatures, prolonged droughts, and shifting precipitation patterns have already caused vegetation loss, increased soil erosion, and growing water scarcity. These environmental stressors undermine biodiversity and ecosystem resilience, directly affecting human activities such as agriculture, fisheries, and urban development by diminishing natural resource availability and increasing the frequency of climate-related hazards (e.g., floods, dust storms).

From a socio-economic perspective, such conditions exacerbate unemployment, migration pressures, and health risks, especially among vulnerable populations with limited adaptive capacity. Therefore, integrating climate adaptation strategies into regional planning – such as water resource management, climate-resilient infrastructure, and ecosystem restoration – is critical for securing long-term livability and sustainability in these regions.

The study by Hedayatnezhad Kashi *et al.* (2024), which examined the livability of cities in Sistan and Baluchestan province from 2010 to 2019, supports the findings of the present study. Their analysis showed that livability levels varied across the cities during the study period, with many – such as Konarak – experiencing a downward trend. Their results further indicated that Zahedan, the provincial capital, exhibited a higher level of livability,

and cities in its vicinity ranked higher in livability scores compared to central and southern (Konarak) cities. The authors attributed this disparity to policy decisions that prioritized the development of the provincial capital, often at the expense of other cities. In this context, Chigbu (2021) believes that livability reflects the broader level of development. Therefore, disparities in development levels indicate natural inequalities, political-economic imbalances, planning system deficiencies, and uneven development that fails to align with population needs – patterns clearly evident in the livability levels of Zarabad, Konarak, and Chabahar counties.

This study employs a comparative analysis to identify methodological parallels and divergences relative to prior ecological livability research. For instance, Gong and Chen (2020) and Fan *et al.* (2021) developed evaluation models to rank ecologically livable cities and identified key factors influencing livability. However, their omission of hydrological and climatic indicators limited their capacity to delineate spatial dependencies and convergence patterns among cities. In contrast, Yu *et al.* (2024) and Cui *et al.* (2022) adopted spatial analysis approaches using multi-source time-series data to compare regional livability metrics. While their methodologies represent progress, these studies similarly overlooked hydrological and climatic variables and relied on a narrow set of indicators. For example, Yu *et al.* (2024) focused exclusively on five urban ecological metrics: greenery, temperature, dryness, water humidity, and atmospheric turbidity. Furthermore, Cui *et al.* (2022)'s relied on a single-year dataset, which limited the temporal scope of their analysis and failed to capture the dynamic nature of livability.

In contrast, the present study distinguishes itself by (i) incorporating a broader and more inclusive set of indicators (particularly hydrological/climatic factors) and (ii) placing explicit emphasis on spatial zoning, a critical aspect often overlooked in earlier work.

5. Conclusion

Livability is a dynamic concept that evolves over time in response to urban development, policy changes, and other factors. Therefore, the present study emphasizes the need to examine livability trends and zoning patterns in vulnerable regions that have received limited attention in previous studies.

The results of this study clearly reveal substantial disparities in ecological livability across the counties of Chabahar, Konarak, and Zarabad. Chabahar demonstrated the highest livability level, driven by strategic infrastructure investments and its advantageous geopolitical position. In contrast, Zarabad consistently ranked the lowest, reflecting

significant ecological vulnerabilities and deficits in essential services. Among all the examined variables, climatic and geological indicators – particularly temperature, drought, soil erosion, and seismic risk – emerged as the most influential determinants of livability. Furthermore, spatial zoning analysis identified the southeastern and eastern zones as the most suitable areas for future human settlement development, based on an integrated assessment of 27 ecological indicators.

These findings highlight that many existing settlements, especially Zarabad, have developed in ecologically unsuitable zones, increasing their vulnerability to environmental degradation and climate-related hazards. The declining livability trends in Konarak and Zarabad underscore the urgent need for targeted interventions to reverse unsustainable development patterns. In contrast, the upward trajectory observed in Chabahar, largely driven by development-oriented policies and investment, demonstrates the positive impact of strategic planning on ecological livability.

This study, by analyzing livability trends and identifying suitable settlement zones based on ecological criteria, yields several policy implications for planners and decision-makers:

5.1. Operational applications

- Urban development plan revisions: The findings provide a scientific basis for revising comprehensive and detailed urban plans across counties to better align future development with ecological sustainability
- Investment guidance: Identifying low-livability zones (e.g., Zarabad and Konarak) facilitates targeted budget allocation for infrastructure improvement.

5.2. Policy consequences

- Migration reduction policies: Given the declining livability trends, policies focused on job creation and service provision should be prioritized in Zarabad and Konarak to reduce outward migration
- Environmental crisis management: The study's emphasis on hydro-climatic indicators underscores the need for climate change adaptation policies.

5.3. Strategic warnings:

- Instability exacerbation: The establishment of Zarabad and other northeast settlements without adequate ecological assessment could intensify instability
- Spatial justice: The stark disparity in livability between Chabahar and other cities highlights the necessity for more equitable resource distribution.

While this study focuses on the unique ecological and geographical conditions of the Chabahar, Konarak,

and Zarabad counties – characterized by an arid climate, coastal proximity, and exposure to seismic and hydrological risks – the analytical framework and multi-dimensional evaluation method employed herein may offer valuable relevance. Similar coastal and semi-arid regions in other countries, particularly those facing ecological fragility, infrastructure limitations, or climatic stress, may benefit from adopting a comparable indicator-based zoning approach for identifying suitable settlement areas. Although direct comparison with other international regions was beyond the scope of the present study, future studies could expand the framework through cross-regional analyses to assess the transferability and adaptability of ecological livability criteria under different geographical and institutional contexts.

Although the findings of this study indicate that the eastern and southeastern areas possess considerable ecological potential for the development and establishment of human settlements, the practical realization of such recommendations requires careful consideration of the feasibility within Iran's local governance framework. The implementation of population relocation or new settlement development policies is contingent upon factors such as institutional and administrative capacity, political commitment at the regional level, and alignment with national development strategies. Furthermore, legal frameworks governing land ownership, internal migration, and regional investment play a pivotal role in enabling or constraining such spatial planning efforts. Therefore, future research is encouraged to incorporate institutional and governance dimensions into ecological livability assessments to facilitate the formulation of more practical and applicable strategies for sustainable settlement development.

Despite the valuable insights gained from this study, it is necessary to acknowledge certain specific limitations that may temper the interpretation of our findings. First, the reliance on data from 2010 to 2022 may constrain the temporal scope of our analysis. Expanding the study's timeframe could provide a more nuanced understanding of long-term trends, particularly in climate-related indicators and their impacts on livability. Second, our focus on the regional level may have overlooked the differences that climatic and geological indicators can exhibit at larger scales. Future research efforts should concentrate on broader scales. Moreover, limitations may stem from the analytical methods employed in our study, such as the use of specific data analysis techniques. Identifying these methodological limitations underscores the need for continuous review and validation of analytical approaches in future studies. In this regard, and to address the aforementioned challenges, the following recommendations are proposed:

- (i) Identifying the influential drivers and analyzing the long-term trends of the indicators
- (ii) Conducting broader-scale zoning using livability indicator simulations and examining the challenges and implications
- (iii) Designing scenarios and assessing potential threats to unsuitable zones.

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Conflict of interest

The authors declare that they have no competing interests.

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Ethics approval and consent to participate

Not applicable.

Consent for publication

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Availability of data

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix

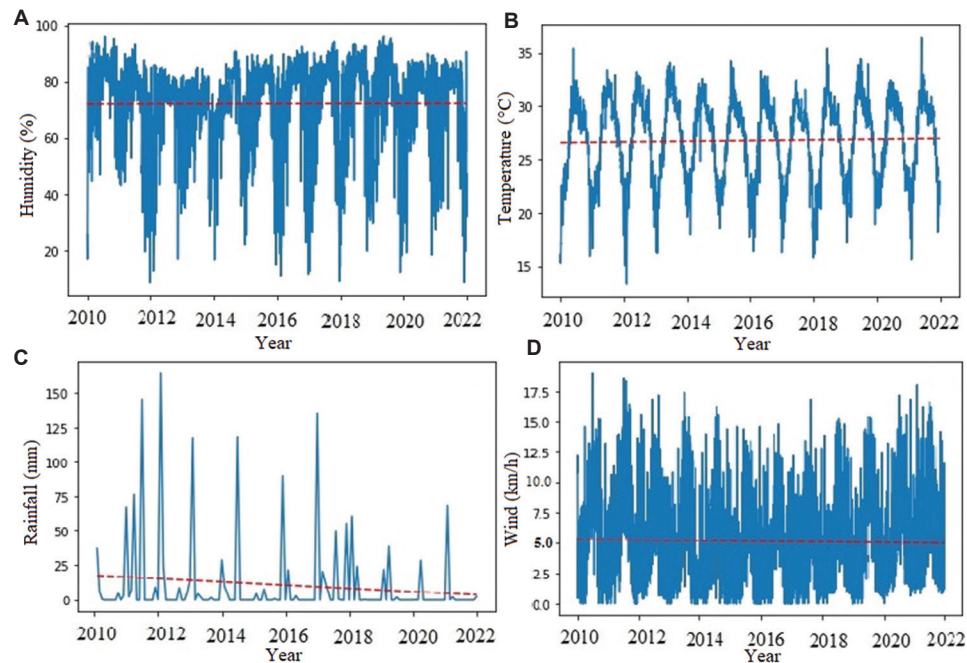


Figure A1. Time series of climatic indicators from 2010 to 2022 in the study region: (A) Relative humidity, (B) temperature, (C) rainfall, and (D) wind speed
Source: Graphs by the authors.

Table A1. Trend analysis of climatic indicators based on Mann–Kendall slope

Climate factors	Slope	p-value
Temperature	Increasing	0.05
Humidity	Increasing	0.006
Wind	Increasing	0.00
Rainfall	Decreasing	0.028