Enhancing Sustainability in Road Infrastructure: A Comprehensive GIS Approach to Vulnerability Mapping in the Marand-Bazargan Freeway, Iran

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Abstract

In this paper, we present a sustainable infrastructural planning using Geographic Information Systems (GISs) for vulnerability mapping of the Marand-Bazargan freeway in Iran. Literature acknowledges that transportation infrastructure is essential for economic development, but it can have significant negative environmental impacts such as land use change, air and noise pollution, and biodiversity loss. In addition, the literature review revealed that EIAs are essential instruments for identifying, mitigating, and/or compensating the environmental impacts of these projects. GIS has emerged as a powerful tool for environmental assessment and transportation planning. However, there is a lack of research on the effectiveness of GIS for road projects in Iran, with most studies focused on site selection and conducted outside the country. This study aims to answer a main research question: How can GIS be used to select the most environmentally friendly route? The analysis conducted detects vulnerable areas and determines the alignment with minimal negative impacts by overlaying maps and utilising ArcGIS Pro and the Analytic Hierarchy Process (AHP). The vulnerability map generated using GIS overlay analysis shows that the majority of the freeway has low to negligible vulnerability, while only limited areas have moderate to high vulnerability. Integrating GIS and the Leopold Matrix enables a comprehensive analysis and ensures sustainable and environmentally-friendly infrastructure development in road construction projects of Iran. Limitations include the constraints geographic scope, AHP subjectivity, and limited range of experts, environmental factors and stakeholders' viewpoints. Further, the use of Leopold Matrix to assess the environmental consequences of micro-activities would be expanded upon.

1. Introduction

Transportation infrastructure is critical for the prosperity and security of a region, providing steady access to products and services, improved transportation, economic development, and a stronger military presence. However, these projects can also have significant negative environmental impacts, such as land use change, air and noise pollution, socioeconomic changes, and biodiversity loss [1]. To achieve sustainability in the transportation sector, an integrated view of the decision-making process is required; in other words, all factors involved in transportation planning, land use, and the environment must be evaluated together. The task of analysing the environmental, social, and economic implications of development projects requires the use of tools such as the Environmental Impact Assessment (EIA), which is flexible but must set sustainability objectives, criteria, and indicators [2].

EIA methodologies can range from basic to complicated and involve identifying, forecasting, and analysing relevant consequences and mitigating them. Matrices, networks, checklists, and Geographic Information Systems (GIS) are commonly used methods for forecasting effects [3]. Despite the potential negative impacts of transportation projects, comprehensive environmental assessment studies are often not conducted, and environmentally friendly options are ignored due to economic considerations. This is particularly true for road projects in Iran. This paper focuses on a case study of the Marand-Bazargan freeway in Iran, which is a minor step toward conserving vital natural and national resources in the building and operation of the roadway.

The Marand-Bazargan freeway, about 185 kilometres long, is part of the East-West international transport and transit corridor and the AH1 Asian highway. It connects Iran's internal traffic to international traffic and links neighbouring countries like Pakistan, Afghanistan, Turkmenistan, and Azerbaijan to Iran, then to Turkey and Europe via the Bazargan border crossing. Numerous routes have been studied for the Marand-Bazargan axis, including the main route (Corridor I) and local variants.

This freeway stretches from Marand in the south to the Maku Free Zone. The first approximately 60 km of the route are located in East Azerbaijan province, and the rest are in West Azerbaijan province [4]. This freeway has 4 tunnels, 29 large bridges, and 7 intersections. In the EIA studies for selecting the best option, three corridors, including the main corridor I and corridors II and III, which are obtained by combining corridor I and local variants, must be compared and evaluated (see Figure 1).

Figure 1. The main route plan and variants for the Marand - Bazargan freeway [4]

The benefits of building this freeway include increasing tourist traffic, strengthening imports and exports of goods, providing communication between neighbouring countries, boosting the economy of the Maku Free Zone, reducing road accidents, saving fuel consumption, increasing national revenue, job creation, improving national security, and the development of transportation infrastructure. However, it is essential to ensure that this infrastructure development is carried out with minimal negative environmental impacts. Therefore, this study focuses on the case of the Marand-Bazargan freeway in Iran to address the need for sustainable infrastructure planning and decision-making.

2. Literature Review

A scientific study must start with a comprehensive understanding of the problem and theoretical foundations, achieved through examining current literature and prior research. The review consists of four stages. The first stage evaluates the environmental impacts of road construction and operation. The second stage focuses on identifying EIA techniques, including GIS technologies. The third stage researches the application of the AHP approach in different projects. The last stage studies how to choose the optimal corridor for road construction based on the EIA results. The search approach concentrates on selecting research papers that closely align with the study's keyword combination, while the article's content alignment with the review's title and study goals serves as the selection criteria.

The literature review conducted as part of this research highlights that transportation infrastructure development, construction, and maintenance are linked to various negative environmental consequences [1], ranging from the most obvious, like the loss of local ecosystems, landscape changes, or air pollution, and noise emissions to more subtle effects, like disturbances and changes in ecosystem quality, or changes in the size of water bodies and the types of land use and land cover [5].

EIA is a crucial legal tool that enables the identification, prediction, prevention, and mitigation of these negative effects, according to all researchers. Variations of proposed activities and investment projects are considered as part of the EIA in order to choose the alternative that is most advantageous from an environmental standpoint.

In the second stage of the review, it is concluded that GIS is a software program that stores and retrieves geographical data, analyses it, and displays it comprehensively. The applications of GIS in environmental studies are diverse and effective, and include environmental assessment, cumulative impact assessment, litigation, transportation planning, and decision-making processes [6]. GIS can access large database, execute dynamic queries based on representations of the actual world, and enable the use of interactive video and digital sound in conjunction with zoning maps to aid planners and decision-makers [6]. GIS is also used to assess territorial implications, calculate the impact of new linear transportation facilities [2] and evaluate suitable locations for development projects based on technological, economic, and environmental aspects.

Additionally, the combination of the Analytic Hierarchy Process (AHP) and GIS has shown promise for infrastructure project planning and environmental impact assessment [7]. AHP is a valuable technique for decision-making, particularly in the field of transportation, land use management planning, landfill site selection, and environmental impact assessment. The AHP approach involved building a hierarchy, generating a pairwise comparison matrix, finding weight values, interpreting consistency, and aggregating individual values. The integration of AHP with other techniques such as GIS and fuzzy logic provides more accurate results in decision-making. The use of AHP has been applied in various studies, such as the assessment of inland surface water quality status, land suitability for wheat production, and the environmental effects of mining activities. The AHP approach assigns weights to all parameters and criteria, which makes it a flexible and effective selection procedure.

Subramani *et al*. [8] and Subramani and Pari [9] found that GIS can be used to identify cost-effective and environmentally friendly routes that reduce travel time and fuel consumption. Jadav, Banerjee, and Tiwari [10] demonstrated the application of GIS in evaluating the environmental impact of highway projects. Panchal and Debbarma [11] revealed the usefulness of GIS in selecting the optimum railway route based on slope, topography, and drainage features. Rangzan *et al*. [12] used GIS and AHP to find an optimal route that avoided environmental consequences. Qi, An, and Liu [13] investigated the impact of highway rehabilitation projects on the natural environment using GIS technologies.

It is recommended by all studies that road construction projects focus on selecting the optimum route that is cost-effective and environmentally friendly, using GIS to minimise negative environmental impacts [14], and achieving optimal overall design [7]. However, there is a lack of research on the effectiveness of GIS for road projects in Iran, with most studies focused on site selection and conducted outside the country.

This study aims to answer the research question: How can GIS be used to select the most environmentally friendly route among several proposed routes for a road construction project? The contributions of this research include providing a comprehensive and integrated methodology for EIA of road construction projects, combining GIS and AHP for route selection, and developing a detailed understanding of the environmental sensitivities of the project to identify the best alignment with minimum negative environmental effects.

3. Methodology

Wilson's Honeycomb [15] has been adopted as a framework to guide the appropriate methodology for this study. This study utilises both quantitative and qualitative data analysis techniques for EIA using GIS tools. The quantitative analysis involves overlaying and analysing raster data layers, while the qualitative analysis involves interpreting the results to identify areas of high vulnerability and potential environmental impacts. To accomplish this, various data analysis techniques are utilised, including Overlay analysis, Buffer analysis, Distance analysis, and Spatial analysis. In addition, the study uses the AHP to provide a structured and systematic approach to prioritise different raster layers and their importance in the overall EIA of the freeway project.

A pragmatic research philosophy has been used, which emphasises practical outcomes and problem-solving. The GIS analysis component involves objective spatial data analysis, while the AHP survey involves subjective opinions and judgements from experts, which are synthesised into a weighted decision model to minimise individual biases. However, there may still be some degree of subjectivity in the AHP approach.

In this research, a deductive research approach will be primarily used, with some elements of abductive reasoning. The use of GIS and AHP to determine the least vulnerable route involves deductive reasoning as using existing knowledge and criteria are used to evaluate and compare the proposed alignments. Specifically, a pre-existing framework (GIS) and a structured decision-making method (AHP) are applied to determine the best alignment based on predefined criteria, which involves a top-down, deductive approach.

The research design is a case study focusing on the Marand-Bazargan Freeway in Iran. The data used in this study can be considered a combination of primary and secondary data. The raster layers obtained from various organisations are secondary data, as they have been collected for their own purposes and not necessarily for this specific research project. However, the survey conducted using the AHP method to determine the importance and weight of these layers is primary data, as it was collected specifically for the study. The survey of environmental experts is a form of non-probability sampling, as the selection of these experts was likely based on their expertise and availability rather than a random selection process.

4. Discussion and findings

The approach of overlaying maps was used for the Marand-Bazargan freeway project to identify the most environmentally vulnerable areas in the immediate vicinity of the proposed freeway route and select the best alignment with the fewest negative environmental impacts. To conduct an EIA and understand project activities, study zones must identify the project's environmental context. The definition of the project's triple impact zones is crucial for this purpose.

- The immediate zone: This study zone includes the lands of the Marand-Bazargan freeway, which is 185 kilometres long and has a 76-metre buffer zone (38 metres on each side). Land use in this area is primarily grazing and human construction. The main activities that lead to environmental changes are levelling, excavation, tunnelling, and other road construction activities.

- Direct influence zone: This area includes a 1-kilometer radius around the freeway axis, which is most affected by the construction of the freeway and is directly affected by the project's implementation. The various impacts resulting from the project's implementation include biological, physical, socio-economic, and cultural effects, as well as potential environmental pollutant emissions, which will have a direct impact on this area.
- Indirect influence zone: This zone includes the area surrounding the freeway that may not experience direct physical changes. It is larger than the direct influence zone and includes adjacent neighbourhoods.

ArcGIS Pro and the AHP method have been used to overlay information layers in order to determine the extent of environmental sensitivities within the direct influence zone.

To build a model in GIS, information layers related to the criteria involved in vulnerability assessment were prepared and made ready for use in the GIS environment. The evaluation criteria in the current project include earthquake centres, rivers, settlements, agricultural and horticultural lands, areas under the management of the Environmental Organisation, and faults.

Figures 2 to 5 (extracted from ArcGIS) show these criteria in the studied area. After the layers are prepared, the categories of each layer are scored. Then, using the AHP, the weight of each layer is determined, and this weight is applied to the scores of each layer, resulting in a vulnerability analysis layer.

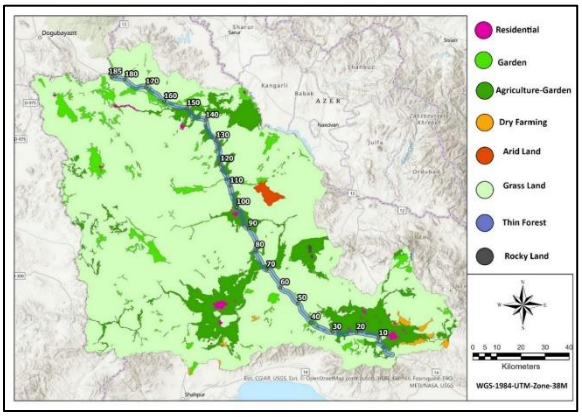


Figure 2. Land use of the study area

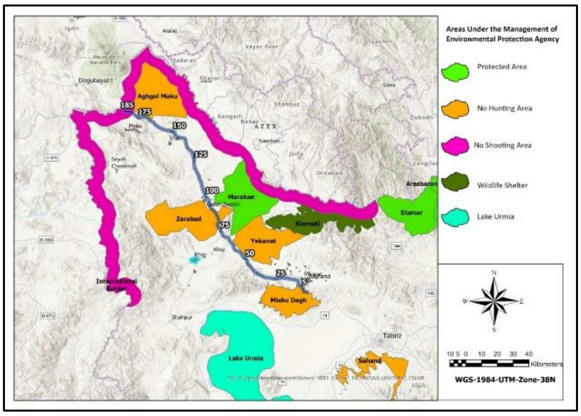


Figure 3. The location of the areas under the management of the environmental protection organisation in relation to Marand-Bazargan freeway

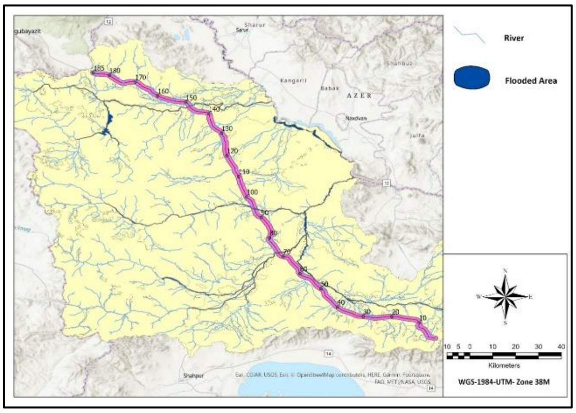


Figure 4. Location of rivers in the study area

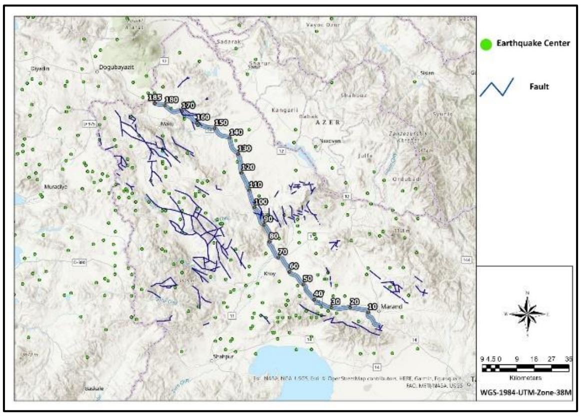


Figure 5. Location of faults and earthquake centres in the study area

4.1. Determining the importance weights of the selected criteria for environmental vulnerability assessment

The AHP method was used in this study to compare the considered criteria with each other and determine the relative importance weight of each criterion. This method, which employs the pairwise comparison strategy, is one of the Multi-Criteria Decision Making (MCDM) methods invented by Saaty [16]. MCDM is the term used to describe the evaluation of many criteria, each of which comprises various qualitative and quantitative information, for a particular goal, which assists in selecting the most logical option while assessing several criteria and analysing the connections between these elements [17].

According to Saaty [18], in this method, factors are compared with themselves and other factors. Numbers are used to fill the matrix of pairwise comparisons to determine the relative importance of each criterion in relation to the evaluation. The important point in forming a pairwise comparison matrix is that when comparing an element with its own criterion, the number 1 is inserted in the matrix. Therefore, the diameter of the matrix will always be a set of numbers of one. In the matrix of paired comparisons, the element in the left column is always compared with the element in the top row, and the number given in the matrix represents the importance of the element in the left column compared to the element in the top row [17]. Judgments should be based on a scale of 1-9 (Table 1).

The AHP integration with GIS is an effective spatial analysis tool that allows for the creation of a complete geographical database that can be utilised by multi-criteria approaches and allows the user to assess different alternatives based on numerous and competing objectives [19]. The weight of criteria in empirical methods like AHP should be determined based on expert opinions. Thus, in this study, a survey was conducted among several engineers and experts in the fields of civil engineering, construction, and environmental engineering, and then, to determine the weight of each factor, these opinions were integrated (see Table 2).

Table 1. Establishing numerical scales for pair-wise comparison (Saaty scale)

Preference Scale	Preferred Level	Considerations
1	Equal	Equal contribution
3	Moderate	slight advantage
5	Strong	Significantly favour
7	Very strong	Very strongly favouring
9	Extreme	Maximum degree of favouritism
2, 4, 6, 8	Intermediate	Balance between weights 1, 3, 5, 7, and 9
Reciprocals	Opposite	Relates to an inverted comparison

Source: From Saini, Gupta and Arora [20]

Finally, the geometric mean of each row was calculated, and the resulting vector was normalised to calculate the weight of each criterion from the pairwise comparison matrix (Table 3). Based on the results obtained from the AHP method, the criteria of distance from protected areas, residential areas, and agricultural lands and gardens are the most important, and other criteria are of lesser importance.

Table 2. Pairwise comparison matrix of criteria used in assessment

Criterion	Earthquake Centre	Fault	Rivers	Agricultural Lands and Gardens	Residential Lands	Protected Areas
Earthquake Centre	1	0.5	0.33	0.25	0.2	0.1667
Fault	2	1	0.5	0.33	0.25	0.2
Rivers	3	1	1	0.5	0.33	0.25
Agricultural Lands and Gardens	4	3	2	1	0.5	0.33
Residential Lands	5	4	3	2	1	0.5
Protected Areas	6	5	4	3	2	1

Table 3. The weight (relative priority) of the criteria used in the assessment

Criteria	Importance Weight
Protected Areas	0.38
Residential Lands	0.25
Agricultural Lands and Gardens	0.16
Rivers	0.10
Fault	0.07
Earthquake Centre	0.04

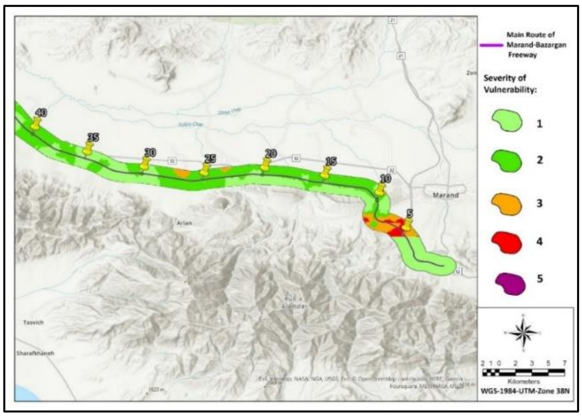
Table 4. Scores related to each criterion

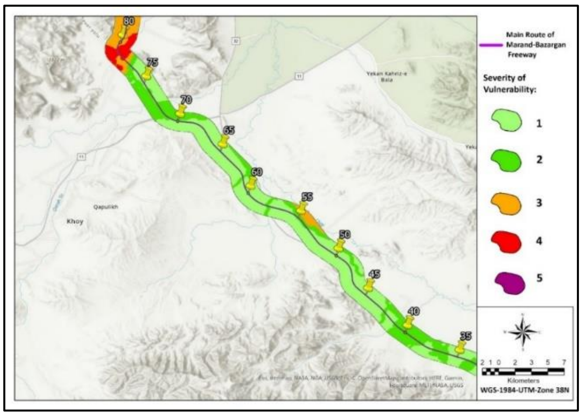
Fault + Protected Areas + Earthquake Centres	Agricultural Lands and Gardens	Residential Areas + Rivers	Vulnerability score
Distance (m)	Distance (m)	Distance (m)	
≤200	≤50	≤100	6
200-400	50-100	100-200	5
400-600	100-150	200-300	4
600-800	150-200	300-400	3
800-1000	200-250	400-500	2
> 1000	> 250	> 500	1

4.2. Determining the vulnerability level of the lands along the freeway and analysing the best environmental option

After applying the weights obtained for the criteria through the AHP method, the results are applied to each layer and in the score columns of these layers (Table 4), which has been fully implemented in ArcGIS software. The classification of each of the studied criteria is modelled in GIS environment based on Table 4. Finally, the intensity synthesis layer was classified using the Reclassify function in GIS to determine the effects, their intensities, and areas where these effects occur. The severity of environmental vulnerability was classified into five groups:

1. Negligible effect
2. Negligible to low effect
3. Low to moderate effect
4. Moderate to high effect
5. High effect





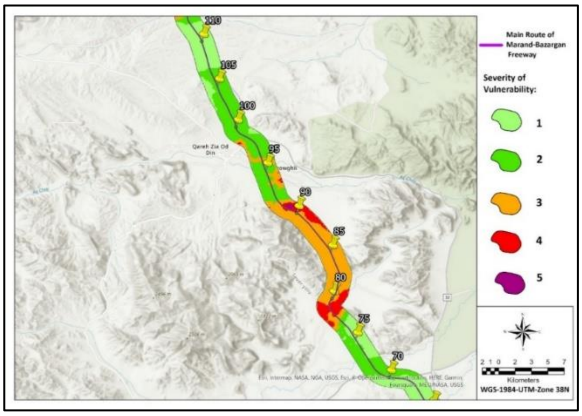
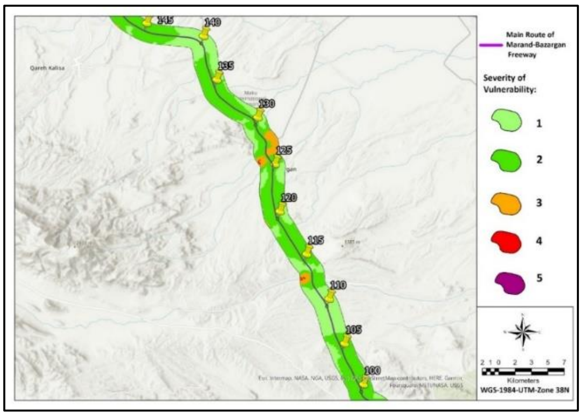
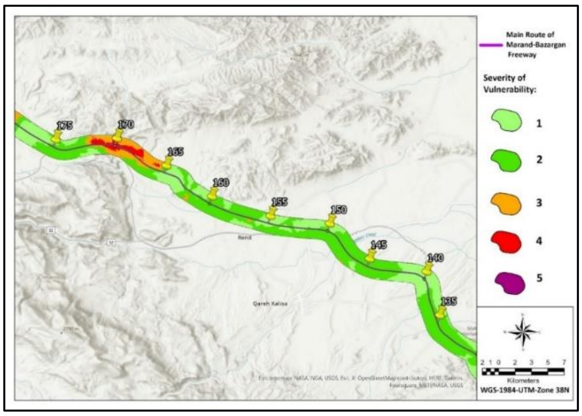


Figure 6. Vulnerability grade map (Km 0-110)

Figures 6 shows the vulnerability grade maps of the Marand-Bazargan freeway within the project's direct influence zone. It should be noted that due to time constraints, only vulnerability maps have been prepared along the main route in this study. To select the best environmental option among the proposed corridors 1, 2, and 3, this process needs to be repeated for the other two corridors as well. Finally, by examining and analysing the results obtained, the best corridor with the lowest vulnerability intensity (minimal negative effects) should be selected.





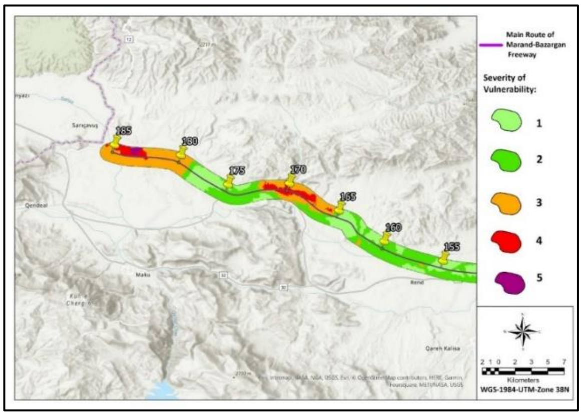


Figure 6. Vulnerability grade map (Km 110-185)

5. Conclusion

The overlaying approach in ArcGIS Pro was used in this study to build a vulnerability map of a freeway route. The criteria utilised were earthquakes, rivers, residential areas, agricultural fields, gardens, protected areas, and faults. The AHP approach was used to assess the relative importance and weight of each criterion, which was then divided into six categories based on its closeness to the freeway axis. Through layer overlaying, an environmental vulnerability map was created by applying the weights acquired from AHP to each layer and its scores.

According to the vulnerability maps, the majority of the freeway's length exhibited negligible to low vulnerability, with only limited areas indicating moderate to high vulnerability. To choose the optimal option, vulnerability maps for various corridors should be created to determine the route with the least vulnerability and the fewest negative effects. ArcGIS software was quite helpful throughout the entire procedure.

6. Recommendations

While this study contributes valuable insights into vulnerability mapping and the environmental impact of transportation projects, several limitations underscore the need for targeted recommendations. To enhance the applicability and robustness of future research endeavors, the following recommendations are proposed to address geographical constraints, mitigate subjectivity in methodology, broaden expert input, and explore additional assessment tools.

First, the geographic scope was confined to a single freeway in Iran, potentially limiting the findings' generalisability to other places or circumstances. As a result, it is recommended that comparable research be conducted in diverse places to confirm and expand on the findings gained here.

Second, the AHP technique requires subjective weighing of criteria, which adds the possibility of bias and may impair the results' validity. To mitigate subjectivity, it is crucial to justify and thoroughly document the criteria used for weighting and ranking.

Finally, the use of a limited number of AHP specialists and a limited range of environmental factors in GIS layers may have reduced the breadth of viewpoints and considerations in the study, thereby affecting the accuracy and reliability of the conclusions. Future studies should attempt to include a larger pool of experts and a broader range of environmental elements to improve the analysis's comprehensiveness and robustness.

In future work, it is recommended that these limitations be addressed by conducting similar studies over a wider period of time and incorporating the views of local communities and stakeholders in the analysis, which could help inform future decision-making processes.

Moreover, future studies can consider employing the Leopold Matrix to assess the type and severity of the project's impact on the environment for two implementation options (construction and operation) as well as non-implementation. Two-dimensional matrices can be used to identify the effects of the relationship between project activities and specific environmental components. In this method, project activities that occur at different stages should be presented on one axis, and environmental components should be presented on the other axis of the table. Each cell in a specific project matrix represents the range of influence, intensity, timing, probability, and type of effect. After determining the effect of each of the project's detailed activities on environmental components, it is possible to estimate and calculate the effects to determine the quantity and magnitude of the effects and ultimately summarise the results.

It is recommended that the EIA Leopold Matrices be presented separately for physical, biological, socio-economic, and cultural environments based on the assumed sub-activities and environmental components during the construction and operation phases.

Overall, by integrating GIS and the Leopold Matrix through a mixed-methods strategy, a comprehensive analysis of the environmental impact of road construction projects, such as the Marand-Bazargan freeway, can be achieved. This integrated methodology can serve as a useful tool for conducting Environmental Impact Assessments (EIA) and promoting sustainable decision-making in infrastructure development.

7. References

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