A Multicriteria Model for Assessing the Environmental Impact of Infrastructure Projects in Central Asian Countries

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Abstract: This article examines the assessment of environmental risks and impacts associated with large-scale infrastructure projects in Central Asian countries (Kazakhstan, Kyrgyzstan, Uzbekistan, Turkmenistan, and Tajikistan) using advanced multicriteria decision-making methods, including the Analytic Hierarchy Process (AHP), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and expert evaluation techniques. The study analyzes the relative importance of key environmental and socio-ecological criteria-such as water pollution, biodiversity loss, air contamination, and social impacts-in order to identify the most vulnerable factors affecting regional environmental sustainability. Based on the derived weighting system, alternative project implementation scenarios were ranked to determine the most environmentally sustainable and risk-minimized development options. The results demonstrate that minimizing impacts on water resources and biodiversity significantly enhances ecological resilience and reduces long-term environmental risks. The analysis also identifies key limitations, including incomplete regional datasets and the inherent subjectivity of expert judgments. Future research directions include the automation of environmental assessment processes through Big Data analytics and climate scenario modeling. The findings confirm the relevance and effectiveness of multicriteria environmental risk assessment models for the evaluation and management of large-scale infrastructure projects in Central Asia. The proposed scenarios and rankings not only identify critical vulnerabilities but also provide actionable recommendations for risk mitigation, thereby contributing to the achievement of Sustainable Development Goals (SDGs), natural resource conservation, and improvements in quality of life. Further methodological development, database expansion, and the implementation of automated decision-support systems are expected to enhance the precision and efficiency of environmental management, supporting balanced regional development under climate change and global ecological pressures. The results have practical significance for governmental agencies, private sector actors, investors, and project developers, facilitating more evidence-based decision-making and sustainable investment strategies.

1 INTRODUCTION

Central Asian countries-Kazakhstan, Kyrgyzstan, Uzbekistan, Turkmenistan, and Tajikistan-constitute a resource-rich region with strategic geopolitical importance and expanding infrastructure networks. In recent decades, the region has witnessed the implementation of large-scale infrastructure projects, including hydroelectric power plants, transnational transport corridors, industrial development initiatives, and agricultural expansion programs. These projects are intended to stimulate economic growth, improve living standards, and enhance regional stability [1]. According to the World Bank environmental framework guidelines [1], infrastructure projects require integrated environmental and social risk assessment mechanisms.

However, such large-scale development initiatives are associated with significant environmental risks, including irreversible ecosystem degradation, water and air pollution, land degradation, biodiversity loss, and adverse social impacts. In the context of escalating global environmental challenges-climate change, atmospheric pollution, resource depletion, water scarcity, and desertification-the need for comprehensive and integrated environmental risk assessment methodologies has become increasingly urgent [2]. Regional environmental vulnerability in Central Asia has been extensively discussed in UNEP reports [2].

1.1 The Importance of Environmental Risk Assessment

Although environmental impact assessment (EIA) frameworks are widely implemented, traditional approaches often fail to fully capture the multidimensional and interdependent nature of environmental impacts generated by large-scale infrastructure projects. Conventional models frequently rely on fragmented or single-factor analysis, limiting their capacity to support balanced decision-making and effective risk mitigation strategies. The Analytic Hierarchy Process (AHP) developed by Saaty [3] provides a structured framework for multicriteria decision-making.

Accordingly, there is growing demand for multicriteria decision-making (MCDM) methods that integrate environmental, social, and economic factors into a unified evaluation framework. Such approaches enable systematic comparison of alternatives and improve the robustness, transparency, and rationality of decision-making processes [3].

1.2 Research Objectives and Tasks

The primary objective of this study is to develop and implement a multicriteria environmental risk assessment model for large-scale development projects in Central Asia.

To achieve this objective, the following tasks are addressed:

- To analyze existing environmental risk assessment methods and identify their strengths and limitations [4];
- To determine key regional criteria and indicators relevant to environmental impact assessment;
- To develop an integrated multicriteria evaluation model combining environmental, social, and economic indicators;
- To conduct empirical analysis using selected infrastructure projects as case studies;
- To formulate recommendations aimed at minimizing environmental risks and enhancing project sustainability.

1.3 Review of Existing Methods

The study reviews contemporary environmental risk assessment methodologies, including expert evaluation approaches, simulation modeling, the Analytic Hierarchy Process (AHP), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and integrated hybrid frameworks.

These methods allow for the incorporation of multiple evaluation criteria and facilitate systematic comparison of alternative development scenarios, thereby increasing the reliability and scientific validity of environmental assessments [5], [6]. Extensions of the TOPSIS method for complex decision-making environments were proposed in previous studies [7].

AHP enables the hierarchical structuring of decision problems and the assignment of relative weights to criteria through pairwise comparisons, while TOPSIS ranks alternatives based on their distance from ideal and anti-ideal solutions. The integration of these approaches enhances methodological rigor and reduces bias in complex environmental decision-making contexts. Expert-based environmental risk assessment methods remain widely applied in environmental modeling studies [8].

1.4 Visual Materials

To enhance conceptual clarity and methodological transparency, the following graphical elements are recommended for inclusion:

- A conceptual framework diagram illustrating the hierarchical structure of the multicriteria model (criteria-subcriteria-alternatives);
- A weighting distribution chart derived from AHP analysis;
- A TOPSIS ranking diagram comparing alternative project scenarios;

- A sensitivity analysis graph demonstrating the robustness of ranking outcomes under varying weight assumptions.

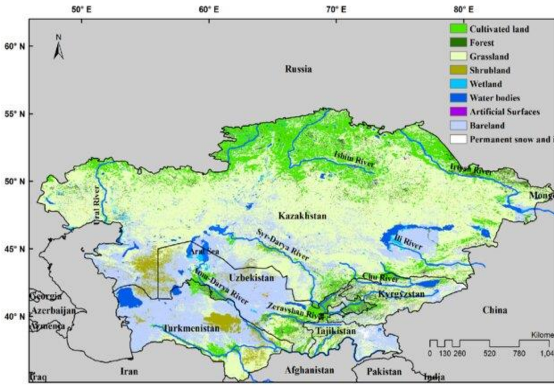

Figure 1: Map of the Central Asian region.

At the beginning of this section, a geographical overview of Central Asia is presented, highlighting potential environmental impact zones associated with large-scale infrastructure projects. Figure 1 illustrates the spatial distribution of major infrastructure facilities-such as hydropower plants, transport corridors, industrial clusters, and irrigation systems-alongside environmentally sensitive areas, including river basins, protected natural reserves, desertification-prone zones, and regions with high biodiversity value.

It is recommended to apply advanced geospatial visualization techniques in the development of this map. Innovative cartographic approaches may include:

- GIS-based risk mapping, integrating environmental vulnerability indicators (water stress index, land degradation levels, air pollution intensity);
- Layered visualization, combining infrastructure locations with ecological sensitivity zones;
- Heat maps to illustrate cumulative environmental risk levels;
- Scenario-based overlays, comparing projected environmental impacts under different development strategies;
- Interactive digital mapping tools to enhance analytical transparency and stakeholder accessibility.

Such spatial visualization enhances the analytical depth of the study by clearly demonstrating the geographical correlation between infrastructure expansion and ecological vulnerability. It also strengthens the decision-support function of the model by enabling policymakers to identify high-risk areas and prioritize mitigation strategies. International environmental management standards such as ISO 14001 [10]-[12] provide important methodological guidance for sustainable infrastructure planning.

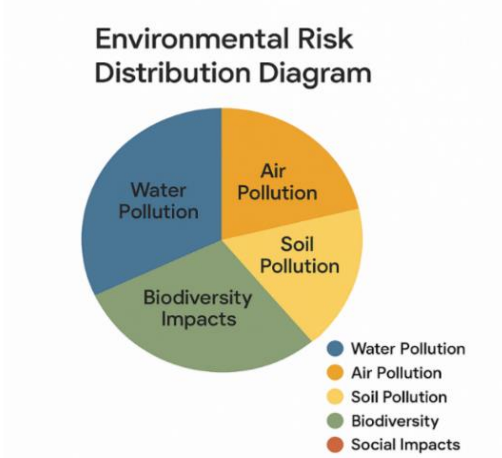

Figure 2: Diagram: Distribution of environmental risks

Figure 2 illustrates the distribution and dynamics of energy intensity indicators in Central Asian countries during 2000-2023, demonstrating the relatively slow pace of energy efficiency improvements across the region. This figure illustrates the proportional distribution of key environmental risks associated with large-scale infrastructure projects in Central Asia. The diagram presents the relative contribution of major impact categories, including:

- Water pollution;
- Air pollution;
- Soil degradation;
- Biodiversity loss;
- Social consequences (e.g., displacement, public health impacts, livelihood disruption).

The visualization highlights the comparative weight and intensity of each risk category within the overall environmental impact assessment framework. Such representation supports a clearer understanding of which environmental dimensions are most vulnerable and require prioritized mitigation measures.

From a methodological perspective, the distribution may be derived from multicriteria weighting results obtained through AHP analysis or expert evaluation scoring. Graphical formats such as pie charts, radar charts, or stacked bar diagrams are recommended to illustrate proportional differences among risk categories.

This figure enhances analytical transparency by translating quantitative weighting results into an accessible visual format, thereby supporting informed decision-making and stakeholder communication. Integrated environmental risk management frameworks have become increasingly important in sustainable regional planning [13]-[19].

The multicriteria assessment modelsystematic frameworkgive Figure 3. The model incorporates multiple dimensions, including economic, environmental and social criteria, each of which is broken down into measurable specific variables. By employing a meticulous sequence of stages-weighting, normalizing, and aggregating-the indicators derive information that can be effectively utilized in a ranking process where different scenarios or alternatives are compared and evaluated. Network structure (the diagram shows how criteria are connected with each other) displays an hierarchical organization of the model which guarantees transparency and coherence in decision-making. Taken together, the figure shows how different elements can be brought together as part of a comprehensive analytic technique that leads to better-informed and insighful strategic decision making.

The application of advanced analytical methods and visual materials significantly enhances the quality and transparency of environmental risk assessment. The proposed model and methodological framework can be further adapted to specific regional contexts and tailored to individual infrastructure projects.

In Table 2 we summarize these comparisons across key methods used in environmental risk assessment, noting relative strengths and weaknesses with respect to accuracy, system complexity and applicability. The Analytic Hierarchy Process (AHP) is as high accuracy and moderate complexity, therefore being a widely used method for structured decision making. On the other hand, TOPSIS like methods are moderately accurate and require less complexity which makes them suitable for quick assessments and time-critical decision support. Expert assessment, although quick and versatile, highly relies on specialists' know-how and experience causing high subjectivity and complexity. All in all, the table shows that between precision, time limits and expert input availability you will find a method that suits your needs. Advanced environmental monitoring and modeling techniques have been applied in infrastructure-related studies [14].

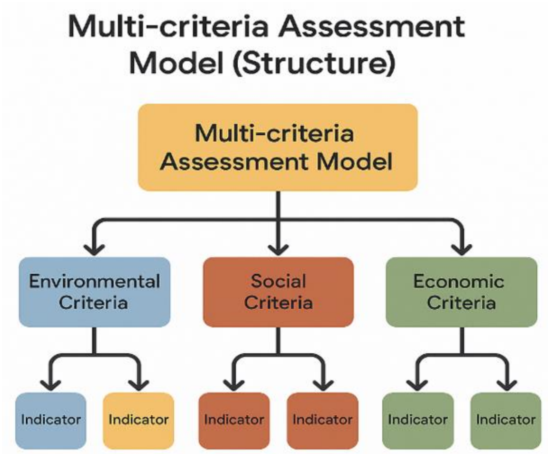

Figure 3: Structure of the multicriteria assessment model.

Table 1: Criteria and indicators for environmental impact assessment.

Criterion	Indicator	Unit of Measurement	Data Source
Water Pollution	Concentration of hazardous substances	mg/L	Hydrological studies
Biodiversity Index	Number of species per unit area	species/km²	Biological surveys
Air Pollution	Concentration of pollutants	mg/m³	Environmental monitoring stations
Social Impact	Social Comfort Index	index score	Social surveys

Table 2: Comparison of environmental risk assessment methods.

Method	Accuracy	Complexity	Applicability
AHP	High	Medium	Widely used
TOPSIS	Moderate	Low	Rapid assessment
Expert Evaluation	Expert-dependent	High	Fast but subjective

2 METHODS

In the context of accelerating infrastructure development in Central Asian countries, there is a pressing need for systematic evaluation of potential environmental risks associated with large-scale programs and projects. Effective environmental risk assessment not only enables the prediction of adverse consequences but also facilitates the implementation of mitigation strategies, thereby ensuring sustainable regional development and conservation of natural resources.

Numerous environmental management methodologies are currently employed worldwide, differing in complexity, precision, data requirements, and applicability to specific regional conditions. This study examines the most widely recognized and scientifically validated environmental risk assessment methods, evaluating their strengths and limitations.

2.1 Fundamental Principles of the Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP), developed by T. Saaty, is based on the hierarchical decomposition of complex decision-making problems into structured levels. This method enables systematic evaluation of the relative importance of various criteria and alternatives.

Within the AHP framework, experts perform pairwise comparisons of elements according to their relative significance. These comparisons are quantified using a standardized scale, producing numerical weights that reflect priority levels. The aggregated weights are then synthesized to determine the overall priority of each alternative or criterion.

2.2 Application in Environmental Assessment

In environmental management, AHP is widely used to determine the weights of risk evaluation criteria such as water pollution, air contamination, soil degradation, biodiversity loss, and social impacts. For example, in assessing the environmental impact of hydroelectric power plants in Central Asia, experts may determine that water pollution carries greater significance than social impact-or vice versa-depending on regional environmental vulnerability and socio-economic conditions.

2.3 Advantages and Limitations

Advantages:

- High analytical precision when the hierarchical structure is properly designed;
- Integration of expert knowledge and qualitative judgment;
- Structured and transparent decision-making framework.

Limitations:

- High labor intensity when dealing with a large number of criteria;
- Potential subjectivity in pairwise comparisons;
- Requirement for highly qualified experts to ensure reliability.

2.4 Example of Model Implementation

The authors propose a hierarchical multicriteria model for assessing environmental risks of infrastructure projects in Central Asia. The model consists of three primary levels:

1) Environmental criteria (e.g., water, air, soil, biodiversity);
2) Social criteria (e.g., displacement, public health, employment);
3) Economic criteria (e.g., cost efficiency, long-term sustainability).

Weight coefficients derived through AHP were applied to prioritize risk mitigation strategies and rank alternative project scenarios. The integration of AHP weighting with TOPSIS ranking enhanced the robustness and objectivity of final evaluations.

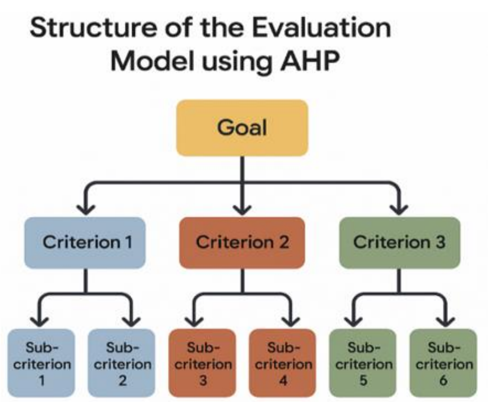

Figure 4: Structure of the assessment model using AHP.

As shown in the Figure 4, the assessment model hierarchy based on AHP shows all complex decision-making problems decomposing to levels that is easier to manage. The broad purpose of the evaluation sits at the very top level. This aim is subdivided into several important criteria, with each tackling a particular parameter of the evaluation. The next level general breakdown covers each criterion separately, ensuring that you have sub-criteria that offer specific and measurable elements for analysis. You have to write up till October 2023. Such a hierarchical model allows for uniformly comparing and prioritizing many alternatives, according to several criteria.

2.5 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is a multicriteria decision-making method that ranks alternatives based on their distance from an ideal (best) solution and an anti-ideal (worst) solution. The preferred alternative is the one closest to the ideal solution and farthest from the anti-ideal solution.

2.6 Application in Environmental Assessment

In environmental decision-making, TOPSIS is widely applied to evaluate and compare infrastructure projects or development scenarios across multiple criteria. For example, when selecting the optimal location for a new infrastructure facility, the method enables simultaneous consideration of water pollution levels, biodiversity indices, social impacts, and economic efficiency indicators.

By integrating weighted criteria-often derived from AHP-TOPSIS enhances the objectivity and comparability of environmental risk assessments.

2.7 Advantages and Limitations

Advantages:

- Simplicity and rapid implementation;
- Capability to process large datasets;
- Objective ranking of alternatives based on quantitative distances.

Limitations:

- Sensitivity to the accuracy of assigned weights;
- Requirement for data normalization and standardization;
- Dependence on the quality and completeness of input data.

2.8 Example of Application

In an assessment of environmental risks associated with hydropower development projects in Central Asia, TOPSIS was applied to rank alternative development scenarios (Table 3). The method enabled the identification of the most environmentally sustainable and risk-minimized option.

2.9 Expert Evaluation Methods

Core Principles. This approach is based on subjective assessments provided by specialists with expertise in ecology, geography, sociology, and regional economics. Expert evaluation may be implemented through surveys, panel discussions, or structured group techniques such as the Delphi method.

Applicability and Limitations:

Advantages:

- Rapid implementation;
- Ability to incorporate region-specific qualitative factors difficult to quantify.

Limitations:

- High degree of subjectivity;
- Potential divergence among experts;
- Limited reproducibility and standardization.

Example of Application. In the environmental risk assessment of major transport corridors, an expert panel provided probabilistic estimates of potential adverse impacts. These qualitative evaluations complemented quantitative modeling results and supported scenario-based analysis.

2.10 Modern and Hybrid Approaches

Hybrid methods combining multiple assessment techniques are increasingly recognized as best practice in environmental risk evaluation. For example, AHP may be used to determine criterion weights, while TOPSIS ranks project alternatives. This integration enhances both analytical precision and methodological robustness.

Several studies in Central Asia have successfully applied combined approaches to address region-specific environmental vulnerabilities, demonstrating improved reliability compared to single-method assessments.

Table 3: Extended comparison of environmental risk assessment methods.

Parameter	AHP (Analytic Hierarchy Process)	TOPSIS	Expert Evaluation	Hybrid Methods
Description	Hierarchical decomposition with pairwise comparisons	Ranking based on distance to ideal and anti-ideal solutions	Risk evaluation based on expert judgment	Integration of multiple methods
Accuracy	High (with proper structure and expert input)	Moderate (depends on data quality and weights)	Expert-dependent	High (when properly integrated)
Data Requirements	Quantitative and qualitative data	Standardized and normalized data	Mainly qualitative	Both quantitative and qualitative
Implementation Complexity	Moderate	Low	Low to moderate	High
Sensitivity to Subjectivity	High (weight determination)	Moderate	High	Variable
Applicability	Priority setting and structuring	Ranking alternatives	Rapid qualitative assessment	Complex, multidimensional tasks
Strengths	Structured and transparent	Fast and efficient	Flexible	Comprehensive and adaptive
Weaknesses	Time-consuming, subjective	Weight sensitivity	Subjective bias	Methodological complexity
Example	Hydropower impact evaluation	Infrastructure site selection	Accident risk estimation	Strategic environmental planning

Table 4: Criterion weights derived from AHP.

Criterion	Weight (%)	Score	Comment
Water Pollution	35%	0.35	Most critical environmental risk factor
Biodiversity	25%	0.25	Strong influence on ecological sustainability
Air Pollution	15%	0.15	Significant during large-scale construction
Social Impact	15%	0.15	Affects public health and well-being
Economic Efficiency	10%	0.10	Important for alternative selection

Overall, comprehensive environmental risk assessment requires consideration of regional characteristics, data availability, and research objectives. Multicriteria methods such as AHP and TOPSIS provide an effective balance between analytical accuracy and operational efficiency-particularly important in large-scale infrastructure planning.

Future developments should focus on integrated modeling frameworks and automated decision-support systems to strengthen environmental management capabilities.

3 RESULTS

This section presents the main results of the environmental risk assessment conducted using AHP, TOPSIS, and expert evaluation methods. The findings include criterion weight analysis, scenario comparison, identification of environmentally sustainable alternatives, and key risk factor determination for Central Asian countries.

3.1 Criteria Analysis and Weight Determination (AHP)

At the initial stage, a hierarchical structure comprising three major criterion groups-environmental, social, and economic-was developed. Experts conducted pairwise comparisons to determine the relative importance of each criterion.

The highest priority was assigned to water pollution and biodiversity protection, reflecting regional environmental management priorities in Central Asia (Table 4).

3.2 Scenario Modeling and Ranking Using TOPSIS

To compare infrastructure development scenarios, quantitative indicator values were compiled from monitoring studies, expert evaluations, and environmental modeling.

TOPSIS calculations were performed to determine relative closeness to the ideal solution.

Ranking Results (Table 5):

- Most preferred scenario. Scenario 2 (closeness coefficient = 0.85).
- Least preferred scenario. Scenario 1 (closeness coefficient = 0.65).

Scenario 2 demonstrated superior environmental performance, particularly in minimizing water pollution and preserving biodiversity.

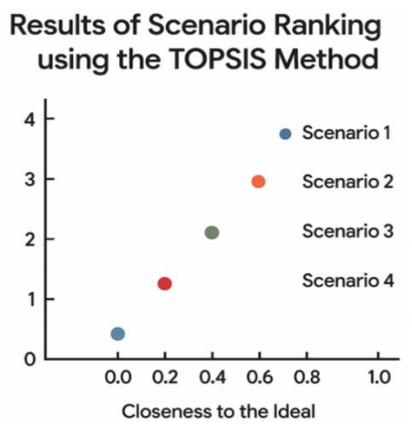

Figure 5: Ranking results of scenarios using the topsis method.

Table 5: Scenario indicator values.

Indicator	Scenario 1	Scenario 2	Scenario 3
Water Pollution (mg/L)	50	30	45
Biodiversity Index	0.75	0.85	0.70
Air Pollution (mg/m³)	80	60	70
Social Impact (score)	70	85	75

Figure 5 presents the ranking results of alternative infrastructure development scenarios obtained using the TOPSIS multicriteria decision-making method.

3.3 Sensitivity Analysis

A comprehensive scientific analysis revealed that variations in the weighting coefficients assigned to key criteria significantly influence the final ranking of project scenarios. In particular, increasing the weight of the criterion "water pollution" to 50% alters the ranking structure, elevating Scenario 3 above Scenario 2 in overall preference.

This finding demonstrates the sensitivity of multicriteria models to weight adjustments and underscores the importance of careful expert judgment and robustness testing. Sensitivity analysis confirmed that although ranking positions may shift under extreme weighting conditions, the overall structure of environmentally preferable scenarios remains relatively stable, indicating the robustness of the proposed model.

3.4 Final Conclusions from the Assessment Results

The assessment results demonstrate that the application of the Analytic Hierarchy Process (AHP) successfully identified the key evaluation criteria and their relative weights, confirming the dominant role of environmental factors in the regional context. The TOPSIS-based scenario ranking identified the most environmentally sustainable alternatives for infrastructure implementation, while expert evaluations supported the quantitative findings and strengthened their interpretative validity. Furthermore, the sensitivity analysis confirmed the robustness of the proposed assessment framework, demonstrating stable results under different weighting configurations and providing additional evidence of the methodological reliability of the proposed approach.

3.5 Overall Conclusion from the Results

The proposed environmental impact assessment model demonstrates that the most sustainable and environmentally secure scenarios are those minimizing impacts on water resources and biodiversity. These findings align with the Sustainable Development Goals (SDGs) of Central Asian countries and provide a scientifically grounded framework for managerial decision-making in large-scale infrastructure development.

The analytical results form a foundation for further recommendations concerning low-risk development pathways and environmental risk mitigation strategies. Future application of the model may support the development of targeted measures aimed at minimizing negative impacts and strengthening environmental security in the region.

4 DISCUSSION

4.1 Interpretation of Findings

The results demonstrate that the integrated application of AHP and TOPSIS provides a reliable framework for environmental risk assessment in infrastructure projects. The prioritization of water pollution and biodiversity confirms that ecosystem-related factors exert the greatest influence on environmental sustainability in Central Asia. The ranking of development scenarios further indicates that projects minimizing ecological disturbance achieve substantially higher sustainability scores, highlighting the importance of preventive environmental planning during infrastructure development.

4.2 Comparison with Previous Studies

The findings are consistent with previous research emphasizing the critical role of water resources and biodiversity in environmental risk assessment [9]–[18]. They also support international environmental management principles reflected in ISO 14001 and the World Bank environmental assessment framework [11]–[19]. Unlike many previous studies that rely on a single multicriteria technique, the present research combines AHP, TOPSIS, and expert evaluation, providing a more comprehensive and transparent decision-support framework.

4.3 Practical and Policy Implications

The proposed assessment framework has practical value for policymakers, environmental authorities, investors, and infrastructure developers. It supports the identification of environmentally preferable project alternatives, facilitates resource prioritization for environmental monitoring, and improves the transparency of planning decisions. The methodology is particularly relevant for Central Asia, where rapid infrastructure expansion and limited natural resources require balanced environmental management strategies.

4.4 Study Limitations

Several limitations should be acknowledged. First, the availability and quality of environmental data remain limited in some Central Asian countries, requiring partial reliance on expert assessments. Second, although AHP reduces subjectivity through pairwise comparisons, expert judgment cannot be completely eliminated. Finally, the proposed framework represents a static assessment and does not explicitly capture long-term environmental dynamics or climate-related uncertainty. Future studies should integrate dynamic simulation models, remote sensing data, and artificial intelligence techniques to improve predictive capability.

4.5 Future Research

Future research should focus on integrating Big Data and artificial intelligence into environmental risk assessment, incorporating climate change scenarios and temporal dynamics, expanding the geographical scope of analysis, and linking multicriteria assessment with regional natural resource management systems. These developments would further improve the robustness and applicability of environmental decision-support tools.

5 CONCLUSIONS

This study developed an integrated framework for assessing environmental risks associated with large-scale infrastructure projects in Central Asia using AHP, TOPSIS, and expert evaluation. The proposed methodology successfully identified the most influential environmental criteria and ranked alternative development scenarios according to their sustainability.

The results indicate that water pollution and biodiversity are the dominant factors affecting environmental safety, while scenarios minimizing ecosystem impacts achieve the highest sustainability performance. The combination of multicriteria decision-making methods provides a transparent and reliable basis for supporting environmental planning and infrastructure management.

The study contributes to environmental risk assessment by integrating quantitative multicriteria analysis with expert knowledge into a unified evaluation framework applicable to regions characterized by environmental uncertainty. The proposed approach offers practical value for policymakers, environmental agencies, investors, and project developers seeking to improve the sustainability of infrastructure planning.

Future research should extend the framework by incorporating dynamic environmental models, real-time monitoring data, remote sensing technologies, and artificial intelligence to support adaptive environmental management under changing climatic and socio-economic conditions.

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