Acadlore Transactions on Geosciences
https://www.acadlore.com/journals/ATG

Prioritization of Coastal Environmental Risks under Climate Change in Quang Ngai, Vietnam: An Integrated Analytic Network Process–Risk Score Approach

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Received: 11-15-2024 **Revised:** 12-19-2024 **Accepted:** 12-24-2024

Citation: V. V. Tuyen, "Prioritization of coastal environmental risks under climate change in Quang Ngai, Vietnam: An integrated analytic network process–Risk score approach," *Acadlore Trans. Geosci.*, vol. 3, no. 4, pp. 237–251, 2024. https://doi.org/10.56578/atg030405.

Abstract: Coastal regions are increasingly threatened by climate change, which amplifies the frequency and severity of extreme weather events and exacerbates environmental vulnerabilities. Quang Ngai Province in central Vietnam, characterized by its complex terrain and high exposure, represents a critical case where climate-induced risks require systematic evaluation and prioritization. In this study, coastal environmental risks were prioritized through the integration of the Analytic Network Process (ANP) with the Risk Score (RS) index. A network structure of risk criteria was developed, and expert knowledge from twelve specialists with substantial academic and practical experience was elicited to perform pairwise comparisons. A hyperlink matrix was constructed, and aggregate weights were derived using a constraint matrix. These weights were linearly interpolated to determine impact levels, which were subsequently combined with probability estimates to compute the RS for each criterion. The results revealed that coastal erosion and landslides represent the most critical risk (RS = 11.45), followed by flooding in low-lying areas (RS = 8.99), while economic and livelihood losses in coastal communities and the occurrence of strong storms and extreme weather events were ranked equally (RS = 5.00). These risks are both highly probable and capable of producing extensive ecological, infrastructural, and socioeconomic disruptions. The methodological framework offers a robust basis for adaptive policymaking, the prioritization of resource allocation, and the incorporation of climate risk management into coastal development planning. The findings underscore the necessity of proactive, evidence-based interventions to safeguard vulnerable coastal systems and communities against intensifying climate change impacts.

Keywords: Analytic Network Process; Risk score; Risk management; Environmental risk; Climate change; Coastal areas; Quang Ngai Province; Vietnam

1 Introduction

Climate change is becoming one of the most serious environmental challenges on a global scale [1]. The impact of climate change is no longer a forecast but is clearly present in many areas, especially coastal areas, where population density is high, many sensitive ecosystems are concentrated, and a high level of dependence on natural resources exists [2]. Phenomena such as rising sea levels, increased frequency and intensity of storms, coastal erosion, flooding, and changes in the hydrological cycle have been negatively affecting infrastructure, water resources, and agricultural land of coastal communities [3, 4]. These risks are not only immediate but also create long-term, complex, chain-like, and unpredictable consequences.

In Vietnam, a country with more than 3,260 km of coastline, coastal areas are identified as the most vulnerable to the impacts of climate change [5]. In particular, Quang Ngai Province, located along the central coastal strip, is faced with many specific risk factors: a coastline of nearly 130 km, terrain fragmented by a river system flowing into the sea, a dense population in coastal estuaries, along with an ecosystem of much mangrove and lagoon vegetation that plays an important role in ecological balance [6]. Similar to other coastal provinces in Vietnam, in recent years, Quang Ngai has been affected by coastal erosion, damage from storms and floods, as well as the decline of coastal natural resources [7]. This context poses an urgent need for the analysis and assessment of environmental risks associated with climate change in order to develop adaptive response solutions, orient sustainable development, and mitigate long-term damage.

However, environmental risks arising in the context of climate change are often multifactorial in nature, with complex interactions between natural, economic, and social environmental components. Many current studies still approach these risks in a discrete or linear manner, while in reality a systematic and integrated approach is required to reflect the interdependent and spreading nature of risk factors. In that context, the ANP method is considered a suitable and effective tool. It is an extension of the hierarchical analysis method [8]. ANP allows the establishment of a network of criteria with interdependencies and two-way feedback, instead of the traditional linear hierarchical structure [9]. With ANP, the interactions between risk groups can be modeled more intuitively and accurately [10]. Furthermore, integrating ANP with the RS model allows for quantification of risk levels in a concrete manner, rather than just a qualitative assessment. This not only improves the feasibility of applying research results into practice but also provides strong support for decision-making, planning, and risk management processes by region or priority level.

Therefore, this study applies ANP integrated with RS to analyze the main environmental risks caused by climate change in the coastal area of Quang Ngai Province, thereby ranking the relative severity of each risk factor and proposing policy implications for management, planning, and enhancing adaptation capacity to climate change. The urgency of the study comes not only from the high vulnerability level of the locality but also from the gap in empirical research related to the application of complex quantitative models such as ANP in environmental risk assessment in Vietnam. The application of modern analytical methods such as ANP combined with RS models to analyze and prioritize environmental risks in the coastal area of Quang Ngai is a research direction that contributes to narrowing the academic gap while meeting the practical needs of the locality. The research results are expected to contribute to providing a scientific and practical basis for developing integrated, adaptive, and effective climate change response strategies locally and in the central region in general.

2 Literature Review

The flexibility, ability to integrate qualitative and quantitative data, and high reliability make ANP an increasingly popular tool in interdisciplinary risk studies. Many studies have applied ANP to solve risk problems in different fields. Nguyen et al. [11] applied ANP to assess the risk of road and bridge projects. Dharma et al. [12] analyzed risk management strategies in the tourism industry through the application of ANP. Cheng et al. [13] applied ANP to assess risks in high-speed rail operations. Suciana et al. [14] applied ANP to analyze flood risks. In addition, Li et al. [15] analyzed risks related to mining activities in the coal and mineral industry.

ANP is also often flexibly combined with many other methods to enhance the applicability and reliability of assessment. Combining ANP with complementary methods not only promotes the strengths of each tool but also creates an integrated analysis system, capable of simulating different risk scenarios and suitable for specific research contexts. Some studies have followed this direction. Khalilzadeh et al. [16] applied fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL)-ANP to assess the risks of projects in the oil and gas industry. Thakkar [17] applied the integrated DEMATEL and ANP methods to quantify supply chain risks in the oil sector. Qi et al. [18] applied a combination of ANP and a risk matrix to assess possible fire and explosion risks in the laboratory. Yazdani et al. [19] conducted a risk assessment of cloud computing by using a combination of fuzzy-ANP and Failure Modes and Effects Analysis (FMEA) methods. In addition, Wang et al. [20] applied a combination of ANP and Back Propagation Neural Network (BPNN) methods in assessing electrical safety risks in fireworks manufacturing enterprises.

Climate change is currently one of the most serious threats to the environment, economy, and society on a global scale. Impacts such as sea level rise, temperature change, and increased frequency and intensity of extreme weather events have been causing many complex consequences, especially in coastal areas—where there are sensitive ecosystems, high population density, and concentrated economic activities. Many studies in the world as well as in Vietnam have shown that coastal provinces are facing increasing levels of environmental risks, in which phenomena such as coastal erosion, saltwater intrusion, landslides, and unusual storms and floods not only threaten the safety of the community but also directly affect sustainable socio-economic development.

Focusing on climate change or referring to the environmental risk aspect under the impact of climate change, many studies have built different scenarios on the impact of climate change. Nayak and Nandimandalam [21] reviewed the impact of climate change and coastal salinity on the risk of heavy metal pollution in the environment along the coast of Odisha, India. The study results showed that seawater intrusion is responsible for increased metal solubility, mineral weathering, leaching, and enhanced ion exchange due to seawater. Tsatsaris et al. [22] reviewed the environmental hazards in the context of climate change. The study suggested that catastrophic natural phenomena and hazards due to climate change on the environment, such as drought, soil erosion, degradation in quantity and quality of groundwater, frost, floods, sea level rise, etc., are increasing. The impacts of these phenomena are devastating to human life and the global economy. Tan et al. [23] examined the links between climate change vulnerability and poverty in coastal provinces of central Vietnam. The study identified a persistent cycle of poverty and livelihood vulnerability in coastal communities, with dependence on nature-based income as the root cause. Cheng et al. [24] considered the impact of climate change on the livestock industry. Halkos and Zisiadou [25] analyzed the impact of climate change on the environment related to weather. Calculli et al. [26] considered the aspect of human perception of climate change and related environmental issues. Kabir et al. [27] analyzed the impact of climate change on the environment, referring to the important index of carbon dioxide concentration.

In Vietnam, studies on climate change phenomena are mainly concentrated in the provinces of the Mekong Delta, the central region, and the northern coastal region, which shows the need to develop risk assessment models suitable for each locality. Gibb et al. [28] generalized analyses of climate change in Vietnam, especially in terms of infrastructure and transportation. Ho et al. [29] analyzed the factors affecting climate change on rice production in the Mekong Delta. Nguyen and Scrimgeour [30] proposed a general view of the impact of climate change on Vietnamese agriculture. Thai et al. [31] mentioned another aspect, which is to consider the impact of climate change on the financial performance of enterprises in Vietnam. In addition, Tuyen [32] mentioned the risks of sea-island tourism activities and emphasized one of the important risks related to climate change.

Although there have been many domestic and foreign studies focusing on climate change, practice shows that there are still significant gaps in the approach and application of modern analytical methods. Quang Ngai Province, a coastal locality in central Vietnam, is often heavily affected by storms, floods, saltwater intrusion, and coastal erosion. In particular, there are very few studies in this locality applying advanced multi-criteria decision-making models such as ANP to model the interaction and feedback relationships between risk factors, while this is an important feature of the environmental risk system. At the same time, the integration of ANP with the RS model to quantify and visualize the level of risk on a geographic map has not been fully exploited in Quang Ngai.

In this study, the ANP method helps to identify and quantify the interaction, dependence and feedback relationships between environmental risk factors. The RS index allows for a comprehensive assessment of the impact level of risks, thereby helping to make scientific risk prioritization decisions. The results of this study are an important basis for policy orientation to effectively adapt to climate change in the coastal area of Quang Ngai Province, Vietnam.

3 Methodology

3.1 Research Process

To prioritize environmental risks due to climate change in the coastal area of Quang Ngai Province, Vietnam, the study integrated the ANP method and the RS index. Figure 1 illustrates the basic steps of the research process.

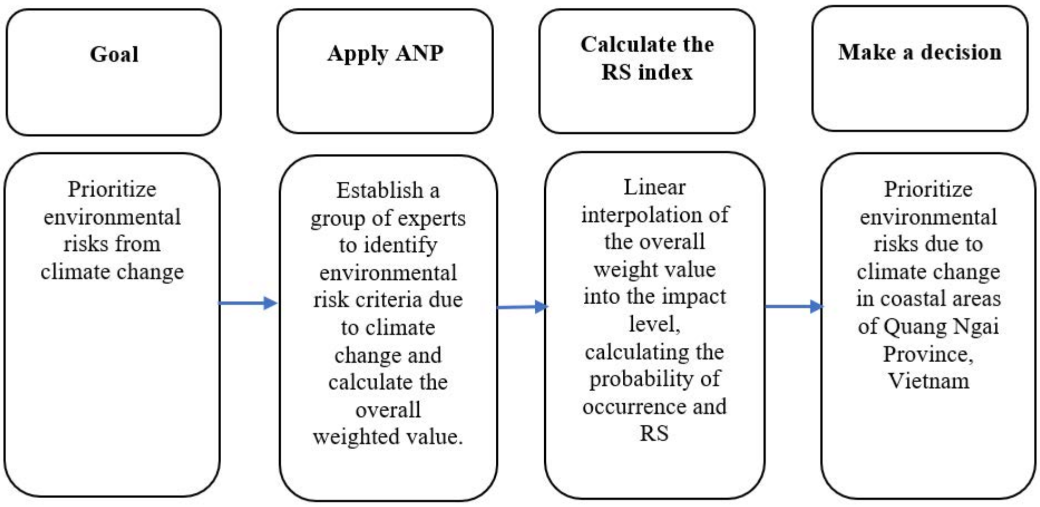

Figure 1. Research framework

3.2 ANP

ANP is a multi-criteria decision-making technique developed from the Analytic Hierarchy Process (AHP) to solve complex problems with interactions and interdependencies between criteria, groups of criteria, or elements in the system [33]. Unlike AHP, which builds models according to a simple hierarchical structure, ANP uses a more complex network structure, allowing elements to not only impact in one direction from top to bottom but also to interact with each other in the same layer or between different layers [34, 35]. This helps ANP handle practical problems that are non-linear, multi-dimensional, and characterized by complex interdependencies, which are difficult to solve effectively using traditional methods.

In terms of characteristics, ANP represents the system structure as a network of clusters of factors, in which each cluster includes related factors and the links between these factors represent the level of mutual influence [36]. Thereby, ANP helps to assess more comprehensively and accurately the relative weights of factors, thereby supporting optimal decision-making in complex, uncertain, or interactive situations [37]. ANP not only helps to determine the level of priority and select optimal options but also contributes to a better understanding of the cause-effect relationship between influencing factors [38]. ANP helps managers and experts make more feasible and sustainable decisions in the long term.

According to Taherdoost and Madanchian [39], the ANP implementation process is carried out through the basic steps below. First, the decision-making goal and related factors are determined, and the factors are grouped into appropriate clusters. Second, a network of factors are built, including establishing the influence relationships between factors within and between clusters. Third, pairwise comparisons between related factors in the network are performed to assess relative priority. Fourth, these assessments are synthesized to build a hyperlink matrix, which shows all the influence relationships between factors. Fifth, the hyperlink matrix is standardized and iterated to find stable weights, thereby determining the final priority of the factors in the network. Finally, based on these weights, the decision-maker can choose a solution or identify priority factors that need to be focused on.

In the framework of this study, the ANP method was implemented below. First, an expert panel was established, including experts with experience in the environmental field, especially knowledgeable about climate change in Quang Ngai Province. To determine the environmental risk criteria due to climate change in coastal areas, an in-depth group discussion was organized with the participation of experts in the fields of environment, climatology, and coastal resource management in the locality. The discussion was designed in a semi-structured manner to facilitate the experts to exchange freely while sticking to the key research contents. Before the discussion, a preliminary document was sent, summarizing potential risk factors related to the impacts of climate change in the locality, thereby serving as a basis for the discussion.

The discussion results not only help establish the initial criteria system for the study but also provide the necessary interdisciplinary perspectives to ensure objectivity and completeness in assessing the risk level using the ANP method. The list of environmental risk criteria due to climate change in the coastal area of Quang Ngai Province is shown in Table 1.

Then an analytical network was built to clearly demonstrate the interactions between factors. Instead of assuming that the criteria are independent, as in traditional hierarchical models like AHP, the ANP method allows for the assessment of the mutual influences between criteria. Based on the constructed network, the quantitative assessment was performed by comparing pairs of interacting criteria. In this process, each pair of risk criteria was considered in parallel to determine the relative priority based on their importance in the overall influence network. The comparison was made using the importance scale presented in Table 2.

After collecting sufficient data from experts, a comparison matrix was built for each pair of risk criteria with respect to their relative importance (Tables A in the Appendix) and for each pair of interrelationships between risk criteria (Table B1-Table B9 in the Appendix). From these results, a hyperlink matrix (W) was built, a typical structure of the ANP method, showing all the mutual influence relationships between factors in the network system. This matrix integrates the relative weights from the comparison pairs and reflects the level of interaction between criteria in each cluster as well as between different clusters.

To ensure reliability and consistency in data processing and calculation, the Microsoft Excel software was used as a calculation support tool. The calculated value is only accepted when the Consistency Ratio $(\mathrm{CR}) \leq 10\%(0.1)$, with the Consistency Index (CI) and CR calculated by the following formula: $CR = CI/RI$, where RI is the random index (Table C in the Appendix), and $CI = (\lambda\max - n)/(n-1)$; $\lambda\max$ is the eigenvalue of the matrix, with $\lambda\max = \sum_{i=1}^{n} wi \times \sum_{j=1}^{n} aij$. The matrix normalization operation was performed and repeated continuously to bring the hyperlink matrix to a convergent state, as shown in Eq. (1). This iterative process was performed until the hyperlink matrix converged, meaning that the weight values reach stability, thereby determining the final priority weight of each risk criterion in the overall system.

$$\lim_{k\to\infty} (W)^k \tag{1}$$

The hyperlink matrix converged when the values in the matrix no longer changed significantly, indicating that it reaches a steady state, which is also called the limit matrix. Then $\lim_{k\to\infty}(W)^k = W_{\text{limit}}$ or $W^k = W^{k+1}$, where W_{limit} is the limit matrix, and k is the number of repetitions, also known as the exponent. These stable weights are important outputs of the ANP model, which represent the final priority of each criterion in the entire network, helping to reflect the overall impact of each criterion in the context of complex and multidimensional interactions such as in the environmental risk issue due to climate change in the coastal area of Quang Ngai Province.

Table 1. Environmental risks due to climate change in coastal areas of Quang Ngai Province

Risk Criteria	Source	Explanation
Coastal ecosystem degradation and biodiversity (C1)	Santojanni et al. [40]	Rising temperatures and sea levels and pollution are destroying ecosystems such as mangroves, tidal flats, and coral reefs, which are home to many aquatic species.
Coastal erosion and landslides (C2)	Pang et al. [41]	It is the phenomenon of soil, sand, and materials on the coast being washed out to sea by waves, strong winds, and currents, narrowing the coastline and losing natural land.
Increased storms and extreme weather events (C3)	Clarke et al. [42]	Climate change is making storms more frequent and stronger and less predictable and increasing extreme weather events such as heavy rain, wind gusts, flash floods, and tornadoes.
Saltwater intrusion and freshwater resource depletion (C4)	Tarolli et al. [43]	Due to rising sea levels and reduced river flows, saltwater from the sea penetrates deep into the mainland, polluting surface and groundwater resources.
Economic loss and livelihood of coastal communities (C5)	Saha et al. [44]	Economic sectors that depend on the sea, such as fisheries, aquaculture, marine tourism, and seaports, are severely affected by natural disasters, climate change, and environmental degradation.
Weakening of coastal infrastructure and urbanization (C6)	Ridha et al. [45]	Construction works such as seawalls, dykes, roads, houses, and schools in coastal areas are corroded and damaged faster due to the impact of salt, strong winds, and floods.
Flooding of low-lying areas (C7)	Hsiao et al. [46]	Extreme rainfall increases the frequency and intensity of flooding in low-lying riverine and coastal areas. Unplanned urbanization and loss of mangrove forests also contribute to the situation.
Phenomenon of acidification and salinization of coastal agricultural land (C8)	Mazhar et al. [47]	The intrusion of salt water and the oxidation of minerals in the soil create alum and salinity, causing severe soil degradation and making it unsuitable for cultivation.
Sea level rise (C9)	Griggs and Reguero [48]	Sea level rise due to melting ice and thermal expansion of seawater.

Table 2. RI index [49]

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

3.3 RS Index

The RS is calculated based on the combination of the impact level and the frequency of occurrence of a risk to comprehensively and scientifically assess the severity of that risk to the system or research area. Basically, this is a quantitative method to prioritize risks based on two important factors: the impact level when the risk occurs and the possibility of that risk occurring in reality.

Impact level represents the intensity or extent of the impact of a risk when it occurs. Frequency reflects the likelihood or probability of a particular risk occurring over a given period of time. This frequency helps assess the frequency and continuity of risk events, thereby providing an overview of the prevalence of the risk. For each risk, the frequency scores from the twelve experts were averaged. To simplify the results and facilitate classification, this average was then rounded up to the nearest positive integer. This rounding method ensures that no risk is underestimated due to the influence of the average and provides a single representative index for each risk, which serves as the basis for the next calculation step.

The RS index was calculated using a simple formula like Eq. (2).

$$\text{Risk Score (RS)} = \text{Impact} \times \text{frequency of occurrence} \tag{2}$$

Multiplying these two factors helps to synthesize the overall impact of the risk in an intuitive and easy-to-understand way. The higher the RS, the more it shows that the risk not only has a large impact but also occurs frequently, thereby being prioritized for early intervention and prevention. The impact and frequency scales are presented in Table 3 and Table 4, respectively.

Table 3. Scale of impact level of risks

Level	Definition of Impact Level	Description
5	Very serious	Very serious impact
4	Serious	Serious impact
3	Medium	Medium impact
2	Mild	Limited impact
1	Very mild	Very low impact

Table 4. Scale of likelihood of risks

Level	Definition of Occurrence Frequency	Description
5	Very high	Very common occurrence
4	High	Frequently occurs
3	Medium	Occurs occasionally
2	Small	Rarely happens
1	Very small	Very rare

In this study, after determining the final weights of the risk criteria through the ANP method, these weights were converted into impact levels using linear interpolation techniques. This transformation aims to align the weights to the same scale as the frequencies, thereby facilitating the integration of quantitative data. Then the impact value of each criterion was multiplied by the corresponding frequency of occurrence, which was collected through an expert opinion survey. The result of this multiplication created a relative risk index for each criterion, reflecting the overall severity based on both the probability and the consequences of the impact. Based on these RS values, the priority levels were ranked among the criteria, thereby proposing environmental risks that need to be prioritized for management or intervention in the context of climate change impacts on the coastal area of Quang Ngai Province.

4 Discussion

4.1 Expert Characteristics

In this study, twelve highly qualified and experienced experts in the fields of environment, natural resources, disaster risk management, and climate change adaptation were consulted. The experts were deliberately selected to ensure convergence between a solid academic background and a deep understanding of local practices, especially in the central coastal region of Vietnam. Most of the experts currently hold key roles in state management agencies and technical consulting organizations related to environment and climate change. All have a master's degree or higher, with an average working time of over ten years. Notably, many experts are deeply interested in climate change issues and truly understand the actual climate change context of Quang Ngai.

4.2 Overall Weighting of Risk Criteria

After comparing the relative priorities of risk criteria in the context of coastal environmental risks in Quang Ngai, the mutual relationships of each pair of these criteria were compared. The hyperlink matrix W was established, as shown in Table 5. This matrix fully reflects the dependency structure and feedback relationship between the criteria, playing a key role in calculating the global weight of the risk criteria.

Table 5. Hyperlink matrix W

	Goal	C1	C2	C3	C4	C5	C6	C7	C8	C9
Goal	0	0	0	0	0	0	0	0	0	0
C1	0.0702	0	0.3022	0.0637	0.0684	0.1864	0.0634	0.3100	0.1795	0.0786
C2	0.2990	0.1397	0	0.1838	0.0386	0.0646	0.1075	0.1069	0.1013	0.0786
C3	0.1998	0.0467	0.1021	0	0.0386	0.0366	0.0347	0.0334	0.0345	0.0435
C4	0.1052	0.2427	0.0606	0.0637	0	0.0646	0.0634	0.0887	0.3093	0.0435
C5	0.0566	0.2427	0.1810	0.3111	0.1926	0	0.1834	0.1824	0.1795	0.3582
C6	0.0362	0.0798	0.1810	0.1838	0.1926	0.3154	0	0.1824	0.1013	0.2217
C7	0.1864	0.1397	0.1021	0.1214	0.1114	0.1093	0.1834	0	0.0601	0.1326
C8	0.0274	0.0798	0.0355	0.0362	0.3190	0.0366	0.0347	0.0629	0	0.0435
C9	0.0192	0.0287	0.0355	0.0362	0.0386	0.1864	0.3294	0.0334	0.0345	0

The hyperlink matrix W was repeatedly multiplied until it converged. Specifically, through the process of multiplying the matrix W15 times in a row, a new matrix (W_{limit}) was created, which is called the hyperlink matrix limit. This matrix represents the stable weights of the criteria, reflecting the relative importance of each coastal environmental risk factor under climate change conditions in Quang Ngai. The results are presented in Table 6.

Table 6. Limited hyperlink matrix W_{limit}

	0	0	0	0	0	0	0	0	0	0
C1	0.1362	0.1362	0.1362	0.1362	0.1362	0.1362	0.1362	0.1362	0.1362	0.1362
C2	0.0874	0.0874	0.0874	0.0874	0.0874	0.0874	0.0874	0.0874	0.0874	0.0874
C3	0.0423	0.0423	0.0423	0.0423	0.0423	0.0423	0.0423	0.0423	0.0423	0.0423
C4	0.0997	0.0997	0.0997	0.0997	0.0997	0.0997	0.0997	0.0997	0.0997	0.0997
C5	0.1823	0.1823	0.1823	0.1823	0.1823	0.1823	0.1823	0.1823	0.1823	0.1823
C6	0.1624	0.1624	0.1624	0.1624	0.1624	0.1624	0.1624	0.1624	0.1624	0.1624
C7	0.1123	0.1123	0.1123	0.1123	0.1123	0.1123	0.1123	0.1123	0.1123	0.1123
C8	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713	0.0713
C9	0.1061	0.1061	0.1061	0.1061	0.1061	0.1061	0.1061	0.1061	0.1061	0.1061

From W_{limit}, the weights of coastal environmental risk criteria under climate change in Quang Ngai were obtained, as shown in Table 7.

Table 7. Overall weighting of coastal environmental risk criteria due to climate change in Quang Ngai

Risk Criteria	Symbol	Overall Weight
Coastal ecosystem degradation and biodiversity	C1	0.1362
Coastal erosion and landslides	C2	0.0874
Increased storms and extreme weather events	C3	0.0423
Saltwater intrusion and freshwater resource depletion	C4	0.0997
Economic loss and livelihood of coastal communities	C5	0.1823
Weakening of coastal infrastructure and urbanization	C6	0.1624
Flooding of low-lying areas	C7	0.1123
Phenomenon of acidification and salinization of coastal agricultural land	C8	0.0713
Sea level rise	C9	0.1061

4.3 RS Results and Priority Ranking of Risk Criteria

After obtaining the aggregate weights of the risk criteria from the hyperlinked matrix, this result was further normalized into the corresponding impact levels through linear interpolation. The interpolation process helped to convert the relative weights into a quantitative scale reflecting the specific impact level of each criterion in the practical context. On that basis, the impact level of each criterion was multiplied by the corresponding probability of occurrence to calculate the RS. The detailed results of the RS for each criterion and their priority ranking are presented in Table 8.

Table 8. RS and prioritization of risk criteria

	Impact	Frequency of Occurrence	RS	Rank
Coastal ecosystem degradation and biodiversity	3.68	1	3.68	5
Coastal erosion and landslides	2.29	5	11.45	1
Increased storms and extreme weather events	1.00	5	5.00	3
Saltwater intrusion and freshwater resource depletion	2.64	1	2.64	8
Economic loss and livelihood of coastal communities	5.00	1	5.00	3
Weakening of coastal infrastructure and urbanization	4.43	1	4.43	4
Flooding of low-lying areas	2.99	3	8.99	2
Phenomenon of acidification and salinization of coastal agricultural land	1.83	2	3.66	6
Sea level rise	2.82	1	2.83	7

The results of the analysis of coastal environmental risks in Quang Ngai through the integrated ANP method with RS are shown in Table 8, showing a significant differentiation between risk groups in terms of both impact level and probability of occurrence. This difference reflects not only the specific nature of each type of risk but also clearly shows the local context, which is affected by multidimensional impacts from climate change. Four environmental risks were identified with the highest priority for the Quang Ngai coastal area in the context of climate change, including erosion and landslides of the coastline, flooding of low-lying areas, economic and livelihood losses of coastal communities, and increased strong storms and extreme weather events. Most notably, the risk of coastal erosion and landslides is ranked as the highest priority with an RS of 11.45. Although the impact level is only average (2.29), but the probability of occurrence is at the maximum level (5). This reflects the common and increasing trend of landslides in many coastal areas of Quang Ngai, especially in river mouths and areas strongly affected by waves and the northeast monsoon. With increasingly frequent occurrence, this type of risk directly threatens coastal land, infrastructure, and disaster prevention works. Agreeing with this view, Pang et al. [41] also said that coastal erosion is a normal natural process; however, the rate of coastal erosion is currently increasing globally due to the impacts of climate change.

Low-lying flood risk is ranked second with an RS of 8.99, which is a typical risk in low-lying coastal areas of Quang Ngai. Those low-lying coastal areas are often flooded because this is the end point of many large rivers in the province. When heavy rains last for a long time, the amount of water flowing from upstream is concentrated in the delta and river mouth, causing water to not drain out to the sea in time, thereby leading to serious flooding. Flooding not only affects agricultural production but also threatens the lives and health of the community and reduces the resilience of the locality. Hsiao et al. [46] also highlighted that in the context of negative developments of climate change, flooding is a phenomenon that has caused serious disasters in coastal areas around the world. The two risks ranked third are economic loss and livelihood of coastal communities and increased strong storms and extreme weather events, with the same RS of 5.00. Although different in nature, i.e., one represents socio-economic consequences, while the other reflects severe natural phenomena, both have direct and indirect impacts on the coping capacity of coastal communities. This is especially important in the context of Quang Ngai with a high coastal population density and relying heavily on coastal fisheries and agriculture, which are vulnerable to climate change.

The livelihoods of coastal communities are being significantly affected by the complex developments of climate change; this issue mainly arises from the heavy dependence on natural resources that are sensitive to the impacts of climate change [44]. High-impact storms have become more common and stronger in the context of climate change [50].

The risk of weakening coastal infrastructure and urban areas is ranked fourth (RS = 4.43), indicating significant concerns about the resilience of technical infrastructure and urban areas to increasingly extreme natural disasters. Along with that, the risk of degradation of coastal ecosystems and biodiversity is ranked fifth, with an RS of 3.68, although it was assessed lower than other risks. However, this is still a necessary warning, especially for mangrove, coral, and seagrass ecosystems that have been severely degraded in recent years due to human and climate pressures. The remaining risks, such as acidification and salinization of coastal agricultural land, sea level rise, saltwater intrusion, and loss of freshwater resources, have lower RS values, reflecting that the probability or level of impact is not too serious at present. However, this does not mean that it can be taken lightly, because these risks tend to increase in the medium and long terms under the impact of rising sea levels and changing rainfall patterns. In particular, saline intrusion and freshwater loss, although currently assessed at a low level (RS = 2.64, ranked 8), are potential long-term risks that can affect water security and agricultural production in the future.

5 Conclusions, Recommendations, and Limitations

5.1 Conclusions

The study applied ANP integrated with RS to analyze and determine the priority level of coastal environmental risks due to climate change in Quang Ngai Province, Vietnam. By combining the overall impact weight of each criterion with the probability of occurrence, the study quantified the risks in a more comprehensive and objective way than traditional unidimensional approaches. The analysis results showed that the four risks ranked at the highest priority level include coastal erosion and landslides, flooding in low-lying areas, economic and livelihood losses of coastal communities, ranked at the same level as strong storms and extreme weather. These are risks with high frequency and widespread impact, clearly demonstrating the urgency and necessity to be prioritized in climate change management and adaptation strategies at the provincial and regional levels.

The study not only provides a scientific basis for prioritizing actions but also contributes to risk assessment methodologies by integrating quantitative factors with expert analysis, thereby creating an assessment model that is flexible, highly scalable, and suitable for the context of coastal areas strongly affected by climate change. In the context of limited resources, correctly identifying priority risks is an important step to improve investment efficiency while creating a premise for building more targeted, feasible, and sustainable adaptation solutions in the future.

5.2 Recommendations

Based on the results of the analysis and ranking of priority levels of coastal environmental risks due to climate change, a number of policy orientations and solutions are commended to enhance adaptive capacity, minimize damage, and improve sustainability in the development of the Quang Ngai coastal area.

1. Control and response to coastal erosion and landslide risks should be prioritized. This is the risk with the highest RS, with a very high probability of occurrence. Therefore, it is necessary to urgently invest in structural and non-structural solutions such as coastal reinforcement, mangrove restoration in estuary areas, applying early warning models, and monitoring shoreline changes using remote sensing technology.

2. Capacity to prevent and adapt to floods in low-lying areas should be strengthened. As the second risk, floods directly affect people's livelihoods and safety. It is necessary to review and adjust drainage planning, upgrade the dike system, and integrate ecological solutions such as developing natural flood storage areas in the downstream of major rivers.

3. Extreme climate factors should be integrated into livelihood development and social security plans. With two risks ranked third, economic and community livelihood losses and strong storms/extreme weather, it is necessary to develop sustainable livelihood strategies, appropriate job transitions, and enhanced community resilience through training, risk communication, and micro-insurance system development.

4. Targeted investment in resilient coastal infrastructure should be focused on. The risk of weakening coastal infrastructure and urban areas is ranked fourth, reflecting the need to improve design standards for coastal works, especially civil works and essential infrastructure such as transportation, electricity, water supply, and drainage.

5. Coastal ecosystems should be protected and restored. Although the risk of ecosystem and biodiversity degradation is not too high, this is a long-term risk that can lead to widespread consequences in the future. There should be a strict policy to protect mangroves, seagrass, and coral areas and control unsustainable exploitation activities of coastal resources.

5.3 Limitations

Although the study applied the ANP method combined with the RS model to systematically and comprehensively analyze coastal environmental risks due to climate change in Quang Ngai, there are still some limitations. Firstly, the number of experts is twelve, which may affect the coverage of the assessment, especially when interdisciplinary areas of expertise require broader participation from stakeholders such as local communities, businesses, and non-governmental organizations. In future studies, it is necessary to expand the spatial scope to compare between different coastal provinces or apply the model according to smaller administrative units to support decision-making at the grassroots level. In addition, integrating quantitative data from climate simulation models, remote sensing, and geographic information systems (GIS) into the ANP analysis structure will help improve accuracy and real-time updating capabilities. The combination of qualitative analysis and big data is also a potential approach to improve the efficiency and objectivity of coastal environmental risk assessments in the context of increasingly complex climate change.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Appendix

Table A. Pairwise comparison matrix of risk criteria

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**Priority Vector**
C1	1	1/4	1/4	1/2	1	2	1/5	4	6	0.0702
C2	4	1	3	4	6	6	2	8	8	0.2990
C3	4	1/3	1	2	4	6	2	6	9	0.1998
C4	2	1/4	1/2	1	2	4	1/2	4	6	0.1052
C5	1	1/6	1/4	1/2	1	2	1/4	2	4	0.0566
C6	1/2	1/6	1/6	1/4	1/2	1	1/6	2	2	0.0362
C7	5	1/2	1/2	2	4	6	1	7	8	0.1864
C8	1/4	1/8	1/6	1/4	1/2	1/2	1/7	1	2	0.0274
C9	1/6	1/8	1/9	1/6	1/4	1/2	1/8	1/2	1	0.0192

$RI = 1.45;\ \lambda\max = 9.5635;\ CI = 0.0704$; and $CR = 0.0485 < 0.1$.

Table B1. Pairwise comparison matrix of the interrelationships between risk criteria (C1)

C1	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**Priority Vector**
C1	-	-	-	-	-	-	-	-	-	0
C2	-	1	3	1/2	1/2	2	1	2	5	0.1397
C3	-	1/3	1	1/5	1/5	1/2	1/3	1/2	2	0.0467
C4	-	2	5	1	1	3	2	3	7	0.2427
C5	-	2	5	1	1	3	2	3	7	0.2427
C6	-	1/2	2	1/3	1/3	1	1/2	1	3	0.0798
C7	-	1	3	1/2	1/2	2	1	2	5	0.1397
C8	-	1/2	2	1/3	1/3	1	1/2	1	3	0.0798
C9	-	1/5	1/2	1/7	1/7	1/3	1/5	1/3	1	0.0287

$RI = 1.41; \lambda\max = 8.0524; CI = 0.0075$; and $CR = 0.0053 < 0.1$.

Table B2. Pairwise comparison matrix of the interrelationships between risk criteria (C2)

C2	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**Priority Vector**
C1	1	-	3	5	2	2	3	7	7	0.3022
C2	-	-	-	-	-	-	-	-	-	0
C3	1/3	-	1	2	1/2	1/2	1	3	3	0.1021
C4	1/5	-	1/2	1	1/3	1/3	1/2	2	2	0.0606
C5	1/2	-	2	3	1	1	2	5	5	0.1810
C6	1/2	-	2	3	1	1	2	5	5	0.1810
C7	1/3	-	1	2	1/2	1/2	1	3	3	0.1021
C8	1/7	-	1/3	1/2	1/5	1/5	1/3	1	1	0.0355
C9	1/7	-	1/3	1/2	1/5	1/5	1/3	1	1	0.0355

$RI = 1.41; \lambda\max = 8.0524; CI = 0.0074$; and $CR = 0.0053 < 0.1$.

Table B3. Pairwise comparison matrix of the interrelationships between risk criteria (C3)

C3	C1	C2	C3	C4	C5	C6	C7	C8	C9	Priority Vector
C1	1	1/3	-	1	1/5	1/3	1/2	2	2	0.0637
C2	3	1	-	3	1/2	1	2	5	5	0.1838
C3	-	-	-	-	-	-	-	-	-	0
C4	1	1/3	-	1	1/5	1/3	1/2	2	2	0.0637
C5	5	2	-	5	1	2	3	7	7	0.3111
C6	3	1	-	3	1/2	1	2	5	5	0.1838
C7	2	1/2	-	4	1/3	1/2	1	3	3	0.1214
C8	1/2	1/5	-	1/2	1/7	1/5	1/3	1	1	0.0362
C9	1/2	1/5	-	1/2	1/7	1/5	1/3	1	1	0.0362
$RI = 1.41; \lambda\max = 8.2081; CI = 0.029$; and $CR = 0.0210 < 0.1$.										

Table B4. Pairwise comparison matrix of the interrelationships between risk criteria (C4)

C4	C1	C2	C3	C4	C5	C6	C7	C8	C9	Priority Vector
C1	1	2	2	-	1/3	1/3	1/2	1/5	2	0.0684
C2	1/2	1	1	-	1/5	1/5	1/3	1/7	1	0.0386
C3	1/2	1	1	-	1/5	1/5	1/3	1/7	1	0.0386
C4	-	-	-	-	-	-	-	-	-	0
C5	3	5	5	-	1	1	2	1/2	5	0.1926
C6	3	5	5	-	1	1	2	1/2	5	0.1926
C7	2	3	3	-	1/2	1/2	1	1/3	3	0.1114
C8	5	7	7	-	2	2	3	1	7	0.3190
C9	1/2	1	1	-	1/5	1/5	1/3	1/7	1	0.0386
$RI = 1.41;\ \lambda\max = 8.0553;\ CI = 0.0078$; and $CR = 0.0056 < 0.1$.										

Table B5. Pairwise comparison matrix of the interrelationships between risk criteria (C5)

C5	C1	C2	C3	C4	C5	C6	C7	C8	C9	Priority Vector
C1	1	3	5	3	-	1/2	2	5	1	0.1864
C2	1/3	1	2	1	-	1/5	1/2	2	1/3	0.0646
C3	1/5	1/2	1	1/2	-	1/7	1/3	1	1/5	0.0366
C4	1/3	1	2	1	-	1/5	1/2	2	1/3	0.0646
C5	-	-	-	-	-	-	-	-	-	0
C6	2	5	7	5	-	1	3	7	2	0.3154
C7	1/2	2	3	2	-	1/3	1	3	1/2	0.1093
C8	1/5	1/2	1	1/2	-	1/7	1/3	1	1/5	0.0366
C9	1	3	5	3	-	1/2	2	5	1	0.1864
$RI = 1.41; \lambda\max = 8.0556; CI = 0.0079$; and $CR = 0.0056 < 0.1$.										

Table B6. Pairwise comparison matrix of the interrelationships between risk criteria (C6)

C6	C1	C2	C3	C4	C5	C6	C7	C8	C9	Priority Vector
C1	1	1/2	2	1	1/3	-	1/3	2	1/5	0.0634
C2	2	1	3	2	1/2	-	1/2	3	1/3	0.1075
C3	1/2	1/3	1	1/2	1/5	-	1/5	1	1/9	0.0347
C4	1	1/2	2	1	1/3	-	1/3	2	1/5	0.0634
C5	3	2	5	3	1	-	1	5	1/2	0.1834
C6	-	-	-	-	-	-	-	-	-	0
C7	3	2	5	3	1	-	1	5	1/2	0.1834
C8	1/2	1/3	1	1/2	1/5	-	1/5	1	1/9	0.0347
C9	5	3	9	5	2	-	2	9	1	0.3294
$RI = 1.41; \lambda\max = 8.0282; CI = 0.0040$; and $CR = 0.0028 < 0.1$.										

Table B7. Pairwise comparison matrix of the interrelationships between risk criteria (C7)

C7	C1	C2	C3	C4	C5	C6	C7	C8	C9	Priority Vector
C1	1	3	7	5	2	2	-	5	7	0.3100
C2	1/3	1	3	2	1/2	1/2	-	2	3	0.1069
C3	1/7	1/3	1	1/5	1/5	1/5	-	1/2	1	0.0334
C4	1/5	1/2	5	1	1/3	1/3	-	1	5	0.0887
C5	1/2	2	5	3	1	1	-	3	5	0.1824
C6	1/2	2	5	3	1	1	-	3	5	0.1824
C7	-	-	-	-	-	-	-	-	-	0
C8	1/5	1/2	2	1	1/3	1/3	-	1	2	0.0629
C9	1/7	1/3	1	1/5	1/5	1/5	-	1/2	1	0.0334
$RI = 1.41; \lambda\max = 8.3074; CI = 0.0439$; and $CR = 0.0311 < 0.1$.										

Table B8. Pairwise comparison matrix of the interrelationships between risk criteria (C8)

C8	C1	C2	C3	C4	C5	C6	C7	C8	C9	Priority Vector
C1	1	2	5	1/2	1	2	3	-	5	0.1795
C2	1/2	1	3	1/3	1/2	1	2	-	3	0.1013
C3	1/5	1/3	1	1/8	1/5	1/3	1/2	-	1	0.0345
C4	2	3	8	1	2	3	5	-	8	0.3093
C5	1	2	5	1/2	1	2	3	-	5	0.1795
C6	1/2	1	3	1/3	1/2	1	2	-	3	0.1013
C7	1/3	1/2	2	1/5	1/3	1/2	1	-	2	0.0601
C8	-	-	-	-	-	-	-	-	-	0
C9	1/5	1/3	1	1/8	1/5	1/3	1/2	-	1	0.0345
$RI = 1.41; \lambda\max = 8.0365; CI = 0.0052$; and $CR = 0.0037 < 0.1$.										

Table B9. Pairwise comparison matrix of the interrelationships between risk criteria (C9)

C9	C1	C2	C3	C4	C5	C6	C7	C8	C9	Priorit y Vector
C1	1	1	2	2	1/5	1/3	1/2	2	-	0.0786
C2	1	1	2	2	1/5	1/3	1/2	2	-	0.0786
C3	1/2	1/2	1	1	1/7	1/5	1/3	1	-	0.0435
C4	1/2	1/2	1	1	1/7	1/5	1/3	1	-	0.0435
C5	5	5	7	7	1	2	3	7	-	0.3582
C6	3	3	5	5	1/2	1	2	5	-	0.2217
C7	2	2	3	3	1/3	1/2	1	3	-	0.1326
C8	1/2	1/2	1	1	1/7	1/5	1/3	1	-	0.0435
C9	-	-	-	-	-	-	-	-	-	0
$RI = 1.41; \lambda\max = 8.0607; CI = 0.0087$; and $CR = 0.0061 < 0.1$.										

Table C. Importance comparison scale with AHP

Definition	Level of Importance	Description
Equal importance	1	Criteria i and j are equally important.
Moderate importance	3	Criteria i is less important than Criteria j.
Important	5	Criteria i is more important than Criteria j.
Very important	7	Criteria i is very important than Criteria j.
Extremely important	9	Criteria i is definitely more important than Criteria j.
Intermediate value	2; 4; 6; 8	