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Developing and Implementing a Risk Analysis-Based Model for Effective Management of Protected Areas

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Abstract: Managing protected areas (PAs) supports protecting biodiversity and preserves ecological functions. Many risks associated with PAs management affect the most important goals of PAs including sustainability, effectiveness, and ecological balance. This work aims to define the most predictable risk factors affecting PAs management as well as to introduce a model for assessing and exploring the influences of the identified risk factors on PAs management. Fifty-four risk factors affecting the PAs management goals are defined under seven risk groups including general and fundamental preparations, monitoring system, protocols, and implementation plans, training, visitors, employees, and activities conducted within the PAs. Many characteristics of risk factors such as presence rate and impacts on sustainability, effectiveness, and ecological balance goals are introduced. Fuzzy logic is utilized in developing the proposed risk model and applied using data collected in the Kingdom of Saudi Arabia. Various relationships are introduced among risk indices that impact PAs management goals, ensuring close relations among all indices. The results highlight various important risk factors, such as the "Absence of mechanisms for early warning of disasters affecting protected areas", and the "Lack of a system for monitoring the occurrence development and spread of disasters". A risk group related to the monitoring system has been identified as causing the highest risk impacting the management of PAs. Further, most of the risk impacts on the three goals are due to protocols and implementation plans group. This work presents a new strategy to support managing PAs in Saudi Arabia, which can be easily adapted for application in other countries.

Keywords: protected areas; sustainability; fuzzy logic; risk analysis

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1. Introduction

Protected areas (PAs) are designated geographical spaces that are recognized, dedicated, and managed to ensure the long-term protection of nature along with its related ecosystem services and cultural values [1]. They are considered the fundamental cornerstone of protecting and sustaining biodiversity, ecosystems, and unique natural resources and cultural values and finding ways in which the interactions between humans and nature coincide with mutually beneficial outcomes [2]. According to the Protected Planet Report of the World Database presented in June 2023, the total number of PAs in the world is 285,415, covering 244 countries and territories [3]. Establishing PAs is considered the major strategy for safeguarding wildlife and plant life from degradation and environmental threats caused by human activities, such as poaching, pollution, and habitat destruction [4]. According to the National Database on PAs in Saudi Arabia, 2024, there are currently a total of 36 designated PAs in the Kingdom. These cover 91,734 km^2 of terrestrial area (18.1%) and 14,382 km^2 of marine habitat (6.45%) [5]. Saudi Arabia is divided into seven main terrestrial physiographic regions, along with two marine regions, as classified by Child and Grainger in 1990 [6]. It can be classified into four realms, 20 eco-regions, and 65 ecosystems [5]. These ecosystems encompass a wide variety of terrestrial habitats, ranging from cool, moist high mountain areas to arid desert steppes and warm, semi-arid coastal plains. Saudi Arabia's PA governance structure is characterized by a state-led management approach, emphasizing centralized monitoring and response mechanisms. This model prioritizes top-down oversight rather than engaging in localized or community-driven participation [5].

Recently, the Uruq Bani Ma'arid property, located at the western edge of Ar-Rub' al-Khali, was recorded on the UNESCO World Heritage site list [7]. This reflects the efforts made by the kingdom to preserve biodiversity and protect natural environments. Establishing more nature PAs is a direct and effective way of biodiversity conservation [8], one of the main objectives of the Kingdom's Vision 2030, as outlined in the Saudi Green Initiative and aligned with the Convention on Biological Diversity (CBD) Global Biodiversity Framework [9], is to protect 30% of the land and sea areas [10].

In addition to protecting biodiversity and safeguarding natural habitats by restricting and prohibiting human activities [11,12], PAs provide numerous environmental, economic, social, and scientific benefits. These benefits comprise developing ecotourism, mitigating the effects of climate change, maintaining ecological balance, and supporting scientific research. Despite their substantial importance in conserving biodiversity, PAs face numerous challenges, including those related to poaching, combating wildfires, illegal resource extraction, and tourism activities in PAs [13–16], which significantly impacts their effectiveness in achieving their goals. The main problems faced by PAs can be classified into three main groups. The first group is related to human encroachment, which includes mining exploration, oil extraction, urban and agricultural expansion, over-tourism, and overgrazing. The second group is related to environmental effects, these effects include chemical and industrial pollution, diseases and epidemics, the spread of invasive species, and climate change [17]. The third group is regarding management issues that include lack of funding, shortage of human resources, and weak environmental legislation.

The success of PAs in achieving their conservation goals largely depends on the quality of their management [18]. Effective management can enhance the conservation outcomes of PAs by reducing or mitigating the effect of other source problems, whereas poor management can lead to biodiversity loss, ecosystem degradation, and reduced benefits. Furthermore, well-managed PAs afford significant sustainable ecosystems, great efficiency in conserving biodiversity, and remarkable ecological balance in PAs. Thus, evaluating the efficiency of PAs management is fundamental. It is a concern that has been given serious attention by the International Union for Conservation of Nature (IUCN) [19] and the World Commission on PAs (WCPA) [20]. In the following, a brief description of the three main goals of Well-managed PAs (Sustainability, Effectiveness, and Ecological balance) is presented.

Sustainability of PAs means managing these areas in a way that guarantees the long-term preservation of biodiversity and ecosystems. Protected areas contribute to the preservation of biological and landscape diversity via the preservation of ecosystems and specific habitats of plant and animal species [21]. Sustainability can be adopted as a common strategy for sustainable economic, social, and environmental goals [22] which could contribute to the development of PAs. In addition to the socio-economic functions, tourism has a significant impact on the development and sustainability of PAs [23]. Properly well-planned tourism development can participate in the sociocultural, economic, and ecological benefits for the destination [24]. So, the second strategy is encouraging sustainable ecotourism which involves implementing restrictions and controls on tourism activities within PAs to minimize the negative impact on the natural habitats and wildlife as followed in Uruq Bani Ma'arid property [5]. It also includes educating visitors about the importance of preserving the PAs and encouraging their responsible behaviors.

The effectiveness of PAs can be defined as their ability to achieve environmental protection goals and conserve biodiversity and ecosystems, along with balancing economic and social needs. In other words, it is the management's capability to protect values and achieve objectives [25]. Evaluating management effectiveness is regarded as an essential element of flexible, proactive PAs management [26]. Measuring the effectiveness of PAs involves several indicators. These indicators could reflect the success of PAs in protecting both living organisms and ecosystems. Implementing plans for conserving endangered species, monitoring changes in the population's wildlife and plant species, adapting to climate change, and preventing human threats and illegal activity are the main indicators of PAs efficiency. Several scholars explore PAs effectiveness by utilizing the technique of restricting and prohibiting human activities [27–29]. Related studies are also presented at both national and regional levels [30,31]. These studies introduce a straightforward and well-organized method for assessing the effectiveness of large or multiple PAs in decreasing human pressure. Conversely, they did not account for sufficient human influence factors due to limitations in data availability [32]. From a global perspective, both the IUCN and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) have conducted extensive analyses on the effectiveness of PAs management, offering essential insights into global strategies [1,33]. One widely recognized approach is the Protected Area Management Effectiveness (PAME) framework, which relies heavily on comprehensive data from PAs [17,25]. Moreover, Ghoddousi et al., proposed a multidimensional conceptual framework to assess effectiveness along three complementary dimensions: ecological outcomes, social outcomes, and social-ecological interactions [34]. In Saudi Arabia, however, there is a significant information gap regarding PAs, and such detailed data are more of an exception than the norm.

Ecological balance refers to the harmony and stability among all components of the ecosystem, including living organisms and non-living elements within the protected area. As they are deemed essential for protecting significant habitats, biodiversity, and the livelihoods of local communities [35], PAs introduce an important role in maintaining ecological balance [36]. Because of its natural wonders' wealth, PAs everywhere are easily accessed by a substantial number of daily visitors [37]. This led to significant environmental influences and affected the ecological balance of this system [38]. The goal of sustaining ecological balance in PAs is to ensure that all components in the protected area interact in a way that prevents any imbalances that might lead to environmental degradation. To maintain ecological balance in PAs, it is essential to adopt comprehensive strategies, such as protecting local species, conducting continuous monitoring, and adapting to environmental changes and natural events that can impact the ecological balance like fires, floods, or droughts.

Risk can be defined as an uncertain event or condition, that if it occurs, has a positive or negative effect on a project's objective. The key element of this definition is that the effect of the uncertainty if it occurs, may be positive or negative on the objectives of the planned endeavor [39]. However, many risks associated with PAs can affect the achievement of the goals. So, it is essential to detect the main risk factors that affect the management of PAs and to investigate the influences of each on the desired goals.

Most methodologies used for assessing the management effectiveness of PAs highlight the significance of describing risks and their external effects. Risks associated with PAs incorporate various barriers including global, regional, and local. So, identifying the risks, studying the root causes, and their impact are essential for successful assessment [40] as well as minimizing their influences and supporting decisions related to PAs management. Many scholars investigate PAs management. For example, Coad et al. presented a study about measuring the impact of PAs management interventions [41]. Whereas He and Cliquet have studied the challenges for PAs management in China [42]. Guala et al. analyzed tourism development linked to PAs [43]. Xin, 2023 investigated the vulnerability of PAs to future climate and land use change and biological invasions [44]. Mandić 2023 examined the effectiveness of Protected area management with COVID-19 in Plitvice Lakes National Park, Croatia [40]. However, up to the authors' knowledge, there is limited research dealing with and evaluating risks that influence PAs management. For example, Shafiee et al. identified 16 risk factors to study the risk assessment of human activities on PAs [45]. Peng et al.

present a framework for integrating ecosystem services indicators with risk assessment systems [46]. Chen et al. identified the areas that have priority for territorial ecological conservation and restoration in Tianjin City, China based on ecological networks [47].

Fuzzy logic can support several decisions related to inaccuracy, uncertainty, and inadequate data [48]. It is considered one of the most widely used modeling techniques [49,50]. Fuzzy logic has facilitated a wide range of successful applications across fields such as engineering, medicine, and agriculture [49–54]. It offers a robust approach to addressing vagueness and effectively handles parameters with complex quantification requirements needed for risk analysis [55]. Further. It can address infinite data and non-statistical uncertainties. One of the main advantages of using fuzzy logic is its capability to deal with linguistic variables using several logical rules for relating the dependencies among objects [56,57]. Fuzzy logic has numerous applications in the management of PAs. A risk analysis model using the fuzzy technique for assessing the effect of risks during the management of wilderness PAs in the Kingdom of Saudi Arabia is developed and applied in this study. Combining the effects of presence rate with the risk impacts on the goals of PAs management is considered an essential step in evaluating risks affecting PAs management. Fuzzy logic is applied to solving many problems in various fields to overcome many problems due to a shortage of data. It can deal with incomplete data for evaluating a certain problem by utilizing various simple linguistic terms and logical rules, which can introduce many relatives among inputs and outputs. Further, fuzzy logic is utilized in evaluating projects and assessing risks in many fields related to PAs. It is used for increasing the resilience of natural PAs [58], in assessing ecosystems' vulnerability to fire in managing natural PAs [59], and in integrating social-ecological data to support overall resilience in marine PAs spatial planning [60] and in risk assessment of wild animal life in PAs [61]. For these advantages, fuzzy logic is used to qualify the linguistics that characterizes a certain organization.

This study aims to explore the influence of risks on the main goals of PAs management (sustainability, effectiveness, and ecological balance) by joining the presence rate and the various impacts of the risk factors. Consequently, a risk analysis model for assessing the influences of risks on PAs management goals is highly required. The fuzzy logic technique is proposed for developing the model. Additional objectives of the study include: (1) defining the primary risk factors affecting PAs management; (2) assessing the prevalence of these risk factors and their various impacts on sustainability, effectiveness, and ecological balance; (3) identifying risk factors with actual indices that influence PA management; and (4) determining the impacts of sustainability, effectiveness, and ecological balance within PAs. The objectives of this research represent a new strategy that helps PAs managers minimize risk impacts on PAs management goals.

This paper begins by providing an introduction to the PAs, their values, and management requirements followed by a description of the methodology. Then, the designing of the model and model application and verification. Then the obtained results are presented. Finally, the discussion limitations and future work are presented before concluding the work.

2. Research Methodology

Through a comprehensive review concerning PAs and PAs management, the barriers and problems concerning PAs management are collected and summarized in the form of risk factors and risk groups. Identifying these risks is considered the first step in this research methodology. Three familiar goals concerning managing PAs and chosen for exploring the effects of risks on these goals. These goals are sustainability, effectiveness, and ecological balance. For obtaining reasonable and useful results, a model for analyzing risks is proposed to be developed as a main objective of this study. This model takes into consideration the combined effect of the presence rate and multiple effects of each risk factor. Further, field surveys are conducted to collect the required data for applying and testing the proposed model. For preparing the initial risk factors, an inclusive literature review and brainstorming meetings with experts in the PAs management area. These sessions were conducted through two meetings in Saudi Arabia with nine experts in the PAs management area in the field of PAs management and their experience ranges between 10–21 years. The discussion was mainly aimed at describing most of the risks and their related groups concerning PAs management.

Using brainstorming sessions, a list of the main risk groups is achieved as well as the risk factors affecting PAs management. The outcomes from this stage conclude with the final risk factors influencing PAs management (fifty-four factors), in addition to seven risk groups. Additionally, the model outputs signify the importance of a definite risk factor that adjoins the influences of two inputs (rate of presence and impact). Next, semi-structured interviews are executed to permit respondents to improve survey results [39]. The interviews aim to choose the most suitable terms for risk factors related to presence rate and impact on sustainability, effectiveness, and ecological balance based on their experiences. These interviews were directed with 21 participants who work in various departments in PAs management field in Saudi Arabia they were asked about each risk factor its presence rate and its effect on the three goals, as well as to verify the logical rules that relate the model inputs and outputs. Based on the collected data, the proposed risk model is developed. The research methodology introduced in this work is depicted in Figure 1.

Figure 1. The research methodology. Abbreviations: PAs, Protected areas; PRI, SI, EI, and EBI are indices for Presence rate, Sustainability, effectiveness and Ecological balance respectively; FIS, FIE, and FIEB are impacts for Sustainability, effectiveness and Ecological balance respectively.

3. Risk Factors Affecting PAs Management

Based on the outlined review described in Section 1, concerning risks related to PAs management, numerous factors are presented and categorized into seven risk groups. A final risk factors list including fifty-four risk factors related to PAs management that affect sustainability, effectiveness, and ecological balance, is obtained as can be seen in Table 1. Further, the identified risk groups cover the following categories: General and fundamental preparations, Monitoring systems, Protocols and implementation plans, Training, Visitors, Employees, and Activities conducted within the PAs.

Table 1. Risk factors and risk groups affecting PAs management.

No.	Risk Code	RG(A): General and Fundamental Preparations Risk Factors
1	RPA(A)_01	Absence of a crisis management team during emergencies.
2	RPA(A)_02	Lack of studies, research, and scenarios to confront expected and recurring disasters.
3	RPA(A)_03	Shortage of water, food, and fuel during long tours inside the protected areas
4	RPA(A)_04	Unavailability of aircraft for conducting aerial search operations when needed in emergency situations.
5	RPA(A)_05	Inadequate documentation of emergency cases for future reference.
6	RPA(A)_06	Absence of a permanent central operations room to receive distress calls.
7	RPA(A)_07	Lack of responsible management for security, safety, and ensuring the necessary readiness for emergencies.
8	RPA(A)_08	Failure to conduct simulation exercises for virtual emergency situations and training for handling such scenarios.
9	RPA(A)_09	Shortage of food and veterinary supplies within the protected area
		RG(B): Monitoring system risk factors
10	RPA(B)_01	Absence of mechanisms for early warning of disasters affecting protected areas.
11	RPA(B)_02	Lack of a system for monitoring the occurrence, development, and spread of disasters.
12	RPA(B)_03	Insufficient coverage of protected areas with wireless communication networks
13	RPA(B)_04	Absence of a system for monitoring vehicle movement within protected areas.
14	RPA(B)_05	Absence of a hotline within 'open-to-public' protected areas.
15	RPA(B)_06	Lack of mini-weather stations for weather forecasting at hikers' centers.
		RG(C): Protocols and implementation plans risk factors
16	RPA(C)_01	Lack of updates on environmental disaster preparedness plans.
17	RPA(C)_02	Absence of management plans for open-to-public protected areas, including visitor routes, permitted activities, and activity regulations.
18	RPA(C)_03	Failure to adhere to approved protocols for emergency management.
19	RPA(C)_04	Failure to adhere to civil defense instructions in facing emergency situations.
20	RPA(C)_05	Failure to comply with World Health Organization protocols regarding epidemics and viruses.
21	RPA(C)_06	Absence of a plan to deal with mass mortality events and epidemic outbreaks.
22	RPA(C)_07	Lack of maps from relevant authorities identifying hazardous areas for non-presence and isolation.
23	RPA(C)_08	Failure to determine the cases that require contacting relevant government entities for disaster management support.
24	RPA(C)_09	Lack of continuous review and development of employee training programs
25	RPA(C)_10	Absence of plans to combat invasive strange species that may have harmful effects on wildlife in protected areas.
		RG(D): Training risk factors
26	RPA(D)_01	Failure to train employees in wilderness survival and first aid skills.
27	RPA(D)_02	Failure to train employees in navigation skills.
28	RPA(D)_03	Failure to train employees in handling minor vehicle breakdowns.
29	RPA(D)_04	Failure to train employees effectively dealing with exotic strange species.
30	RPA(D)_05	Failure to train employees in assessing the environmental impacts of licensed projects.
31	RPA(D)_06	Failure to train employees in handling emergencies of all types (such as floods and fires).
32	RPA(D)_07	Lack of workshops and seminars specifically focused on environmental disaster management and crisis management.

Table 1. *Cont.*

		RG(E): Visitors risk factors
33	RPA(E)_01	Lack of visitor awareness regarding potential risks within the protected areas.
34	RPA(E)_02	Failure to clarify areas without communication network coverage within the protected area for visitors.
35	RPA(E)_03	Absence of informative signs warning visitors of any dangers such as road damage or rough terrain.
36	RPA(E)_04	Inappropriate selection of visitor activity sites which may result in conflicting activities.
37	RPA(E)_05	Allowing visitors entry during the possibility of natural disasters.
38	RPA(E)_06	Failure to provide printed maps of visitable areas within the protected area to assist visitors.
39	RPA(E)_07	Visitors' non-compliance with protected area management instructions and regulations.
		RG(F): Employees risk factors
40	RPA(F)_01	Insufficient availability of security and safety resources with security and protection personnel.
41	RPA(F)_02	Lack of necessary tools to respond to emergencies and conduct rescue operations.
42	RPA(F)_03	Non-compliance with designated patrol routes.
43	RPA(F)_04	Inadequate monitoring of patrol movements and returns.
44	RPA(F)_05	Lack of experience among staff and decision-makers.
45	RPA(F)_06	Lack of clarity in responsibilities and task distribution.
46	RPA(F)_07	Poor organization and lack of cooperation among management personnel.
47	RPA(F)_08	Allowing locals to use protected areas as grazing areas.
		RG(G): Activities conducted within the PAs risk factors
48	RPA(G)_01	Non-compliance of licensed projects, such as mines, quarries, and farms within protected areas, with the environmental regulations stipulated in the licenses.
49	RPA(G)_02	Failure to require companies to rehabilitate the site after the end of the activity period.
50	RPA(G)_03	Lack of environmental impact assessment by companies applying for licenses during their operations within the protected area.
51	RPA(G)_04	Poor coordination with relevant authorities in regulating work procedures, preventive measures, detailed precautions, and precautions.
52	RPA (G)_05	Non-compliance with civil defense instructions in facilities within protected areas.
53	RPA(G)_06	The existence of conflicts within the work environment.
54	RPA(G)_07	Unauthorized use of toxins or chemicals within the protected area.

4. Fuzzy Model for Analyzing Risks Related to PAs (FMARPA)

The proposed model aims to qualitatively assess the risk factors influencing PAs management. The assessment process covers the proposed PAs goals: sustainability, effectiveness, and ecological balance. Instead of assessing the risk effects separately based on the PR of risk factors detached from their impact, the proposed model incorporates various relationships using logical rules between PR and other risk impacts, with the model outputs represented as fuzzy risk indices. Three fuzzy indices are suggested to signify the severity of each risk factor associated with a certain goal. The Fuzzy Risk Index for Sustainability (FRIS) is the severity that resulted in combining the Presence rate (PR) and Impact on sustainability (SI). On the other hand, the Fuzzy Risk Index for Effectiveness (FRIE) is the severity according to related PR and Impact on Effectiveness (EI). Lastly, the Fuzzy Risk Index for Ecological Balance (FRIEB) is the outcome of PR and Impact on Ecological Balance (EBI).

For calculating the Presence Rate Index (PRI), SI, EI, and EBI, the data of risk factors characteristics which are collected from the field survey including presence rate, and impacts on the proposed three goals, are utilized as a weighted average for each choice (from very low to very high). For each case of the three goals (sustainability, effectiveness, and ecological balance), there are two inputs and one output, as well as 5×5 logical rules are presented to relate the model inputs with outputs. The output is determined by the same range from very low (V-L) to very high (V-H). Further, the proposed logical rules relate model inputs with outputs using fuzzy associated memories (FAMs) shown in Table 2.

Table 2. FAMs rules for calculating the FMARPA output.

Risk Scale		Risk Impact Index				
		Very Low	**Low**	**Medium**	**High**	**Very High**
Presence Rate	Very Low	V-L	V-L	L	L	M
	Low	V-L	L	L	M	M
	Medium	L	L	M	M	H
	High	L	M	M	H	V-H
	Very High	M	M	H	V-H	V-H

One of the main steps in fuzzy logic modeling is choosing a suitable membership function. These functions exemplify a numerical values linguistic term [62]. In addition, they signify linguistic terms ranges either for input or for output. The triangular membership function, shown in Figure 2, is the most familiar shape to be used in risk analysis and risk management, so it is suggested to be used in FMARPA to represent the ranges of inputs and outputs.

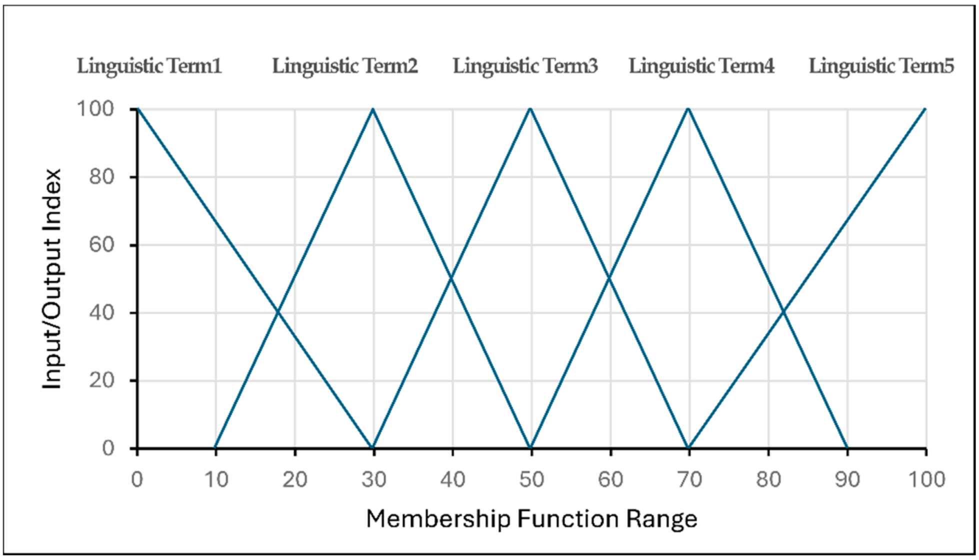

Figure 2. The proposed triangular membership function used in FMARPA.

4.1. FMARPA Application

For evaluating risk factors affecting PAs management using FMARPA, various field survey stages are executed as explained before to collect data concerning characteristics of the identified risk factors that impact PAs management (*PRI*, *SI*, *EI*, and *EBI*). These items represent the model inputs and are summarized in Table 3. These indices are determined according to several equations. The presence rate is exemplified in Equation (1) while the remaining indices which are related to impacts on goals are represented by Equations (2)–(4), while Equation (5) represents the influence of the experiences of the participants.

$$PRI = \left(\sum_{i=1}^{5} Pri * Ni * EF\right)/Y \quad (1)$$

$$SI = \left(\sum_{i=1}^{5} si * Ni * EF\right)/Y \quad (2)$$

$$EI = \left(\sum_{i=1}^{5} ei * Ni * EF\right)/Y \quad (3)$$

$$EBI = \left(\sum_{i=1}^{5} ebi * Ni * EF\right)/Y \quad (4)$$

$$Y = N_{i(<10)} * EF_1 + N_{i(10:15)} * EF_2 + N_{i(15:20)} * EF_3 + N_{i(>20)} * EF_4 \quad (5)$$

where: *PRI*: presence rate index; *Pri*: the presence weight; *Ni*: number of applicants who responded to selection *i*; *SI*: Sustainability Index; *si*: the impact weight for sustainability;

EI: Effectiveness Index; *ei*: the impact weight for effectiveness; *EBI*: Ecological balance index; *ebi*: the impact weight for Ecological balance; *EF* is the experience factor, (EF_1 = 1 for 5–10 years, EF_2 = 1.6 for 10–15 years, EF_3 = 2.3 for 15–20 years and EF_4 = 3 for above 20 years).

Table 3. Top two risk factors affecting Pas management.

Risk Code	Ranking Due to		
	Sustainability	Effectiveness	Ecological Balance
RPA(B)_01	1	1	6
RPA(B)_02	2	2	3
RPA(C)_10	6	7	1
RPA(G)_03	5	9	2

The three model outputs (FIS, FIE, and FIEB) are calculated using MATLAB software (version 9.11) and attached in Appendix A, along with the ranks for all risk factors according to each goal. Table 3 summarizes the top two risk factors associated with each goal. More details for the analysis of these results will be discussed in the model results and discussion section.

4.2. Verification of FMARPA

The severity of each risk factor can be indicated by the following equations [63]:

$$SSI = PRI \times SI \tag{6}$$

$$SEI = PRI \times EI \tag{7}$$

$$SEI = PRI \times EBI \tag{8}$$

where *SSI*, *SEI*, and *SEBI* are the severity indices for Pas sustainability, effectiveness, and ecological balance respectively. The FMARPA is applied to all risks influencing Pas resulting in FIS, FIE, and FIEB. Spearman's test is utilized and the correlation coefficient factor is determined to rank the risk factors according to the three goals. For +ve correlation factor value, the resurrection is to +1, the more direct the relationship is. On the other hand, a negative value expresses an inverse relationship, and as it approaches −1, the relationship increases, while a zero value indicates that there is no relationship. The results of the correlation coefficient are presented in Table 4. It is clear that all results have positive values and are higher than 88%, which verifies the model results.

Table 4. Correlation coefficient factors for FMARPA verification.

Indices	FIS and SSI	FIE and SEI	FIEB and SEBI
Correlation coefficient factors	0.965	0.884	0.915

5. Results

5.1. Correlations Between Pas Risk Indices and Fuzzy Risk Indices

A correlation test based on Spearman test principles is introduced to declare the association between Pas presence rate and Pas impact indices (model inputs), and between the fuzzy risk indices (model outputs). Figure 3 presents these relationships and declares that the correlation coefficient between the presence rate and impact indices varies from −0.262 to 0.111. A positive relation with the sustainability index is observed, whereas negative relationships are noted with the effectiveness and ecological balance indices. Conversely, the correlation coefficient among the impact indices, which are positively correlated, ranges from 0.19 to 0.589. The effectiveness and ecological balance indices have the weakest relation, while the sustainability and ecological balance indices have the strongest relation. Figure 4 illustrates the relationships between the fuzzy model outputs.

The effectiveness and ecological balance fuzzy risk indices have the lowest coefficient value, indicating the weakest relationship, whereas the sustainability and ecological balance indices have the highest relation, with a coefficient value of 0.728. It is noted that all fuzzy risk indices are positively correlated.

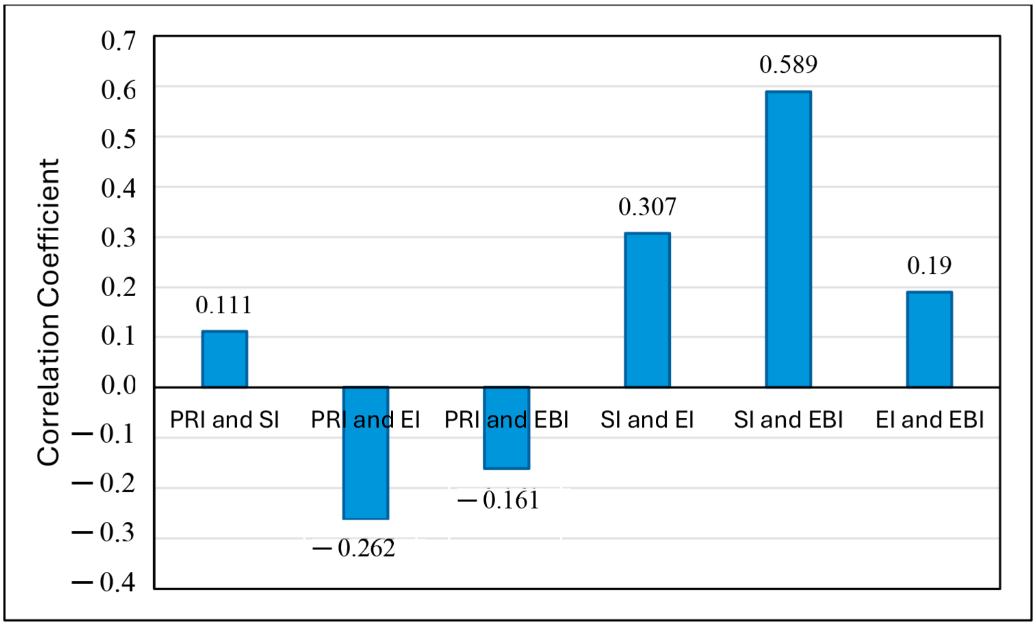

Figure 3. Correlation coefficient FMARPA risk indices.

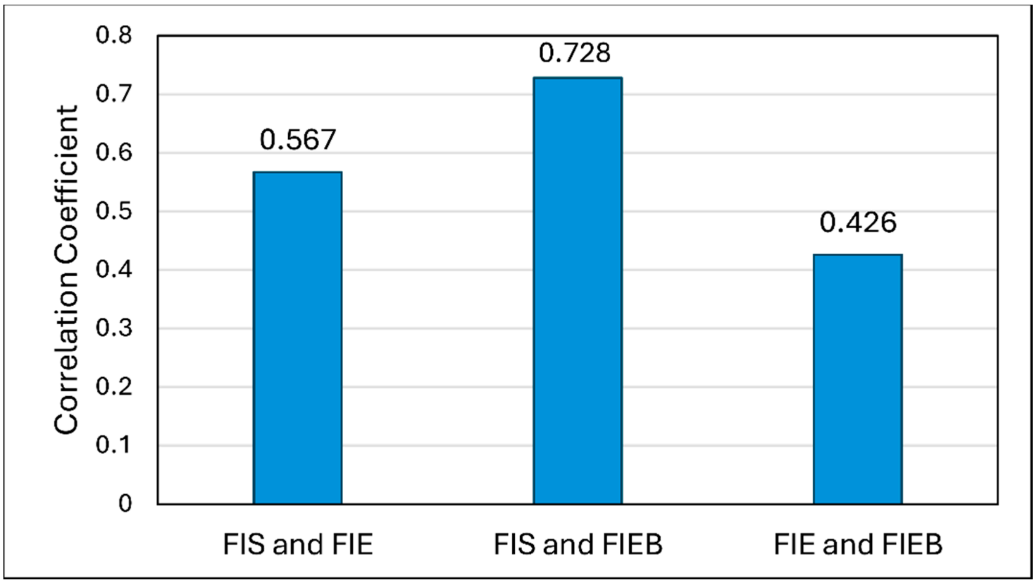

Figure 4. Correlation coefficient for FMARPA fuzzy risk indices.

5.2. FMARPA Inputs and Outputs Investigation

The boxplot diagram displays various statistical features, including the center, spread, range, and outlier points that fall outside the range. The box represents 50% of the data, with the 75th percentile and 25th percentile marking the upper and lower edges of the box, respectively. The median is indicated by a line in the middle of the box [64]. Figure 5 introduces a comparison of the PRI with other impact indices SI, EI, and EBI. PRI exhibits the widest distribution, while EI has the smaller distribution among the impact indices. All impact indices have values close to the lower limit, except for EI, which has a different lower limit. In addition, the values converge near the median without any outliers.

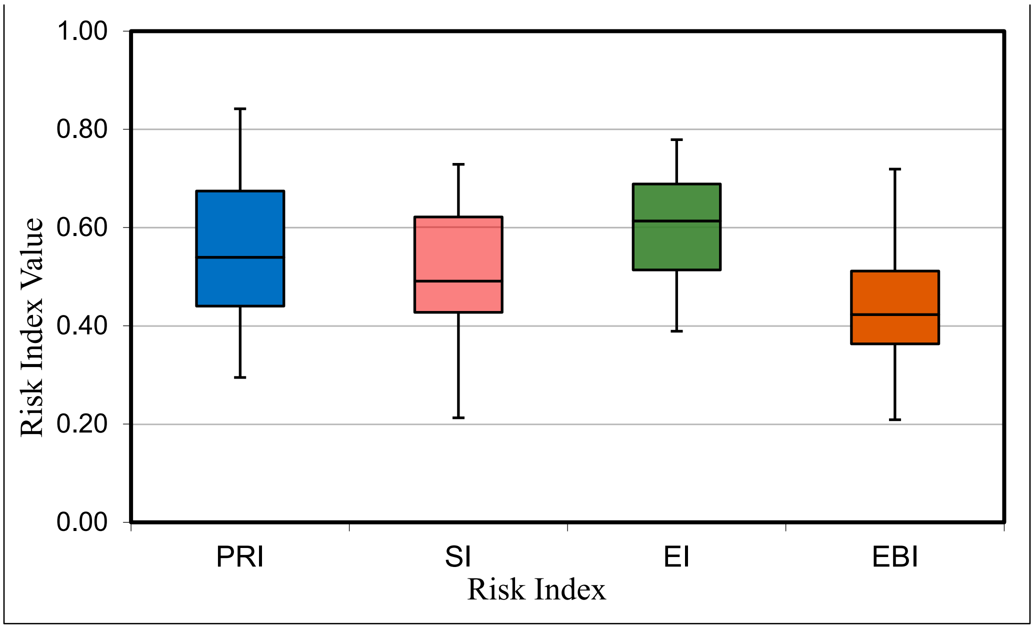

Figure 5. A comparison between FMARPA inputs.

The boxplot in Figure 6 compares various risk indices related to Fuzzy indices. FIS shows the widest distribution range, with the highest upper limit and the lowest lower limit values. Outliers are observed in the effectiveness and ecological balance risk plots (FIE and FIEB). Excluding these outliers, the distribution ranges of these indices are quite similar, with only minor differences in their upper and lower limits. Comparing the inputs and outputs, FIS has the broadest distribution space, indicating that sustainability issues are most influenced by the investigated risk factors.

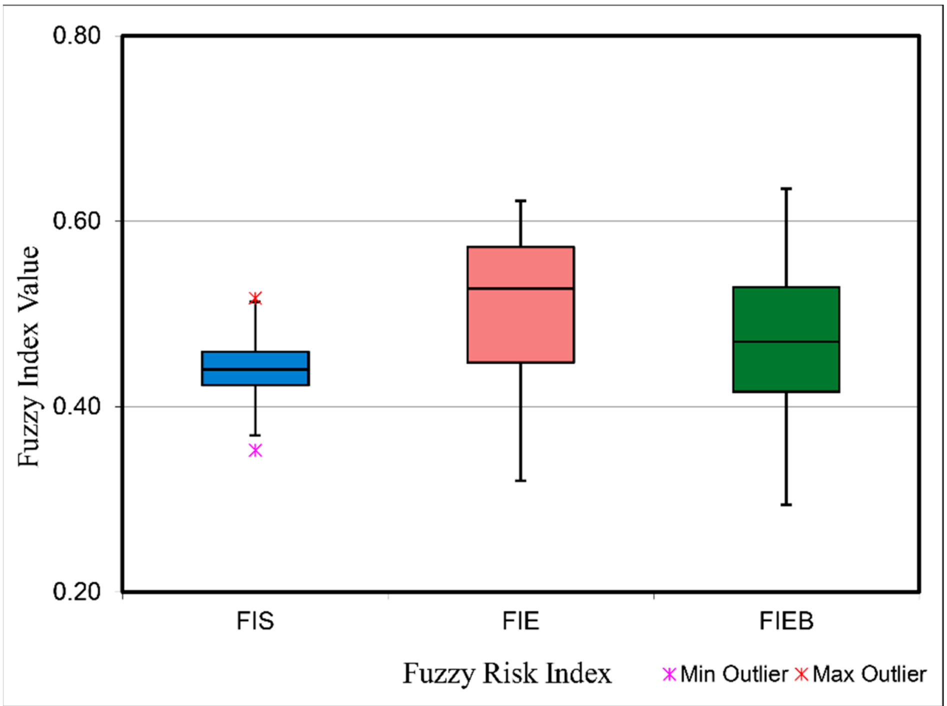

Figure 6. A comparison between FMARPA outputs.

5.3. Analysis of Risk Groups

5.3.1. Analysis of Risk Groups Based on Sustainability

As explained before, the risk factors affecting Pas management are grouped under seven risk groups. The relationship between FIS and various risk groups is presented in Figure 7. FIS exhibits a broad relationship with all groups, particularly showing the widest distribution space for group RG(F) (employees). Additionally, concerning Table 5, the values of the cumulative group index and average FIS reflect that RG(C) (protocols and implementation plans) is the most substantial risk group for its high influences on sustainability, followed by RG(A) (general and fundamental preparations).

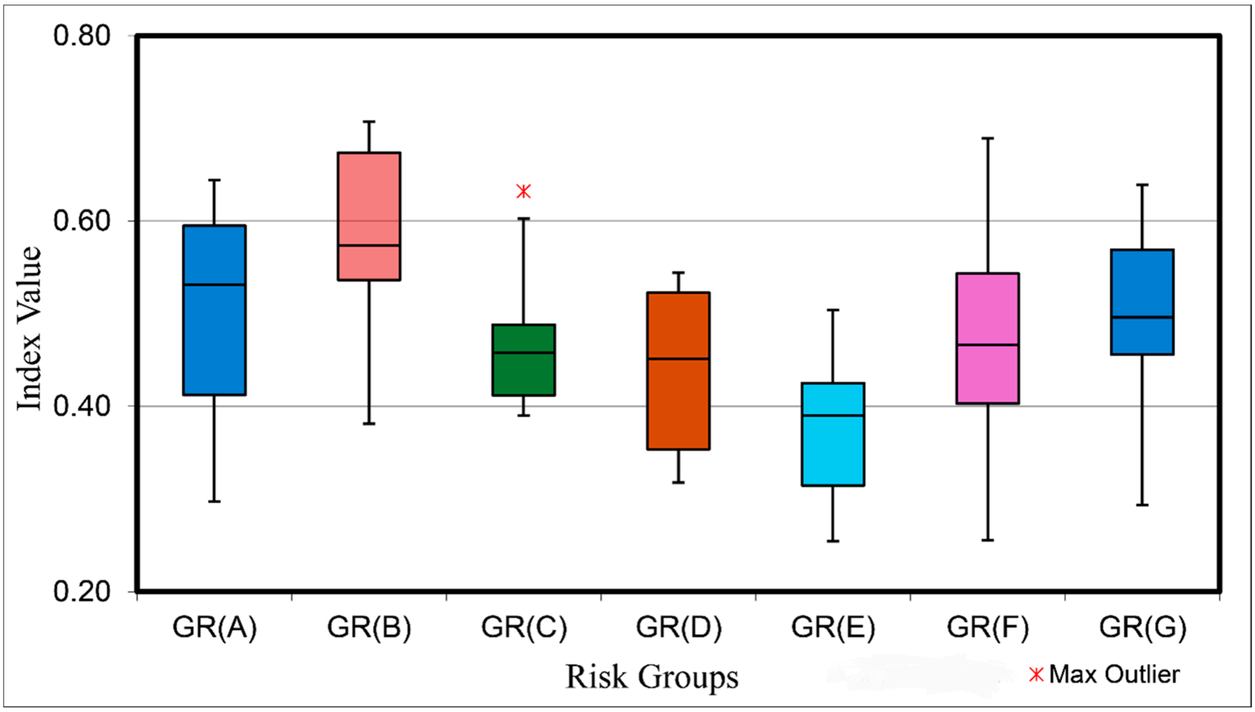

Figure 7. Pas risk groups comparison based on sustainability goal.

Table 5. Cumulative group index and average FIS for Pas risk groups in case of sustainability.

	RG(A)	RG(B)	RG(C)	RG(D)	RG(E)	RG(F)	RG(G)
Cumulative group index	4.528	3.466	4.721	3.064	2.626	3.762	3.478
Average FIS	0.503	0.578	0.472	0.438	0.375	0.470	0.497

5.3.2. Analysis of Risk Groups Based on Effectiveness

Regarding Figure 8, it is clear that FIE has a wide distribution space with groups RG(E) (visitors) and RG(F) including outliers. Conversely, groups RG(C) and RG(D) (training) have the narrowest distribution spaces. For the same reason, the largest number of factors belongs to RG(C) with 10 risk factors, so its cumulative index is the highest, followed by RG(A) with 9 risk factors as declared in Table 6.

Table 6. Cumulative group index and average FIE for Pas risk groups in case of effectiveness.

	RG(A)	RG(B)	RG(C)	RG(D)	RG(E)	RG(F)	RG(G)
Cumulative group index	4.577	3.691	4.649	3.471	3.536	3.877	3.457
Average of FIE	0.509	0.615	0.465	0.496	0.505	0.485	0.494

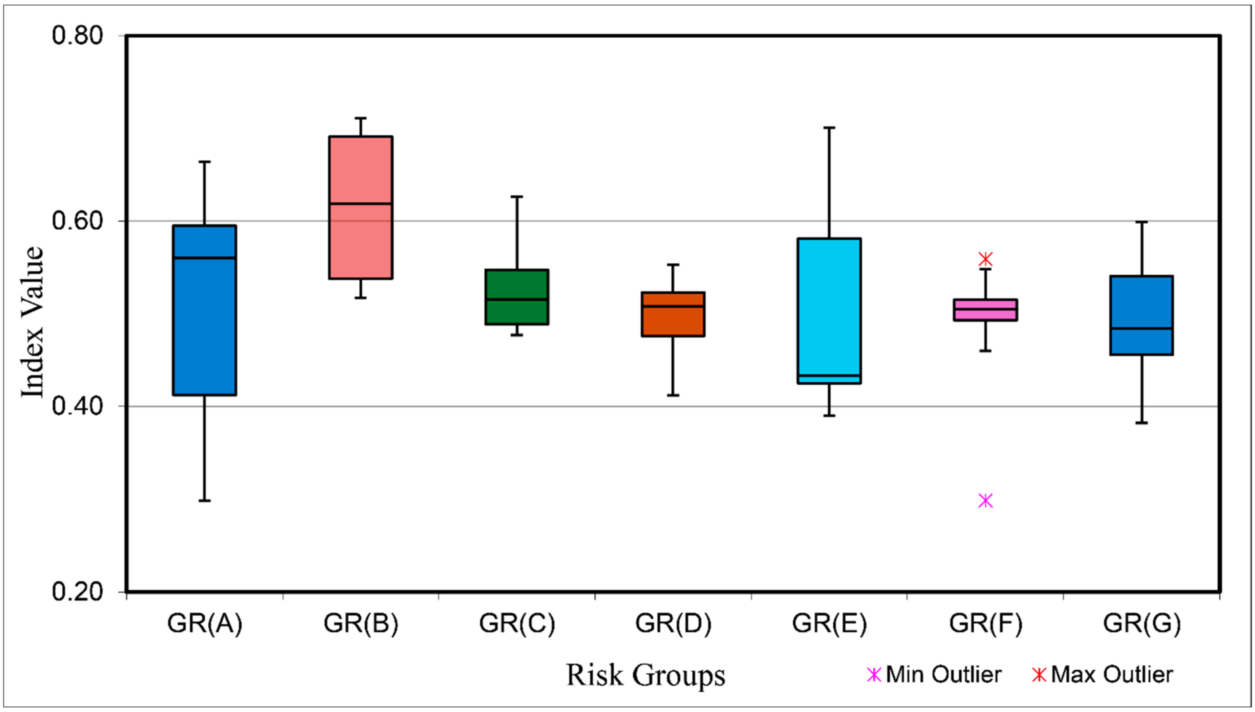

Figure 8. Pas risk groups comparison based on effectiveness goal.

5.3.3. Analysis of Risk Groups Based on Ecological Balance

Figure 9 and Table 7 display the relation between FIEB and the seven risk groups. The widest distribution spaces are for the groups RG(B) (monitoring system) and RG(G) (activities conducted within the Pas), with very close values. While group RG(C) has the narrowest distribution spaces.

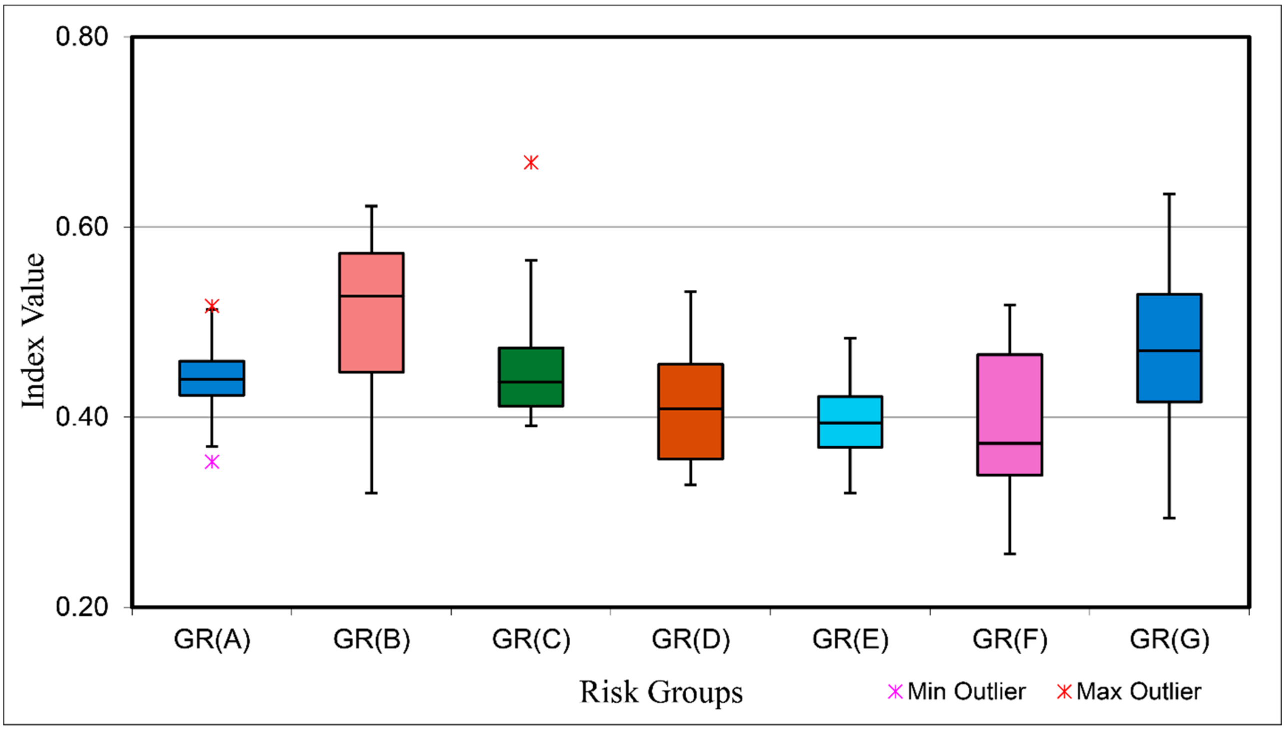

Figure 9. Pas risk groups comparison based on ecological balance goal.

Table 7. Cumulative group index and average FIEB for Pas risk groups in case of ecological balance.

	RG(A)	RG(B)	RG(C)	RG(D)	RG(E)	RG(F)	RG(G)
Cumulative group index	3.945	3.005	3.925	2.893	2.777	3.127	3.289
Average of FIEB	0.438	0.501	0.393	0.413	0.397	0.391	0.470

5.3.4. Analysis of Risk Groups Based on Fuzzy Risk Analysis

Regarding Figure 10, a detailed analysis for each risk group is conducted to compare the fuzzy risk indices. Figure 10a compares various fuzzy risk indices related to RG(A). This group considers nine different factors related to general and fundamental preparation risks. The ecological balance index has the smallest distribution space with two outliers and no high values, and the values are close. On the other hand, the distribution range for sustainability and effectiveness is close with no outliers. Figure 10b presents a comparison among the model outputs related to risk group RG(B) which are related to monitoring system risk factors. This group contains the first two risk factors in ranking in sustainability and effectiveness, (RPA(B)_01″ Absence of mechanisms for early warning of disasters affecting protected areas", and RPA(B)_02 "Lack of a system for monitoring the occurrence, development, and spread of disasters." This group considers the least risk factors number (6 factors only). The ecological fuzzy risk index has lower risk values than sustainability and effectiveness.

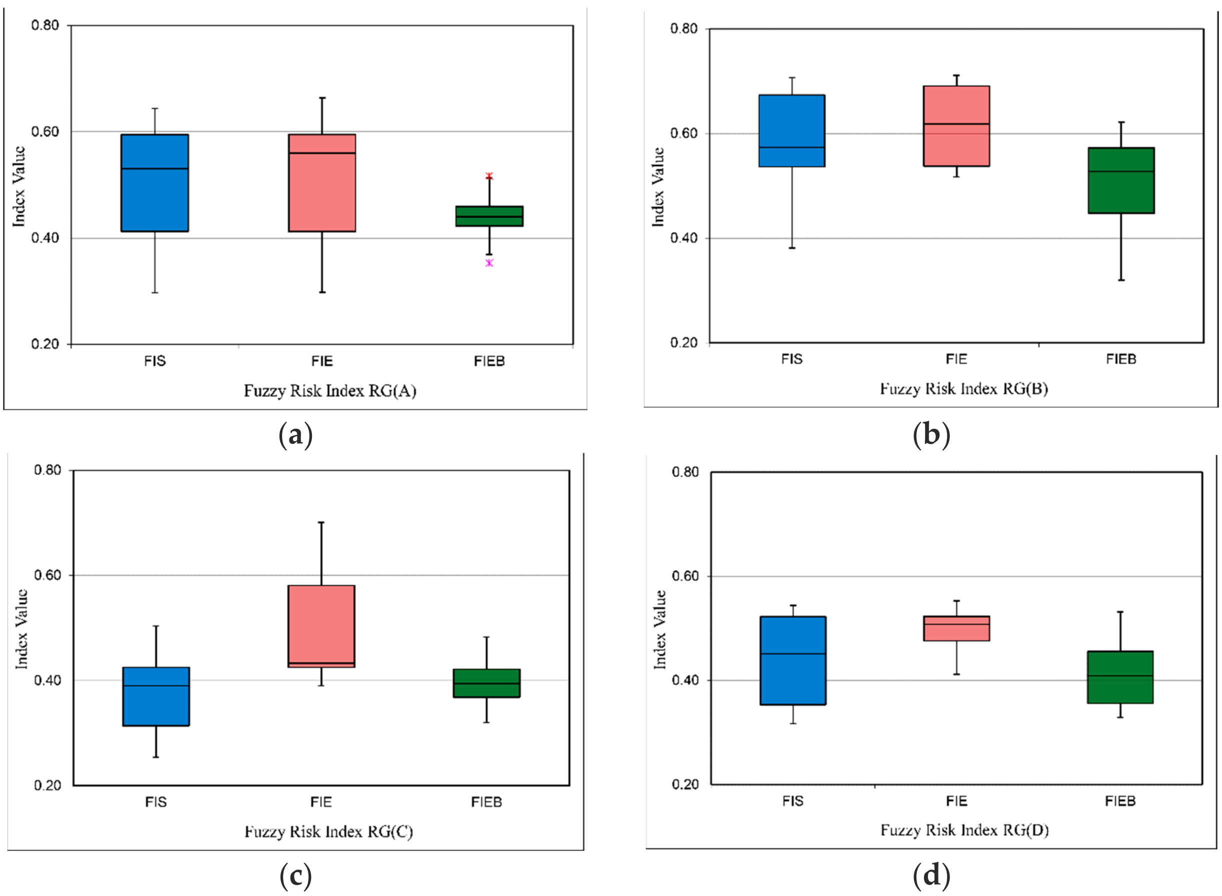

Figure 10. *Cont.*

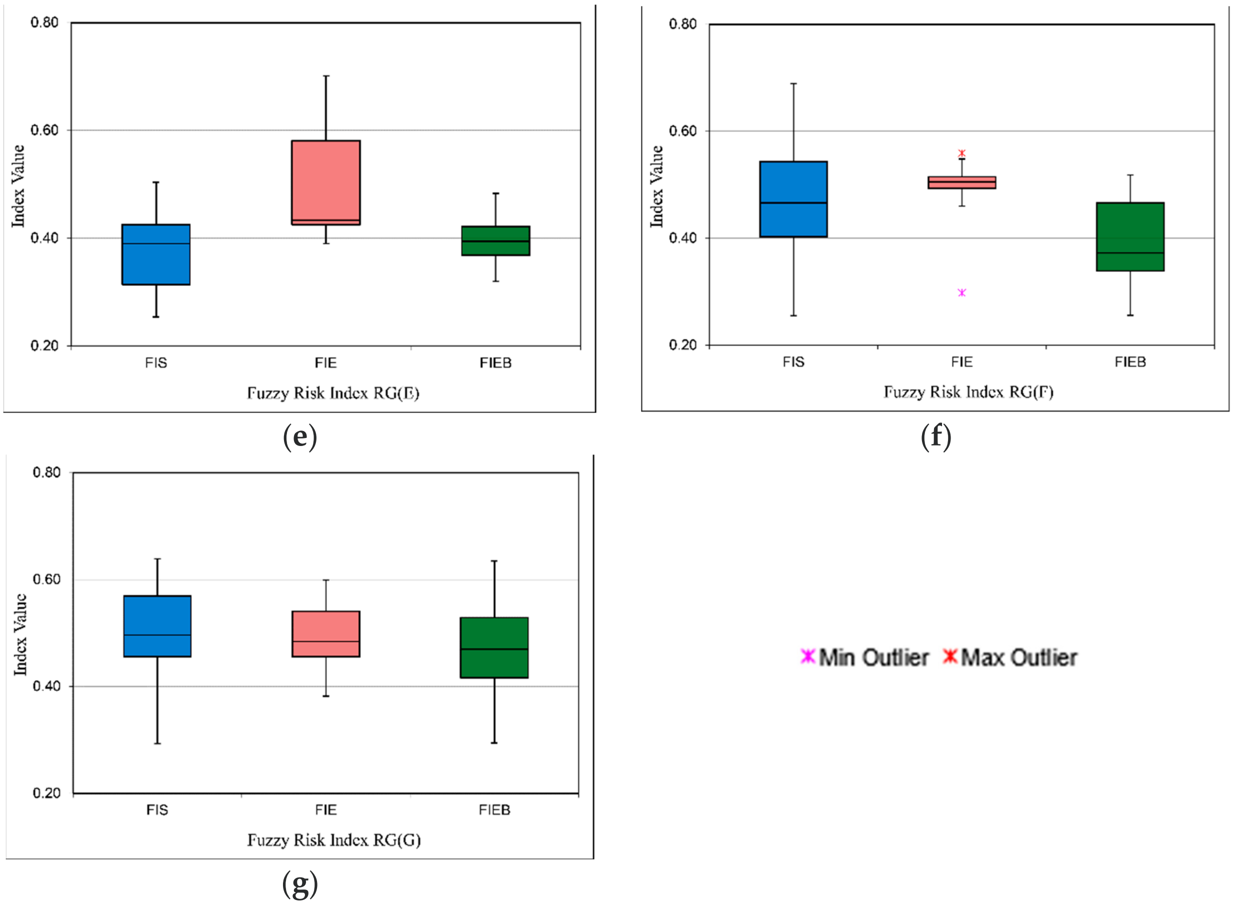

Figure 10. Fuzzy risk indices Comparison for all risk groups; (**a**) for group RG(A), (**b**) for group RG(B), (**c**) for group RG(C), (**d**) for group RG(D), (**e**) for group RG(E), (**f**) for group RG(F), and (**g**) for group RG(G).

Figure 10c shows a comparison among fuzzy risk indices related to risk group RG(C) which are related to protocols and implementation plans risk factors. It is clear that RPA(C)_10 "Absence of plans to combat invasive strange species that may have harmful effects on wildlife in protected areas", is located as an outlier in the case of sustainability and ecological balance. Its order is 6 in sustainability and 1 in ecological balance while its order is 7 in effectiveness. Most of the risk factors in ecological balance are with low values, unlike the effectiveness which the values are high. Without taking into account the outliers, the higher range is for sustainability. Seven risk factors are related to training in this risk group. It is noted that from Figure 10d, the highest range is for sustainability followed by ecological balance. The three fuzzy risk indices have adjacent higher limits and diverse lower limit values.

Figure 10e compares fuzzy risk indices related to RG(E) (visitors) which considers seven different risk factors. The effectiveness fuzzy risk index has the longest distribution space, peak upper, and higher lower limit values. Sustainability and ecological balance indices come after that in descendent rank. No outliers, in all indices. Figure 10f declares a comparison among different fuzzy risk indices associated with RG(F) which is related to Employees and contains 8 risk factors. It is clear that the higher the range is for sustainability, and the lower is for effectiveness, regardless of outliers. In the effectiveness, it is noted that the lowest point for factor RPA(F)_03 (Non-compliance with designated patrol routes) is far from the box limits with a smaller value. A comparison between various fuzzy risk indices associated with RG(G) is indicated in Figure 10g. The group considers seven different risk factors related to activities conducted within the PAs. It is noted that the lowest range is for effectiveness, while the ranges are close and higher for sustainability and ecological balance.

5.4. Significant Risk Factors Affecting PAs Management

Table 8 exemplifies the highest ten significant risk factors according to fuzzy risk indices influencing PAs management. Amongst fifty-four risk factors, eighteen factors formed the top ten registers for all indices. Four factors are repeated with the three fuzzy risk indices; they are RPA(B)_01, RPA(B)_02, RPA(G)_03, and RPA(C)_10. RPA(B)_01 (Absence of mechanisms for early warning of disasters affecting protected areas), and RPA(B)_02 (Lack of a system for monitoring the occurrence, development, and spread of disasters.) are ranked first and second in sustainability and effectiveness while they have relatively low ranks in ecological balance. Those two factors belong to RG(B) which is related to the monitoring system. The group that included the most repetitions of several factors at the top is RG(B) with several 9 factors followed by RG(A) with 7 factors, while the group with the least is RG(D) and included one factor.

Table 8. Highest ten significant risk factors influencing PAs management.

Rank	Sustainability			Effectiveness			Ecological Balance		
	Factor No.	FIS	Risk Group	Factor No.	FIE	Risk Group	Factor No.	FIEB	Risk Group
1	RPA(B)_01	0.707	B	RPA(B)_01	0.711	B	RPA(C)_10	0.668	C
2	RPA(B)_02	0.703	B	RPA(B)_02	0.702	B	RPA(G)_03	0.635	B
3	RPA(F)_06	0.689	F	RPA(E)_07	0.701	E	RPA(B)_02	0.622	G
4	RPA(A)_02	0.644	A	RPA(A)_08	0.664	A	RPA(B)_03	0.583	B
5	RPA(G)_03	0.639	G	RPA(B)_03	0.658	B	RPA(G)_01	0.578	D
6	RPA(C)_10	0.632	C	RPA(A)_01	0.629	A	RPA(B)_01	0.54	F
7	RPA(A)_01	0.627	A	RPA(C)_10	0.626	C	RPA(D)_04	0.532	A
8	RPA(G)_01	0.626	G	RPA(E)_02	0.626	E	RPA(F)_08	0.518	B
9	RPA(A)_04	0.595	A	RPA(D)_05	0.599	G	RPA(A)_06	0.517	A
10	RPA(C)_01	0.594	C	RPA(A)_04	0.595	A	RPA(B)_06	0.515	B

6. Discussion

This study developed and applied a fuzzy logic-based risk model to assess the risks faced by PAs management in Saudi Arabia. Through a structured qualitative risk analysis, the model identifies significant risks that threaten PAs goals (sustainability, effectiveness, and ecological balance). The effectiveness was interpreted as the capacity to achieve intended outcomes, not as an independent goal equivalent to sustainability or ecological balance. The findings provide valuable insights into the needs of Saudi Arabia's PAs management system, considering both national and global contexts.

The study identified monitoring systems, Protocols, and implementation plans as the most critical risk groups affecting the goals of protected areas, particularly in terms of sustainability and effectiveness. Key factors such as the " Absence of mechanisms for early warning of disasters affecting protected areas " and the " Lack of a system for monitoring the occurrence, development, and spread of disasters " were ranked as top priorities. These findings align with Saudi Arabia's arid climate and vulnerability to natural hazards (e.g., flash floods, and extreme temperatures), where robust monitoring systems are essential for disaster preparedness. Additionally, the absence of a national framework for managing invasive species emerged as another significant risk factor, ranking as a primary concern for ecological balance. Globally, managing invasive species is a critical component of PAs effectiveness, as highlighted by the IUCN guidelines [1]. This gap in Saudi Arabia's PAs system suggests an area for improvement, which could greatly benefit from adaptation strategies based on successful global practices, such as coordinated regional efforts for invasive species monitoring and control.

In evaluating the effectiveness of PAs in Saudi Arabia, this study highlights several factors that align partially with, but also diverge from, global best practices. The IUCN's PAME framework, widely adopted internationally, emphasizes the necessity of co-management systems and continuous monitoring, particularly concerning risks related to natural and human threats [25]. Similarly, the IPBES report on values and valuations of nature emphasizes the importance of community-led management models, such as co-management, which integrate local knowledge and enhance conservation effectiveness through increased community engagement [33]. This study demonstrates that Saudi Arabia's current PAs strategies prioritize risk mitigation and centralized management over community-based co-management models. This difference reflects Saudi Arabia's unique PAs governance structure, where management is primarily state-led, focusing on centralized monitoring and response frameworks rather than local participation.

7. Limitations and Future Research

The use of brainstorming sessions with experts as the primary knowledge-elicitation method in this study due to the absence of data related to PAs in Saudi Arabia served to capture high-level risk insights, yet it also presents limitations. Brainstorming, generally more suited for generating ideas rather than capturing established expert knowledge, may not have been the ideal choice for a formal risk assessment framework. Moreover, while fuzzy logic modeling provides flexibility in handling incomplete data and assessing risk levels, it does introduce some subjectivity. The inherent dependency on expert-provided weights and inputs could affect replicability, particularly when applied to PAs in different geographic or ecological settings.

Future research should incorporate longitudinal data for performing a quantitative analysis of the effectiveness of Saudi Arabia's current PAs that align with international standards, focusing on three outcome-oriented dimensions: ecological outcomes, social outcomes, and social-ecological interactions, and Integrating data from satellite monitoring and climate projections to yield a more comprehensive understanding of how Saudi Arabia's PAs respond to long-term environmental pressures, thereby guiding adaptive management strategies. Additionally, it is recommended to develop the proposed model for quantifying risks and to cover risk management processes for supporting a multi-criteria decision analysis related to PAs management.

8. Conclusions

Protected areas management is considered an important issue for success and achieving the goals of these areas. On the other hand, there are various risks affecting the management of PAs goals, such as sustainability, effectiveness, and ecological balance. In this work, field surveys are directed to explore the risks associated with PAs management and affect the sustainability, effectiveness, and ecological balance. A model for analyzing these risks based on a fuzzy logic technique is developed and applied to evaluate the severity of these risks. Fifty-four risk factors are categorized under seven risk groups, including General and fundamental preparations, monitoring systems, Protocols and implementation plans, Training, Visitors, Employees, and Activities conducted within the PAs. Four indices are determined and used as the model inputs, while three fuzzy risk indices, relating to the model inputs, are determined as model outputs. The model is verified using data collected from PAs in Saudi Arabia as a case study. Several conclusions are briefed in the next points:

1. The risk factor RPA(B)_02 (Lack of a system for monitoring the occurrence, development, and spread of disasters) is rated as the most repeated factor; as well as it has an important effect on the three goals. On the other hand, RPA(B)_01 (Absence of mechanisms for early warning of disasters affecting protected areas) has the biggest influence on sustainability and effectiveness while RPA(C)_10 (Absence of plans to combat invasive strange species that may have harmful effects on wildlife in protected areas) has the biggest influence on the ecological balance.
2. Four factors are repeated with the three indices RPA(B)_01, RPA(B)_02, RPA(G)_03 and RPA(C)_10. RPA(B)_01 (Absence of mechanisms for early warning of disasters affecting protected areas), and RPA(B)_02 (Lack of a system for monitoring the

occurrence, development, and spread of disasters.) are ranked first and second in sustainability and effectiveness while they have relatively low ranks in ecological balance. Those two factors belong to RG(B) which is related to the monitoring system. The group that included the most repetitions of several factors at the top is RG(B) with several 9 factors followed by RG(A) with 7 factors, while the group with the least is RG(D) and included one factor.

3. Risk indices' correlations declared that the relationship between presence rate and both effectiveness and ecological balance is an adverse relation, while the relationship is slightly direct with sustainability. Regarding model outputs, all correlations are positive, and the highest correlation is between sustainability and ecological balance.

Regarding risk activity groups, RG(C) which is related to Protocols and implementation plans risk factors, is the most substantial group due to its high effects on the three goals, in addition to it contains the largest number of factors followed by RG(A). Although RG(B) which is related to monitoring system risk factors, contains the least risk factors number (6 factors only), it contains the first two highest risk factors in ranking according to sustainability and effectiveness, (RPA(B)_01 and RPA(B)_02).

This study has several important theoretical and practical implications for the field of PAs management. Theoretically, the fuzzy logic model developed in this study can be adapted and applied to other PAs systems worldwide, especially those facing similar challenges and limited monitoring resources, or complex governance structures. Also, the research provides a foundation for future studies exploring the integration of fuzzy logic with other risk assessment frameworks, such as multi-criteria decision analysis, to enhance the reliability and applicability of risk management models. From a practical point of view, it is a guide for Saudi Arabia's PAs management to identify the critical risk factors and support proactive management practices, reducing the likelihood of adverse outcomes and enhancing the overall effectiveness of conservation efforts. Furthermore, Policymakers can leverage the model presented in this research to guide investments in PAs infrastructure, such as disaster response mechanisms and ecological monitoring technologies.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

PAs	Protected Areas
PRI	presence rate index
SI	Sustainability Index
FIS	Fuzzy index for Sustainability
EI	Effectiveness index
FIE	Fuzzy Index for Effectiveness
EBI	Ecological balance index
FIEB	Fuzzy index for Ecological balance

Appendix A

Table A1. Risk factors affecting PAs management.

Risk Code	Model Input				Model Results			Ranking due to		
	PRI	SI	EI	EBI	FIS	FIE	FIEB	Sustainability	Effectiveness	Ecological Balance
RPA(A)_01	0.620	0.723	0.727	0.455	0.627	0.629	0.441	7	6	23
RPA(A)_02	0.670	0.652	0.432	0.423	0.644	0.459	0.459	4	43	21
RPA(A)_03	0.415	0.421	0.537	0.655	0.412	0.412	0.44	36	48	25
RPA(A)_04	0.815	0.436	0.492	0.221	0.595	0.595	0.423	9	10	30
RPA(A)_05	0.543	0.489	0.592	0.345	0.484	0.560	0.353	25	15	46
RPA(A)_06	0.682	0.524	0.561	0.512	0.531	0.568	0.517	17	14	9
RPA(A)_07	0.390	0.583	0.578	0.389	0.392	0.392	0.391	40	50	40
RPA(A)_08	0.632	0.534	0.779	0.315	0.546	0.664	0.426	14	4	28
RPA(A)_09	0.295	0.427	0.469	0.719	0.297	0.298	0.495	50	53	11
RPA(B)_01	0.731	0.695	0.698	0.512	0.707	0.711	0.54	1	1	6
RPA(B)_02	0.842	0.635	0.612	0.476	0.703	0.702	0.622	2	2	3
RPA(B)_03	0.805	0.465	0.608	0.365	0.586	0.658	0.583	11	5	4
RPA(B)_04	0.783	0.347	0.512	0.209	0.561	0.579	0.425	12	12	29
RPA(B)_05	0.512	0.376	0.519	0.216	0.381	0.517	0.32	45	25	51
RPA(B)_06	0.518	0.618	0.677	0.511	0.528	0.524	0.515	18	22	10
RPA(C)_01	0.676	0.593	0.512	0.355	0.594	0.517	0.467	10	26	19
RPA(C)_02	0.589	0.321	0.486	0.226	0.391	0.477	0.391	41	41	39
RPA(C)_03	0.579	0.478	0.689	0.468	0.467	0.583	0.455	29	11	22
RPA(C)_04	0.421	0.436	0.713	0.538	0.417	0.514	0.417	35	27	32
RPA(C)_05	0.456	0.656	0.708	0.682	0.448	0.508	0.475	32	29	17
RPA(C)_06	0.487	0.679	0.552	0.693	0.482	0.481	0.49	26	38	12
RPA(C)_07	0.536	0.413	0.616	0.401	0.410	0.551	0.401	37	18	36
RPA(C)_08	0.487	0.387	0.686	0.412	0.390	0.482	0.41	42	37	33
RPA(C)_09	0.528	0.493	0.673	0.423	0.490	0.536	0.419	24	19	31
RPA(C)_10	0.728	0.623	0.615	0.663	0.632	0.626	0.668	6	7	1
RPA(D)_01	0.312	0.469	0.765	0.353	0.317	0.518	0.329	49	23	49
RPA(D)_02	0.326	0.493	0.708	0.369	0.333	0.508	0.337	48	30	48
RPA(D)_03	0.368	0.429	0.762	0.374	0.374	0.553	0.375	46	17	42
RPA(D)_04	0.521	0.723	0.689	0.706	0.544	0.528	0.532	15	21	7
RPA(D)_05	0.687	0.512	0.489	0.486	0.517	0.485	0.482	20	35	14
RPA(D)_06	0.435	0.729	0.677	0.503	0.528	0.467	0.429	19	42	27
RPA(D)_07	0.552	0.461	0.415	0.411	0.451	0.412	0.409	31	49	34
RPA(E)_01	0.387	0.213	0.389	0.363	0.254	0.390	0.375	54	51	43
RPA(E)_02	0.652	0.289	0.632	0.429	0.444	0.626	0.441	33	8	24
RPA(E)_03	0.524	0.387	0.577	0.403	0.390	0.536	0.402	43	20	35
RPA(E)_04	0.421	0.363	0.645	0.393	0.373	0.433	0.394	47	44	38
RPA(E)_05	0.215	0.417	0.721	0.512	0.255	0.430	0.32	52	46	52
RPA(E)_06	0.487	0.407	0.425	0.354	0.406	0.420	0.362	39	47	44
RPA(E)_07	0.689	0.503	0.736	0.358	0.504	0.701	0.483	22	3	13
RPA(F)_01	0.469	0.531	0.715	0.492	0.461	0.514	0.461	30	28	20
RPA(F)_02	0.315	0.609	0.705	0.517	0.407	0.505	0.323	38	31	50
RPA(F)_03	0.216	0.412	0.498	0.266	0.255	0.298	0.256	53	54	54
RPA(F)_04	0.551	0.387	0.677	0.318	0.390	0.559	0.359	44	16	45
RPA(F)_05	0.456	0.749	0.698	0.382	0.542	0.497	0.386	16	34	41
RPA(F)_06	0.687	0.716	0.449	0.429	0.689	0.481	0.48	3	39	15
RPA(F)_07	0.478	0.509	0.705	0.336	0.471	0.505	0.344	28	32	47
RPA(F)_08	0.479	0.756	0.719	0.719	0.547	0.518	0.518	13	24	8
RPA(G)_01	0.567	0.783	0.621	0.588	0.626	0.576	0.578	8	13	5
RPA(G)_02	0.478	0.697	0.689	0.654	0.496	0.484	0.47	23	36	18

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