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Holistic Environmental Risk Index for Oil and Gas Industry in Colombia

Miguel A. De Luque-Villa [1,*], Daniel Armando Robledo-Buitrago [2] and Claudia Patricia Gómez-Rendón [1]

[1] Maestría en gestión del riesgo y desarrollo, Escuela de Ingenieros Militares, Carrera 54 # 26 – 25, Bogotá D.C., Colombia; claudia.gomez@esing.edu.co

[2] Universidad de Cundinamarca, Facultad de Ciencias agropecuarias- ingeniería ambiental, grupo de investigación Cundinamarca Agroambiental; Facatativá, Colombia; drobledo@ucundinamarca.edu.co

* Correspondence: miguel.luque@esing.edu.co

Abstract: Risk management for technological hazards mainly focuses on the consequences on human lives. Although technological risk analysis evaluates environmental vulnerability, it does not reflect the consequences on environmentally exposed elements, such as rivers, water springs, flora, and fauna. This paper's objective was to propose a conceptual framework and create a multidisciplinary evaluation model for environmental risk analysis in the oil and gas industry. Initially, the problem was approached from a global perspective to justify the necessity of a holistic environmental risk analysis methodology in the oil industry, using environmental risk factors as well as underlying factors, such as environmental fragility and lack of resilience. The holistic assessment was carried out based on probabilistic risk analysis methodologies to obtain a holistic environmental risk index, HERI. This methodology was applied to an oil and gas industry company in Colombia. This allowed greater disaggregation of the results to establish priorities for risk reduction actions and identify the company's weaknesses.

Keywords: environmental risk index; holistic approach; environmental fragility; aggravating factors; oil and gas industry

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1. Introduction

Environmental risk is the quantitative or qualitative evaluation of the danger of an adverse impact on the environment—which refers to the probability of the occurrence of an unfavorable situation that may lead to the destruction of ecosystems, alongside the disappearance or gradual deterioration of biodiverse populations, loss of quality of life and natural resources, and an impact on energy—due to the economic activity in a certain area [1]. Anthropogenic activities have caused the overexploitation of natural resources, resulting in biodiversity loss in ecosystems worldwide [2]. Another significant environmental concern affecting these ecosystems is accidental or chronic oil pollution [3]. In 2010, the largest oil spill in United States history that occurred on the coast of the Gulf of Mexico caused one of the most significant environmental disasters in history [4]. In 2018, the Lizama 158 well located in the municipality of Barrancabermeja, Santander, Colombia, presented an oil outcrop, which caused, according to official figures, the deaths of 2,442 animals and affected 5,507 trees [5]. In Colombia, the operational risk in the hydrocarbon transportation phase is mainly due to repetitive actions carried out by third parties, such as external fraud, fortuitous events, and terrorist acts, which can lead to the collapse of sensitive ecosystems [6–8].

The concept of risk pertains to something uncertain, tied to random chance and potentiality, regarding events that have not yet occurred. It is abstract, complex, and can only exist in the future. Recent efforts to assess disaster risk for management purposes have revolved around calculating the potential economic, social, and environmental impacts of a physical event at a specific location and time. However, there has been a lack of comprehensive conceptualization of risk; instead, fragmentation has prevailed as different disciplinary approaches estimate or calculate risk separately. Achieving an interdisciplinary estimation of risk requires consideration not just of projected physical damage and casualties or economic losses but also of social dynamics along with organizational and institutional aspects [9].

A global bibliographic review was conducted followed by a specific focus on Colombia to assess the ecological impact of technological events in the oil and gas industry on the environment. The initial findings reveal that environmental disasters resulting from hydrocarbon project activities, particularly oil spills, have had significant negative effects on marine ecosystems [10–15], including on corals, benthic organisms, fish, mollusks, birds, plankton, mangroves, marine mammals, and reptiles. The consequences range from obstructing the sunlight necessary for photosynthesis to contaminating the food chain and reducing biodiversity [16–21]. For Colombia, only a spill that occurred in Cabo Manglares in the department of Nariño in 1976 [22] was found, where the sinking of the Tanker St. Peter caused an oil leak, impacting the fishing industry and mangroves in the Tumaco municipality. While ocean spills have catastrophic effects, they rarely occur, especially in Colombia. However, from 1980 to 2020, over 2,800 terrorist attacks on oil infrastructures led to more than 3.7 million barrels of hydrocarbons spilling into the environment. This has impacted the soil quality and various ecosystems, including surface waters, flora, fauna (including birds, mammals, and reptiles), amphibians, and fish [8]. Therefore, terrorist attacks are the major hazard for oil spills in Colombia [8,23,24].

Vulnerability can be defined as an internal risk factor of a subject or system exposed to a hazard, corresponding to its intrinsic predisposition to be affected or susceptible to suffering damage [9]. Ecological vulnerability in this study refers to the predisposition or susceptibility of the environment to be affected or suffer damage in case of an oil spill. The susceptibility of ecosystems, flora, and fauna to be affected initially depends on the volume and characteristics of the oil. However, ecosystems at risk may vary in their levels of vulnerability because oil sensitivity is inherent to the environment, which may be less or more sensitive depending on its characteristics [25–28]. Ecological vulnerability is a term used to describe how easily a specific system can change due to internal or external disturbances, reflecting its sensitivity and lack of adaptation capacity. Researchers believe that vulnerability consists of three elements: exposure, sensitivity, and adaptive capacity. Exposure measures a system's susceptibility to environmental and social stresses. The value of vulnerability determines the potential degree of system damage under the influence of accidents, while sensitivity reflects the unit's response to stressors [29–36].

A holistic approach to risk assessment encompasses risk from a complete viewpoint. This involves considering the potential ecological damage directly related to hazard events, as well as understanding how non-hazard-dependent factors, such as social, economic, and environmental elements, exacerbate existing ecological risk conditions in terms of anticipatory capacity, resistance, response, and recovery capabilities [37]. Based on the holistic approach for the case of urban seismic risk evaluation and evaluating risk from a holistic perspective to improve resilience at a global level [37–39], we define environmental risk as the interaction between hazard, exposure, and vulnerability, where hazard typically pertains to ecological impacts resulting from oil spill events. Exposure indicates the susceptibility of the flora, fauna, and ecosystems to be damaged (ecological vulnerability directly associated with oil spill events), along with underlying non-oil-spill-dependent factors that exacerbate existing risk conditions due to a lack of capacity to anticipate, resist, respond to, or recover from adverse impacts and environmental fragility (Figure 1). The main objective of this paper was to develop a holistic methodology to evaluate the environmental risk associated with projects in Colombia's hydrocarbon sector.

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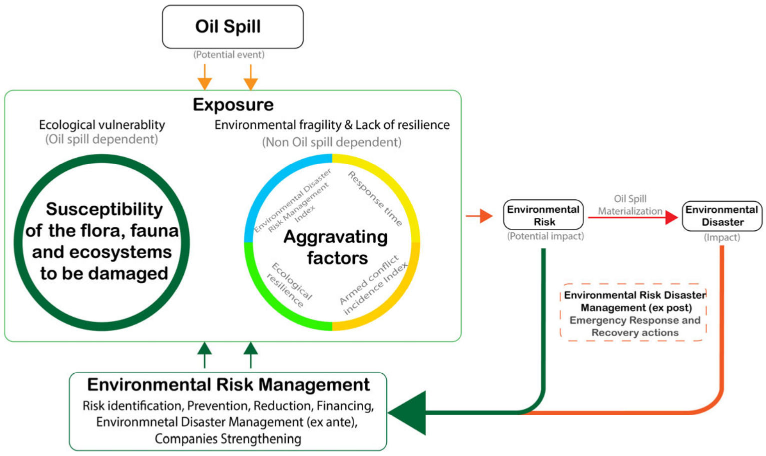

Figure 1. Conceptual framework of the holistic approach to environmental disaster risk. Adapted from Cardona and Barbat [38], Carreño et al. [39], and Marulanda-Fraume et al. [37].

2. Materials and Methods

2.1. Holistic Environmental Risk Index

The holistic environmental risk index definition was based on the holistic risk evaluation methodology proposed by Cardona [38], Carreño et al. [39], and Marulanda Fraume et al. [37] and is calculated using the following equation:

$$HER_I = E_R(1 + F) \tag{1}$$

This expression, referred to as Moncho's Equation in the literature, is formulated by combining an ecological risk index denoted as E_R and an aggravating coefficient called F. Both are constructed using composite indicators [37,39]. This coefficient, F, depends on the weighted sum of a set of aggravating factors related to environmental fragility and lack of resilience.

To adapt the methodology, for the E_R variable, we designed probabilistic risk measures for indicators such as the affected area, affected fauna, affected land cover, and ecological impact. For variable F, we considered the environmental fragility of the study area and the lack of resilience of the company responsible for operations. According to a holistic approach, these conditions can magnify ecological damage to the environment. Indicators including ecological resilience, the armed conflict index, the time response, and an environmental disaster risk management index adapted from Carreño and Cardona were also considered in this process [40–42]. Figure 2 illustrates the structure of the indicators utilized to evaluate the holistic environmental risk index. According to Equation 1, it is assumed that the total risk's maximum value can be twice that of the ecological risk. This suggests that as the indices of aggravating factors decrease, so too does the environmental impact; conversely, a higher index signifies a greater impact on the environment.

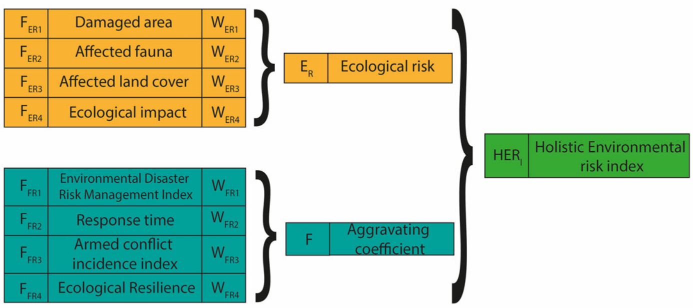

Figure 2. Structure of indicators used for the holistic environmental risk evaluation.

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Expressing the E_R and F index results as a linear combination of relative indicators may overlook potential interactions and variations in weighting. While this simplification may be acceptable due to data uncertainties, adopting non-linear functions for risk indices could be more suitable and enable better comparisons. This approach requires defining specific function forms with expert support based on past disaster information [43]. Sigmoidal functions are commonly used to determine the physical vulnerability factors in risk assessment. These functions solve the problem of descriptor unit incommensurability and establish a unified normative scheme for risk assessment [37,39,43,44]. Expert opinions and information on previous oil spills were considered when determining the limit values that correspond to the maximum or minimum factor values (1 or 0) at the bottom of each curve. The x-axis represents descriptor values, while the y-axis represents respective risk or aggravation factor values.

2.1.1. Ecological Risk

The ecological risk index E_R was calculated following Equation (2), where m is the total number of descriptors, F_{ERi} are the component factors, and W_{ERi} are their weights.

$$E_R = \sum_{i=1}^{m} F_{ERi} \times W_{ERi} \tag{2}$$

The descriptors used included the damaged area, represented as the oil spill volume. This information was computed considering potential risk situations, according to the guide for consequence analysis and quantitative risk analysis [45]. According to the reviewed bibliography, the maximum point of risk is when a spill is greater than 2000 bbl. The second descriptor was the affected fauna, which corresponds to the probable number of dead animals. The maximum risk point was set when the number of deaths was equal to or greater than 100. The third descriptor was the land cover affected. The spilling of oil into the environment affects the land cover; therefore, it is defined as the area in ha of affected land cover. The maximum risk point was set when the area affected was equal to or greater than 100 ha [46]. The last descriptor was the ecological impact. In Colombia, projects in the hydrocarbon sector require an environmental license based on an environmental impact assessment. This assessment evaluates the environmental sensitivity of the ecosystems that could be impacted by the activity. The risk level is determined by the environmental management zoning specified in the environmental license: a sensitivity rating of 1 indicates minimum risk (intervention areas), while a rating of 5 corresponds to maximum risk (exclusion areas). Finally, transformation functions for ecological risk were developed using sigmoidal functions for all cases (Figure 3).

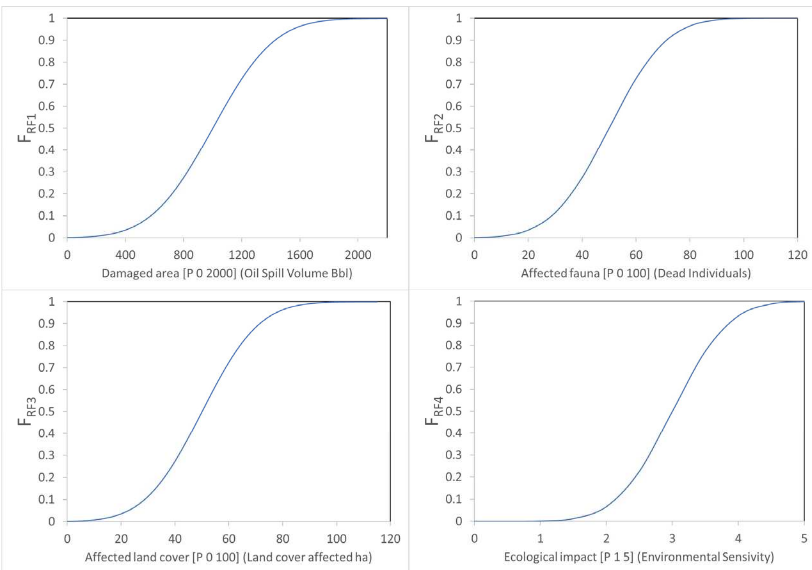

Figure 3. Transformation functions used to standardize the ecological risk factors.

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An analytic hierarchy process [39,43,47–52] was conducted to calculate the weight for each of the descriptors. Expert opinions were considered using the Delphi method [53–58].

Table 1. Weights of the ecological risk factors.

Factor	Weight	Weight Value
F_{ER1}—damaged area	W_{ER1}	0.41
F_{ER2}—affected fauna	W_{ER2}	0.13
F_{ER3}—affected land cover	W_{ER3}	0.14
F_{ER4}—ecological impact	W_{ER4}	0.32

2.1.2. Aggravating Coefficients

The aggravating coefficient F was calculated following Equation (2), where n is the total number of descriptors, F_{FRi} are the aggravating factors, and W_{FRi} are their weights.

$$F = \sum_{i=1}^{n} F_{FRi} \times W_{FRi} \quad (3)$$

Weaknesses in hazard identification and monitoring and a lack of efficient risk reduction measures and disaster risk management in oil spills significantly increase the environmental impacts [59–62]. In this case, 4 descriptors were used to evaluate the lack of resilience of companies and the fragility and resilience of the environment when an oil spill occurs.

The first descriptor was the environmental disaster risk management index. Carreño et al. [40,41] designed a disaster risk management index to evaluate the performance and effectiveness of a country's disaster risk management considering the measure of resilience. The index was adapted for our case, which will be explained in detail. The second descriptor was the response time. It has been proven that a quick response reduces the environmental impact of an oil spill [63,64]. In our case, the response time refers to the number of hours it takes the company to reach the site and stabilize the oil spill. Per the bibliographic review, the maximum point of risk is when the response time is equal to or greater than 250 hours, and the minimum point of risk is when the response time is equal to or lower than 50 hours. The National Planning Department of Colombia designed and calculated the armed conflict incidence index (IICA) to identify Colombian municipalities impacted by conflict [65]. This index measures eight variables: armed actions, homicide, kidnapping, antipersonnel mines, forced displacement, coca crops, homicide of leaders and human rights defenders, and homicides against ex-combatants. The index defines five categories: low, moderate low, moderate, high, and very high. Therefore, the maximum risk point is an IICA of 5, while the minimum risk point is an IICA of 1. The last indicator is ecological resilience. In this study, ecological resilience was defined as the return time to a stable state following a perturbation. Expert opinions were considered to define the risk values, where the maximum risk point was 15 years and the minimum risk point was 1 year. Transformation functions were used for the 4 descriptors. The weights of the aggravating coefficients were calculated with the same methodology used for the ecological risk (Table 2).

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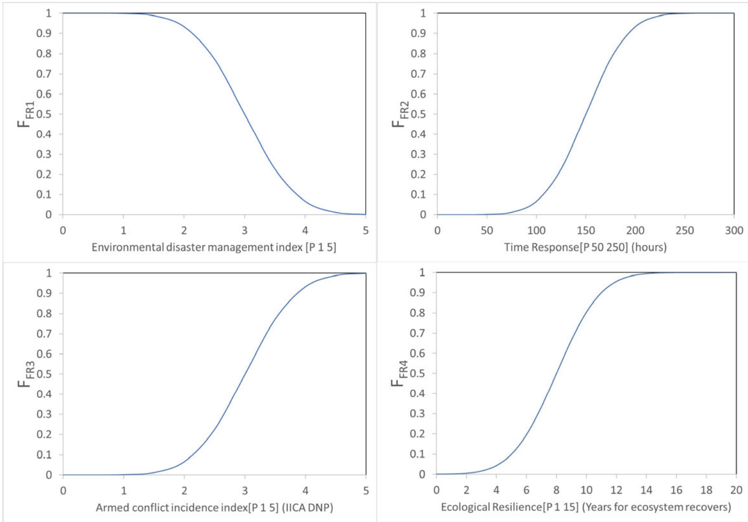

Figure 4. Transformation functions used to standardize the aggravating coefficients.

Table 2. Weights of the aggravating coefficients.

Factor	Weight	Weight Value
F_{FR1}—environmental disaster risk management index	W_{ER1}	0.42
F_{FR2}—response time	W_{ER2}	0.10
F_{FR3}—armed conflict incidence index	W_{ER3}	0.26
F_{FR4}—ecological resilience	W_{ER4}	0.22

2.1.3. Environmental Disaster Risk Management Index

The environmental disaster risk management index was built considering Decree 2157, which adopts general guidelines for preparing a disaster risk management plan for public and private entities [66]. After analyzing the standards, the four main pillars of disaster risk management were determined to be risk identification, risk reduction, disaster management, and financial protection. Based on this, an index composed of 4 indicators was adapted from the study by Carreño et al. [40,41].

$$EDRM_i = \frac{RMI_{RI} + RMI_{RR} + RMI_{DM} + RMI_{FP}}{4} \quad (4)$$

Figure 5 shows the descriptors used for each indicator, which were defined considering the expert opinions. These indicators were evaluated based on five performance levels that correspond to a range from 1 (low performance) to 5 (very high performance). The weights for each indicator were calculated with the same methodology used for the ecological risk (Table 3).

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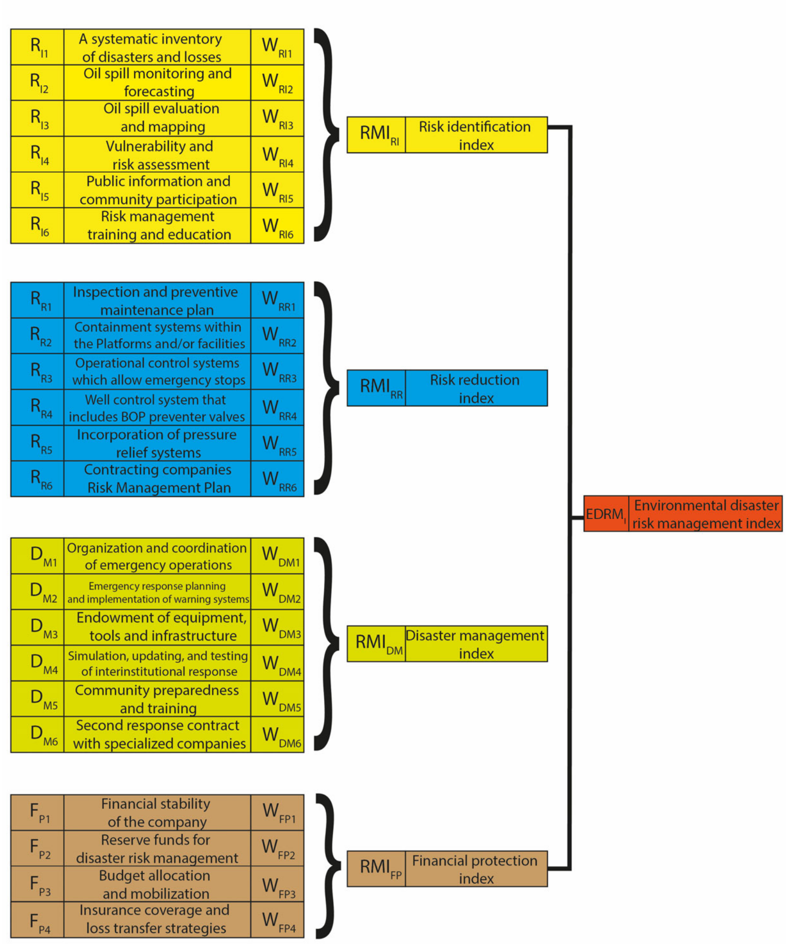

Figure 5. Structure of indicators used for the environmental disaster risk management index. Adapted from the study by Carreño et al. [40,41].

Table 3. Weights of the environmental disaster risk management index factors.

Index	Factor	Weight	Weight Value
RM_I—risk identification index	R_{I1}—systematic inventory of disasters and losses	W_{RI1}	0.09
	R_{I2}—oil spill monitoring and forecasting	W_{RI2}	0.21
	R_{I3}—oil spill evaluation and mapping	W_{RI3}	0.20
	R_{I4}—vulnerability and risk assessment	W_{RI4}	0.20
	R_{I5}—public information and community participation	W_{RI5}	0.09
	R_{I6}—risk management training and education	W_{RI6}	0.21
RI_I—risk reduction index	R_{R1}—inspection and preventive maintenance plan	W_{RR1}	0.24
	R_{R2}—containment systems within the platforms and/or facilities	W_{RR2}	0.19
	R_{R3}—operational control systems that allow emergency stops	W_{RR3}	0.19
	R_{R4}—well control system that includes BOP preventer valves	W_{RR4}	0.17
	R_{R5}—incorporation of pressure relief systems	W_{RR5}	0.14
	R_{R6}—contracting companies' risk management plan	W_{RR6}	0.07

DM_I—disaster management index	D_{M1}—organization and coordination of emergency operations	W_{DM1}	0.19
	D_{M2}—emergency response planning and implementation of warning systems	W_{DM2}	0.17
	D_{M3}—endowment of equipment, tools, and infrastructure	W_{DM3}	0.31
	D_{M4}—simulation, updating, and testing of interinstitutional response	W_{DM4}	0.14
	D_{M5}—community preparedness and training	W_{DM5}	0.07
	D_{M6}—second response contract with specialized companies	W_{DM6}	0.12
FP_I—financial protection index	F_{P1}—financial stability of the company	W_{FP1}	0.24
	F_{P2}—reserve funds for disaster risk management	W_{FP2}	0.21
	F_{P3}—budget allocation and mobilization	W_{FP3}	0.21
	F_{P4}—insurance coverage and loss transfer strategies	W_{FP4}	0.35

2.2. Environmental Risk Acceptance Criteria

Risk management commonly involves using the ALARP criteria. The ALARP principle focuses on reducing risks to be as low as reasonably practicable. Mitigation measures should be implemented until the costs appear disproportionate to the achievable benefits. Threshold values are defined for "acceptable" and "tolerable" risks in this context, requiring necessary risks to be reduced below the tolerance threshold as they are unacceptable. Risks falling between these thresholds require mitigation until reasonably practicable, while those above the acceptability threshold do not need further mitigation efforts [67–74]. The present study standardized the environmental risk classification using a sigmoidal function, which considered the results from the holistic environment risk index (Figure 6).

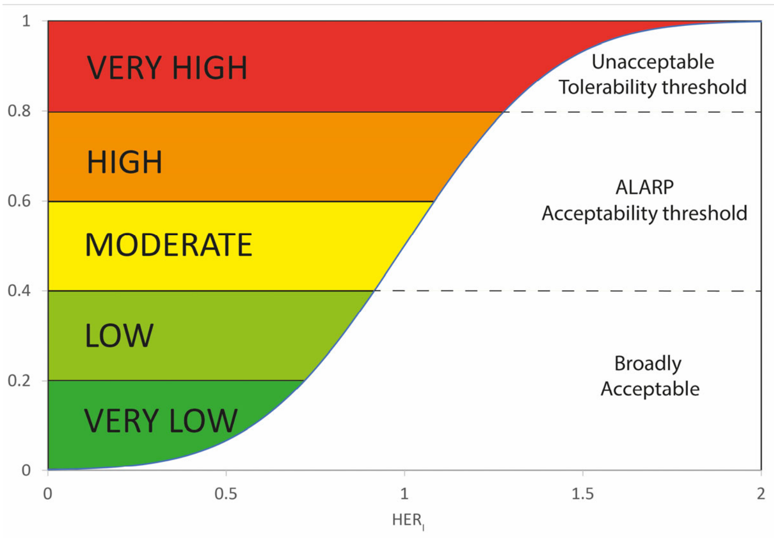

Figure 6. Environmental risk acceptance criteria.

3. Results

A case study was conducted to evaluate the proposed methodology in an oil pipeline between the municipalities of Maní in the department of Casanare and Puerto Gaitán in the department of Meta, Colombia (Figure 7).

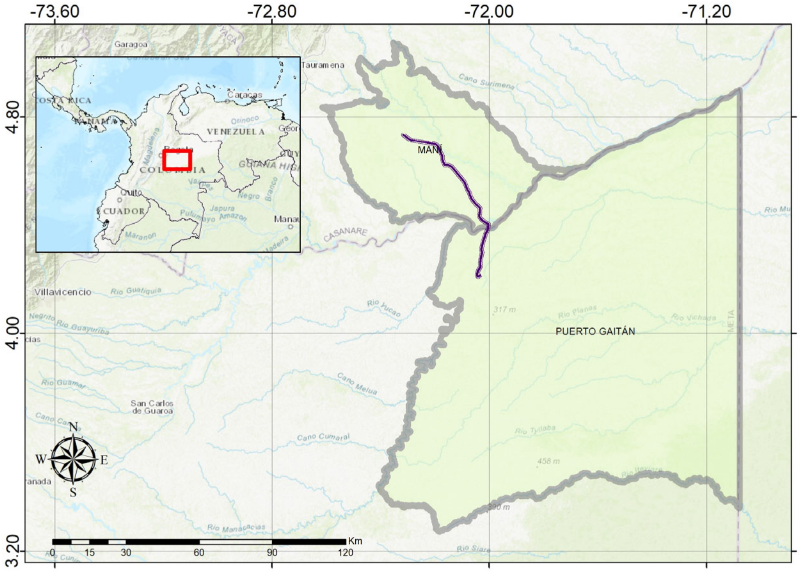

Figure 7. Case study localization.

A scenario was initially defined, assuming the worst case of a catastrophic rupture in the pipeline at one of its initial points. After determining the oil spill volume, the ArcHydro Tools plugin in the ArcMap software was used to determine the oil spill routes based on slopes derived from a digital elevation model of the study area. This initial stage helped us understand the overall context of the risk scenario, enabling us to proceed with its evaluation. The damaged area variable corresponds to the volume of spilled barrels, specifically 907 BBL, according to the quantitative risk assessment. We consolidated data on individuals affected by previous oil spills and consulted expert biologists to determine the affected fauna variable. As for the affected land cover variable, we determined the area in hectares of main land covers that would be impacted by analyzing modeled spill routes. In terms of ecological impact, we referred to environmental management zoning developed by the company based on environmental impact assessment. Our evaluations and ratings for each variable are presented in Table 4. Assessing individual areas affected by spills divided according to land cover was essential within this specific risk scenario. The ecological risk factor for each variable, as shown in Table 5, was obtained according to the sigmoidal functions described above. The spatial distribution of ecological risk derived from this classification is presented in Figure 8. The environmental disaster risk index was determined via a multi-criteria analysis, which involved analyzing factors related to identification, reduction, management, and financial protection against environmental risks. The index qualification was made in a participatory workshop with the company in charge. The response time was determined based on historical emergency response data in the country, indicating that it can range from hours to more than two months depending on the spill volume and geophysical conditions. The army conflict incidence index was assessed as medium-low for our study area. Finally, the ecological resilience assessment process considered land cover and expert input regarding post-disaster ecosystem recovery timelines. Details about the variables are presented in Table 6. The aggravating coefficients for each impacted land cover are shown in Table 7 using the previously described sigmoidal functions. Figure 9 illustrates the spatial distribution. Finally, the holistic environmental risk index is shown in Table 8.

Table 4. Descriptor values of the ecological risk—E_R.

Land Cover	F_{ER1}	F_{ER2}	F_{ER3}	F_{ER4}
Burnt areas	907	50	4902.6	2
Permanent crops	907	50	4902.6	2
Water courses	907	50	4902.6	5

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Table 5. Factors values of ecological risk—E_R.

Land Cover	F_{ER1}	F_{ER2}	F_{ER3}	F_{ER4}	E_R
Burnt areas	0.39	0.5	1	0.067	0.386
Permanent crops	0.39	0.5	1	0.067	0.386
Water courses	0.39	0.5	1	1	0.685

Table 6. Descriptor values for the aggravating coefficients.

Land Cover	F_{FR1}	F_{FR2}	F_{FR3}	F_{FR4}
Burnt areas	3.41	200	2	2
Permanent crops	3.41	200	2	5
Water courses	3.41	200	2	10

Table 7. Factors values of aggravating coefficients—F.

Land Cover	F_{FR1}	F_{FR2}	F_{FR3}	F_{FR4}	F
Burnt areas	0.137	0.933	0.0668	0.005	0.169
Permanent crops	0.137	0.933	0.0668	0.099	0.190
Water courses	0.137	0.933	0.0668	0.804	0.345

Table 8. Holistic environmental index values.

Land Cover	Er	F	HER_i
Burnt areas	0.386	0.169	0.452
Permanent crops	0.386	0.190	0.460
Water courses	0.685	0.345	0.921

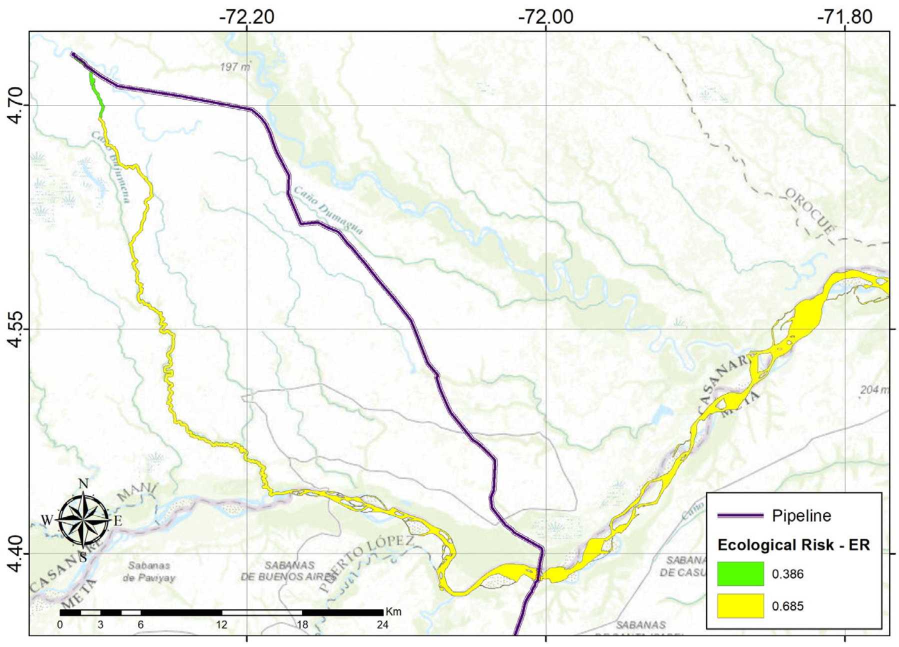

Figure 8. Spatial distribution of ecological risk—E_R.

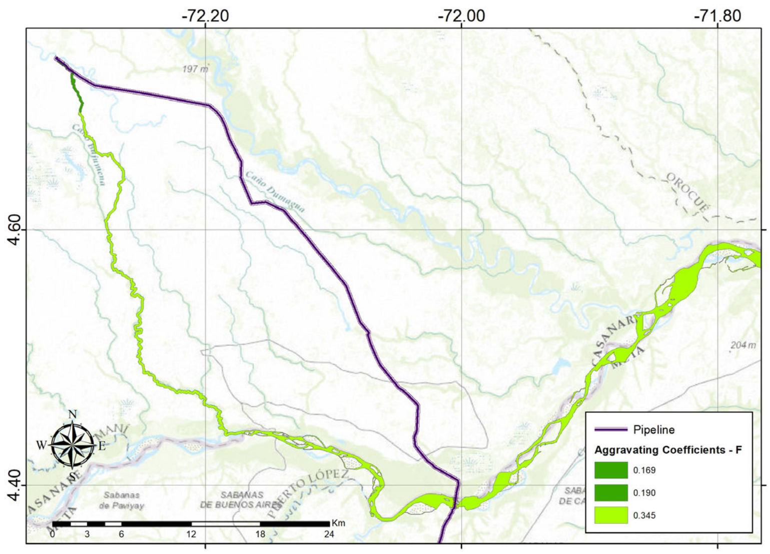

Figure 9. Aggravating coefficients of spatial distribution.

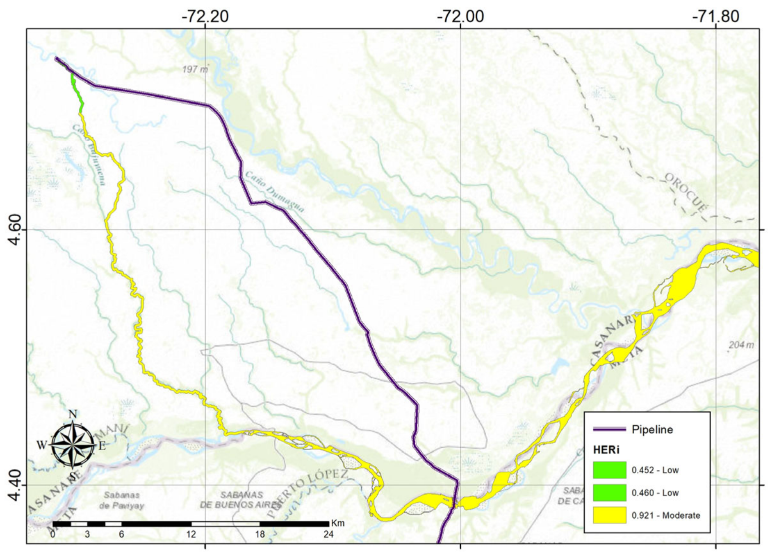

Figure 10. HERI spatial distribution.

4. Discussion and Conclusions

This is the first time a holistic approach has been used to evaluate environmental risk in hydrocarbon projects. This evaluation allowed us to determine, at the Colombian level, which factors do not depend on the spill that increase or decrease the risk. During the workshop held with the company in the case study, it was observed that although the company was aware of its shortcomings, it was not aware that these shortcomings increased the environmental risk. Conducting a self-assessment of its performance in the risk management of environmental disasters allowed the company to identify improvement actions, clarifying that risk reduction measures must be identified using integrated models and comprehensive analysis [37].

This study presented a conceptual framework and a multidisciplinary assessment model for environmental risk analysis in the oil and gas industry in Colombia and introduced the holistic environmental risk index. This study's findings show that while companies in the industry are aware of their shortcomings, there is a lack of awareness regarding how these shortcomings contribute to increased environmental risk. The armed conflict in Colombia has a significant impact on environmental risk, particularly affecting the most sensitive ecosystems with high levels of risk.

These findings have profound potential to assist companies in improving their processes and prioritizing actions to reduce risks. They also emphasize the need to intensify efforts to resolve armed conflict as a strategy for reducing environmental risk at the national level, while highlighting the importance of mitigation measures for vulnerable ecosystems.

This study presented an innovative approach to assessing environmental risks in hydrocarbon projects from both practical and theoretical perspectives. This groundbreaking assessment identified critical factors beyond oil spills influencing environmental risk and provides a solid basis for informed decision making on risk management. However, like any rigorous evaluation, this initial methodology has uncertainties; therefore, it is recommended to conduct further workshops with different sector companies to assess additional descriptors or modifying factor weights. This collaborative approach will help refine the HER_I index and promote greater awareness toward more effective sustainable management actions in Colombia's oil and gas industry.

Author Contributions: Conceptualization, M.A.D.V. and D.A.R.B.; methodology, M.A.D.V. and D.A.R.B.; validation, M.A.D.V., D.A.R.B., and C.P.G.R; formal analysis, M.A.D.V. and D.A.R.B.; M.A.D.V., D.A.R.B., and C.P.G.R.; data curation, M.A.D.V., D.A.R.B., and C.P.G.R; writing—original draft preparation, M.A.D.V. and D.A.R.B; writing—review and editing, C.P.G.R.; visualization, M.A.D.V.; supervision, C.P.G.R. All authors have read and agreed to the published version of the manuscript.

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

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