

Article

Holistic Environmental Risk Index for Oil and Gas Industry in Colombia

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Abstract: Risk management for technological hazards mainly focuses on the consequences for human lives. Although technological risk analysis evaluates environmental vulnerability, it does not reflect the consequences of environmentally exposed elements. This paper's objective is to propose a conceptual framework and create a multidisciplinary evaluation model for environmental risk analysis in the oil and gas industry. A holistic assessment was carried out based on probabilistic risk analysis methodologies to obtain a holistic environmental risk index, HERi. Moncho's Equation was adapted by combining ecological risk, E_R , and an aggravating coefficient, F . Transformation functions were utilized to represent the risk probability distributions. The results from the holistic environment risk index were standardized in a sigmoidal function using the ALARP criteria. Finally, the methodology was applied in two case studies in Colombia, comparing the results with an alternative model. This study found that Colombian armed conflict is a key factor that increases environmental risk in oil and gas projects. The proposed methodology takes a holistic approach by integrating socioeconomic factors and resilience considerations into the risk assessment process. This approach provides a more comprehensive understanding of the environmental risks associated with oil and gas projects in Colombia and promotes more effective sustainable management actions.

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 the history of the United States 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 2442 animals and affected 5507 trees [5]. In Colombia, 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 [16–20]. For Colombia, only a spill that occurred in Cabo Manglares in the department of Nariño in 1976 [21] 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 2800 terrorist attacks on oil infrastructures led to more than 3.7 million barrels of hydrocarbons spilling into the environment. This has impacted soil quality and various ecosystems, including surface waters, flora, fauna (including birds, mammals, and reptiles), amphibians, and fish [8]. Therefore, terrorist attacks are a major hazard for oil spills in Colombia [8,22,23].

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 the 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 [24–27]. 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 [28–35].

Environmental risk assessment (ERA) is predominantly a scientific activity that involves a critical review of the available data for the purpose of identifying and possibly quantifying the risks associated with a potential threat [36]. The ERA process aims to identify, analyze, and evaluate risks in order to determine the most effective management actions when faced with uncertainty. Environmental risk is calculated by first identifying hazards and then evaluating their probability of occurrence and potential consequences on the environment. Environmental risk is commonly expressed as follows [37]:

$$R = Probability \times Consequence \quad (1)$$

A bibliographic review was conducted to gather information on the existing methodologies for environmental risk assessment in the oil and gas industry. The initial findings are qualitative methods; the most prominent examples of this type of risk assessment method are matrix-based techniques. A risk matrix is created in three steps. First, ordinates to the probability are assigned ranks, and then abscissas are applied to the results of the severity/ranks. The combination of these ranking levels determines the ranking of risks [38]. For this methodology, five papers were revised [36,39–42]. The main findings

reveal that while the risk matrix methodology is efficient and requires minimal data, the lack of consideration of statistical data in assessing the probability and consequences leads to a higher level of uncertainty in the results.

Environmental risk assessment methodologies often rely on indices to calculate the potential risks posed by various pollutants. For example, Murat's [43] environmental risk methodology focuses on the risks associated with oil pollution in coastal areas, using indices and methodologies to determine the impact on marine environments and the effectiveness of pollution prevention measures. Similarly, Celis-Hernandez et al. [44] studied used indices like the enrichment factor (EF), geo-accumulation index (Igeo), adverse effect index (AEI), and pollution load index (PLI) to assess the pollution levels in mangrove ecosystems due to oil pollution. Zhu et al. [45]'s study combined automatic identification system data with other data to assess oil spill risks in coastal China. The study used indices like the oil spill rate and accident probability to analyze the risk of oil spills in different areas. Lastly, Qi Zhou [46] constructed a risk assessment system for water sources under the influence of oil spill accidents. This system includes indices for determining the risk of oil spill accidents and their impact on water sources. In summary, these studies demonstrate the importance of using indices in environmental risk assessment to understand the potential risks posed by different variables.

Different probabilistic methods have been developed to reduce uncertainty in environmental risk assessment. Guo [47] developed a statistical risk assessment model that combines a wave–current model, an oil spill model, and a probabilistic methodology using Monte Carlo simulation. It predicts the risk of oil spills in seven steps: the characterization of spilled oil, selection of spill timing, evaluation of environmental conditions, simulation of transport and fate of the oil slick, repetition of simulations for stability statistics, analysis of hypothetical spill data, and integration with environmental sensitivity to develop a risk map. This methodology's great advantage is its ability to spatially identify the areas in which the environment is most likely to be impacted. However, it does not explore the vulnerability of the environment; instead, it focuses solely on the hazard component.

Developing a probabilistic method can also be achieved through Bayesian networks, which are graphical representations defined by a set of nodes and directed arcs. Each node is associated with a probability table called a conditional probability table. This method offers certain advantages as it reveals a more comprehensive risk profile of causes and effects [48]. Arzaghi et al. [49] proposed a methodology based on the US EPA framework for the probabilistic analysis of ecological risk arising from the release of oil from a subsea pipeline in the Arctic region. The exposure analysis and modeling of the fate and transport of spilled oil are crucial components in estimating risk. This methodology differs from previous studies by giving equal importance to both threat and vulnerability, thereby putting greater confidence in environmental risk assessment.

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 [50]. 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 [50–52], 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. To achieve this, the following specific objectives were established: (1) Identify and characterize the

operational, environmental, social, and economic factors influencing the environmental risk of oil and gas projects in Colombia to integrate them into the proposed methodology. (2) Propose a method for evaluating the effectiveness of companies' environmental risk management performance in the hydrocarbon sector in Colombia. (3) Validate the proposed methodology through its application in two case studies and compare it with an alternative model to assess its effectiveness and applicability within the Colombian context.

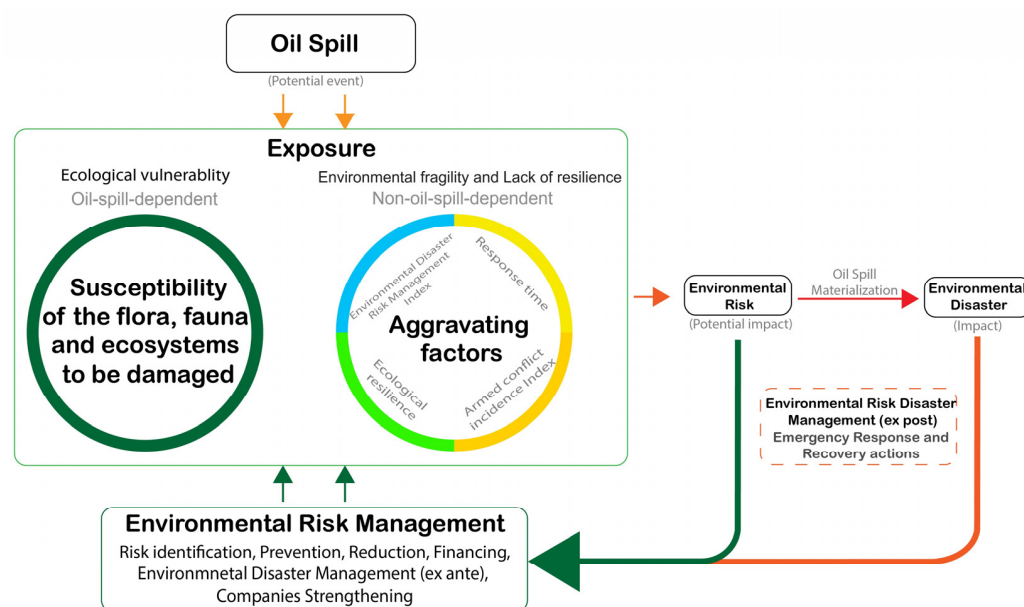


Figure 1. Conceptual framework of the holistic approach to environmental disaster risk. Adapted from Cardona and Barbat [51], Carreño et al. [52], and Marulanda-Fraume et al. [50].

Environmental risk management in oil and gas projects is a crucial challenge for ensuring the sustainability and protection of ecosystems, especially in biodiverse regions such as Colombia. Despite the promulgation of Decree 2157 of 2017 [53], which established guidelines for disaster risk management plan development, there is a notable gap in applying holistic methodologies that fully integrate the environmental, social, and economic dimensions in the oil and gas sector. This research aims to design a holistic methodology to determine the environmental risks within risk management plans for oil and gas projects in Colombia. The significance of this study lies in its potential to offer a holistic approach that meets the demands set by the aforementioned decree while ensuring protection of people's property and their natural, cultural, and productive environment. Through this approach, we aim to identify underlying factors and intrinsic characteristics of society that can influence environmental risk management. This project will not only address an important gap in the scientific literature by offering perspectives from a holistic vision but will also contribute to formulating more effective sustainable policy practices for Colombia's oil and gas industry, enhancing resilience against disasters while minimizing negative environmental impacts.

2. Materials and Methods

2.1. Holistic Environmental Risk Index

The definition of the holistic environmental risk index was based on the holistic risk evaluation methodology proposed by Cardona [51], Carreño et al. [52], and Marulanda Fraume et al. [50] and is calculated using the following equation:

$$HER_I = E_R(1 + F) \quad (2)$$

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 [50,52]. 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 damaged 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, response time, and an environmental disaster risk management index adapted from Carreño and Cardona were also considered in this process [54–56]. Transformation functions were utilized to represent the outcomes of E_R and F , resembling risk probability distributions. Though this approach is not universally viewed as realistic, it has been embraced in specific situations due to uncertainties and imprecise data, along with the need to streamline analysis. Employing progressively refined nonlinear functions may be more fitting and advantageous considering the inherent complexity of risk and its role in enabling comparisons among diverse results [57]. The weights of each variable were determined using the AHP methodology and the Saaty matrix [58]. This instrument was applied to eight (8) professional risk experts from three (3) companies in Colombia's hydrocarbon sector, allowing them to rate the importance of each evaluated variable and index. The resulting weights were then averaged based on the evaluations of all participants.

Figure 2 illustrates the structure of the indicators utilized to evaluate the holistic environmental risk index. According to Equation (2), it is assumed that total risk's maximum value can be twice that of ecological risk. This suggests that as the indices of aggravating factors decrease, so too does environmental impact; conversely, a higher index signifies a greater impact on the environment.

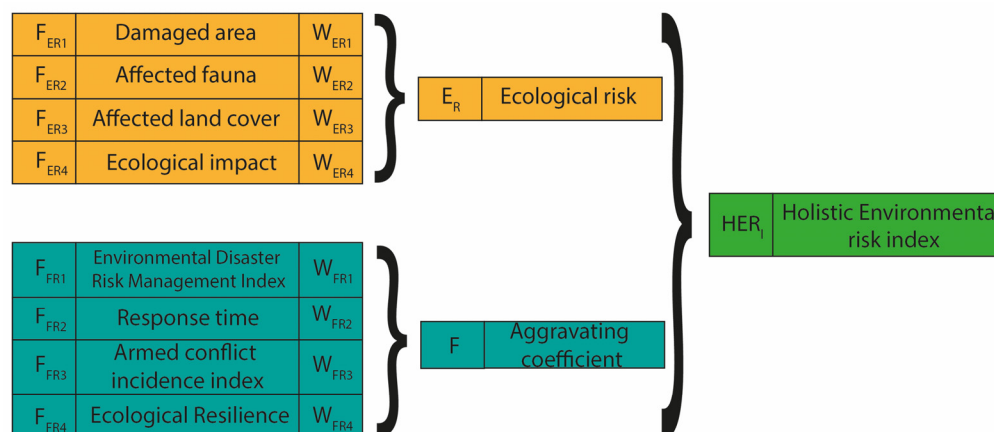


Figure 2. Structure of indicators used for the holistic environmental risk evaluation.

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 nonlinear 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 [57]. 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 [50,52,57,59]. 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 (3), where m is the total number of descriptors, F_{ERi} denotes the component factors, and W_{ERi} represents their weights.

$$E_R = \sum_{i=1}^m F_{ERi} \times W_{ERi} \quad (3)$$

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 [60]. 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 the affected land cover. The maximum risk point was set when the area affected was equal to or greater than 100 ha [61]. The last descriptor was 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).

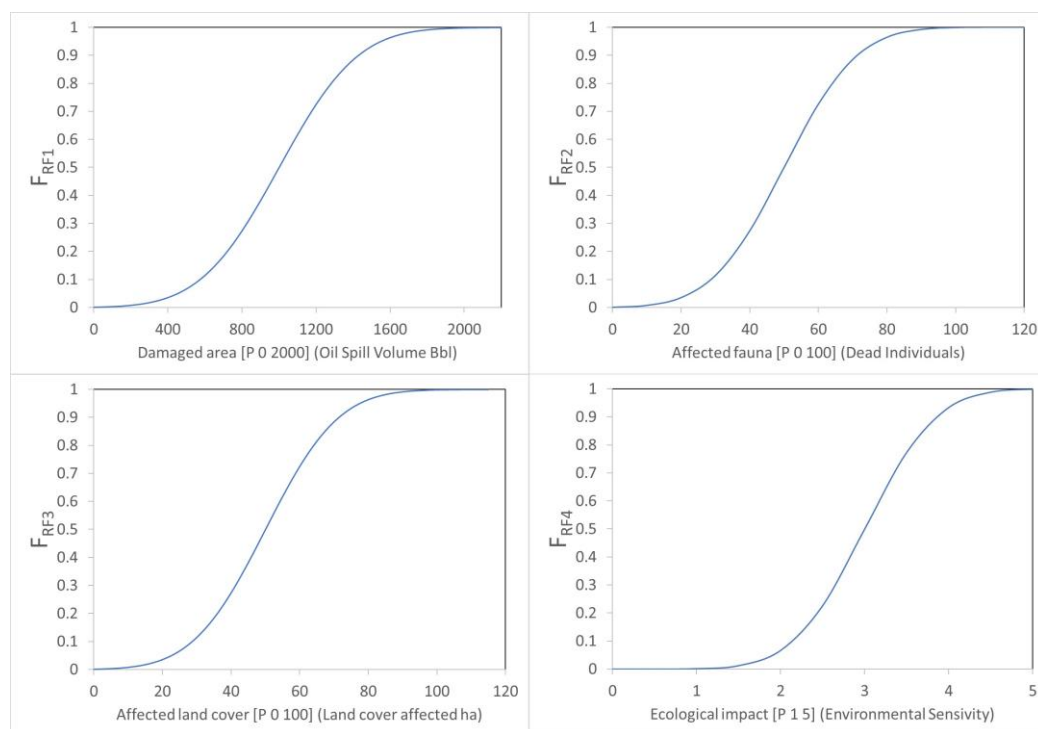


Figure 3. Transformation functions used to standardize the ecological risk factors.

An analytic hierarchy process [28,52,57,62–66] was conducted to calculate the weight for each of the descriptors (Table 1). Expert opinions were considered using the Delphi method [67–72].

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 (4), where n is the total number of descriptors, F_{FRi} denotes the aggravating factors, and W_{FRi} represents their weights.

$$F = \sum_{i=1}^n F_{FRi} \times W_{FRi} \quad (4)$$

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 [73–76]. 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. [54,55] 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 response time. The time of response to oil spills is crucial due to the significant and long-lasting impacts on the environment, society, and the economy. For instance, the 2010 Deepwater Horizon incident caused damage to marine biodiversity. An effective response is essential to mitigate environmental impacts, restore ecological balance, and reduce costs associated with cleanup and restoration [77]. It has been proven that a quick response reduces the environmental impact of an oil spill [78,79]. 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 h, and the minimum point of risk is when the response time is equal to or lower than 50 h. The National Planning Department of Colombia designed and calculated the armed conflict incidence index (IICA) to identify Colombian municipalities impacted by conflict [80]. 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 (Figure 4). The weights of the aggravating coefficients were calculated with the same methodology used for ecological risk (Table 2).

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

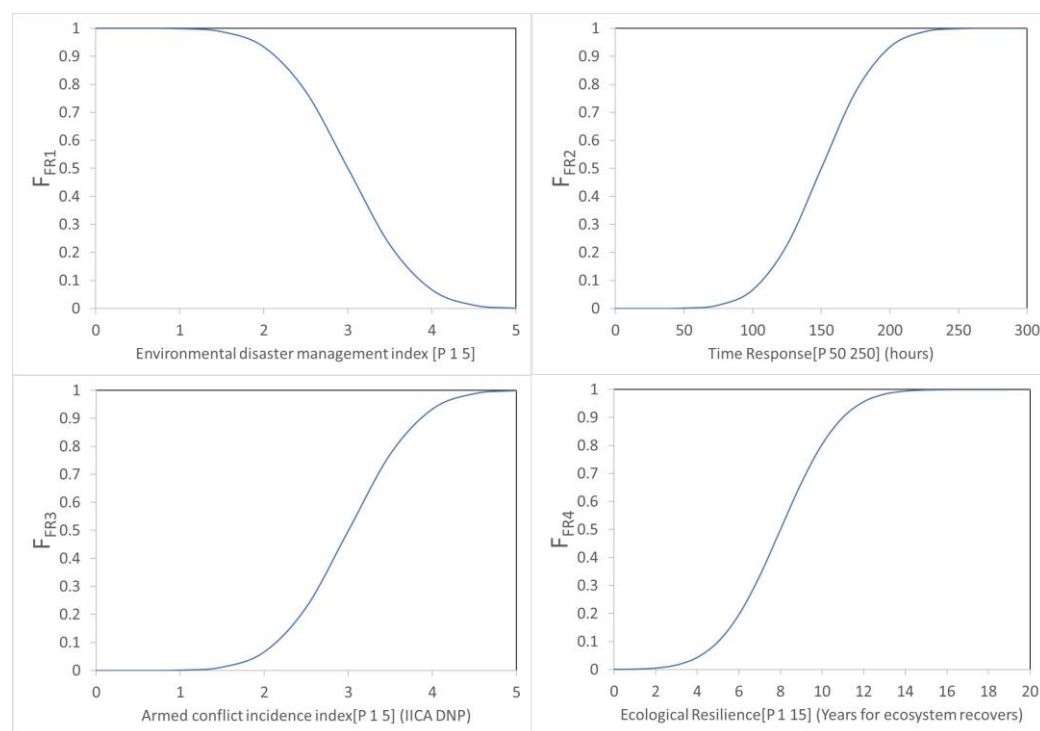


Figure 4. Transformation functions used to standardize the aggravating coefficients.

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 [53]. 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. [54,55].

$$EDRM_i = \frac{RMI_{RI} + RMI_{RR} + RMI_{DM} + RMI_{FP}}{4} \quad (5)$$

Figure 5 shows the descriptors used for each indicator, which were defined considering 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 ecological risk (Table 3).

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

Index	Factor	Weight	Weight Value
RMI —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 —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

Table 3. Cont.

Index	Factor	Weight	Weight Value
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}	0.205
	F_{P3} —budget allocation and mobilization	W_{FP3}	0.205
	F_{P4} —insurance coverage and loss transfer strategies	W_{FP4}	0.35

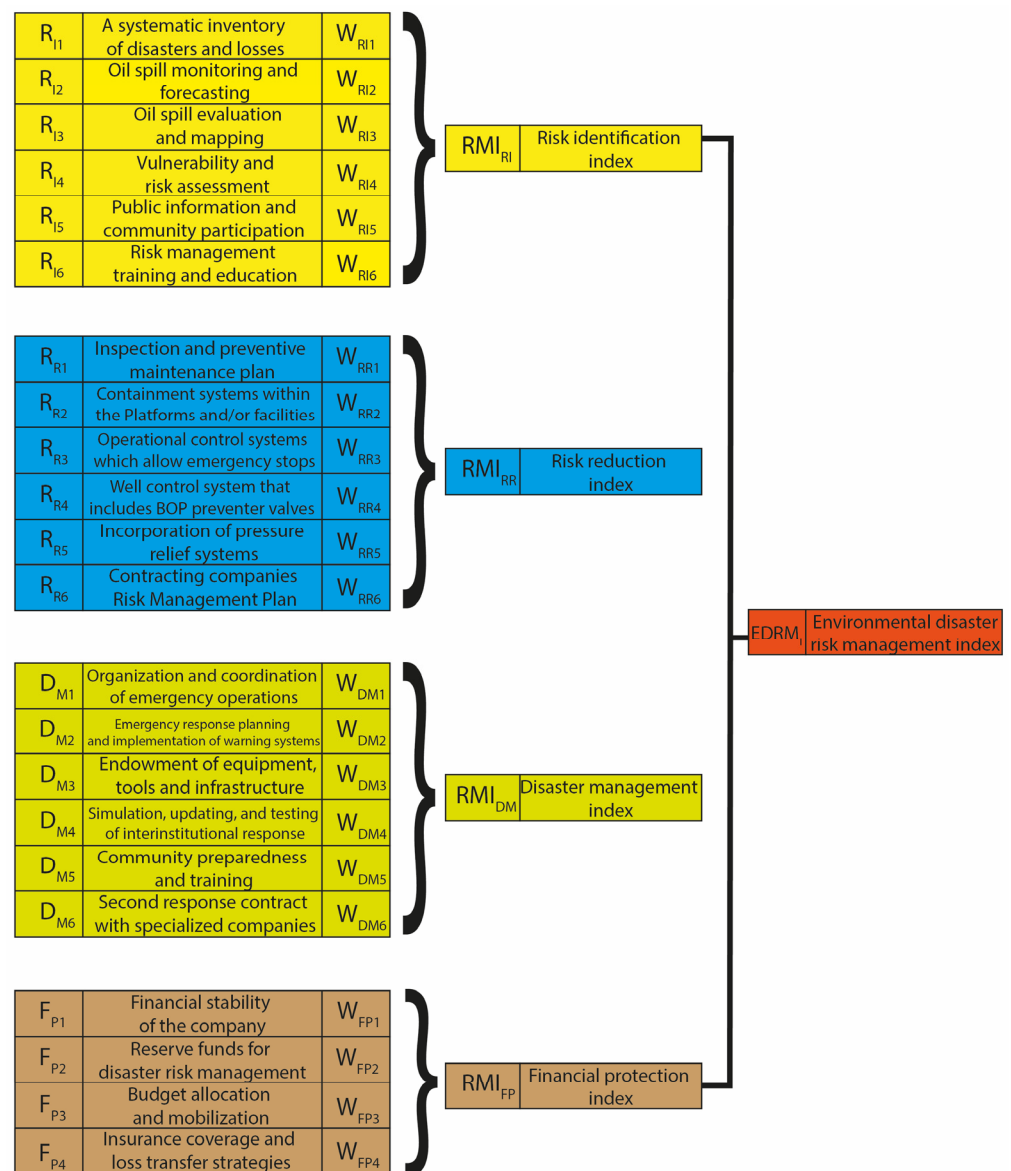


Figure 5. Structure of indicators used for the environmental disaster risk management index. Adapted from the study by Carreño et al. [54,55].

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 to be 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 [81–88]. The present study standardized environmental risk classification using a sigmoidal function, which considered the results from the holistic environment risk index (Figure 6).

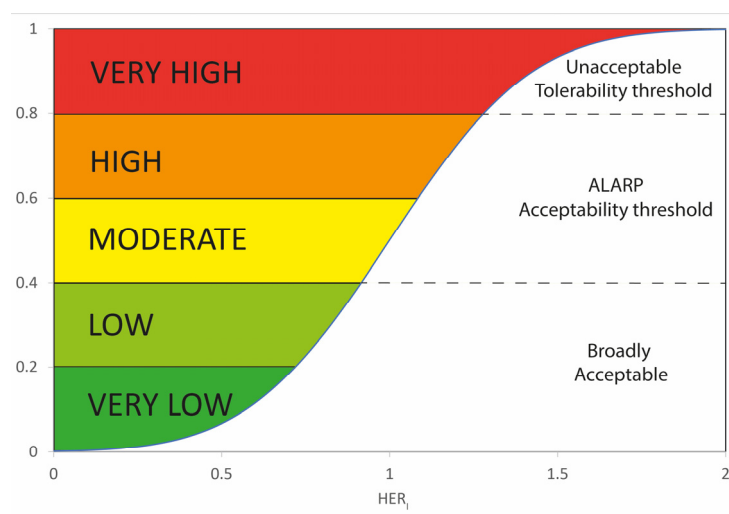


Figure 6. Environmental risk acceptance criteria.

3. Results

Two case studies were conducted to evaluate the proposed methodology, an oil pipeline (pipeline 1) between the municipalities of Maní in the Department of Casanare and Puerto Gaitán in the Department of Meta and an oil pipeline (pipeline 2) between the municipalities of Arauquita and Saravena in the Department of Arauca (Figure 7).

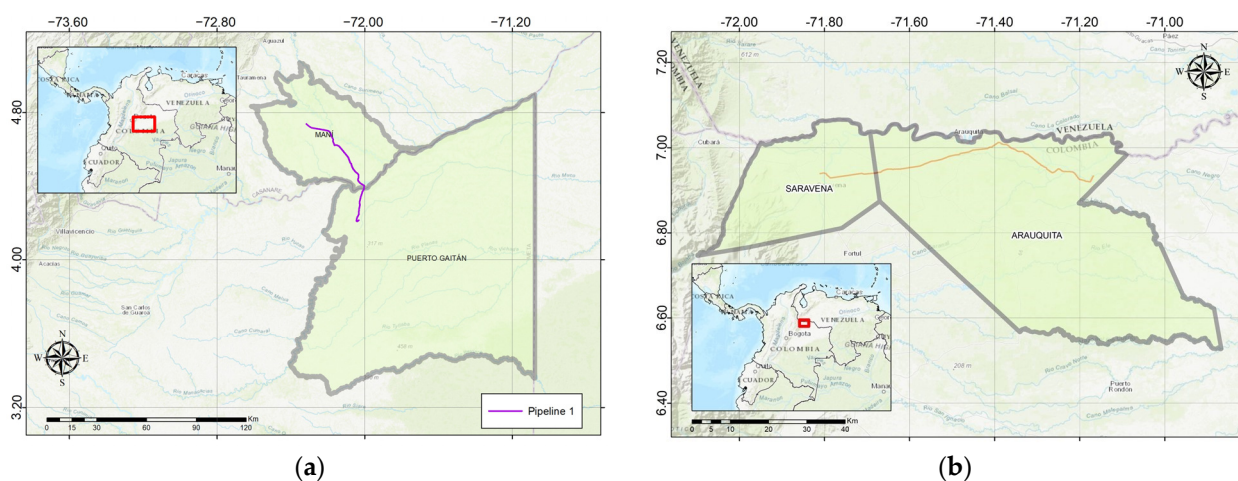


Figure 7. Case study localization: (a) pipeline 1, Casanare and Meta Department; (b) pipeline 2, Arauca Department.

A scenario was initially defined, assuming the worst case of a catastrophic rupture in the pipelines at one of its initial points. After determining the oil spill volume, the

ArcHydro Tools plugin in the ArcMap 10.8 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 the environmental management zoning developed by the companies 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 companies 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 pipeline 1 and very high for pipeline 2. 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 and Figure 10.

Table 4. Descriptor values of ecological risk— E_R .

Pipeline 1				
Land Cover	FER1	FER2	FER3	FER4
Burnt areas	907	50	4902.6	2
Permanent crops	907	50	4902.6	2
Water courses	907	50	4902.6	5
Pipeline 2				
Pastures	907	50	496.7	2
Mixed forest	907	50	496.7	5
Water courses	907	50	496.7	5

Table 5. Factors values of ecological risk— E_R .

Pipeline 1					
Land Cover	FER1	FER2	FER3	FER4	ER
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
Pipeline 2					
Pastures	0.39	0.5	1	0.067	0.386
Mixed forest	0.39	0.5	1	1	0.685
Water courses	0.39	0.5	1	1	0.685

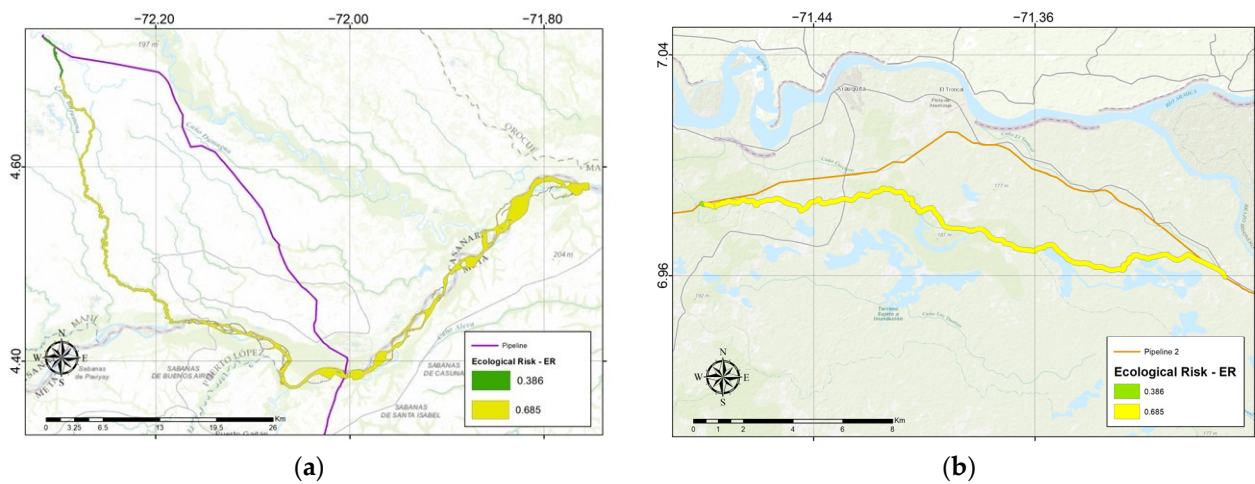


Figure 8. Spatial distribution of ecological risk— E_R : (a) pipeline 1, Casanare and Meta Department; (b) pipeline 2, Arauca Department.

Table 6. Descriptor values for the aggravating coefficients.

Pipeline 1				
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
Pipeline 2				
Pastures	3.85	200	5	2
Mixed forest	3.85	200	5	10
Water courses	3.85	200	5	10

Table 7. Factors values of aggravating coefficients— F .

Pipeline 1					
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
Pipeline 2					
Pastures	0.098	0.933	1	0.005	0.395
Mixed forest	0.098	0.933	1	0.804	0.571
Water courses	0.098	0.933	1	0.804	0.571

Table 8. Holistic environmental index values.

Pipeline 1			
Land Cover	E_r	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
Pipeline 2			
Pastures	0.386	0.395	0.781
Mixed forest	0.685	0.571	1.256
Water courses	0.685	0.571	1.256

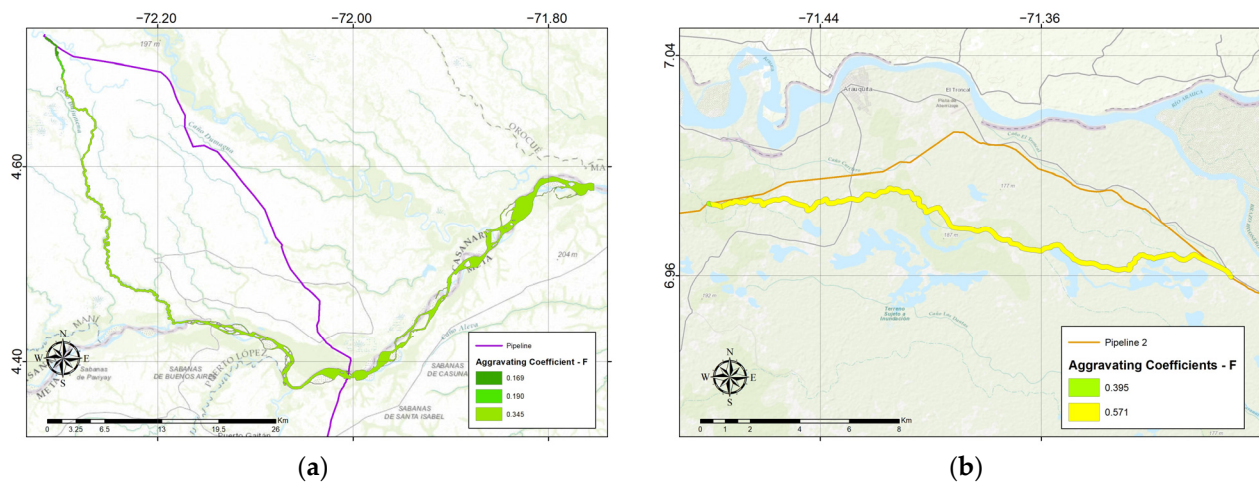


Figure 9. Aggravating coefficients of spatial distribution: (a) pipeline 1, Casanare and Meta Department; (b) pipeline 2, Arauca Department.

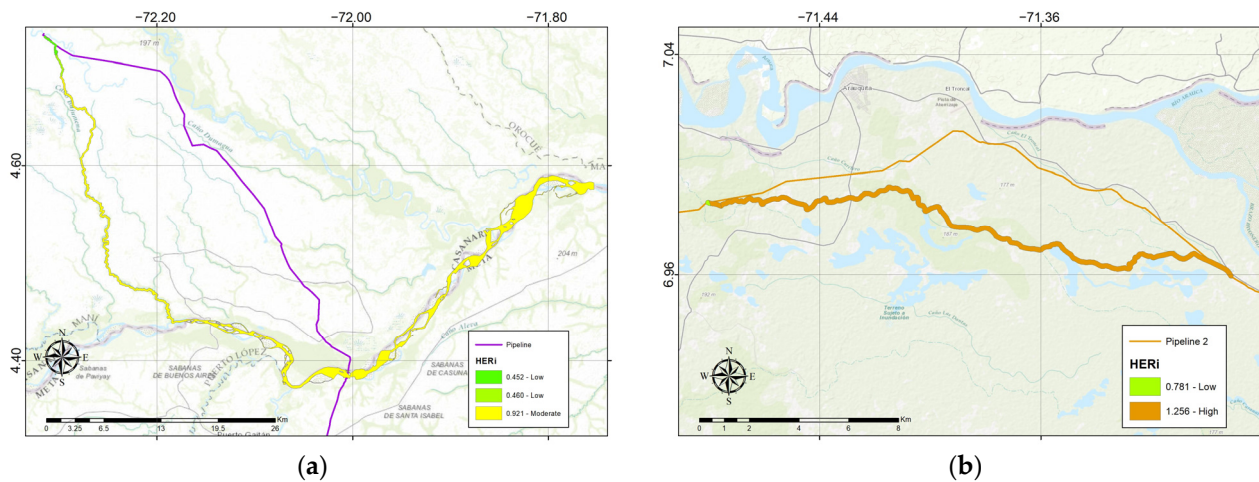


Figure 10. HERI spatial distribution: (a) pipeline 1, Casanare and Meta Department; (b) pipeline 2, Arauca Department.

Comparison Alternative Models

A comparative analysis of the proposed methodology was conducted. We applied the methodology proposed by ECOPETROL S.A. [89]. The calculation of environmental risk is based on Equation (6):

$$R_j = \sum_i \underbrace{[(P1_i) \times (Area(Pol_i \cap Pol_j) \times I_e)]}_{\text{Consequences}} \times \underbrace{(P2_i)}_{\text{Probability}} \quad (6)$$

R_j = Total risk to environmentally sensitive area;

i = Final success;

j = Environmentally sensitive area;

$P1_i$ = Final success frequency of occurrence given the loss of containment;

Pol_i = Final success i polygon;

$\cap$ = Intersection;

Pol_j = Environmentally sensitive area polygon;

I_e = Environmentally sensitive area importance;

$P2_i$ = Probability of impact on the environmentally sensitive area given final event i .

Figure 11 illustrates the environmental risk spatial distribution using the methodology proposed by ECOPETROL S.A. It can be observed that although similar classifications were obtained for pipeline 1, for pipeline 2, there was an underestimation of the risk level in ECOPETROL S.A.'s proposed methodology. It showed a moderate level compared to the high level indicated by the holistic methodology. ECOPETROL S.A.'s methodology assesses only the probability and consequences of oil spills. In contrast, this study's proposed methodology takes a holistic approach by integrating socioeconomic factors and resilience considerations into the risk assessment process. By considering a broader range of variables and potential impacts, this approach provides a more comprehensive understanding of the environmental risks associated with oil and gas projects in Colombia.

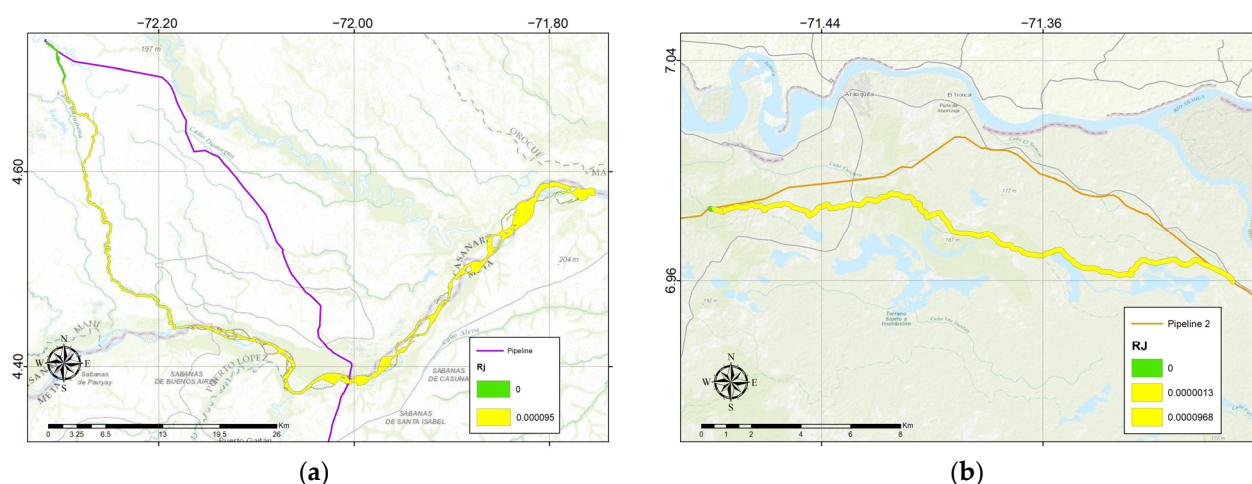


Figure 11. Environmentally sensitive area total risk spatial distribution: (a) pipeline 1, Casanare and Meta Department; (b) pipeline 2, Arauca Department.

4. Discussion

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 risk. During the workshop held with the company in the case study, it was observed that the company was aware of its shortcomings, including the deficit in quantifying losses despite having a record of disaster events and the lack of equipment for monitoring spills or possible leaks, since this process is carried out in an analogous manner through visual tours. In addition, although the personnel are trained to deal with fires or occupational accidents, there is no training in terms of oil spills, and finally, the company does not prepare communities to deal with disasters, considering that they are the first responders when an emergency occurs. This shows that the companies were not aware that these shortcomings increased 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 [36]. This study also found that environmental risk may be underestimated if socioeconomic variables are not considered.

Previous research has primarily focused on the probability and consequences of oil spills. However, this study takes a multidisciplinary approach, considering not only the ecological impact but also the socioeconomic, organizational, and institutional aspects related to the exploration and exploitation of hydrocarbons. This broader perspective contributes to a more comprehensive risk assessment.

The methodology proposed in this study introduces a significant innovation by considering Colombian armed conflict as a key factor that increases environmental risk in oil and gas projects. This inclusion is based on international evidence demonstrating how armed conflicts can trigger environmental disasters, both through the use of pollutants

as weapons and the direct destruction of oil infrastructure. For instance, during the 2006 Lebanon War, Israel attacked oil storage facilities, leading to an oil spill with severe effects on marine and coastal life [90]. In the 1991 Gulf War, Iraqi forces burning Kuwaiti oil fields caused a massive spill, severely affecting the environment and human health [91]. More recently, in Yemen's Safer oil tanker, abandonment during armed conflict poses imminent risks of an oil spill with devastating consequences for its ecosystems [92]. These examples underscore the importance of considering armed conflict as an environmental risk factor in oil and gas projects while highlighting the need for a holistic methodology addressing this complex interaction between armed conflict and environmental risks. This variable's inclusion represents a significant advance toward understanding and managing the risks associated with Colombia's oil industry by emphasizing not only security but also its impact from an environmental sustainability perspective. These findings have profound potential to 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.

Although this methodology is designed to be replicated for any project in Colombia, it could also be applied in other countries by evaluating the specific underlying factors of that territory. For example, the 2019 oil spill on the northeastern coast of Brazil was associated with largely ineffective government actions. It took 30 days for the federal government to initiate a response, which amplified the impacts. This situation was attributed to the context of installed government, as public policies supporting environmental protection and health were dismantled [93].

Limitations of this study exist due to the lack of clear statistical data on oil spill losses, making it difficult to assess variables like affected fauna. Although data on oil spills in Colombia exist, they are not always available for the direct comparison and quantitative assessment of environmental losses. Additionally, limited and often non-disaggregated wildlife data make assessing specific impacts on local biodiversity challenging. Furthermore, other impacted components, such as air quality during crude oil burning, were not considered; this could release air pollutants with negative effects on the environment [94,95]. However, specific data on air quality in affected areas were unavailable for inclusion in our risk assessment. Workshops held with sector companies aimed to identify and evaluate influencing variables, but they may have missed some relevant factors. As research progresses, new variables may emerge that should be included in a more comprehensive evaluation tool.

It is crucial to remember that indicators, in general, are not intended to pinpoint risk management measures. These measures should be identified using integrated models and thorough analysis.

5. Conclusions

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. Other factors that should be considered for environmental risk assessment include ecological impact, land cover, and response time, among others.

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 that further workshops are conducted with different sector companies to assess additional descriptors or modifying factor weights. This collaborative approach will help refine the HERi index and promote greater awareness toward more effective sustainable management actions in Colombia's oil and gas industry.

The application of the HERi methodology in the case studies revealed that areas with more sensitive and less resilient coverages tend to have a higher level of moderate risk compared to other areas with artificialized or agricultural coverages. In contrast, the two Arauca cases showed that the dynamics of armed conflict have a greater impact on risk assessment, with a high index value.

The HERi methodology provides a more accurate evaluation of environmental risk compared to other methodologies as these tend to underestimate risk by not taking into account variables such as armed conflict. Given the complex dynamics and context in Colombia, it is crucial for companies to include this factor in their studies.

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