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A Novel Framework for Comprehensive Risk Assessment of Fuel Stations: Integrating Exposure and Adaptive Capacity for Sustainable Operations

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Abstract

This study introduces a comprehensive framework for the risk assessment and vulnerability evaluation of fuel stations, addressing a diverse range of hazards, including fire, explosion, environmental pollution, air quality impacts, and traffic-related risks. The methodology follows a systematic approach, beginning with the delineation of a 500-meter study area to capture all potential risks while ensuring compliance with regulatory and scenario-specific needs. The risk evaluation framework integrates indicators from global standards, national regulations, and expert insights, incorporating physical, human, environmental, and socio-economic factors for a multidimensional analysis of station vulnerability. Advanced statistical methods and GIS technology are used to quantify hazard severity and probability, generating risk maps and adjusting risk profiles based on adaptive capacity indicators. This data-driven approach helps prioritize mitigation efforts by focusing on the most critical hazards. The study also explores root cause identification using sensitivity and event tree analysis, providing deeper insights into risk factors and enabling targeted hazard prevention strategies. The final phase includes expert workshops and risk model validation, incorporating corrective actions to refine risk profiles and enhance their practical applicability. This dynamic, evolving model offers an effective tool for ongoing risk management and resilience planning, ultimately improving the safety, sustainability, and adaptive capacity of fuel stations and offering valuable insights for operators, policymakers, and risk managers.

Keywords Risk assessment, Fuel stations, Environmental hazards, Adaptive capacity

Introduction

Fuel stations play a critical role in global transportation and industrial systems, providing the energy needed to fuel economic growth [1]. However, their placement in urban and densely populated areas introduces significant risks to public health, safety, and environmental stability [2,3]. Hazards such as fires, explosions, spills, and

contamination of air, water, and soil are inherent to their operations. Without proper management, these risks can lead to severe long-term impacts on human and ecological well-being [2]. As urban landscapes increasingly incorporate fuel stations, there is an urgent need for a comprehensive risk assessment framework to address these threats effectively [4]. A robust framework for assessing



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fuel station risks must integrate two critical dimensions: exposure and adaptive capacity. Exposure refers to the probability and severity of hazards arising from station operations. Air pollution from volatile organic compounds (VOCs) like benzene and toluene can cause serious health issues, including cancer and neurological disorders. Additionally, fuel spills can result in significant soil and groundwater contamination, disrupting ecosystems and threatening public health [2,5]. With fuel stations exposed to multiple hazards simultaneously, risks often compound, creating complex scenarios requiring in-depth analysis. Such cumulative impacts on vulnerable populations and ecosystems underscore the importance of detailed exposure assessments. Adaptive capacity, the second dimension, represents the ability of fuel stations to mitigate and manage risks effectively. This involves implementing advanced safety technologies, maintaining stringent safety protocols, and providing regular staff training [6,7]. Furthermore, the socio-economic and infrastructural context surrounding a station—especially in urban or ecologically sensitive areas—shapes its resilience [8]. Collaboration with local authorities, regulators, and communities is essential for aligning risk mitigation measures with broader urban development and environmental goals [9,10].

Integrating exposure and adaptive capacity into a unified framework enables a holistic approach to risk management. This approach allows operators and policymakers to identify vulnerabilities, quantify risks, and prioritize mitigation strategies. Such a framework not only enhances the safety and sustainability of fuel station operations but also contributes to urban resilience and long-term sustainability. This paper proposes an integrated framework combining exposure and adaptive capacity dimensions, serving as a foundational tool for risk assessment and hazard management in these critical infrastructures.

3. Material and Methods

The development of the risk assessment process for fuel stations in this study adheres to standards, including ISO 16923, 18683, 45003, and 31010, as well as HSE guidelines. The process begins with analyzing data from field visits and historical records, integrating hazard probability and adaptive capacity (Fig. 1). The first step involves identifying environmental hazards and evaluating their severity and likelihood using methods like Fault Tree Analysis (FTA) and the Delphi Technique. Adaptive capacity is assessed by considering structural, economic, social, and environmental factors that influence risk mitigation strategies. GIS tools, particularly ArcGIS Pro, are employed to generate comprehensive risk profiles, integrating multiple data sources. The framework defines

risk as a function of sensitivity, adaptive capacity, and potential hazards. Exposure analysis measures the frequency, intensity, and probability of hazards, while adaptive capacity focuses on socio-economic factors, equipment conditions, and crisis management capabilities. The overall process includes hazard identification, severity calculation, adaptive capacity assessment, and risk profile generation in ArcGIS Pro, further refined through sensitivity analysis. The results provide actionable recommendations for risk mitigation and offer cost-benefit evaluations, ensuring that proposed solutions are not only effective but also economically feasible.

3.1. Phase 1: Data Collection and Risk Evaluation Indicators

3.1.1. Determining the Evaluation Unit

Effective risk assessment at fuel stations requires a well-defined scope to address all potential hazards comprehensively. This scope depends on the station's operations and surrounding environmental conditions. Key risks include fire, explosions, environmental pollution, air quality impacts, and traffic-related issues. For fire and explosion hazards, the study area typically ranges from 50 to 300 meters, based on storage capacity and operational practices, with guidelines from the National Fire Protection Association (NFPA) often determining these distances. Environmental pollution risks, such as soil and groundwater contamination, require a broader assessment area of 500 meters or more, especially in regions with porous soils. Air quality concerns focus on volatile organic compounds (VOCs) like benzene and toluene, with a recommended evaluation radius of 200 to 500 meters, influenced by weather patterns and nearby sensitive zones. Traffic-related risks, stemming from delivery vehicles and customer activity, generally impact a 100 to 200-meter radius. Urban planning regulations typically mandate minimum distances of 50 to 200 meters between fuel stations and sensitive locations. For worst-case scenarios, such as large explosions, the study area may extend up to 1 kilometer. A 500-meter radius provides a balanced approach, ensuring comprehensive risk evaluation while allowing for scenario-specific adjustments.

3.1.2. Selecting Risk Evaluation Indicators

Once the study area is defined, the next step is to develop a comprehensive list of indicators for assessing the risks and vulnerabilities of fuel stations. This list is based on global studies, standards like ISO 16923, 18683, 45003, and 31010 and HSE guidelines specific to fuel stations. It also considers the station's conditions and national hazard analysis. The indicators are grouped into categories to cover all risk aspects:

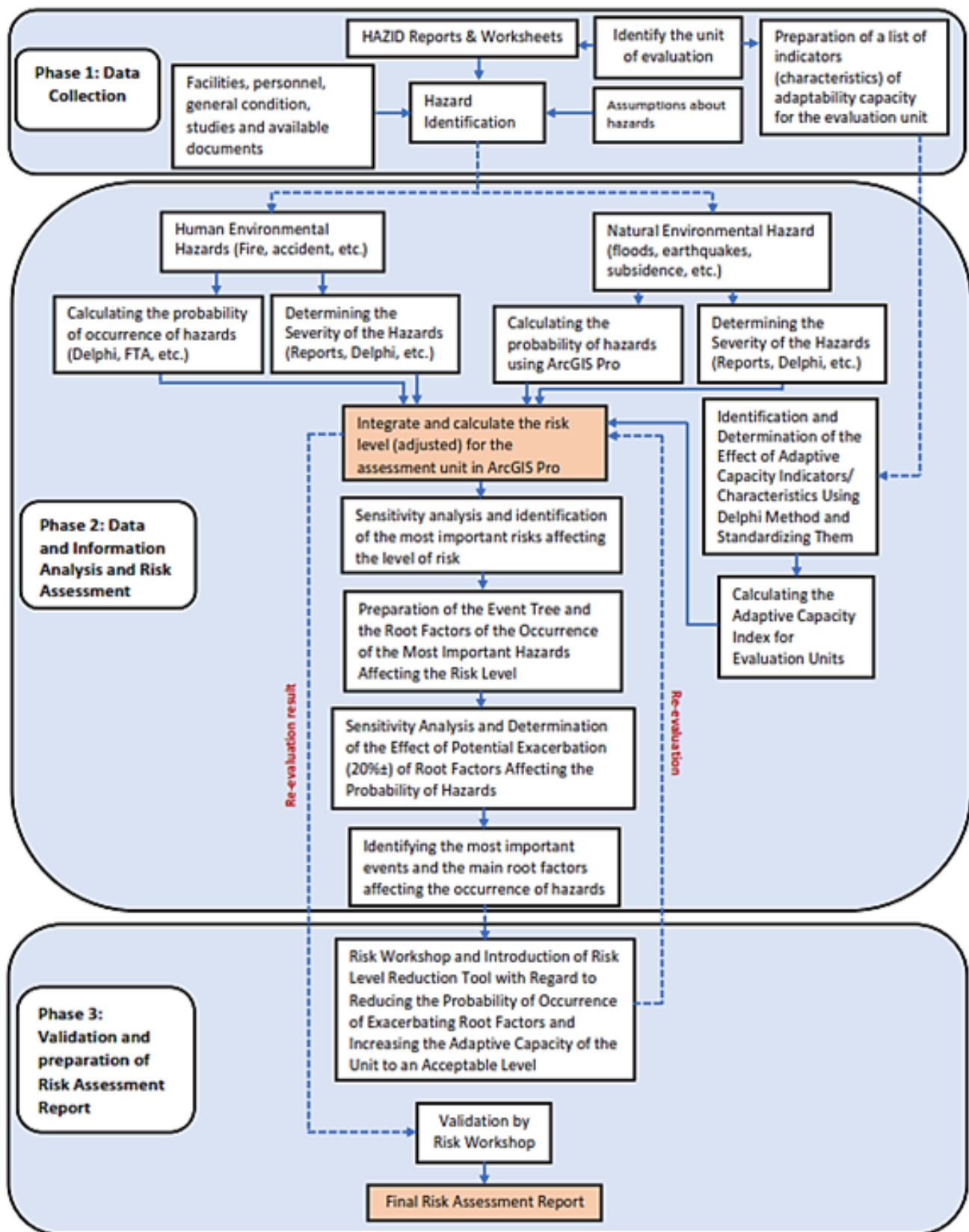


Fig. 1: The methodology framework developed by this study to assess the risk of fuel stations

- **Physical Indicators:** Assess the station's structural integrity, including fuel tank safety, pipeline quality, fire suppression systems, and technical standards compliance.
- **Human Indicators:** Focus on workforce factors such as employee training, safety awareness, crisis management skills, and experience, which influence the station's risk profile.
- **Environmental Indicators:** Include factors like ecosystem sensitivity, soil permeability, groundwater resources, and local weather conditions (e.g., flood or temperature risks).
- **Social and Economic Indicators:** Examine the broader impact of hazards on the local community and economy, such as population density, proximity to sensitive locations, local income levels, and the community's reliance on the station.

Table 1 summarizes some key indicators that can be used to assess fuel station risks, providing a structured framework for comparing stations' vulnerabilities and adaptive capacities. By integrating internationally recognized standards with local contextual factors, these indicators strengthen vulnerability assessments and promote resilience, ultimately enhancing safety and advancing risk management practices for fuel stations worldwide.

3.1.3. Practical Applications and Methodological Refinement

To enhance the clarity of the indicator selection process, practical case study examples have been incorporated to illustrate the real-world applicability of the selected metrics. These examples highlight the effectiveness of key indicators in addressing diverse risk scenarios associated with fuel station operations:

- **Proximity to Residential Areas:** A case study in a densely populated urban setting demonstrated that fuel stations located within a 200-meter radius of residential zones exhibited significantly elevated levels of volatile organic compounds (VOCs), including benzene and toluene. These elevated VOC concentrations surpassed established air quality thresholds, posing notable health risks to nearby residents. This example underscores the criticality of proximity as a determinant in assessing environmental and public health risks [11].
- **Underground Tank Leak Rate:** Analysis of historical data from a suburban fuel station revealed that aging underground storage tanks with higher leakage rates were directly linked to substantial groundwater contamination. The environmental ramifications posed significant challenges to both ecosystem restoration and public health, emphasizing the necessity of incorporating this indicator into comprehensive environmental risk assessments [12].

- **Distance to Emergency Services:** In a rural context, a fuel station located at a considerable distance from emergency response facilities experienced prolonged delays during a fire incident. This delay exacerbated the severity of the damage and resulted in extended operational disruptions. This case study highlights the vital role of proximity to emergency services as an indicator of adaptive capacity and operational resilience [13].

The indicator selection process was further refined through iterative expert consultations utilizing the Delphi technique. Experts systematically evaluated and prioritized indicators based on their relevance to safety, environmental sustainability, and operational efficiency. This iterative approach ensured the inclusion of metrics that are both scientifically rigorous and practically relevant. To solidify the linkage between theoretical constructs and real-world conditions, empirical data and GIS-based simulations were integrated into the framework. This methodological integration enabled the generation of spatially and contextually relevant risk profiles, ensuring the framework's applicability across diverse operational and regulatory environments. By incorporating these case study examples and methodological enhancements, the manuscript offers a well-justified rationale for indicator selection, demonstrating their practical significance and utility. This strengthened foundation ensures that the proposed framework serves as a robust tool for holistic risk assessment and adaptive capacity evaluation in the context of fuel station operations.

This approach evaluates hazard impacts while considering the station's capacity to mitigate and respond effectively. The process begins with data collection on multi-hazard environmental risks and associated economic, social, structural, and human indicators. Following this, Hazard Identification (HAZID) worksheets are completed, and expert sessions are conducted. These sessions involve field specialists analyzing critical environmental hazards and adaptive capacity indicators relevant to fuel stations. Both potential and actual hazards are assessed alongside the station's vulnerabilities and response capacities. Key environmental hazards identified may include fire, explosion risks, environmental pollution, air quality issues, floods, earthquakes, landslides, and similar threats. Adaptive capacity indicators encompass crisis response capabilities, human resource availability, equipment readiness, and emergency preparedness. The assessments rely on data from digital indicator layers sourced from national authorities, prior studies, and other reliable datasets. These layers enable accurate evaluations of the interrelations between hazards, adaptive capacity, and their effects on station performance and safety. Ultimately, this

Table 1: Example of Indicators for Exposure, Sensitivity, and Adaptive Capacity Dimensions for Fuel Station Risk

Dimension	Indicator
Exposure (E)	Magnitude of the impact of landslides on the fuel station
	Magnitude of the impact of subsidence on the fuel station
	Magnitude of the impact of floods on the fuel station
	Magnitude of the impact of earthquakes on the fuel station
	Magnitude of the impact of fires on the fuel station
	Magnitude of the impact of accidents within the fuel station premises
	Magnitude of the impact of electrical shock incidents within the fuel station premises
	Percentage of areas within 500 meters of fault lines in the surrounding region of the fuel station
	Proximity to Residential Areas (meters)
	Frequency of Fuel Deliveries (deliveries per week)
	Underground Tank Leak Rate (liters per year)
	Volatile Organic Compound (VOC) Emissions (ppm)
	Age of Infrastructure (years)
	Traffic Volume in Station Vicinity (vehicles per hour)
	Soil and Groundwater Contamination Levels (mg/L)
	Ambient Air Quality Index (AQI)
	Distance to Emergency Services (kilometers)
	Percentage of areas with unhealthy air quality for sensitive groups within 500 meters of the fuel station
	Risk of exceeding the summer maximum temperature threshold of 40°C with in 500 meters of the fuel station
Adaptive Capacity (AC)	Total hours of training per year provided to employees on fire, spill, and evacuation procedures
	Percentage of functioning fueling nozzles at the fuel station
	Number of safety-standard compliant and functional tools and equipment at the fuel station
	Percentage of workforce at the fuel station that has undergone periodic medical examinations
	Number of preventive maintenance checks performed annually on equipment and underground storage tanks
	Amount of annual funding allocated for safety upgrades (e.g., fire suppression systems, spill containment)
	Percentage of underground storage tanks equipped with advanced leak detection systems
	Mean time between failures (MTBF) for fuel dispensing equipment
	Proportion of hazardous waste handled and disposed of in compliance with environmental regulations
	Number of fully operational fire extinguishers, spill kits, and emergency alarms per station
	Average distance (in kilometers) to the nearest fire station, hospital, or environmental response team
	Percentage of the station area under real-time monitoring for leaks, emissions, and unauthorized access
	Number of trained staff per 100 daily customers, ensuring adequate oversight and rapid incident response
	Total number of emergency phone signs, Material Safety Data Sheets (MSDS), and first aid kits
	Length and balanced distribution of work shifts for fuel station personnel
	Number of health and medical infrastructures in the surrounding region
	Population density in the region surrounding the fuel station
	Density of roads with a width greater than 6 meters in the surrounding region
	Density of emergency road networks in the surrounding region

phase guides the development of targeted strategies to reduce risks, improve safety, and enhance the resilience of fuel stations in urban and vulnerable areas.

3.2. Data Analysis and Risk Assessment

3.2.1. Calculating the Risk Profile in the Evaluation Unit

In this study, the risks of natural and human-related environmental hazards at the evaluation unit level will be assessed by determining the severity and probability of each hazard. Data from relevant organizations and research findings will be used to create risk maps within Geographic Information System (ArcGIS Pro), showing the geographical distribution of natural hazards. These maps will help evaluate the severity and probability of each hazard more accurately. The severity of each natural hazard's impact will be determined through existing studies, reports, and expert opinions, using statistical methods like the Delphi method. Expert views will be collected to assess the severity based on scientific and empirical criteria. For human-related hazards, severity will also be assessed using studies and expert input. The probability of occurrence of each human-related hazard will be calculated using methods like Delphi, Fault Tree Analysis (FTA), Bayesian Analysis, Markov Chains, and Monte Carlo Simulations. These methods analyze root causes and simulate probabilities under different conditions. By integrating the probabilities and severity of both natural and human-related hazards in ArcGIS Pro, a comprehensive risk map will be generated. These maps will be crucial for calculating the risk profile of each fuel station. The integration of data and analysis will allow for scenario simulations, supporting risk management at fuel stations to improve decision-making, reduce risks, and enhance resilience.

3.2.2. Calculating the Adaptive Capacity Profile and Adjusting the Risk Profile in the Evaluation Units

To improve the risk profile and obtain an accurate risk level for the stations, a list of indicators related to structural, economic-social, and environmental factors will be prepared based on international research and similar national studies. These indicators are crucial in assessing the adaptive capacity of the stations, enabling them to manage environmental hazards effectively. The indicators will cover the physical structure of the stations, the surrounding area's economic and social conditions, local environmental features, and human and technical capabilities. Once the list is prepared, the Delphi method will be used to refine the indicators. Expert opinions will be gathered in multiple rounds to reach a consensus on the most important adaptive capacity factors. Afterward, the

values of these indicators will be calculated using existing documents, reports, and field visits. These values will be normalized to a uniform scale and then multiplied by the previously determined hazard severity values. This integration combines the severity of hazards with adaptive capacity indicators to generate a unified adaptive capacity profile. Finally, these profiles will be entered into the Geographic Information System (ArcGIS Pro), where they will be integrated into the overall risk profile for each station. This process adjusts and refines the risk profiles, providing a clear understanding of each station's risk and adaptive capacity. The final profile will serve as a valuable tool for decision-making and hazard management planning.

3.2.3. Identifying the Major Causes and Events Affecting Hazard Occurrence

To identify key environmental hazards affecting risk, hazards will be identified, and their probability and severity determined. Sensitivity analysis will assess how changes in hazard probabilities impact overall risk, helping pinpoint the hazards with the greatest effect. An event tree will be developed to illustrate the pathways of hazard occurrence, from initial events to final consequences. Root causes contributing to hazards will be identified and categorized. Sensitivity analysis will also evaluate the combined impact of multiple hazards. The results will be validated with empirical data or statistical methods to ensure accuracy. Findings will be presented in sensitivity charts, event trees, and reports, guiding effective control measures.

3.3. Phase 3: Validation and Reporting of the Risk Assessment of the Evaluation Unit

In this phase, after identifying key events and root causes affecting environmental hazards, the risk analysis will be validated and optimized. A specialized workshop will be held with relevant experts to gather and analyze their opinions on adaptive capacity indicators, root causes, and key events. Based on this analysis, tools and strategies to reduce risk will be proposed, including management changes, infrastructure improvements, or new policies. Risk calculations will be reviewed, and the severity and probability of each hazard will be recalculated. This updated information will be used in ArcGIS Pro for modeling and spatial analysis of the adjusted risk profile. The final output will include updated risk maps, analyses, and a detailed report for decision-making in risk management.

3.4. Phase 4: Analyzing Results and Developing Solutions to Eliminate/Reduce the Risk Level

In this phase, the results of the risk assessment and val-

idation for fuel stations will be analyzed to identify patterns, weaknesses, and improvement opportunities. The process includes:

1. Reviewing and Analyzing Results: The final data on the station's risk levels will be reviewed through quantitative and qualitative analysis, using charts and GIS maps to identify spatial risk distribution and high-priority areas. Root causes contributing to increased risk will also be analyzed.

2. Setting Priorities: Fuel stations will be prioritized based on hazard severity and probability, aiding in the development of targeted operational strategies.

3. Designing Risk Elimination or Reduction Solutions: Solutions will include hazard elimination (e.g., process changes, infrastructure improvements) and risk reduction (e.g., safety measures, advanced technologies).

4. Cost-Benefit Evaluation: Proposed solutions will be evaluated for feasibility, cost, and impact, with priority given to cost-effective measures.

5. Final Report and Action Plan: A detailed report will be prepared, outlining solutions, an action plan, and a monitoring strategy.

This approach ensures fuel stations are better equipped to manage and reduce risks, enhancing resilience to environmental hazards.

4. Conclusion

Fuel stations are vital infrastructure that underpin modern transportation and economic systems. However, their operations expose them to multifaceted risks that can have profound consequences for safety, environmental integrity, and public health. This study presents a scientifically grounded and comprehensive risk assessment framework that integrates hazard exposure with adaptive capacity, offering a robust methodology for evaluating and mitigating vulnerabilities in fuel station operations. The findings emphasize that risk management requires a multidimensional approach. Exposure analysis highlights the severity and probability of hazards such as fires, explosions, and environmental contamination. Meanwhile, adaptive capacity assessments reveal the critical role of factors like safety protocols, employee training, and infrastructure resilience in mitigating risks. Combining these dimensions enables the development of targeted strategies to address high-risk areas, ensuring resources are allocated efficiently. The integration of advanced methodologies, including GIS mapping, Fault Tree Analysis, and sensitivity analysis, further enhances the framework's accuracy and applicability. These tools provide actionable insights that empower operators, policymakers, and stakeholders to prioritize interventions and implement effective mitigation measures. This study reinforces the

importance of aligning fuel station risk management with broader urban planning and environmental sustainability goals. By adopting this comprehensive framework, stakeholders can proactively safeguard fuel station operations, minimize environmental impacts, and enhance resilience against future challenges. The dynamic nature of the framework allows for continuous improvement, making it a valuable tool for fostering safe, sustainable, and efficient fuel station systems. This approach ultimately contributes to long-term community and environmental well-being.

The study acknowledges several potential limitations that could influence the applicability and effectiveness of the proposed risk assessment framework. One key limitation is the availability and quality of data, which can significantly affect the accuracy and reliability of the risk assessment outcomes. In regions where data on hazards, vulnerabilities, and adaptive capacity is scarce or incomplete, the framework's performance may be compromised. For example, in areas with limited access to high-resolution geographical data or where data collection practices are inconsistent, the ability to conduct thorough risk assessments may be hindered, thus impacting the overall effectiveness of the proposed framework. Another limitation pertains to the scalability of the framework across regions with differing regulations, resources, and institutional capacities. The framework is designed to be adaptable to various contexts, but the implementation of risk assessments may face challenges due to regional differences in regulatory environments, available technological infrastructure, and human resources. For instance, regions with well-established risk management frameworks and advanced technological capabilities may be able to implement the proposed framework with greater ease, while others with less institutional support or financial resources may encounter difficulties in fully operationalizing the framework. Additionally, the variability in regulatory frameworks across different jurisdictions could impact the standardization and integration of risk assessments. For example, different regions may have unique legal frameworks, hazard classifications, and disaster management protocols, which could complicate the harmonization of risk assessment processes and limit the comparability of results across regions. Furthermore, while the framework offers a comprehensive approach, its reliance on both qualitative and quantitative data may introduce challenges related to the integration of diverse data types. In some regions, the capacity to conduct qualitative assessments (e.g., community consultations or stakeholder workshops) may be limited, which could affect the framework's ability to capture local knowledge and socio-cultural factors that are essential for un-

derstanding risks and adaptive capacity. In conclusion, while the proposed framework provides a valuable tool for risk and adaptive capacity assessments, it is important to recognize these limitations in terms of data availability, regional variability, regulatory differences, and resource constraints, which may affect its implementation and scalability across diverse geographical and socio-political contexts. Future research and case studies in various regions will be necessary to further validate the framework and address these challenges.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Received: Dec. 2024 Accepted: Jan. 2025

Published online: Jan. 2025

DOI: 10.22034/ASAS.2025.493012.1067

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