Assessing the Sustainability of Small Hydropower Potential in the Threats of Natural Disasters: an Analytic Hierarchy Process-Based Approach

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Abstract: This study assesses the sustainability of small hydropower installations amidst natural hazards, employing the Analytic Hierarchy Process (AHP) to rank disaster risks like earthquakes, floods, landslides, forest fires, and drought. Focusing on four potential small hydropower sites in the Citarum watershed, West Java, Indonesia, the research integrates geographical and disaster risk maps to create a framework for evaluating locations prone to natural disasters. The results identify high-risk zones (Locations 2 and 4) with concentrated small hydropower potential. Additionally, moderate-risk locations (1 and 3) are recognized as viable opportunities for development. The findings aid decision-making for policymakers and stakeholders, promoting resilient small hydropower systems.

Keywords: Small Hydropower; Natural Disaster; Sustainability; AHP

1. Introduction

Evaluating potential locations for small hydropower projects in the context of natural hazard risk is essential for multiple reasons[1–3]. Firstly, it ensures the safety and resilience of these energy facilities, protecting them from damage or destruction during floods, landslides, earthquakes, or extreme weather events[4,5]. Secondly, it reduces economic risks by mitigating the potential for costly damage or disruption, thus safeguarding the financial investments in these projects[6–8]. Thirdly, it helps minimize environmental impacts by preventing accidents during natural disasters that could exacerbate habitat disruption and water quality changes[9]. Compliance with regulatory guidelines is also crucial for permitting and operational status. Furthermore, assessing natural hazard risk contributes to the long-term sustainability of small hydropower facilities. It ensures a reliable energy supply while safeguarding public safety, mainly when these facilities are near populated areas[1].

The utilization of small hydropower holds immense promise in the ever-evolving landscape of renewable energy sources[10]. These projects, harnessing the energy of flowing water, contribute significantly to the global quest for sustainability and reduced carbon emissions[11]. However, while small hydropower offers substantial benefits, it is not exempt from nature's potent and unpredictable forces. Natural disasters, including earthquakes, landslides, floods, and extreme weather, pose severe risks to small hydropower installations' environmental sustainability, economic viability, and safety. This manuscript critically examines the intricate relationship between small hydropower potential and the threats posed by natural disasters.

Small hydropower projects, often nestled in environmentally sensitive areas, serve as both a beacon of clean energy and a potential vulnerability in the face of nature's fury[12]. The economic investments required for their development and the long-term energy supply they promise to make them vital components of our sustainable energy future[13]. However, they also stand as susceptible targets, potentially affected by the destructive forces of natural hazards, with the potential to disrupt energy production, harm ecosystems, and endanger nearby communities.

Our approach, rooted in the Analytic Hierarchy Process (AHP), seeks to provide a structured and comprehensive framework for evaluating these risks[14]. This analysis is crucial for the safety and resilience of small hydropower projects and the long-term sustainability of renewable energy solutions in a world where the impact of natural disasters is becoming increasingly significant. By shedding light on the intricate balance between harnessing the power of water and the threats of nature, we hope to offer insights that can guide policymakers and developers in making informed decisions about small hydropower projects in areas prone to natural disasters.

2. Material and Methods

2.1.Study Area

The Citarum River Basin, locally known as DAS Citarum, located at 106° 51'36" - 107° 51' E and 7° 19' - 6° 24'S (see Fig. 1), with an area of ±11.323 Km², is vast in West Java, Indonesia, supporting diverse activities across multiple regions. It encompasses seven

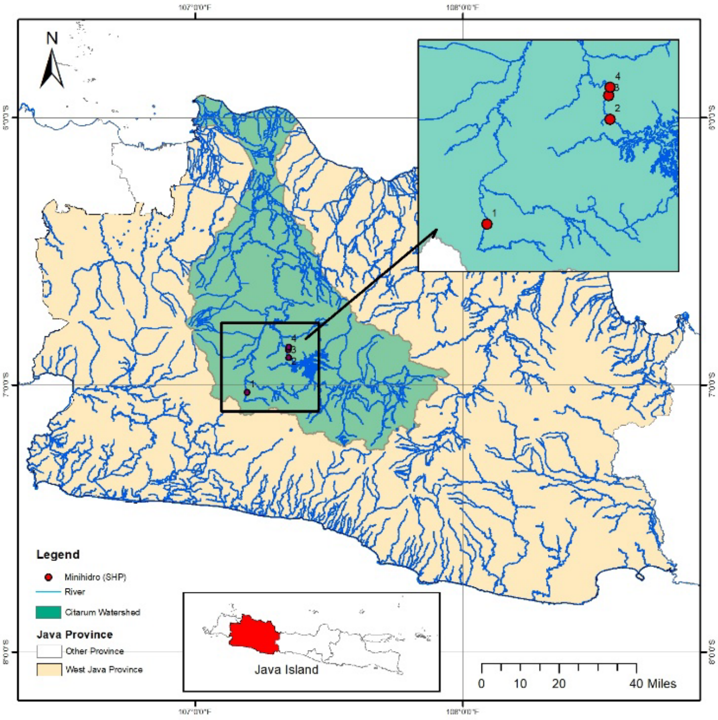

Fig.1. Study Area Map

Districts and two cities within West Java. West Java experienced many natural disasters in 2022, totaling 680 incidents, including 115 floods, 16 earthquakes, 2 droughts, 289 twisters, and 258 landslides[15].

2.2.Small Hydropower Potential

Pranoto et al. (2021) have conducted a technical study on the potential of hydro energy in Indonesia, including West Java [16]. Figure 1 is author generated based on data processing from Bono Pranoto (2021) by filtering watershed boundaries and small hydropower generation capacity. The data is processed, and then the map is redrawn. The methodology used by Bono Pranoto is to perform calculations based on the following formula:

$$P = Q\ x\ H\ x\ g\ x\ \eta \qquad (1)$$

Where (P) involves the dependable discharge (Q), head (H), gravity (g), and total efficiency (η). The study has 18 potential small hydropower locations in the Citarum watershed (see Fig. 1). The study only mentions potential sites and capacity that can be generated without any sustainable assessment.

Several hydropower sustainability assessment studies have investigated the potential occurrence of hazards, particularly geological hazards. In particular, the works of Ali Washakh et al. (2019), Dhaubanjar et al. (2021), and Kuniyal et al. (2019) stand out in this domain. Geohazards include natural events such as floods, landslides, and earthquakes. These studies collectively contribute to a comprehensive understanding of the vulnerability and resilience of hydropower projects in the face of these hazards[2,3,17]

Focusing on specific elements in geohazards, landslides and earthquakes requires different attention. Dhaubanjar et al. (2021) and Kuniyal et al. (2019) offer insights for assessing landslide and earthquake potential. Both studies carefully examine the geological and seismic conditions around hydropower projects, highlighting the importance of evaluating these specific hazards[2,3]

In this paper, the author tries to conduct a sustainability assessment based on multi-disaster risks to these potential locations. No references have been found to assess potential small hydropower (SHP) locations before a feasibility study related to the risk of multi-disaster potential[2,3,17].

2.3.Hazards Potential

The comprehensive methodology for assessing disaster risk involves multiple stages: data acquisition, processing, analysis, and presenting study findings in tabular (table 1) and spatial formats. Throughout this process, several guiding principles shape the approach. Firstly, priority is given to official data obtained from authorized institutions, incorporating all available event records. Secondly, integration occurs by analyzing the probability of disaster events, drawing from the expertise of professionals and the collective wisdom of local communities. The analysis calculates potential impacts on lives, property losses, and environmental damage. Ultimately, the risk assessment results can be translated into overarching policies to reduce and manage disaster risks.

The types of disaster risks studied occur on land only, such as earthquakes, landslides, floods, flash floods, forest fires, volcanic eruptions, extreme weather, and drought. The risk of these hazards can affect changes in water discharge and river head.

The Disaster Management Capacity of the National Agency for Disaster Management (BNPB) uses these methodologies to generate a Hazard Potential map of Indonesia.

The methodology for assessing earthquake hazards is based on JICA's (2015)[18] methodology and the Indonesian Earthquake Hazard Map (Ministry of Public Works, 2010)[19]. The analysis considers the intensity of surface shaking. It uses AVS30 (Average Shear-wave Velocity in the upper 30m), determined from the Digital Elevation Model (DEM) raster data to calculate soil amplification factor data.

Flood hazards are assessed according to BNPB Regulation No. 2 for 2012[20], utilizing flood-prone region data and inundation depth. The flood hazard index is calculated using fuzzy logic, considering the slope and distance from the river in flood-prone areas.

Landslide hazards follow the SNI for the Preparation and Determination of Ground Motion Vulnerability Zones[21], with PVMBG's definition of ground motion vulnerability zones adjusted for slopes greater than 15%.

Drought hazards are evaluated using the Standardised Precipitation Index (SPI) for three months, based on the meteorological drought approach[22].

Forest fire hazards are characterized according to BNPB Regulation No. 2 of 2012[20], considering factors such as forest and land type, climate, and soil type, with each parameter forming a class scored by its level of influence.

Extreme weather hazards are assessed using a scoring method for parameters including land openness, slope, and annual rainfall, following BNPB Regulation No. 2 of 2012[20].

Flash flood hazards are determined based on recommendations from the Ministry of Public Works (2011) and a modified approach, factoring in landslide hazard areas upstream, potential damming by landslide material, and topographic conditions around the river flow[23].

2.4.Risk Index

An evolution in disaster risk assessment has been evident, emphasizing the linkages between vulnerability, capacity, and hazards. The concept of vulnerability has evolved to not only be defined as exposure to hazards. It also includes the capacity to cope, withstand, and recover from its impacts. This shift is reflected in the risk equation, where vulnerability now interacts with capacity, effectively described as Risk Potential = Hazard (H) x Vulnerability (V) / Capacity (C)[22]. Recognizing capacity as a critical component means acknowledging the role of human capabilities in mitigating hazard impacts[24].

However, there is an essential gap in disaster-related sustainability assessments - the absence of comprehensive risk assessments incorporating disaster capacity evaluations. While many studies have explored the potential occurrence of hazards and associated vulnerabilities, the inclusion of disaster capacity assessments remains relatively limited. The integration of capacity assessments is critical to a holistic understanding of the resilience of hydropower projects to disasters. Along with developments in the field, bridging this gap in sustainability assessments can improve the accuracy and effectiveness of risk evaluations[24]

Calculating hazards entails evaluating the spatial probability, frequency, and intensity of natural events such as earthquakes, floods, and landslides. Vulnerability is measured through socio-cultural, economic, physical, and environmental factors. Capacity is gauged using a regional resilience framework, emphasizing seven key areas: (1) Strengthening policies and institutions; (2) Conducting risk assessments and integrated planning; (3) Developing systems for information, training, and logistics; (4) Addressing disaster-prone areas systematically; (5) Improving disaster prevention and mitigation efforts; (6) Enhancing disaster preparedness and emergency management; and (7) Establishing systems for disaster recovery[22)].

The disaster risk index, a product of its constituent factors—hazard, vulnerability, and capacity—is influenced by the weight assigned to each element. Specifically, the hazard component contributes 40%, the vulnerability component 30%, and the capacity component 30% to determine the disaster risk index.

2.5.Analytic Hierarchy Process (AHP)

The decision-making method referred to as Thomas L. Saaty formulated the Analytic Hierarchy Process (AHP)[25)]. It facilitates the resolution of intricate decision challenges by systematically assessing numerous criteria and alternatives. References like Singh & Nachtnebel (2016) demonstrate the application of the AHP in reinforcing hydropower strategies, underscoring its relevance in the energy sector[26)]. Similarly, studies such as Bargues & Gisbert (2015) highlight the effectiveness of the AHP in selecting optimal locations for hydropower plants, emphasizing its practical utility in decision-making processes related to energy infrastructure[27)].

The Analytic Hierarchy Process (AHP) is invaluable for determining optimal locations for small hydropower projects with minimal risk of future natural disasters [28)]. The complexity of this decision, which involves multiple factors such as earthquakes, floods, landslides, drought, forest fire, extreme weather, and flash flood hazards, makes AHP an ideal tool. It allows for a comprehensive multi-criteria evaluation by assigning a relative weight to each criterion based on its importance. Its transparency and consistency in the decision-making process ensure that the judgments are rational and free from bias. The AHP's sensitivity analysis capabilities make measuring the impact of changes in criteria weights or input data possible, a significant feature when dealing with uncertain factors.

The AHP methodology allows for the incorporation of variable weight factors, as discussed by Wang *et al.* (2021), enabling the adjustment of weights over time or space to accommodate changing circumstances or priorities[29)]. This adaptability enhances the applicability of the AHP in dynamic decision-making contexts, such as selecting optimal locations for infrastructure projects like hydropower development. AHP facilitates engaging stakeholders through their input in pairs.

2.6.Weighting

The determination of the weight per hazard type is based on the relationship between the frequency of occurrence and the presence of warnings (see Table 1)

Table 1. Weighting comparison hazard

Hazard	WW	NW	LFO	HFO	W
Flash Floods	No	Yes	No	Yes	5
Landslides	No	Yes	No	Yes	5
Earthquake	No	Yes	Yes	No	4
Storm	Yes	No	No	Yes	4
Floods	Yes	No	No	Yes	4
Forest Fire	Yes	No	No	Yes	4
Volcanic Eruption	Yes	No	Yes	No	3
Drought	Yes	No	Yes	No	3
Extreme Weather	Yes	No	Yes	No	3

W = With Warning; NW = No Warning; LFO = Low Frequency Occurrence; HFO = High Frequency Occurrence; W = Weight

From Table 2, we can create a pairwise comparison between hazard types. Pairwise comparison is crucial in AHP. It helps assess relative importance. This comparison is vital in decision-making. The validity of the weights derived in the AHP process is essential and is typically evaluated based on the pairwise comparison matrix's consistency, as Ristono (2019) emphasized[30)].

Decision-makers use a numerical scale. It expresses the importance of one element over another. A consistency check ensures reliability. Inconsistencies are detected and corrected. The matrix analysis yields eigenvalues and eigenvectors. These quantify the overall priority. Derived weights calculate relative importance.

3. Results and discussions

3.1.Risk Index

The disaster risk index uses the risk formula (equation 2), and interpretation is divided into three classes: low, moderate, and high. $0 < r <= 0.3$ is low risk, $0.3 < r <= 0.6$ is moderate risk and $0.6 < r <= 1.0$ is high risk. Figure 2 shows the eight types of disaster risk at each potential small hydropower site. The risk potential map in Fig. 2 is generated by multiplying the hazard (H) of each type and vulnerability (V) and then dividing the result by the capacity (C)

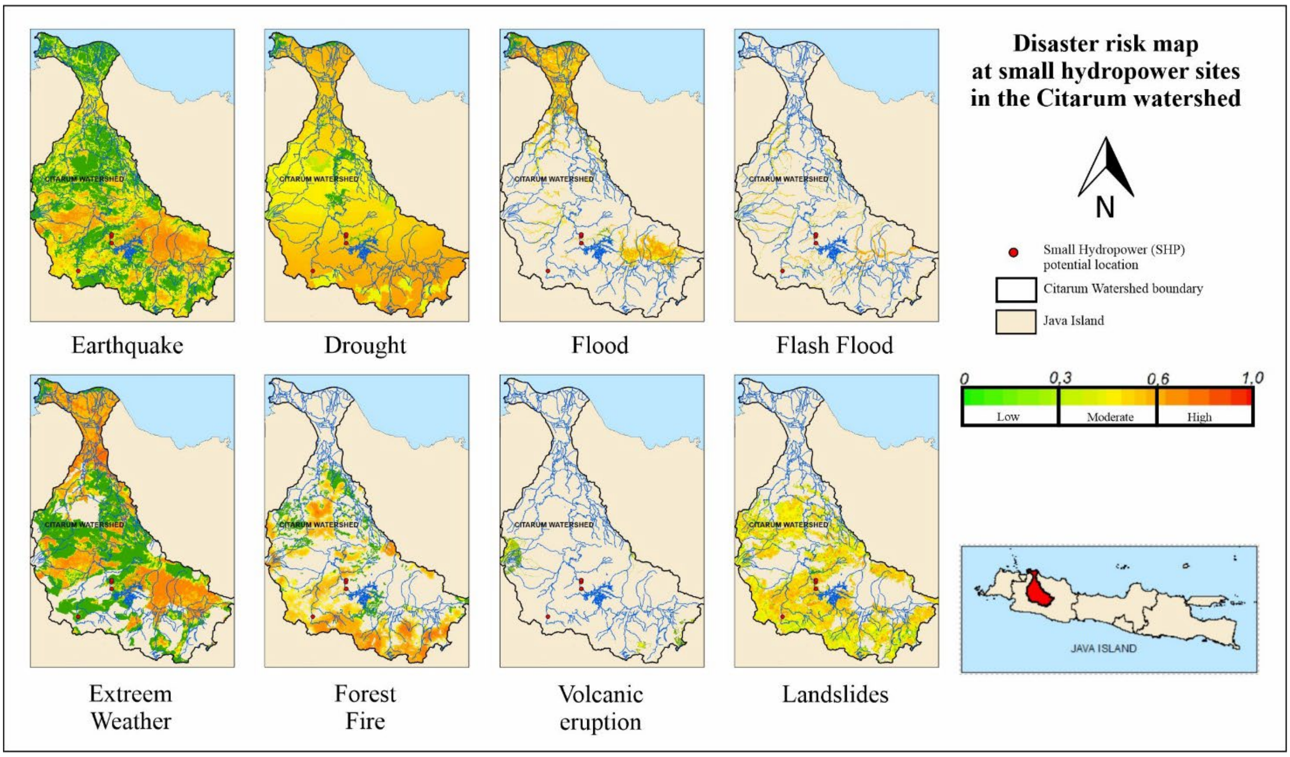

Fig.2: Disaster risk map at Small Hydropower (SHP) sites in Citarum watershed

The analysis of disaster risk index values for the four locations in Fig. 2 and Table 2 reveals a diverse risk profile, reflecting susceptibility to hazards. Across the dataset, variations in risk are evident, with some areas consistently exhibiting high risk. In contrast, others show a mix of low and moderate risk, and there is no location in the volcano eruption area.

Table 2. Risk Index in potential SHP sites

Site No	Earthquake	Landslides	Flash floods	Floods	Forest Fire	Drought	Extreme Weather
1	0.48	0.43	0.00	0.00	0.00	0.75	0.16
2	0.42	0.66	0.00	0.00	0.58	0.68	0.36
3	0.56	0.40	0.04	0.00	0.00	0.66	0.28
4	0.40	0.69	0.09	0.00	0.00	0.65	0.20

The computed risk index values consider earthquakes, landslides, flash floods, floods, forest fires, drought, and extreme weather. Notably, earthquakes and landslides contribute significantly to risk in multiple locations, while extreme weather events, drought, and forest fires also play distinct roles. The disaster risk values for each site can be interpreted as follows:

Site 1 faces a moderate risk of earthquakes and landslides, with values of 0.48 and 0.43, respectively. There is no risk of flash floods, floods, or forest fires as their values are 0.00. However, there is a high risk of drought, indicated by a value of 0.75, and a low risk of extreme weather, with a value of 0.16.

Site 2 has a moderate risk of earthquakes at 0.42 but a high risk for landslides and drought, with values of 0.66 and 0.68. The risk of forest fires is also moderate at 0.58, and there is a low to moderate risk of extreme weather, with a value of 0.36.

Site 3 exhibits a moderate risk for earthquakes and landslides, with values of 0.56 and 0.40. Flash floods present a shallow risk at 0.04, with no risk for floods or forest fires. Drought risk is high at 0.66, and there is a low to moderate risk of extreme weather at 0.28.

Site 4 Shows a moderate risk of earthquakes at 0.40 and a high risk of landslides at 0.69. Flash floods have a low risk at 0.09, with no risk of floods or forest fires. Drought has a high-risk value of 0.65, and extreme weather is at a low risk of 0.20.

The analysis underscores the importance of a comprehensive risk assessment that includes multiple hazards, providing insights for policymakers and communities to prioritize resource allocation, emergency planning, and infrastructure development. Overall, this information aids in implementing effective measures tailored to the specific vulnerabilities of each location, contributing to resilient and prepared communities.

3.2.Analytic Hierarchy Process (AHP)

Table 4 outlines the outcomes of the Analytic Hierarchy Process (AHP) and presents a comprehensive assessment based on total, normal, and ideal values, with corresponding rankings and risk classifications. Risk classification based on ideal values is divided into three classes: low, moderate, and high. $0 < r <= 0.3$ is low risk, $0.3 < r <= 0.7$ is moderate risk and $0.7 < r <= 1.0$ is high risk. Locations 2 and 4 emerge as the top contenders with the highest potential, all classified as "High" risk. This consistency in high-ranking locations suggests a concentrated region with significant small hydropower potential, providing valuable information for targeted development efforts. The transition to "Moderate" risk for locations 3 and 1 indicates that while these areas may not exhibit the same level of potential as the top two, they still present viable opportunities for small hydropower projects.

Table 4. AHP Result

Sites	Total	Normal	Ideal	Rank	Risk
Loc 2	0.1631	0.3264	1.0000	1	High
Loc 4	0.1395	0.2789	0.8546	2	High
Loc 3	0.1018	0.2036	0.6238	3	Moderate
Loc 1	0.0955	0.1910	0.5853	4	Moderate

The normalization and ideal values, integral to the AHP methodology, contribute to the systematic comparison of alternatives, enhancing the scientific rigor of the assessment. Policymakers and stakeholders can use these results to allocate resources and investments strategically, prioritizing regions with high potential while considering moderately ranked locations for future development. To decide on the best location, you can also use several other alternative options depending on the aspects to be assessed, as done by Bargues and Gisbert (2015); the main criteria identified in their study for the selection of RoR plants are protected fauna, fish population, water quality, landscape quality, flow regime, and vegetation[27)].

Overall, the AHP results offer a scientifically grounded basis for decision-making, aiding in identifying areas suitable for small hydropower projects with varying levels of risk.

3.3.Mitigation

Threats to multi-disaster potential are mitigated based on the type of threat in each location.

Site No 2: With high risks of landslides, forest fires, droughts, and extreme weather events, Site No 2 requires comprehensive mitigation measures. Afforestation and vegetation management can reduce the likelihood and severity of forest fires and landslides. Implementing firebreaks and controlled burns can also help manage forest fire risks. Water conservation measures and drought-resistant crop varieties can mitigate the impacts of droughts. Additionally, early warning systems and community evacuation plans are crucial for preparedness against extreme weather events.

Site No. 4: Given the combination of moderate to high risks of landslides, floods, forest fires, and droughts, mitigation efforts at Site Number Four should prioritize a multi-faceted approach. Afforestation and reforestation initiatives can help reduce the risk of forest fires and landslides by stabilizing slopes and improving soil moisture retention. Implementing floodplain management strategies, such as constructing levees and floodwalls, can mitigate flood risks. Drought preparedness measures, including water conservation practices and developing alternative water sources, are essential to address water scarcity. Community-based fire prevention programs and early warning systems can enhance resilience to forest fires and extreme weather events.

Site No 3: Mitigation strategies at this site should concentrate on structural and non-structural elements to address the combination of moderate to high risks. Implementing erosion control measures and slope stabilization techniques can reduce landslide risks. Floodplain zoning and the construction of flood defenses can mitigate the impacts of flash floods and floods. Drought mitigation strategies may include water-efficient practices in agriculture and promoting alternative livelihoods that are less dependent on water resources. Enhancing community awareness and preparedness through education and training programs can also improve resilience to extreme weather events.

Site No 1: Here, there is a moderate to high danger of landslides, droughts, and extreme weather events. As such, early warning systems and infrastructure reinforcement should be the main priorities of mitigation measures. Soil stabilization measures can help reduce landslide risks, while water management strategies such as rainwater harvesting and efficient irrigation can mitigate drought impacts. Installing weather monitoring stations and establishing community disaster response plans can enhance preparedness for extreme weather events.

3.4.Policy

Policy-related mitigation strategies can play a significant role in enhancing disaster resilience.

Strengthening Regulatory Frameworks: Establishing and enforcing robust regulatory frameworks specific to hydropower development can help mitigate disaster risks. This work includes comprehensive environmental impact assessments (EIAs) and stringent building codes considering potential natural hazards such as landslides, floods, and earthquakes. These measures should be complemented by disaster risk management plans and emergency response protocols to improve preparedness and coordination among stakeholders[31)]. Using a risk-analysis methodology, Vadya et al. (2021) conclude that effective risk management, the facilitation of efficient financial markets, and the promotion of equitable and cordial cross-border energy trading will determine the future of hydropower. Regulations should also mandate the implementation of disaster risk management plans and emergency response protocols to ensure preparedness and coordination among stakeholders.

Integrated Land-Use Planning: Implementing integrated land-use planning policies can minimize vulnerability to natural hazards in hydropower project areas. The Organisation for Economic Cooperation and Development (OECD) report (2023) suggests land use planning plays a crucial role in preventing wildfires by considering existing and projected wildfire hazards in decision-making processes[32]. This work involves zoning regulations restricting development in high-risk areas prone to landslides, floods, and other hazards. Promoting sustainable land management practices and preserving natural ecosystems such as forests and wetlands can serve as natural buffers against disasters, reducing the likelihood and severity of impacts on hydropower infrastructure.

Incentivizing Resilient Infrastructure: Governments can offer incentives or subsidies to construct resilient hydropower infrastructure incorporating disaster-resistant design principles. This role includes reinforced dam structures, flood-resistant powerhouse facilities, and landslide mitigation measures. Financial mechanisms such as insurance schemes and risk-sharing agreements can also incentivize private sector investment in disaster-resilient infrastructure. United Nations Office for Disaster Risk Reduction (UNDRR) (2022) outlined principles for resilient infrastructure, including the importance of considering disaster risk reduction measures in infrastructure design and construction[33]. It also discusses the need for financial mechanisms such as insurance schemes and risk-sharing agreements to incentivize private sector investment in disaster-resilient infrastructure.

Stakeholder Engagement and Community Participation: Policies should prioritize stakeholder engagement and community participation in decision-making processes related to hydropower development and disaster risk management. This role includes consulting local communities and indigenous groups to ensure their perspectives and traditional knowledge are integrated into planning and implementation efforts. Empowering communities through training programs on disaster preparedness, early warning systems, and evacuation procedures can enhance their resilience and capacity to respond to emergencies effectively. Witvorapong *et al.* (2015) suggest empowering communities through training programs enhances their preparedness and strengthens their ability to contribute to disaster response and recovery efforts actively[34].

Transboundary Cooperation: Given that hydropower projects often span multiple jurisdictions, fostering transboundary cooperation and information-sharing mechanisms is essential for managing shared disaster risks effectively. Bilateral or multilateral agreements can facilitate collaboration among neighboring countries to address common challenges such as flood management, sedimentation, and dam safety. Giordano *et al.* (2013) review joint monitoring and early warning systems can help anticipate and mitigate potential cross-border impacts of natural hazards on hydropower infrastructure[35]. It is the same view as that of Barua *et al.* (2019) that transboundary cooperation in the context of hydropower development involves the establishment of formal arrangements like treaties, agreements, joint mechanisms, and river basin organizations to promote collaboration and information exchange among riparian countries. These agreements aim to enhance coordination and address challenges related to water management, hydropower development, and disaster risk reduction across borders[36]

By integrating these policy-related mitigation strategies into the planning and development of hydropower projects, governments and stakeholders can enhance disaster resilience, protect critical infrastructure, and ensure sustainable energy production in the face of natural hazards.

This study is a comprehensive assessment of hydropower sites, examining their susceptibility to various multi-disaster risks, including landslides, earthquakes, floods, flash floods, forest fires, droughts, and extreme weather events. This approach represents a significant advancement in sustainability assessments for hydropower projects.

Compared to Dhaubanjar et al. (2021)[2], where disasters were considered in the context of sustainability assessments, the focus was primarily on landslides and earthquakes as indicators, emphasizing the potential for disaster. However, the measurements of vulnerability and capacity were notably absent from their analysis. The current research, on the other hand, identifies potential disaster risks and incorporates crucial elements such as vulnerability and capacity into the assessment, providing a more comprehensive understanding of the risks associated with hydropower sites.

In contrast, the study by Kuniyal *et al.* (2019)[3] concentrated on assessing the location of hydropower facilities concerning the potential for flooding and landslides. Similar to the work of Dhaubanjar et al., their analysis primarily focused on vulnerability and disaster aspects, neglecting the evaluation of capacity or the determination of overall risk values. This study adds considerably to the body of knowledge on hydropower site evaluations by addressing a wider range of multi-disaster risks and incorporating vulnerability, capacity, and risk potential in the assessment.

This comprehensive approach adopted by the current research advances the understanding of the potential threats of various disasters. It provides a more holistic perspective, considering the interplay between vulnerability, capacity, and overall risk. Including these factors is crucial for developing more effective risk mitigation strategies and enhancing the sustainability of hydropower projects in the face of a diverse range of potential hazards.

4. Conclusion

The analysis of the disaster risk index for potential small hydropower sites in the Citarum watershed reveals significant variability in risk levels across different locations. The average risk scores for the sites are as follows: Site 1 has an average risk of 0.3525, indicating moderate vulnerability, while Site 2 shows a higher average risk of 0.5875, reflecting greater susceptibility to multiple hazards. Site 3 also exhibits a high average risk of 0.6175, and Site 4 stands out with the highest average risk of 0.75375, highlighting its significant exposure to natural disasters.

These findings suggest that Sites 2, 3, and 4, in particular, require more robust disaster risk management and mitigation strategies due to their higher average risk levels. Site 1, with a moderate risk, still necessitates adequate preparedness measures but may present fewer challenges than other sites. The data underscores the critical need for tailored disaster resilience plans to ensure the sustainable development of small hydropower projects in these regions.

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