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Loss Damage Analysis & Risk Mitigation Modelling of Operational Phases Hydropower Due To Natural Calamities in Nepal

by

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A THESIS

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ABSTRACT

This report presents a detailed Quantitative Risk Assessment (QRA) of the Radhi Hydropower Project (4.4 MW) to evaluate the vulnerability of hydropower operations during operational phase to natural hazard in Nepal. A unified risk model (Risk = Hazard × Vulnerability × Exposure) was used to analyze Relative Importance Index (RII) values generated through expert consultation along with empirical operational data.

The main results show that the overall risk profile of this project is mainly controlled by external geomorphologic & hydrologic hazards instead of internal mechanical failure. Landslides (RII= 0.96) and floods (RII= 0.84) are identified as the two greatest risks to the project. Both landslides and floods pose great danger to what we term "weak link" elements of the project’s infrastructure including transmission lines (RII= 0.98) and intakes.

An integrated approach was utilized to determine the area at which landslide hazard intersected with transmission exposure as the highest risk scenario (Risk Score= 0.94). In terms of economic evaluation, it has been determined that there is a large 'resilience gap' within this type of project. Routine hazards produce manageable losses while tail risk events (e.g., the 2080B.S. flood) could potentially generate revenue loss more than Nrs. 1.36 million (or over 22% of the total project cost) per annum. Furthermore, while structural flood defenses show high efficiency (82.11%), sediment management systems (41.05%) remain significantly underpowered.

The report concludes that Nepalese hydropower is "structurally robust but operationally fragile". It recommends a transition toward adaptive risk management, prioritizing the hardening of off-site infrastructure, implementing real-time sediment monitoring, and integrating climate-change projections into future design criteria to ensure long-term energy security.

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LIST OF ABBREVIATIONS

CBE	Cloud Burst Event
CF	Capacity Factor
DRI	Disaster Risk Index
E	Exposure
EWS	Early Warning System
GLOF	Glacial Lake Outburst Flood
GWh	Gigawatt-hour
H	Hazard
HCR	Hazard Contingency Reserve
HPP	Hydropower Project
HVOF	High-Velocity Oxygen Fuel coating
ICIMOD	International Centre for Integrated Mountain Development
IPPAN	Independent Power Producers' Association of Nepal
LDOF	Landslide Dam Outburst Flood
MW	Megawatt
MWh	Megawatt-hour
NEA	Nepal Electricity Authority
NPR / NRs	Nepalese Rupees
NPV	Net Present Value
PGA	Peak Ground Acceleration
PPA	Power Purchase Agreement
PSHA	Probabilistic Seismic Hazard Assessment

CHAPTER 1: INTRODUCTION

1.1 Background

Hydropower is one of the most important renewable energy sources globally and plays a dominant role in Nepal's energy sector. In Nepal, electricity access has expanded significantly, reaching about 99% of the population in FY 2023/24, with hydropower serving as the primary source of electricity generation(NEA, 2024). Nepal possesses immense hydropower potential due to its abundant water resources and steep topography, with an estimated theoretical capacity of approximately 83,000 MW and economically feasible potential of about 42,000 MW(Shrestha, 1966). Despite this, only a small fraction of this potential has been harnessed, resulting in continued energy deficits and supply instability, particularly during the dry season(Alam, Alam, Reza, Alam, Saleque, & Chowdhury, 2017). This highlights the urgent need for sustainable and resilient hydropower development.

Hydropower projects are inherently complex and capital-intensive infrastructure systems that involve multiple stakeholders, long construction timelines, and significant environmental and socio-economic interactions. Due to the scale and complexity hydropower projects are exposed to a wide range of risks, including technical, financial, environmental, political, and operational uncertainties(Shaktawat & Vadhera, 2021; Ojha, Baral, & Mishra, 2025; Gurung, 2020). Risk is an inherent characteristic of any project, and its likelihood and consequences tend to increase with project size and complexity. Effective risk analysis is therefore essential for ensuring project feasibility, optimizing investment decisions, and enabling the development of cost-effective mitigation strategies(Huikku, Karjalainen, & Seppälä, 2026; Mammadova & Agayev, 2025).

In hydropower projects, Risk management is systematic processes of risk identification, assessment, prioritization, and mitigation. The primary objective of the risk analysis is to eliminate risks before their occurrence or to minimize their impacts(Mulholland & Christian, 1999). In construction and infrastructure projects, risks arise from various sources such as geological uncertainty, hydrological variability, design deficiencies, financial constraints, and regulatory challenges(Kucukali , 2011; Tripathi & Shrestha, 2017). If risks are not properly managed, they can lead to cost overruns, delays in project completion, reduced operational efficiency. In extreme cases, the risks can even lead to the failure of the project.

Due to country's fragile geology, steep terrain and climatic condition, Nepalese hydropower projects are highly affected by natural hazards. The region is highly prone to landslides, floods, debris flows, earthquakes, and Glacial Lake Outburst Floods (GLOFs), which significantly affect both construction and operational phases of hydropower systems(Kadel, Chaudhary, & Khadka). Recent climate change trends have further intensified these risks by increasing the frequency and magnitude of extreme weather events, altering precipitation patterns, and accelerating glacier retreat in the Himalayan region(Sati , 2025). These changes have led to increased occurrences of flash floods, sedimentation, and water-induced disasters, thereby posing serious threats to hydropower infrastructure.

Climate change impacts in Nepal are particularly severe due to its diverse topography and limited adaptive capacity. Rising temperatures, changing rainfall patterns, and increasing intensity of extreme events have amplified hazard exposure in river basins, directly affecting hydropower generation system(Khatri & Pandey, 2021). Furthermore, glacial retreat in the Himalayan region has increased the risk of GLOFs, which can cause catastrophic damage to downstream infrastructure, including hydropower plants(ICIMOD, 2011; Chen, Liang, Zhao, & Maharjan, 2025).

Hydropower Projects are very important for the development of a country. Despite the growing importance, Nepalese hydropower projects face problems such as delays, cost overruns, and operational inefficiencies. In addition, recent record-breaking floods and landslides of September 2024 have shown us that even operational phase hydropower plants are vulnerable to disruptions induced by natural hazard. It resulted in substantial energy and financial losses, including a temporary 57% reduction in national power output and over NPR 3 billion in direct infrastructure damage(Urja Khabar, 2025).

Although there has been numerous risk analysis conducted during the planning and construction phases, relatively limited attention has been given to risk assessment during the operational phase of small hydropower projects. Moreover, there is a lack of integrated approaches that combine risk quantification, operational loss assessment, and evaluation of mitigation measures.

In order to address these gaps, this study focuses on the Radhi Hydropower Project to evaluate hazard-induced risks and their impacts on plant operation. The study focuses on identifying critical risk factors, quantifying associated energy and financial losses, and assessing the effectiveness of mitigation measures. Hence, the findings are expected to contribute to informed decision-making and enhance the resilience of operational phase hydropower in Nepal.

1.2 The Run-of-River Model and its Inherent Vulnerabilities

The run-of-river hydropower model dominates Nepal's installed hydropower capacity. In such hydropower system, a portion of river flow through a series of civil structures, intake weir, desander basin, headrace canal or tunnel, forebay tank, penstock, powerhouse to drive turbines before returning water to the river. In contrast to storage hydropower plants, RoR hydropower plants provide limited capacity in terms of flow regulation. Therefore, they are directly exposed to the variability and extreme behavior of natural river discharge conditions.

A number of risks are inherent in this type of hydropower development design. Firstly, the entire hydraulic system, from intake to tailrace, is permanently in contact with the river environment. This makes each hydrometeorological extreme an automatic operational challenge. Secondly, the RoR facility is geographically extensive i.e., the distance between headworks and powerhouse can amount to several kilometers, while the location of the transmission line can lie several kilometers away from the powerhouse site. Due to this, the infrastructure is exposed to hazards across a large geographical location. And thirdly, the financial framework of RoR hydropower projects relies on maximizing energy production during the monsoon period. During monsoon period river flows are high which enables greater power generation. However, this period also coincides with lower grid prices and an increased likelihood and magnitude of natural hazards, creating significant operational and financial risks.

The simultaneous occurrence of all these factors generates an inherent operational paradox where the most favorable conditions for energy production also generate the highest probability of disruption in operation of hydropower plants from natural hazards. This operational paradox forms the central question to be answered in this report.

1.3 Problem Statement

Despite the increasing vulnerability of hydropower plants to risk induced from natural hazards, there is a lack of a systematic framework for:

- Quantifying operational loss and damage
- Linking hazard, vulnerability, and exposure into a unified risk model
- Estimating energy and financial losses due to disruptions
- Evaluating the effectiveness of mitigation measures

In the context of Nepal, most of the existing studies focus on either structural design safety or hydrological modelling but operational risk and economic loss assessment remain insufficiently addressed.

Hence, this gap limits the ability to make informed decisions regarding risk mitigation, investment prioritization, and long-term sustainability of Nepalese hydropower plants.

1.4 Objectives

1.4.1 Main Objective

To assess operational loss and damage in hydropower plants due to natural hazards and to develop a risk-based mitigation framework.

1.4.2 Specific Objectives

- To identify and rank major natural hazards affecting hydropower operation
- To evaluate vulnerability of critical hydropower components
- To develop a risk assessment model integrating hazard, vulnerability, and exposure
- To estimate energy and financial losses due to operational disruptions
- To evaluate the efficiency of mitigation measures

1.5 Scope of Study

The focus of this study is limited to the operational phase of the Radhi Hydropower Project. The parameters for the analysis of risks are as follow:

1.5.1 Hazard Scope

The six primary natural hazards that would be considered during the analysis are floods, landslides and slope failures, debris flows, sedimentation and sediment-induced erosion, earthquakes, and Glacial Lake Outburst Floods (GLOFs). This selection incorporates all types of hazards identified as operationally relevant by the project's operational history and the broader Himalayan hydropower literature.

1.5.2 Infrastructure Scope

The seven major infrastructure categories which are assessed for its vulnerability towards natural hazards are transmission lines, intake structures, desander basins, turbines, penstocks, generators, and powerhouse buildings. This encompasses all major components in the hydropower plants from water intake to electricity distribution.

1.5.3 Analytical Limitations

This current analysis does not incorporate detailed finite element structural analysis (FEA) of individual hydropower components, hydrodynamic flood modeling, probabilistic seismic hazard assessment (PSHA), and climatic condition projections. It should be noted that the above topics are identified as important research directions for further development of the analysis.

The exposure assessment framework adopted in this study is based on a semi-quantitative scoring approach. It simplifies complex spatial and physical phenomenon into discrete categories. While this enables systematic comparison across components, it may not fully capture localized variations in topography, micro-scale hazard pathways, or dynamic changes in river morphology. The introduction of geospatial analysis tools or physics-based exposure modeling can provide additional benefits.

Although Relative Importance Index (RII) approach is effective in capturing expert judgment and prioritizing risk factors, it is inherently influenced by expert opinion and the process of prioritizing risk factors. Therefore, the results should be interpreted with other secondary data sources and case study studies that function as a form of validation tool.

CHAPTER 2: LITERATURE REVIEW

2.1 Hydropower and Natural Hazards

In the context of Nepal, Hydropower plants are dependent on hydrological and geological conditions, making them sensitive to risk of natural hazards. It was found that floods and landslides are the most frequent hazards impacting the operation of hydropower plants. Their impact is intensified by the steep slopes and fragile rock masses of the region (Regmi & Dahal, 2024). This was evidenced by recent data, showing that extreme weather events in 2023 and 2024 caused damage to more than 60 hydropower facilities in Nepal, with a cumulative lost capacity of 1,100 MW(Urja Khabar, 2025).

2.1.1 Hydro-meteorological Hazards

Floods are the most significant threat to run-of-river hydropower plants in Nepal. Nepal experiences high monsoon rains that occur mainly during summer, specifically between June and September, resulting in significant changes in river discharge, and hence creating both opportunities and challenges for RoR hydropower projects(Kadel, Chaudhary, & Khadka). Cloud Burst Events (CBEs), where localized rain intensity is extremely high at above 100 mm per hour, have been identified to result in flash floods capable of overwhelming the intake structures within minutes, leaving no sufficient time for preventive shutdown.

The hydraulic effects of flood events on hydropower facilities involve several aspects of damage. Hydraulically, flood events result in flow volumes exceeding the design discharge capacity, resulting in weir crest overtopping, backwater flooding of desander basins, and uplift pressure on structural foundations. In addition, flood events can also result in an increase in suspended sediment concentration and bedload transport, thereby increasing the abrasion potential of sediment throughout turbine. Morphologically, flood events result in channel migration, which causes erosion of intake foundations, transmission tower footings, and permanent changes in hydraulic geometry utilized by the project's hydraulic system(Sah, Gautam, Pokharel, Gautam, & Silwal, 2025). Moreover, high river flows can cause major damage to transmission lines because riverbank erosion weakens the foundations of the towers. (NEA, 2024).

The correlation between the volume of floods and their impact on operations does not follow a linear trend. The floods whose volume remains in line with or only slightly exceeds the design discharge can be controlled by following operational protocols, adjusting gates, and temporary shutdowns. But when the volume of floods is high and substantially exceeds the design level, there will be entirely new forms of failure such as demolition of intake structures, shifting of penstocks, and flooding of the powerhouse. The 2080 B.S. flood event analyzed in this study represents this extreme category.

2.1.2 Geological and Sedimentological Hazards

Nepalese Hydropower plants are significantly affected by geological hazards like landslides, debris flows, and rock falls. All these geological hazards arise due to the fragile and heavily fractured geology of the young Himalayan range. The Himalayan region is constantly affected by tectonic forces that create cracks and weak zones in rocks which leads to the formation of naturally unstable slopes. During the monsoon, heavy rainfall soaks the soil and increases water pressure inside it. This phenomenon often triggers landslides and other slope failures in these already vulnerable areas.

The Nepalese river basins originated from higher Himalayas which naturally carries massive sediment influx during the monsoon. Several studies show that suspended sediments, primarily quartz, cause severe erosion of turbines. The erosion of turbines significantly reduces the operational efficiency and increases the maintenance costs of hydropower project(Thapa, Shrestha, Dhakal, & Thapa, 2004). In addition, landslides and debris flows further affects the hydropower project by causing physical blockages of intake structure(Regmi & Dahal, 2024).

In the context of Nepal, when a landslide blocks a river, it can form a temporary natural dam that stores a large amount of water. This dam may eventually fail due to overflowing water, erosion, or seepage through the deposited material. When the dam breaks, it releases a powerful flood carrying debris from both the landslide and the stored water. Such floods can be much larger and more destructive than normal rainfall floods, causing severe damage to downstream infrastructure that was not designed to handle such extreme events.

2.1.3 Compound and Cascade Hazards

The recent literature highlights the impact of cascade hazards, such as Landslide Dam Outburst Floods (LDOFs) and Glacial Lake Outburst Floods (GLOFs). These hazards can create a domino effect where a single geological failure upstream can release a surge of water and debris. This powerful flow can overwhelm downstream infrastructure which are designed only for normal flood conditions(ICIMOD, 2011; Mir, Jain, Ahmed, & Farooq, 2025).

2.1.4 Seismic Hazards and Glacial Lake Outburst Floods

Nepal lies in one of the most earthquake-prone regions in the world because it is located between the Indian and Eurasian tectonic plates. This creates a constant risk of earthquakes. The 2015 2015 Gorkha earthquake, with a magnitude of 7.8, showed how destructive such events can be. However, many operating hydropower projects experienced less damage than expected. This is partly because the earthquake occurred at a favorable time and hydraulic structures of hydropower are generally massive and stable.

Glacial Lake Outburst Floods (GLOFs) are becoming an increasing threat to Nepalese hydropower plants due to climate change, which is causing glaciers in the Himalayan region to melt and expand glacial lakes. Studies by (Chen, Liang, Zhao, & Maharjan, 2025)shows that the exposure of Nepalese hydropower to GLOFs is increasing, with particular concern for projects located in upper river catchments where glacial lake are growing rapidly. (ICIMOD, 2011)has prepared an important inventory of glacial lakes in Nepal and identified many lakes as potentially dangerous.

Although the Radhi Hydropower project is not currently in direct GLOF risk zone, glacial lakes continue to change over time. Therefore, regular reassessment and monitoring are necessary in order to ensure safety of hydropower projects.

2.2 Risk Assessment Framework

In the context of hydropower plants, risk is defined as the potential for damage or loss caused by the interaction between natural hazards and hydropower components. This research uses the widely accepted Disaster Risk Index (DRI) framework. According to DRI framework, Risk (R) depends on following three main factors:

$$Risk = Hazard \times Vulnerability \times Exposure \tag{1}$$

This tripartite risk assessment model is commonly used for quantifying potential losses in hydropower plants and climate adaptation studies(IPPC, 2023; Kron, Flood Risk = Hazard • Values • Vulnerability, 2005).

In the context of hydropower plants, these three components are defined as follows:

2.2.1 Hazard (H)

Hazard refers to the likelihood of a physical event occurring at a certain location and time with a particular intensity. In hilly region catchment area, the hazard includes both hydro-meteorological events such as major floods and secondary geological events like landslides and GLOFs. The intensity of these hazards is normally measured using factors like peak discharge, flow velocity, or peak ground acceleration (PGA) during earthquakes(Kadel, Chaudhary, & Khadka). The recent studies by World Bank highlight that climate change has made these hazards “non-stationary”. It means that past records alone are no longer enough to accurately predict future extreme events. (World Bank Group, 2021).

2.2.2 Vulnerability (V)

Vulnerability refers to how likely a hydropower system is to be damaged when exposed to a hazard of a certain intensity. It can be divided into two categories:

- Physical Vulnerability: This relates to the structural weakness of components such as the dam, intake, and desander basin, which may fail or overflow during extreme events.(Sayers, et al., 2013).
- Functional Vulnerability: This refers to the risk of operational failure in electromechanical systems like turbines, generators, and control panels. It is often due to problems such as heavy sediment deposition or flooding in the powerhouse(Sah, Gautam, Pokharel, Gautam, & Silwal, 2025).

2.2.3 Exposure (E)

Exposure refers to how much a hydropower component is located within or near a hazard-prone area. It determines how severely it may be affected during a hazard event(Kadel, Chaudhary, & Khadka; United Nations). Instead of considering the exposure of hydropower component as simply exposed or not exposed, this study used a scale from 0 to 1. This score represents the exposure level of each component in Radhi HPP. The exposure value of major hydropower component is assigned based on evaluation of two criteria(Kometa, Olomolaiye, & Harris, 1995):

i. The physical location of hydropower components relative to the primary hazard-prone area, and

ii. The degree of protection or burial of the hydropower component.

In the context of Nepalese hydropower plants, the exposure value is often high. It is because the hydropower projects are often built in narrow and steep river valleys which are highly vulnerable to natural hazards like floods, landslide and debris flow(Independent Power Producers' Association, 2025).

For the standardization of exposure assessment, exposure is classified into four categories as presented in Table 1.

Table 1: Exposure Classification Criteria

Exposure Category	Description
Direct Exposure	Component is located in the active hazard zone (e.g., riverbank, unstable slope) with no physical protection and in immediate contact with the hazard source.
High Exposure	Component is situated in close proximity to the hazard zone (e.g., near the river) with slight offset or limited natural buffering.
Moderate Exposure	Components are partially buried or structurally enclosed, reducing direct interaction with the hazard environment but not fully protected.
Low Exposure	Components are fully enclosed within engineered structures or adequately shielded, significantly limiting exposure to external hazards.

2.3 Loss and Damage Assessment

The assessment of losses in the hydropower sector includes not only physical damage to infrastructure but also the economic and operational impacts. After the occurrence of natural hazard, losses can be classified into two categories:

- Direct tangible losses: It includes the physical damage to the hydropower structure due to natural hazards.
- Indirect tangible losses: It includes the losses caused by operational shutdowns, reduced electricity generation and revenue reduction(Meyer, et al., 2023).

2.3.1 Quantification of Operational Losses

Operational losses are mainly determined by how long the hydropower system remains out of service. The Energy Loss (E_{loss}) due to the operational loss can becalculated by using the following equation:

$$\text{Energy Loss} = \text{P} \times \text{Toutage} \tag{2}$$

Where,

P: It is the installed Capacity (MW) of the hydropower project,

Toutage: It is the total duration of downtime (hours) needed for debris removal, structural repairs, or restoration of electromechanical system.

In the context of Run-of-River (RoR) hydropower plants in Nepal, operational losses are strongly affected by seasonal flow. During wet season, river discharge is at its peak and the generation potential is highest. Hence, most of the operational energy loss occurs during the wet (monsoon) season. As a result, even short outage duration during wet season can lead to major energy losses. However, outages during the dry season have a comparatively lower impact on the operational loss of the hydropower project.

2.3.2 Financial and Systemic Impacts

The financial Loss to the hydropower project depends on the amount of energy that could not be generated due to natural hazards and is the function of the energy shortfall and the prevailing Power Purchase Agreement (PPA) rate. It can be calculated using the following formula:

$$\text{Financial Loss} = \text{Energy Loss} \times \text{Tariff} \tag{3}$$

However, this equation cannot fully capture the total economic impact of the hydropower project. For example, the September 2024 floods in Nepal highlighted additional losses such as penalties for failing to supply electricity to the national grid and the extra cost of importing emergency electricity to maintain grid stability.(Urja Khabar, 2025)(Independent Power Producers' Association, 2025)(Wang, He, Wu, & Teng, 2025).

2.3.3 Infrastructure Damage and Rehabilitation Costs

The direct infrastructure damage includes the cost of repairing or rebuilding civil structures of hydropower plants such as headworks and desander basins, as well as electromechanical equipment like turbines and generators.

In the Himalayan region, these costs are often much higher because hydropower projects are located in remote areas. It is also increased due to damage to access roads which can delay transportation and increase the expense of bringing heavy equipment and repair materials to the project site.(Regmi & Dahal, 2024).

2.4 Mitigation Measures

Mitigation strategies in hydropower projects aim to reduce either the magnitude of the hazard or the vulnerability of the hydropower components. These measures can be divided into two categories: Structural measures and non-structura lmeasures(World Bank Group, 2021).

2.4.1 Structural Mitigation Measures

The structural mitigation measures include physical measures to protect the hydropower components from natural hazards.

- Flood and Debris Control: For the protection of hydropower components from the impact of flood and debris, guide bunds, spurs, and floodwalls are constructed. To counter GLOFs and debris flows, check dams and flexible debris barriers are increasingly utilized to dissipate the energy of moving masses before they reach the headworks(Regmi & Dahal, 2024).
- Slope Stabilization: Given Nepal's fragile geology, bioengineering combined with hard engineering (e.g., shotcreting, rock bolting, and drainage galleries) is critical to prevent landslide-induced damage to access roads and penstock pipes(Timilsena , 2023).

2.4.2 Sediment Management and Operational Challenges

Literature suggests that while structural measures are generally effective for flood control, sediment management remains a persistent challenge in the Himalayan region. High concentrations of abrasive minerals (primarily quartz) during the monsoon lead to severe turbine erosion.

- Mitigation Techniques: Common practices include the use of S-trap desanding basins and periodic sediment flushing through bottom outlets.
- Advanced Coatings: Recent studies emphasize the adoption of High-Velocity Oxygen Fuel (HVOF) thermal spray coatings to extend the operational life of runner blades, though these require frequent re-application and high maintenance costs(Yu, et al., 2022).

2.4.3 Non-Structural Measures

Modern risk management also integrates non-structural strategies, such as Early Warning Systems (EWS) and insurance mechanisms. Real-time monitoring of upstream river levels and glacial lakes can provide the necessary lead time to shut down turbines and close intake gates, thereby preventing electromechanical damage during extreme events (Kadel et al., 2024).

2.5 Research Gap

Despite the extensive body of literature on disaster risk, several critical gaps persist in the context of Himalayan hydropower development. This study specifically targets the following deficiencies:

- **Limited Focus on Operational Phase Losses:** Existing research heavily prioritizes the construction phase, where delays and cost overruns are most visible, often neglecting the long-term operational risk profile. There is a lack of high-resolution data on the recurring "micro-losses" from annual monsoon sediment and downtime, which can cumulatively exceed the cost of initial construction failures.
- **Lack of Integrated Risk Models:** Most studies treat hydrological (floods) and geological (landslides) hazards as isolated variables. However, the 2024 disaster highlighted that risks are often compounded or cascading(Urja Khabar, 2025). Current frameworks lack the integration necessary to model how a landslide-induced dam failure upstream specifically translates into electromechanical failure downstream.
- **Insufficient Evaluation of Mitigation Efficiency:** While many structural measures (e.g., floodwalls, check dams) are proposed, there is a distinct shortage of post-disaster forensic evaluation to determine their actual performance under extreme conditions. There is no standardized benchmark in the Nepalese context to compare the cost-benefit ratio of "hard" structural interventions against "soft" measures like early warning systems or insurance.

By addressing these gaps, this research aims to provide a more holistic and operationally-focused risk assessment for Nepal’s hydropower sector.

CHAPTER 3: METHODOLOGY

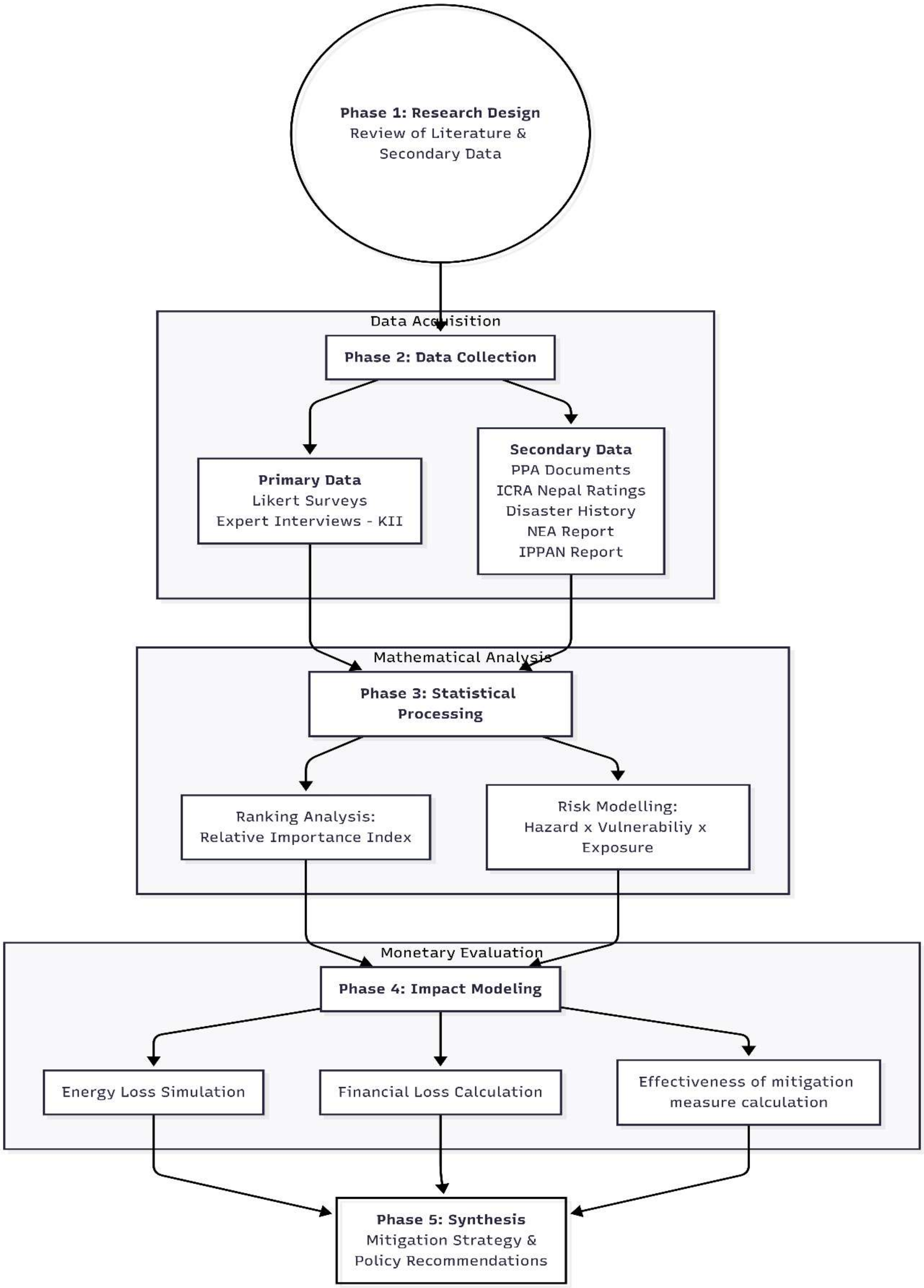


Figure 3.1: Methodological Framework for Hydropower Risk and Financial Impact Assessment

The Figure 3.1 illustrates a structured, five-phase analytical framework designed to evaluate natural hazard risks and their financial implications for the Radhi Hydropower Project.

- **Foundation and Data Acquisition:** The process begins with Phase 1 (Research Design), which involves a comprehensive review of existing literature and secondary data to establish the study's context. This leads into Phase 2 (Data Collection), categorized under Data Acquisition. Here, primary data is gathered through Likert-scale surveys and Key Informant Interviews (KII), while secondary data is sourced from critical industry documents such as Power Purchase Agreements (PPA), ICRA Nepal ratings, NEA/IPPAN reports, and historical disaster records.
- **Analytical Processing:** In Phase 3 (Statistical Processing), the acquired data undergoes rigorous Mathematical Analysis. This phase utilizes two core techniques: Ranking Analysis via the Relative Importance Index (RII) to prioritize hazards, and Risk Modelling, which calculates risk as a product of hazard, vulnerability, and exposure. These statistical outputs provide the technical basis for understanding how various threats interact with the project's infrastructure.
- **Impact and Synthesis:** The final stages transition into Phase 4 (Impact Modeling), which focuses on Monetary Evaluation. This involves simulating energy losses, calculating direct financial consequences, and assessing the effectiveness of current mitigation measures. The entire process culminates in Phase 5 (Synthesis), where the technical and financial findings are integrated to formulate a comprehensive Mitigation Strategy and specific Policy Recommendations aimed at enhancing the project's long-term resilience.

3.1 Research Design

This study employs a Quantitative Risk Assessment (QRA) approach, specifically tailored for the mountainous context of the Radhi Hydropower Project. The design integrates the Relative Importance Index (RII) with empirical operational data to quantify the interplay between physical threats and system resilience. This framework adheres to the Intergovernmental Panel on Climate Change risk characterization(United Nations), structured around three dimensions:

- **Hazard (H):** The frequency and intensity of natural events.

- **Vulnerability (V):** The sensitivity of the project's civil and electromechanical components.
- **Exposure (E):** The degree to which assets are subjected to hazardous conditions.

3.2 Study Area: The Radhi Hydropower Project

3.2.1 Project Location and Physical Setting

Figure 3.2: Radhi Hydropower Project

The Radhi Hydropower Project is a 4.4 MW run-of-river installation located on the Radhi River, a tributary of the Marsyangdi River system, in Lamjung District of Gandaki Province, Nepal. The project site lies within the physiographic zone known as the High Himalaya, characterized by steep valley gradients, extensively jointed metamorphic and igneous bedrock, and a monsoon-dominated precipitation regime that delivers approximately 1800-2200 mm of annual rainfall, with marked seasonal concentration.

The Radhi River basin exhibits several geomorphological features that are particularly significant from a hazard perspective: active debris flow channels feeding from unstable hillslopes into the main river channel; evidence of historical landslide-dammed lake formation in the upper catchment; and a bedload composition dominated by angular, quartz-rich clasts derived from the weathering of high-grade metamorphic rocks, the primary source of turbine-abrasive sediment.

3.2.2 Project Technical Specifications

Table 2: Radhi Hydropower Technical and Financial Specifications

Parameter	**Value**
Installed Capacity	4.4 MW
Type	Run-of-River (RoR)
Annual Generation (Design)	26.26 GWh
Wet Energy	21.17 GWh
Dry Energy	5.09 GWh
Total Project Cost	NPR 613 million
Debt-to-Equity Ratio	70:30
Commissioning Year	2014 A.D.
River Basin	Radhi River (Marsyangdi tributary)
District	Lamjung, Gandaki Province
PPA Base Tariff (Wet)	NPR 4.00/kWh
PPA Base Tariff (Dry)	NPR 7.00/kWh
Escalation Rate	3% annually over 9 years
Geographical location	28°23′48″N to 84°25′45″E

3.3 Data Collection

3.3.1 Primary Data

Primary insights were gathered via Structured Questionnaire Surveys and Expert Consultations involving hydropower engineers and disaster risk specialists. Following the methodology of Likert(Likert, 1932), a 5-point scale was utilized to capture expert perceptions of hazard severity, component fragility, and the perceived efficiency of existing mitigation works.

The questionnaire, reproduced in Annex I, was organized into nine thematic sections covering: general project specifications; natural hazard severity assessment; infrastructure component vulnerability; hazard-specific operational impacts (flood, landslide, sedimentation, debris flow, earthquake, GLOF); historical hazard timeline reconstruction; financial loss and insurance assessment; mitigation measure effectiveness; and overall risk perception.

Table 3: Likert Scale

Likert Scale	Meaning
1	Very Low
2	Low
3	Moderate
4	High
5	Very High

3.3.2 Secondary Data

To ground expert perception in reality, secondary data were sourced from:

- Operational records of Radhi Hydropower Project
- Outage and energy generation data
- Published literature on hydropower risk and Himalayan hazards

3.4 Relative Importance Index (RII)

The RII is a recognized statistical tool used to transform qualitative expert opinions into quantifiable ranks(Kometa, Olomolaiye, & Harris, 1995). It is calculated as:

$$RII = \frac{\sum W}{A \times N} \tag{4}$$

Where W is the weight given to each factor by respondents, A is the highest weight (5), and N is the total number of respondents. RII values (0-1) provide a prioritized list of hazards and vulnerabilities.

3.5 Risk Assessment Framework

Following the Sendai Framework for Disaster Risk Reduction(United Nations), the risk for each project component is calculated as:

$$Risk = Hazard \times Vulnerability \times Exposure \tag{5}$$

In this model, Hazard and Vulnerability are derived from the RII values, while Exposure is treated as a binary or weighted factor based on the component's physical location relative to the hazard zone.

3.6 Operational Loss Assessment

To quantify the economic burden of hazards, the study uses the Standard Energy Equation adapted for Run-of-River (RoR) systems:

$$Energy\ Loss = P \times Toutage \tag{6}$$

$$Financial\ Loss = Energy\ Loss \times Tariff \tag{7}$$

3.7 Efficiency of Mitigation Measures

The effectiveness of structural and non-structural interventions is evaluated using the Mitigation Efficiency Ratio:

$$Efficiency = \frac{Mean\ Score}{5} \tag{8}$$

This metric identifies the "Gap" between theoretical protection and actual performance during extreme events, helping to identify which systems require upgrading.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Hazard, Vulnerability and Exposure of Hydropower Components

The results for the Radhi Hydropower Project (4.4 MW) show a hazard landscape which is dominated by geomorphological and hydrological processes. Based on RII results, Landslides and Floods are the severe risk to the operation of hydropower project.

4.1.1 Hazard Identification and RII Analysis

The potential hazards on Radhi Hydropower projectwere identified based on expert surveys by using a 5-point Likert scale (1 = Very Low to 5 = Very High) to rate severity of the hazard.

The Table 4 ranks natural hazards in terms of the Relative Importance Index (RII).It is showing that the primary threats of the project are surface-level and hydrological and not geological hazards taking place at a deeper level. The critical hazards areLandslides and floods. While, Earthquakes (0.20) and GLOFs (0.23) are ranked the lowest in terms of the RII values.

Table 4: RII Results of Potential Hazard in Radhi HPP

Hazard	RII	Rank	Risk Level
Landslides	0.96	1	Very High Risk
Flood	0.84	2	Very High Risk
Debris Flow	0.64	3	High Risk
Sedimentation	0.40	4	Moderate Risk
GLOF	0.23	5	Very low Risk
Earthquake	0.20	6	Very low Risk

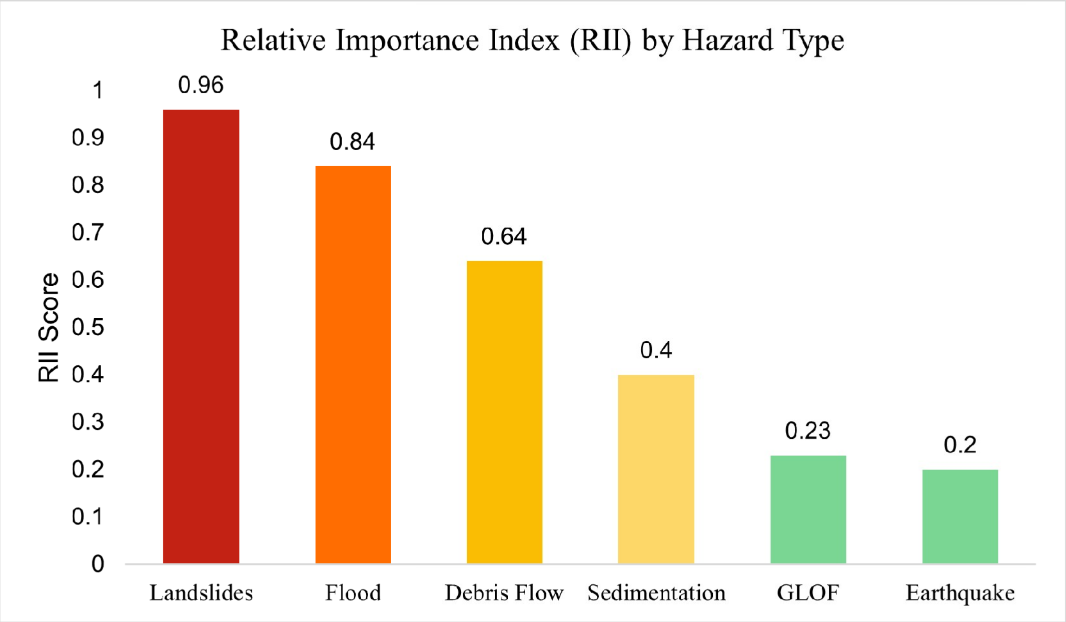


Figure 4.1: RII Score by Hazard Type

Key Hazard Profiles

- **Landslides (RII = 0.96):** It is identified as the most severe threat which directly impacts the project's transmission lines and access roads. In July 2023, a major landslide and flood event damaged the headworks and headrace pipe and halted the energy production can verify the vulnerability of projects towards landslides.
- **Flood (RII = 0.84):** It is ranked as the second most severe hazard which causes operational instability and structural risk. During the catastrophic September 2024 monsoon, run of river projects like Radhi Hydropower project was vulnerable to intake damage and increased sediment flow.
- **Debris Flow (RII = 0.64):** It represents a high-level operational challenge.Debris flow often results in blockage of intake structures requiring significant maintenance. This was one of the critical factor during the 2021 and 2023 monsoon cycles across the Marsyangdi corridor.
- **Sedimentation (RII = 0.40):** It can be regarded as a moderate but chronic hazard. The primary impact of sedimentation is turbine wear and reduced efficiency. Its impact is seen

particularly during the peak monsoon months when the Radhi River carries high bed loads.

- **GLOF (RII = 0.23) and Earthquake (RII = 0.20):** These hazards are generally regarded as low-severity hazards for Radhi HPP. The Radhi HPP site has no direct exposure to GLOF. Also, the historical records show no significant structural damage to the project from 2015 Gorkha earthquake.

According to the analysis, the greatest risks for the project lie in geomorphology (landslides) and hydrology (floods). This is supported by landslide induced damage in mid-July 2023 which resulted in non-operational period of Radhi HPP for seven months.

4.1.2 Vulnerability Analysis

The vulnerability of the major components of Radhi Hydropower Project (HPP) calculated to determine their degree of risk when subjected to natural hazards. This analysis was done using Relative Importance Index (RII). The RII values were determined on the basis of primary data from 19 industry professionals, including plant managers, operation engineers, and environmental specialists.

The Table 5 gives a clear hierarchy of vulnerability of components within the Radhi HPP. The results show how natural hazards impact specific components of hydropower. According to RII value, the transmission line is the weakest link of Radhi HPP with an extremely high RII of 0.98. It is due its extensive geographical covering the highly unstable slopes. This is followed by the components like the intake structure and desander basins (0.80), which face continuous stress from direct river contact. On the other hand, inhouse components such as the generator and powerhouse (0.44) are found to be the most resilient components due to their robust structural designs and relative protection from river's direct impacts.

Table 5: RII Results of Vulnerability of Radhi HPP Components

Component	RII	Rank	Interpretation
Transmission line	0.98	1	Extremely high vulnerability
Intake structure	0.80	2	Very high vulnerability
Desander basin	0.80	2	Very high vulnerability

Component	RII	Rank	Interpretation
Turbine	0.59	3	Moderate to high vulnerability
Penstock	0.44	4	Moderate vulnerability
Generator	0.44	4	Moderate vulnerability
Powerhouse	0.44	4	Moderate vulnerability

Component-Specific Vulnerability Profiles

- **Transmission Line (RII = 0.98):** From RII results, Transmission line is categorized as the most vulnerable element. It could be taken as a weak point of the Radhi HPP. Its high vulnerability is attributed to its large geographical extent making it highly prone to slope instabilities, landslides, and windstorm conditions. This corresponds to recent sector reports which state that line breaks are common reasons for extended outage periods in Nepal's hilly topography(Independent Power Producers' Association, 2025).

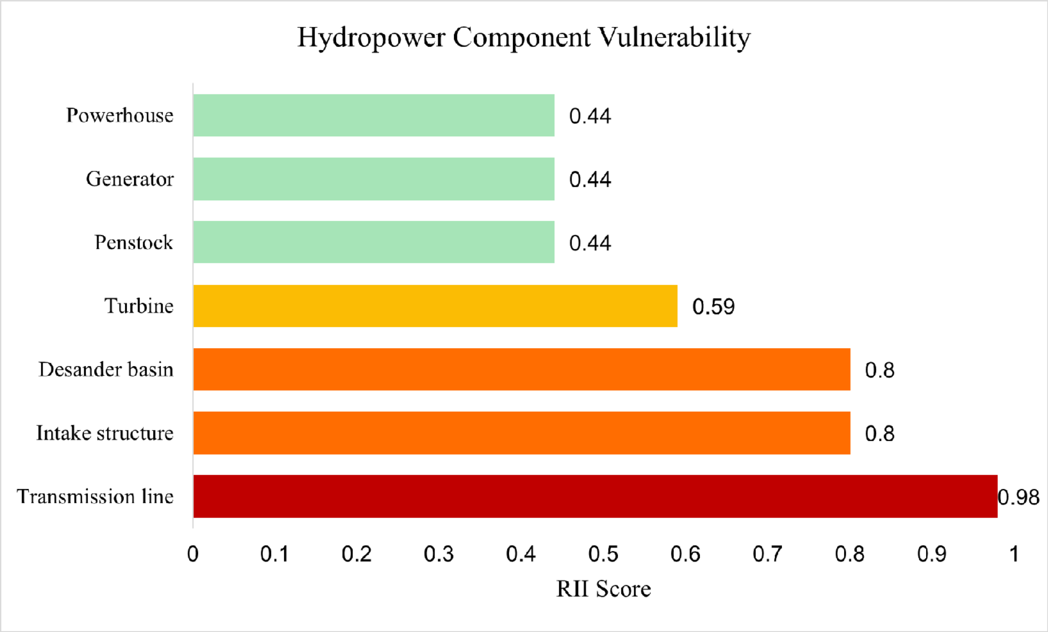


Figure 4.2: Hydropower Component Vulnerability by RII Score

- **Intake Structure and Desander Basin (RII = 0.80):** The high vulnerability of these components of Radhi HPP is due to their direct contact with the Radhi River. The intake structures are highly prone to blockage from debris flow and flood-induced scour. On the other hand, the desander basin experiences repetitive operational stress from high monsoon sediment loads. The high vulnerability of these componentsis due to their vital function in filtering physical hazards before they enter the internal system.

- **Turbine (RII = 0.59):** Turbines show medium to high vulnerability mainly because of erosion by sedimentation. Despite having the functional desander basins, fine quartz particles can pass which causes significant wear on runner blades and decreasing overall generation efficiency of Radhi HPP.
- **Penstock, Generator, and Powerhouse (RII = 0.44):** These primary components of both civil and electrical nature are considered the most resilient components of the Radhi HPP. The lower value of RII is based on strong engineering design (reinforced concrete for powerhouse), as well as limited exposure to geomorphological changes compared to intake or transmission lines.

Hence, the analysis confirms that external infrastructure (Transmission Lines) and interface components (Intake/Desander) are more vulnerable than internal plant systems. This indicates that future disaster resilience efforts should focus on reinforcing the off-site infrastructure and the enhancement of sediment-handling capacity of the Radhi HPP.

4.1.3 Exposure Analysis

In order to better capture the varying degrees of exposure of Rahi HPP components, Exposure is analyzed using a continuous scoring scale from 0 to 1.

The two key factors have been considered to determine the exposure score for each component of Radhi HPP by following the approach of (Kometa, Olomolaiye, & Harris, 1995):
(i) the position of the component with respect to the primary hazard area, and
(ii) the extent of protection, enclosure, or burial of the component.

The Table 6 summarize the exposure value of major hydropower components of Radhi HPP. The results show a clear distinction in exposure levels depending on location of component, proximity to hazard area, and the extent of structural protection.

Table 6: Component Level Exposure Value

Component	Location	Hazard Zone Proximity	Exposure Score
Transmission Line	Off-site, unstable slopes	Direct exposure	1

Component	Location	Hazard Zone Proximity	Exposure Score
Intake Structure	Riverside, riverbank	Direct exposure	1
Desander Basin	Near river	High exposure	0.8
Penstock	Partially buried	Moderate exposure	0.6
Turbine	Inside powerhouse	Moderate exposure	0.5
Generator	Inside powerhouse	Low exposure	0.4
Powerhouse	Engineered structure	Low exposure	0.4

Component Specific Exposure Analysis:

The Transmission Line and Intake Structure show the highest exposure value of 1.0. This indicates direct interaction with hazardous environments. The transmission line which is located on off-site unstable slopes, is particularly susceptible to landslides and slope failures.While the intake structure, positioned along the riverbank, is highly exposed to hazards like floods and debris flow events.

The Desander Basin has a slightly lower exposure value (0.8) and can be classified as high exposure. Despite being located near the river, it benefits from minor geographical offset or partial natural buffering due to which exposure value reduces but does not completely eliminate its susceptibility to hazards.

Penstock (0.6) and Turbine (0.5) have medium exposure levels. The penstock's partial burial provides some degree of protection against external forces.However, it remains vulnerable to slope instability and ground movement. Although the turbine is housed inside the powerhouse, it is not entirely isolated from external hazards. In case of structural failure or extreme flooding, turbine is vulnerable to these hazards.

The generator and Powerhouse have the lowest exposure score of 0.4 each. The exposure value reflects their placement within engineered and enclosed environments. Due to structural protection, these components have limited interaction with hazards. Having said that, their non-zero exposure value indicates the risk under extreme of cascading failure scenarios.

Therefore, the results suggests that components located closer to natural hazard pathways, such as corridors and unstable slopes, experience significantly higher exposure value. But structurally enclosed and engineered components show lower exposure value. This underscores the importance of protective design measures in mitigating hazard impacts.

4.2 Risk Assessment of Hydropower Components

The risk assessment is based on the existing Hazard (H), Vulnerability (V) and Exposure (E) indices to assess the potential operational threat to the Radhi Hydropower Project. Based on Sendai Framework(United Nations), the risk value for each hazard-component interaction is calculated as follows:

$$Risk = Hazard \times Vulnerability \times Exposure$$

Where:

Hazard and Vulnerability are the Relative Importance Index (RII) values.

Exposure is the component specific exposure score (0 to 1) based on position and degree of protection of component from natural hazards.

4.2.1 Risk Analysis and Ranking

The interaction between six major natural hazards and seven major components of Radhi HPP was analyzed using the risk assessment framework. As shown in Table 7 the risk is non-uniform across the plant. It is highest when severe hazard interacts with the most vulnerable component.

The Table 7 provides the value of risk by combining hazard, vulnerability, and exposure. It is observed that the highest operational risk (0.94) occurs at the intersection of landslide and transmission line. The other high-risk scenarios include floods affecting transmission lines (0.82) and landslides impacting the intake structures (0.77). It should be noted that the total risk of the project is concentrated on external facilities and interface elements rather than powerhouse equipment, which has the minimum risk index (0.04).

Table 7: Risk Analysis of Natural Hazard and Hydropower component Interaction

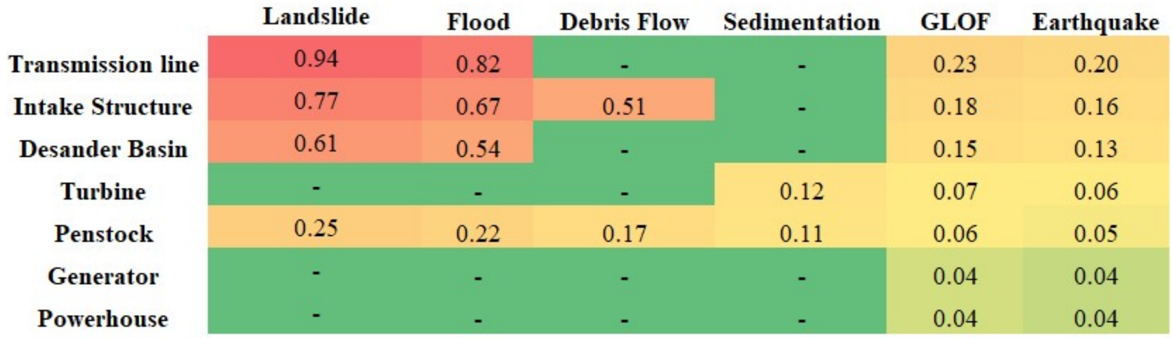
Natural Calamities	Component	Hazard	Vulnerability	Exposure	Risk
Landslide	Transmission line	0.96	0.98	1.00	0.94
Flood	Transmission line	0.84	0.98	1.00	0.82
Landslide	Intake Structure	0.96	0.8	1.00	0.77

Natural Calamities	Component	Hazard	Vulnerability	Exposure	Risk
Flood	Intake Structure	0.84	0.8	1.00	0.67
Landslide	Desander basin	0.96	0.8	0.80	0.61
Flood	Desander basin	0.84	0.8	0.80	0.54
Debris Flow	Intake Structure	0.64	0.8	1.00	0.51
Landslide	Penstock	0.96	0.44	0.60	0.25
GLOF	Transmission line	0.23	0.98	1.00	0.23
Flood	Penstock	0.84	0.44	0.60	0.22
Earthquake	Transmission line	0.2	0.98	1.00	0.20
GLOF	Intake Structure	0.23	0.8	1.00	0.18
Debris Flow	Penstock	0.64	0.44	0.60	0.17
Earthquake	Intake Structure	0.2	0.8	1.00	0.16
GLOF	Desander basin	0.23	0.8	0.80	0.15
Earthquake	Desander basin	0.2	0.8	0.80	0.13
Sedimentation	Turbine	0.4	0.59	0.50	0.12
Sedimentation	Penstock	0.4	0.44	0.60	0.11
GLOF	Turbine	0.23	0.59	0.50	0.07
GLOF	Penstock	0.23	0.44	0.60	0.06
Earthquake	Turbine	0.2	0.59	0.50	0.06
Earthquake	Penstock	0.2	0.44	0.60	0.05
GLOF	Generator	0.23	0.44	0.40	0.04
GLOF	Powerhouse	0.23	0.44	0.40	0.04
Earthquake	Generator	0.2	0.44	0.40	0.04
Earthquake	Powerhouse	0.2	0.44	0.40	0.04

4.2.2 Categorization of Risk Levels

Based on calculated risk values, the findings can be divided into three levels:

4.2.2.1 Top Risk Combinations (0.6 to 1):



	Landslide	Flood	Debris Flow	Sedimentation	GLOF	Earthquake
Transmission line	0.94	0.82	-	-	0.23	0.20
Intake Structure	0.77	0.67	0.51	-	0.18	0.16
Desander Basin	0.61	0.54	-	-	0.15	0.13
Turbine	-	-	-	0.12	0.07	0.06
Penstock	0.25	0.22	0.17	0.11	0.06	0.05
Generator	-	-	-	-	0.04	0.04
Powerhouse	-	-	-	-	0.04	0.04

Figure 4.3: Risk analysis and ranking

The highest risk is associated with landslides impacting the transmission line (0.94). This is primarily due to the placement of transmission towers on unstable slopes, resulting in near-total exposure to geomorphological processes. Similarly, flood impacts on the transmission line (0.82), landslides affecting the intake structure (0.77) and desander basin (0.61), as well as flood impacts on the intake structure (0.67), are categorized as very high risk.

These components function as critical interface structures between the natural environment and the hydropower system, making them the first to experience the effects of riverine flooding and slope instability. Their high exposure and limited protection significantly amplify the overall risk.

4.2.2.2 Moderate Risk Combinations

Flood impacts on the desander basin (0.54) and debris flow affecting the intake structure (0.51) fall within the moderate risk category. Additionally, the impact of landslides on penstock (0.25) is also classified as moderate.

Although these hazards may occur relatively frequently, their effects are generally progressive and cumulative rather than immediately catastrophic. The moderate risk levels reflect partial protection (e.g., burial or structural shielding) combined with continued exposure to hazard processes.

4.2.2.3 Low to Very Low Risk Combinations

Risks associated with GLOFs and earthquakes across all components (ranging from 0.04 to 0.23) are categorized as low to very low. In the context of the Radhi project, the relatively low probability of these events offsets the inherent vulnerability of the infrastructure.

Furthermore, internally housed components such as the generator and powerhouse consistently exhibit the lowest risk scores (approximately 0.04), indicating effective structural protection and minimal direct exposure to external hazards.

The analysis reveals three critical insights for hydropower resilience:

- **External Vulnerability:** Off-site infrastructure (Transmission Lines) and interface structures (Intake/Desander) carry the bulk of the project's risk profile.
- **Hazard Dominance:** Hydrological (Flood) and Geomorphological (Landslide) processes are the primary drivers of risk in the Radhi basin, far outweighing seismic or glacial threats.
- **Core Resilience:** Internal components like the Generator and Powerhouse exhibit the lowest risk scores (0.04), suggesting that standard civil engineering protections for these areas are currently effective.

4.3 Impact of Hazards:

Based on questionnaire survey with experts and historical events in the Radhi River basin, the impact of each hazard on the 4.4 MW project is analyzed below.

4.3.1 Flood

The operational impact of flood events on the Radhi Hydropower Project was quantified using the Relative Importance Index (RII). Expert feedback from 19 professionals indicates that the primary threat posed by floods is operational and sediment logical rather than purely structural.

The Table 8 reveals that the primary threat of flood is functional and sedimentological rather than structural. The most significant impact is the surge in sediment inflow (RII = 0.64), followed closely by the blockage of intake and desander structures (RII = 0.60). Interestingly, structural damage to the intake (RII = 0.41) ranks the lowest, suggesting that while the civil works are robust enough to survive the hydraulic forces, the influx of debris effectively "blinds" the system and forces operational shutdowns.

Table 8: Impact of Flood

Impact Factor	RII	Rank	Interpretation
Increase in sediment inflow	0.64	1	Most significant impact
Blockage of intake/desander	0.60	2	High impact
Disruption of plant operation	0.59	3	High impact
Forced plant shutdown	0.44	4	Moderate impact
Damage to intake structures	0.41	5	Moderate:low impact

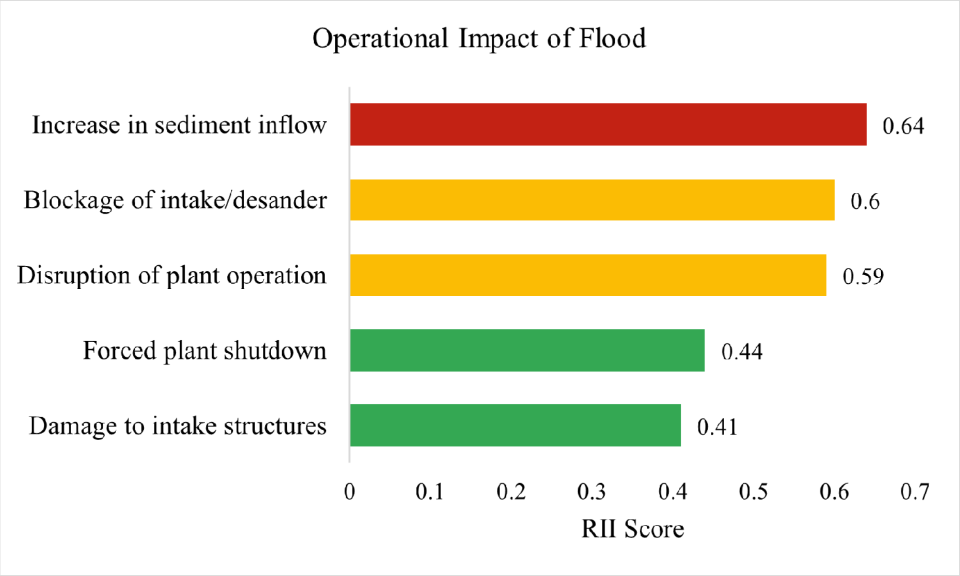


Figure 4.4: Operational Impact of Flood

Key Impact Findings

- **Sediment Inflow (RII = 0.64):** Floods act as the primary catalyst for sediment transport. For a run-of-river project like Radhi, this results in severe turbine abrasion and a measurable reduction in generation efficiency. Research suggests that during peak monsoon floods, suspended sediment concentrations can increase by several magnitudes, making sedimentation the most persistent operational challenge.
- **Intake and Desander Blockage (RII = 0.60):** Floods transport significant organic debris and bedload that frequently choke the intake racks. This necessitates immediate

maintenance and causes temporary water scarcity in the desander, directly interrupting power production.

- **Disruption of Plant Operation (RII = 0.59):** Beyond catastrophic failures, floods introduce "operational noise", fluctuating head levels and mechanical stress—that forces engineers to constantly adjust gate openings and turbine loads, deviating from optimal performance.
- **Forced Shutdown (RII = 0.44) and Structural Damage (RII = 0.41):** Interestingly, these factors ranked lowest. This suggests that the Radhi HPP's civil structures are perceived as sufficiently robust to survive the hydraulic forces of a flood. Forced shutdowns are often a preemptive management choice to protect electromechanical equipment from sediment rather than a result of structural failure.

Figure 4.5: Impact of Flood

The analysis reveals that flood impacts are characterized by functional vulnerability. While the dam and intake may remain physically intact, the influx of sediment and debris effectively "blinds" the system. This underscores a critical finding for Nepalese hydropower: "Flood-induced sedimentation and debris accumulation are the most critical factors affecting performance, emphasizing the need for advanced sediment management systems rather than solely focusing on structural reinforcement".

4.3.2 Landslide:

The operational impact of landslides on the Radhi Hydropower Project was evaluated using the Relative Importance Index (RII). Expert consensus from 19 professionals indicates that landslides are the most disruptive hazard in the study area, with their primary impact concentrated on external infrastructure and river morphology.

The Table 9 identifies landslide as the definitive threat to power evacuation, with the disruption of transmission lines receiving a perfect RII score of 1.00. Experts highlight that because transmission towers are situated on steep, geologically fragile slopes, they are highly susceptible to collapse. While landslides also act as a massive point-source for sediment influx into waterways (RII = 0.80), their effect on the stability of anchored or buried components like the penstock (RII = 0.40) is considered much more moderate.

Table 9: Impact of Landslide

Impact Factor	RII	Rank	Interpretation
Disruption of transmission lines	1.00	1	Extremely high impact
Sediment influx into waterways	0.80	2	Very high impact
Effect on access roads & infrastructure	0.40	3	Moderate impact
Effect on penstock alignment/stability	0.40	3	Moderate impact

Key Impact Findings

- **Disruption of Transmission Lines (RII = 1.00):** With a perfect RII score, landslides are identified as the definitive threat to power evacuation. Because transmission towers are often situated on steep, geologically fragile slopes, they are highly susceptible to tower collapse and line breakage. This creates a critical "transmission bottleneck" where the plant may be fully functional, but unable to deliver power to the national grid, resulting in 100% revenue loss.

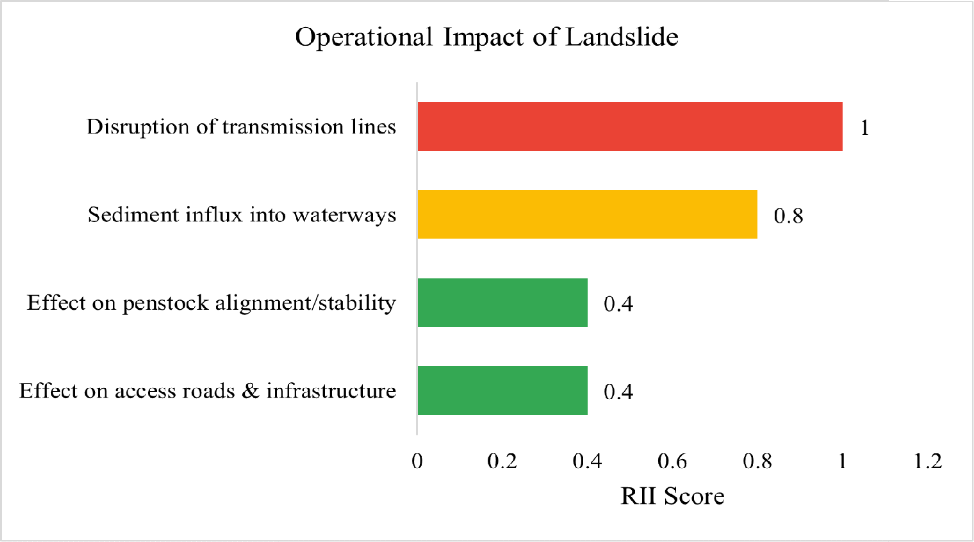


Figure 4.6: Operational Impact of Landslide

- **Sediment Influx into Waterways (RII = 0.80):** Landslides act as a massive point-source of sediment. When a slope fails directly into the Radhi River or its tributaries, it introduces a surge of boulders and silt that bypasses standard desanding capacities. This indirectly degrades hydraulic and mechanical performance, leading to accelerated turbine erosion and frequent maintenance shutdowns.

- **Impact on Access Roads & Infrastructure (RII = 0.40):** While landslides frequently block the narrow mountain roads in Lamjung, this is perceived as a moderate operational impact. Its primary consequence is logistical delaying the mobilization of technical teams and spare parts during emergencies.

- **Effect on Penstock Stability (RII = 0.40):** The relatively low ranking for penstock impact suggests high confidence in the project's structural engineering. Through deep anchoring, rock bolting, or partial burial, the penstock system is perceived as resilient to surface-level slope movements compared to the exposed transmission towers.

Figure 4.7: Impact of Landslide

The analysis confirms that landslides pose the greatest threat to off-site infrastructure, specifically the transmission network. This finding shifts the focus of risk mitigation from internal plant systems to external network protection. As noted in the results, "Based on RII analysis, landslides are found to have a critical impact on transmission line stability and sediment influx, while their effect on structural components such as penstock and plant infrastructure is comparatively moderate.

4.3.3 Sedimentation

The operational impact of sedimentation on the Radhi Hydropower Project was evaluated using the Relative Importance Index (RII). Expert feedback indicates that sedimentation is a chronic operational constraint that primarily disrupts the "interface" between the river and the plant, specifically at the intake.

The Table 10 characterizes sedimentation as a chronic "internalized" hazard that compromises the project's ability to process water efficiently. The most critical factor is sediment deposition affecting intake operation (RII = 0.81), which necessitates frequent manual flushing. While the high monsoon sediment load (RII = 0.61) and resulting turbine blade abrasion (RII = 0.59) represent significant high-impact challenges, the gradual reduction of hydraulic efficiency in the basins (RII = 0.41) is seen as a more manageable, moderate impact.

Table 10: Impact of Sedimentation

Impact Factor	RII	Rank	Interpretation
Sediment deposition affects intake operation	0.81	1	Very high impact
Sediment load during monsoon significantly affects plant operation	0.61	2	High impact
Sediment causes abrasion of turbine blades	0.59	3	High impact
Sediment accumulation reduces hydraulic efficiency	0.41	4	Moderate impact

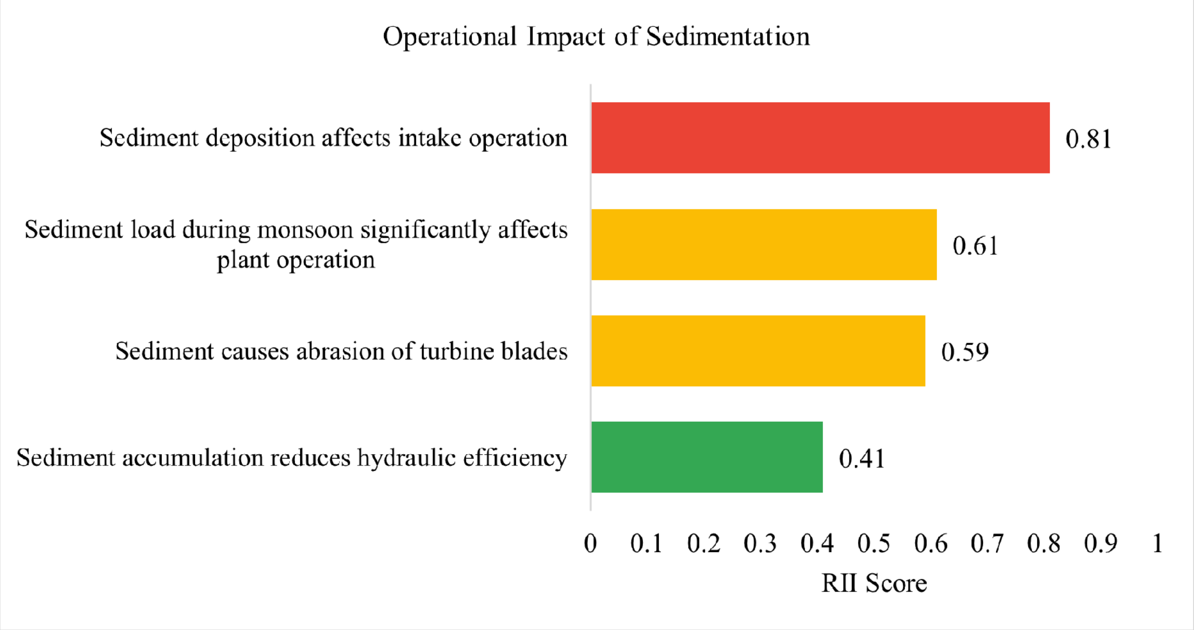


Figure 4.8: Operational Impact of Sedimentation

Key Impact Findings

- **Intake Operation Interference (RII = 0.81):** Ranked as the most critical sediment-related factor, deposition at the intake structures directly compromises water availability. The accumulation of bedload and coarse sand leads to blockage of intake gates and necessitates frequent, often manual, flushing operations. This represents a primary bottleneck for continuous power generation.

- **Monsoon Seasonal Load (RII = 0.61):** The seasonality of Himalayan rivers means that sediment risk is concentrated within a four-month window. During this period, the high concentration of suspended particles creates operational instability, often forcing preemptive shutdowns to avoid catastrophic internal damage when the desander capacity is exceeded.
- **Turbine Blade Abrasion (RII = 0.59):** Mechanical wear is a significant concern for the Radhi project. Fine, hard minerals (quartz) that pass through the desander cause hydro-abrasive erosion of the turbine runners. This results in a dual economic hit: the immediate cost of specialized repairs/coatings and the long-term loss of efficiency as the blade profiles degrade.
- **Reduction in Hydraulic Efficiency (RII = 0.41):** While sediment accumulation in the headrace and desander basins reduces the effective flow area, it is perceived as a moderate impact. The gradual nature of this degradation allows for scheduled desilting, making it less disruptive than the sudden blockage of intake structures.

The analysis reveals that sedimentation is an "internalized" hazard that disrupts hydraulic and mechanical processes. Unlike landslides, which threaten the project's connectivity to the grid, sedimentation threatens the project's ability to process water efficiently. As identified in the research, “Based on RII analysis, sedimentation is found to have a critical impact on intake operation and seasonal plant performance, while its effects on turbine abrasion and hydraulic efficiency are comparatively moderate to high.”

4.3.4 Debris Flow

The operational impact of debris flow on the Radhi Hydropower Project was quantified using the Relative Importance Index (RII). Expert findings suggest that debris flowa mixture of water, large boulders, and organic matteris perceived as a manageable operational burden that primarily drives up labor and maintenance costs rather than causing catastrophic structural failure.

The Table 11 indicates that debris flow is perceived more as a persistent maintenance burden than a source of catastrophic failure. The highest impact is the increase in maintenance requirements (RII = 0.61), as the influx of boulders and organic matter requires a surge in manual and mechanical labor. Other factors, including intake blockage, damage to diversion weirs, and plant shutdowns, all received a uniform moderate score (RII = 0.40), suggesting that debris flow is a manageable challenge that primarily inflates the operational budget.

Table 11: Impact of Debris Flow

Impact Factor	RII	Rank	Interpretation
Debris flow increases maintenance requirements	0.61	1	High impact
Debris flow blocks intake structures	0.40	3	Moderate impact
Debris flow damages diversion weirs	0.40	3	Moderate impact
Debris flow causes plant shutdowns	0.40	3	Moderate impact

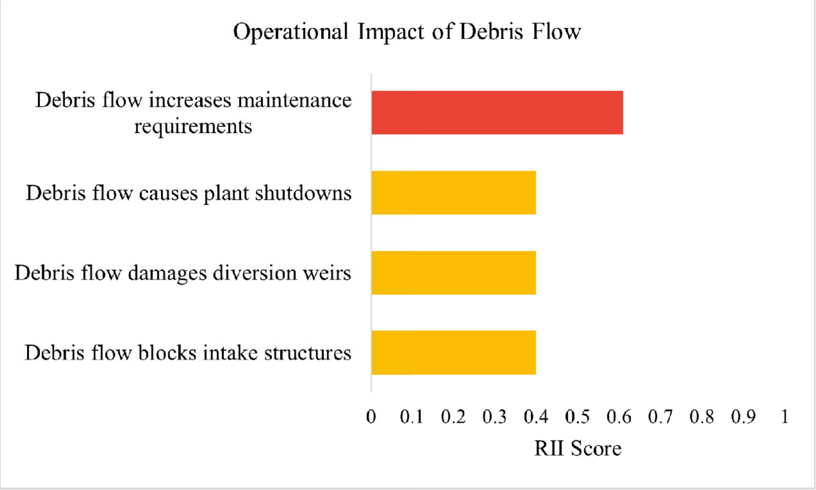


Figure 4.9: Impact of Debris Flow at Intake

Key Impact Findings

- **Maintenance Burden (RII = 0.61):** Ranked as the most significant impact, debris flow necessitates a surge in operational workload. The influx of boulders, logs, and coarse material requires frequent manual and mechanical clearing of the intake area and waterways. This indicates that the primary "cost" of debris flow is the diversion of human and financial resources toward cleaning and restorative maintenance.
- **Intake Blockage (RII = 0.40):** Debris flow is found to have a moderate impact on intake systems. While large debris can choke the trash racks and reduce water inflow, the impact is perceived as less critical than the fine-sediment deposition discussed in earlier sections. This is likely due to the physical nature of debris, which is easier to trap with standard surface barriers compared to suspended silt.
- **Diversion Weir Integrity (RII = 0.40):** The moderate score for structural damage to weirs suggests that these components at Radhi HPP are designed with sufficient hydraulic and structural resilience. While high-velocity debris causes surface abrasion and minor structural stress, it rarely leads to the total breaching of the diversion works.
- **Operational Interruptions (RII = 0.40):** Plant shutdowns triggered by debris flow are generally categorized as preventive and short-term. Operators may halt generation during extreme events to protect the gates and intake, but these outages are typically manageable once the surge passes and the intake area is cleared.

The analysis reveals that debris flow is a distributed hazard with a relatively uniform impact across various factors. Unlike landslides, which can cause 100% loss through transmission failure, debris flow represents a "persistent nuisance" that inflates the operational budget. As identified in the study, “Based on RII analysis, debris flow is found to primarily increase maintenance requirements, while its impact on intake blockage, structural damage, and plant shutdowns remains moderate, indicating a manageable but persistent operational challenge.”

4.3.5 Earthquake and GLOF

For the Radhi HPP (4.4 MW), the historical record of the operational period shows no documented instances of major damage or revenue loss attributed to seismic or glacial events.

4.3.5.1 Earthquake Impact: Negligible Observed Impact

Despite Nepal’s location in a high-seismic zone, the Radhi project has maintained structural integrity through recent events, including the 2015 Gorkha earthquake.

- Structural Resilience: The low perceived impact (RII = 0.20) suggests that the powerhouse, dam, and penstock were constructed with adequate seismic design coefficients.
- Localized Stability: The absence of high-magnitude epicenters in the immediate vicinity of the Radhi River basin during the project's lifespan has prevented the realization of potential seismic risks, such as dam cracking or powerhouse misalignment.

4.3.5.2 GLOF Impact: No Observed Impact

Similarly, GLOFs remain a theoretical tail-risk rather than an operational reality for this specific site.

- Hydrological Safety: Unlike projects located directly downstream of rapidly expanding glacial lakes (such as those in the Tsho Rolpa or Imja regions), Radhi is shielded by favorable upstream topography and a lack of immediate GLOF pathways.
- Exposure Gap: The low RII (0.23) reflects that while GLOFs are catastrophic when they occur, the Radhi basin has not experienced an upstream outburst during the 2014:2026 operational window.

The lack of recorded damage from these hazards suggests that they have had minimal practical impact on the project's bottom line thus far. However, as noted in your findings:

- Site-Specificity: These results are unique to Radhi's location and cannot be generalized to projects in more exposed basins.
- Future Uncertainty: The increasing trend of glacier retreat and the non-stationarity of seismic cycles mean that "zero historical impact" does not equate to "zero future risk."

4.4 Linkage Between Hazards and System Components

The vulnerability assessment, conducted through Relative Importance Index (RII) and Mean Index analysis, establishes a direct correlation between specific environmental stressors and the project's physical infrastructure. The results confirm that transmission lines are the most vulnerable component, followed by intake structures and desander basins. This hierarchy is primarily driven by their high spatial exposure to external geomorphological and hydrological processes.

Table 12: Hazard-Component Interaction Matrix

Hazard	Primary Affected Component	RII-Based Vulnerability Rank
Flood	Intake, Desander, Transmission line	High
Landslide	Transmission line, Penstock	Extremely High
Sediment	Turbine	Moderate to High
Debris Flow	Intake	Moderate

The assessment concludes that exposure is the primary driver of vulnerability for the Radhi HPP. Components situated outside the primary plant boundary (transmission lines) or those that directly engage with river discharge (intake) lack the structural "shielding" found in core plant components like the generator or powerhouse, thus carrying the highest susceptibility to disaster-induced failure.

4.5 Impact of climatic conditions on the hydropower operation:

While natural hazards represent discrete, catastrophic events, climatic conditions exert a continuous and systemic influence on the Radhi Hydropower Project. The operational impact was evaluated using the Relative Importance Index (RII), with results highlighting that hydrological variability is the most significant constraint on energy reliability.

The Table 13highlights that hydrological variability is the single most significant constraint on energy reliability. Seasonal variation in river flow received a maximum RII score of 1.00, confirming that as a Run-of-River (RoR) project, Radhi is entirely dependent on natural discharge, leading to extreme generation disparities between the monsoon and dry seasons. Drought conditions (RII = 0.80) and high monsoon sediment loads (RII = 0.80) are also ranked as very high impacts, as they compromise plant efficiency and degrade mechanical components. The growing trend of climate change and extreme rainfall (RII = 0.60) introduces "non-stationarity," making long-term financial forecasting increasingly difficult.

Table 13: Impact of Climatic Conditions

Impact Factor	RII	Rank	Interpretation
Seasonal variation in river flow affects energy generation	1.00	1	Extremely high impact
Drought conditions reduce plant efficiency	0.80	2	Very high impact
High sediment load during monsoon affects turbine performance	0.80	2	Very high impact
Extreme rainfall affects plant operation	0.60	3	High impact
Climate change has increased operational uncertainty	0.60	3	High impact

Key Climatic Drivers

- **Seasonal Hydrological Variability (RII = 1.00):** With a maximum RII score, seasonal flow variation is the dominant factor governing the project's economics. As a Run-of-River (RoR) plant, Radhi is entirely dependent on natural discharge. The extreme disparity between monsoon surplus and dry-season scarcity leads to significant fluctuations in power output, forcing the project to operate well below its 4.4 MW capacity for several months of the year.

- **Drought and Low-Flow Conditions (RII = 0.80):** Prolonged droughts directly compromise plant efficiency. Reduced water availability not only lowers total energy generation but can also prevent turbines from operating at their optimal efficiency point, further diminishing the financial return per unit of water.

- **Monsoon Sedimentation (RII = 0.80):** This factor bridges the gap between climate and mechanical wear. The high-intensity rainfall during the monsoon accelerates erosion in the catchment, delivering a high sediment load that degrades turbine runners. This confirms that in the Himalayas, water "quality" (sediment concentration) is as critical as water "quantity."

- **Extreme Rainfall and Operational Uncertainty (RII = 0.60):** Experts identify a growing trend of "non-stationarity" in weather patterns. Extreme rainfall creates operational instability through sudden surges in inflow, while the overall unpredictability of the monsoon makes long-term energy planning and financial forecasting increasingly difficult.

The analysis demonstrates that the Radhi HPP is highly sensitive to the Himalayan hydrological cycle. Unlike landslides or floods, which cause physical damage, climatic factors primarily cause "Energy Loss" through generation shortfalls and efficiency degradation. As noted in the discussion, "Climatic factors exert a continuous and systemic influence on hydropower operation, affecting both short-term performance and long-term sustainability."

4.6 Impact of hydropower projects on environment:

While the primary focus of this study is the risk posed by natural hazards to the project, it is equally important to evaluate the reciprocal impact of the Radhi Hydropower Project on the surrounding environment. This assessment utilized the Relative Importance Index (RII) to gauge expert perceptions of the project's ecological and geomorphological footprint.

Table 14: Impact of Hydropower Projects on Environment

Impact Factor	**RII**	**Rank**	**Interpretation**
Project contributes to erosion or riverbank instability	0.40	1	Moderate impact
Hydropower operation affects local biodiversity	0.40	1	Moderate impact
Project operation has altered natural river flow	0.20	2	Low impact
Sediment trapping affects downstream river morphology	0.20	2	Low impact
Aquatic ecosystem is affected by plant operation	0.20	2	Low impact

Key Environmental Findings

- **Erosion and Riverbank Instability (RII = 0.40):** The project is perceived to have a moderate impact on the physical stability of the river corridor. These effects are primarily localized near the tailrace discharge and weir areas, where changes in water velocity can cause minor bank scouring. However, these geomorphological changes are not classified as severe or widespread.
- **Local Biodiversity (RII = 0.40):** Impact on terrestrial and riparian biodiversity is also ranked as moderate. This suggests that while the construction and presence of the 4.4

MW facility have introduced minor disturbances to local habitats, the ecological footprint remains relatively controlled and does not significantly threaten local species.

- **Hydrological and Sedimentological Alteration (RII = 0.20):** Interestingly, factors such as the alteration of natural flow regimes and downstream sediment trapping received the lowest scores. Because Radhi is a Run-of-River (RoR) project with limited storage, it maintains a near-natural flow bypass, ensuring that the downstream river morphology and sediment balance are not fundamentally disrupted.
- **Aquatic Ecosystem (RII = 0.20):** The impact on aquatic life is perceived as low. This suggests that the project's operation, including the intake screening and environmental flow (e-flow) management, is effectively minimizing disturbances to fish migration and aquatic habitats in the Radhi River.

The analysis indicates that the Radhi Hydropower Project maintains a balanced interaction with its surrounding environment. The environmental impacts are categorized as minimal to moderate, with most factors receiving low ratings. This reflects the relatively small scale of the project (4.4 MW) and suggests that current environmental management practices are successfully mitigating significant ecological disruption.

4.7 Operational Loss and Damage Assessment

This section quantifies the economic and operational consequences of the previously identified hazard-component risks. By integrating risk levels with plant specifications and historical case data, the study establishes a direct link between natural hazards and financial performance.

4.7.1 Energy and Financial Loss Calculation

Operational losses were estimated using the plant's installed capacity (4.4 MW) and tariff rate of wet and dry season of NRs5.22/kWh and NRs 9.13 /kWh. Outage durations were assigned based on the calculated risk levels, ranging from 10 to 110 hours per year for routine disruptions.

Table 15: Assumption of Outage hours Based on Risk

Risk Level	Range	Assumed Outage (hrs./year)
Very High	>0.7	100:120

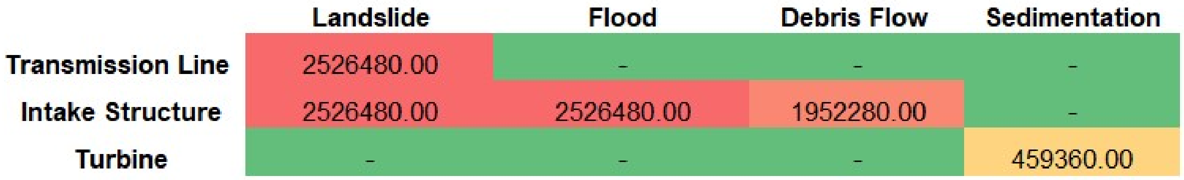
High	0.5:0.7	70:100
Moderate	0.3:0.5	40:70
Low	<0.3	<40

The majority of energy loss occurs during the wet (monsoon) season, when river discharge is at its peak. Hence, we use wet season tariff for the calculation of loss due natural hazards.

The table 16 translates the technical risks into significant economic consequences based on assumed annual outages. Under routine conditions, landslide-induced transmission failures are estimated to cause approximately NRs 2.52 million in losses per 110 hours of downtime. However, the report identifies a major "tail-risk" problem through a case study of the 2080 B.S. flood, where a seven-month shutdown resulted in a revenue loss exceeding NRs 136 million, representing over 22% of the total project cost in a single year.

Table 16: Energy and Financial Loss of Radhi HPP-Wet Season

Hazard	Component	Risk	Outage (hrs.)	Energy Loss (MWh)	Financial Loss (NRs.)	Rank	Interpretation
Landslide	Transmission Line	0.94	110	484.00	2,526,480.00	1	High impact
Landslide	Intake Structure	0.77	110	484.00	2,526,480.00	1	High impact
Flood	Intake Structure	0.82	110	484.00	2,526,480.00	1	High impact
Debris Flow	Intake Structure	0.51	85	374.00	1,952,280.0	2	Moderate impact
Sedimentation	Turbine	0.12	20	88.00	459,360.00	5	Low impact



	Landslide	Flood	Debris Flow	Sedimentation
Transmission Line	2526480.00	-	-	-
Intake Structure	2526480.00	2526480.00	1952280.00	-
Turbine	-	-	-	459360.00

Figure 4.10: Financial Loss (NPR) Due to Hazard-Component Interaction

Key Findings from RII-Based Analysis:

- **Transmission Line Failures:** Landslide-induced damage to transmission lines represents the highest economic threat, causing approximately NRs 2.52 million in losses per 110 hours of downtime. This confirms that off-site infrastructure is the most critical financial bottleneck.
- **Intake Vulnerability:** Floods and landslides affecting the intake structures result in substantial revenue hits (NRs. 2.52 million each), highlighting the necessity of continuous water flow for generations.
- **Chronic vs. Acute:** While sedimentation is frequent, its immediate financial impact (NRs 0.459 million) is significantly lower than sudden geomorphological or hydrological events.

4.7.2 Case Study: Flood-Induced Shutdown and Associated Losses (2080 B.S.)

To validate the risk model against real-world extremes, the study analyzed the catastrophic flooding event of 2080 B.S., which resulted in a seven-month shutdown (Shrawan to Magh) for the Radhi Hydropower Project.

- Total Outage Duration: 5,040 hours (7 months i.e. from Shrawan to Magh, 2080 B.S.)
- Energy Loss Calculation: The estimated energy loss during the wet season is 15,840.00 MWh, while the dry season accounts for 6,336 MWh, resulting in a total energy loss of 22,176.00 MWh.
- Financial Impact: Based on tariff rates of NPR 5.22/kWh for the wet season and NPR 9.13/kWh for the dry season, the total revenue loss is estimated at NRs. 136.79 million.

Of this, approximately NRs. 80.46 million is attributed to wet season losses, while NRs. 56.32 million corresponds to losses during the dry season.

This case study reveals a stark contrast between routine operational risks and "tail-risk" events. While the RII-basedanalysis captures the most frequent disruptions (amounting to millions in losses), extreme events can result in losses exceeding NRs 136 million, representing over 25% of the total project cost (NPR 613 million) in a single year. This underscores that while small-scale disruptions are manageable, low-frequency, high-duration floods pose an existential threat to the project's financial viability.

4.8 Efficiency of Risk Reduction Measures:

Efficiency in this context is defined as the functional capacity of a mitigation strategy to minimize structural damage, operational downtime, and overall system vulnerability. To evaluate the performance of the Radhi Hydropower Project's defensive infrastructure, an efficiency index was derived from expert survey data (1:5 Likert scale) and normalized as follows:

$$Efficiency = \frac{MeanScore}{5}$$

The results identify a significant performance gap between purely structural flood defenses and the systems intended to manage geomorphological and sedimentological hazards.

TheTable 17 evaluates the current defensive measures and exposes a critical performance gap. While flood protection structures show high efficiency at 82.11%, sediment management systems (41.05%) and debris barriers (42.11%) remain significantly underpowered. This imbalance confirms the study's conclusion that the project is "structurally robust but operationally fragile," meaning it can survive the hydraulic force of a flood but remains highly susceptible to the functional "blinding" caused by the sediment and debris that follow.

Table 17: Effectiveness of Mitigation Measures

Mitigation Measure	Efficiency (%)	Rank	Interpretation
Flood Protection Structures	82.11	1	Very high effectiveness
Slope Stabilization	58.95	2	Moderate to high effectiveness
Debris Barriers	42.11	3	Moderate effectiveness

Sediment Flushing System	41.05	4	Moderate effectiveness

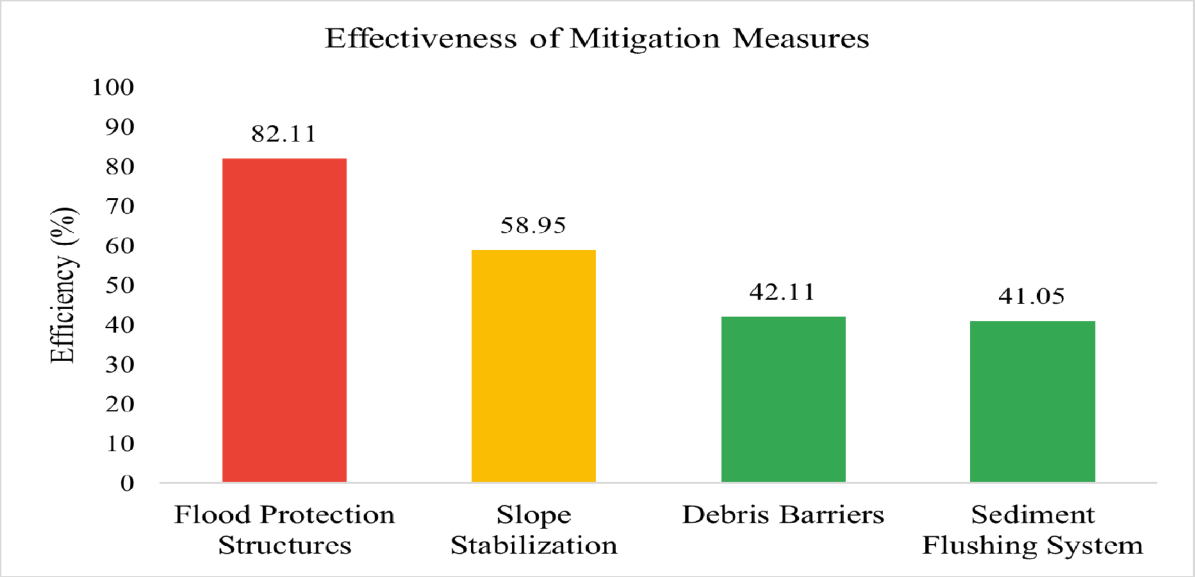


Figure 4.11: Effectiveness of Mitigation Measures

Analysis of Mitigation Performance

- **Flood Protection Structures (82.11%):** Ranked as the most effective strategy, these structures provide robust protection against high-flow events. Their high efficiency reflects their success in shielding core plant infrastructure and maintaining operational safety during the annual monsoon, effectively reducing the "Flood-Intake" risk.

- **Slope Stabilization (58.95%):** These measures, including bioengineering and rock bolting, show moderate to high effectiveness. While they contribute to localized terrain stability, their lower efficiency compared to flood defenses indicates that geotechnical risks remain a significant challenge, particularly for the expansive transmission line network.

- **Debris Barriers (42.11%):** The moderate efficiency of debris barriers suggests they are effective for routine sediment transport but struggle during high-intensity debris flows. These barriers often experience overtopping or structural stress when subjected to large boulders and organic matter, limiting their ability to prevent intake blockage.

- **Sediment Flushing Systems (41.05%):** Identified as the least efficient measure, flushing systems face persistent challenges. The incomplete removal of fine silts and the operational constraints imposed during high-sediment monsoon periods result in a "residual risk" that manifests as turbine abrasion. This low score underscores that sediment management is a dynamic operational problem that cannot be solved by structural design alone.

The analysis reveals a "Resilience Imbalance" within the Radhi HPP. Hydrological risks are well-managed through highly efficient structural interventions, whereas sediment and debris management systems are significantly less efficient. This highlights a critical need for the project to transition from purely structural defenses to more adaptive, "soft" mitigation strategies, such as real-time sediment monitoring and enhanced maintenance protocols, to address the most persistent operational threats.

4.9 Overall Risk Perception:

The final component of the results analysis examines the broader perception of risk within the Nepalese hydropower sector. Expert consensus from 19 industry professionals was quantified using the Relative Importance Index (RII) to establish a baseline for future industry resilience and planning.

The Table 18 provides a final synthesis of how industry professionals view the broader risk landscape for hydropower in Nepal, moving beyond site-specific data to address systemic challenges. A primary finding from this table is the significant "Resilience Gap" regarding financial protection, where experts indicate that while insurance coverage for natural hazards is high, it often falls short of covering the full magnitude of extreme "tail-risk" events. Furthermore, the analysis reveals a high perception of an operational risk maturity gap, suggesting that while the sector is technically proficient in construction, it remains under-prepared for the long-term management of recurring monsoon stressors. Finally, the table reflects a very high level of concern regarding the unpredictability of future hazards driven by climate change; the shift toward "non-stationary" weather patterns is seen as a major threat that makes long-term energy planning and investment stability increasingly difficult to maintain.

Table 18: Overall Risk Perception of Hydropower Projects

Impact Factor	RII	Rank	Interpretation
Hydropower plants in Nepal are highly vulnerable to natural disasters	0.80	1	Very high agreement
Climate change will increase future hydropower risk	0.80	1	Very high agreement
Better risk modelling is necessary for plant operation	0.80	1	Very high agreement
Current mitigation measures are sufficient	0.41	4	Moderate to low agreement

Analysis of Perception Drivers

- **Vulnerability and Climate Trends (RII = 0.80):** There is a definitive consensus that Nepal’s hydropower infrastructure is operating under high-risk conditions. The "Very High" agreement regarding climate change indicates that professionals no longer view extreme weather as an anomaly, but as a shifting baseline that threatens the long-term sustainability of Run-of-River (RoR) projects like Radhi HPP.
- **The Modeling Gap (RII = 0.80):** The strong demand for improved risk modeling reflects a transition in the industry. Experts acknowledge that traditional engineering safety factors are insufficient for the "non-stationary" hazards of the Himalayas. This highlights an urgent need for integrating real-time climate data and predictive geomorphological modeling into daily plant operations.
- **The Mitigation Paradox (RII = 0.41):** The lowest RII score was recorded for the sufficiency of current mitigation measures. This "Moderate to Low" agreement serves as a critical finding; while engineers are building floodwalls and desanders, they lack full confidence in these structures' ability to withstand the increasing magnitude of Himalayan hazards. It suggests that the industry recognizes a "residual risk" that existing structural designs cannot fully eliminate.

The analysis reveals a professional landscape characterized by high risk-awareness but low confidence in current defensive strategies. The alignment of the first three factors suggests that the industry is ready for more sophisticated, data-driven planning tools. The findings reinforce the central thesis of this study: the most critical path forward for Nepal's energy security is not just more construction, but the enhancement and innovation of risk assessment and mitigation frameworks.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Summary of Major Findings

By integrating primary expert survey data, operational records and case study, Quantitative Risk Assessment of the Radhi Hydropower Project (4.4 MW) was carried out. The main purpose of this study was to establish a multi-dimensional risk profile of operational-phase vulnerability to natural hazards in Radhi Hydropower Project. The major findings of this are as follows:

5.1.1 Hazard Profile

Landslides (RII = 0.96) and floods (RII = 0.84) are the most extreme risk which causes severe impact to the operational phase of Radhi HPP. These reflect the fundamental geomorphological and hydrological attributes of the Lamjung district. Debris flow (RII = 0.64) represents a significant but manageable operational burden. Sedimentation (RII = 0.40), although chronic and progressive, is considered as a moderate hazard. GLOF (RII = 0.23) and earthquakes (RII = 0.20) represent very low current operational risk but they can be significant tail-risk potential under future climate and seismic events.

5.1.2 Vulnerability Hierarchy

From the analysis, we can notice the clear distinction in vulnerability between external and internal components. The high-risk components are transmission lines (RII = 0.98), intake structures, and desander basins (both RII = 0.80). Among the internal plant components, turbines (0.59), penstocks (0.44), generators (0.44), and powerhouse (0.44) have a moderate vulnerability that is due to their geographical isolation from the potential hazards provided by enclosures and burials.

5.1.3 Critical Risk Scenarios

The integrated risk matrix indicatesthat the Landslide × Transmission Line combination as the highest risk scenario (Risk Score = 0.94), followed by Flood × Transmission Line (0.82) and Landslide × Intake/Desander (0.77 and 0.61 respectively). These combinations demand for the highest investment priority in risk reduction efforts.

5.1.4 Financial Loss Magnitude and the Tail Risk Problem

Based on RII-derived outage assumptions,routine hazard events cause annual financial losses ranging from NPR 0.459 to 2.52 million for each hazard-related component failure. However, the catastrophic flood of 2080 B.S. caused a much larger revenue loss of NPR 136.79 million due to a seven-month shutdown. This shows that extreme events can have disproportionately severe financial impacts. Rare but high-magnitude disasters therefore pose a serious threat to the financial viability of hydropower projects, which routine risk models often fail to capture accurately.

5.1.5 Mitigation Efficiency and the Resilience Imbalance

The efficiency of flood protection structures is 82.11%. This reflects well-engineered hydraulic defense system. However, the efficiency of sediment flushing systems (41.05%) and debris barriers (42.11%) is considerably lower than what is necessary for effective operation.Slope stabilization (58.95%) measures provide moderate protection but fall short of the capability required to adequately protect the transmission network from geomorphological hazards.

5.1.6 Sector-Wide Risk Maturity Gap

The analysis across overall risk perception shows that people are highly aware of their vulnerability and the risks caused by climate change (both RII = 0.80). However, they have low confidence in the current measures used to reduce these risks (RII = 0.41). This shows a gap where people understand the problem well, but effective solutions are still lacking. Therefore, there is a need to develop better, flexible, and research-based risk management strategies.

5.2 Conclusion

This analysis provides a risk profile of the Radhi Hydropower Project (4.4 MW) by integrating hazard analysis, vulnerability assessment, and economic impact evaluation. The results has shown that the project's sustainability is determined more by external geomorphological and hydrological factors rather than by internal mechanical failure.

The hazard analysis identifies landslides (RII = 0.96) and floods (RII = 0.84) as the primary threats to the Radhi HPP. These hazards are driven by the fragile geology of the Lamjung district and intensifying monsoon variability. Although GLOFs and earthquakes currently have lower value of operational risk, they can be comecritical tail risks that could cause catastrophic damage if triggered.

The vulnerability analysis of Radhi HPP components shows a significant "Resilience Gap between internal and external components. Transmission lines (RII = 0.98) and intake structures (RII = 0.80) are the most vulnerable components to natural hazards. The risk analysis also confirms that the intersection of landslide hazards and transmission line exposure in Radhi HPP site leads to the most critical risk scenario (Risk Score = 0.94). Hence, these failures can result in total power evacuation loss.

The economic analysis of Radhi HPP reveals that routine hazards cause annual losses in the millions. However extreme events such as the 2080 B.S. flood have led to seven-month shutdown along with financial loss of NRs 136.79 million. Hence, such extreme but rare events pose threat to the sustainability of the Radhi HPP. Lastly, the evaluation of efficiency of mitigation measures of Radhi HPP shows that flood defenses are highly effective (82.11%) but sediment and debris management systems (41.05%) are significantly underperforming. Hence, from this evaluation we can conclude that current risk management procedure is structurally robust but operationally fragile.

5.3 Recommendations

In order to increase the resilience of the Radhi Hydropower Project and similar hydropower projects in the Himalayan region of Nepal, the following recommendations on the basis of analysis are suggested:

5.3.1 Hardening of "Weak-Link" Infrastructure

Priority 1: Transmission line Enhancement

The apex risk scenario (Landslide × Transmission Line, Risk Score = 0.94) demands immediate and substantial investment in transmission infrastructure hardening. Recommended actions include:

- Geotechnical assessment of all transmission tower foundations in landslide-susceptible zones, with priority upgrading of towers identified as being on unconsolidated or historically unstable slopes.

- Where topographically and economically feasible, evaluate the cost-benefit of transitioning critical transmission segments to underground cabling. While capital costs are substantially higher, the elimination of surface-level exposure to slope failures and wind events may generate positive long-term NPV through reduction in outage frequency and duration.
- Establish rapid response transmission restoration protocols, including pre-positioned emergency repair materials (conductor, insulators, fittings) at strategic accessible locations, and contractual arrangements with specialized restoration contractors who can be mobilized within 48 hours of a fault event.
- Implement continuous transmission line monitoring through patrol drones during the monsoon season, providing early detection of tower displacement or conductor damage before complete failure occurs.

Priority 2: Intake Armoring and Automation

The very high vulnerability of intake structures (RII = 0.80) to both flood and landslide impacts warrant targeted structural upgrades:

- Retrofit intake trash racks with high-strength, hardened steel grilles capable of withstanding the impact loads of large debris carried by extreme flood and debris flow events.
- Install automated gate control systems linked to upstream water level telemetry, enabling rapid protective closure of intake gates when flood or debris surge thresholds are detected, reducing the risk of electromechanical damage from sudden debris ingestion.
- Construct secondary debris deflection barriers upstream of the intake structure to intercept large boulders and organic matter before they reach the trash rack, reducing cleaning frequency and protecting gate mechanisms.

5.3.2 Transitioning to Adaptive Sediment Management

The identified efficiency gap in sediment management (41.05% vs. 82.11% for flood protection) represents the most significant operational risk reduction opportunity in the project's mitigation portfolio. Recommendations include:

- Implement real-time sediment monitoring through turbidity sensors installed at the intake, desander inlet, and desander outlet. Continuous monitoring data enables adaptive operational decisions, including preventive load reduction or temporary shutdown when suspended sediment concentrations exceed turbine protection thresholds, replacing reactive responses to damage with proactive protection of assets.
- Adopt High-Velocity Oxygen Fuel (HVOF) thermal spray coatings on turbine runner blades, as recommended by (Yu, et al., 2022). While the initial investment and periodic reapplication costs are significant, the economic case for HVOF is compelling given the dual cost of turbine refurbishment (direct) and generation efficiency degradation (indirect).
- Redesign sediment flushing protocols to incorporate flow-weighted flushing triggers rather than calendar-based schedules. Flushing effectiveness is highest when bed sediment concentration is elevated; aligning flushing events with peak sediment deposition periods maximizes removal efficiency and reduces the residual turbine exposure risk.
- Investigate the technical feasibility and economic case for desander basin augmentation or redesign to improve fine particle removal efficiency. Current S-trap designs may be supplemented with vortex tube separators or lamella plate settlers to improve capture of the sub-100-micron quartz particles responsible for turbine erosion.

5.3.3 Integrated Slope and Watershed Protection

Given that the apex risk driver is landslide hazard acting on transmission infrastructure, effective risk reduction requires intervention not just at the plant level but across the broader watershed and corridor that encompasses the transmission network:

- Commission a comprehensive geomorphological corridor assessment of the transmission line route, mapping all landslide-susceptible zones and debris flow pathways within a defined buffer of tower locations. This assessment should form the basis for a targeted slope stabilization investment program.
- Implement intensive bioengineering interventions, including deep-rooted pioneer vegetation, live fascines, and brush layering, on slopes adjacent to transmission towers,

combined with hard engineering measures (retaining walls, rock bolts) on slopes where immediate failure risk is assessed as high.

- Deploy upstream hydrological early warning systems comprising rain gauges, river level sensors, and slope displacement monitors linked through real-time telemetry to the plant control room. Target lead times of at least 30 minutes for flood surges and 60 minutes for predictable landslide triggers (sustained rainfall thresholds) to enable protective operations.
- Establish collaborative watershed management arrangements with local government authorities and community forest user groups for the sustainable management of vegetation cover in the upper catchment, reducing surface runoff rates and long-term erosion risk.

5.3.4 Climate-Resilient Financial and Operational Planning

The 2080 B.S. case study demonstrates that conventional financial risk management frameworks are inadequate for the tail-risk environment in which Nepalese hydropower operates. Specific recommendations include:

- Establish a dedicated Hazard Contingency Reserve (HCR) funded by a fixed percentage (recommended: 3:5%) of annual gross revenue during normal operations. The HCR should be ring-fenced from operational expenditure and accessible only for hazard-induced restoration costs, providing a first-response financial buffer that reduces dependency on emergency borrowing.
- Engage with Nepal's emerging parametric insurance market to develop products that provide automatic payouts triggered by measurable physical parameters (river gauge levels, rainfall intensity, MODIS-based landslide detection) rather than requiring post-disaster damage assessment. Parametric products can substantially reduce the claims settlement timeline, providing liquidity during the critical early restoration period.
- Undertake a rigorous review of PPA force majeure provisions in consultation with the NEA, ensuring that extreme hazard events of the character of the 2080 B.S. flood are adequately covered and that deemed generation provisions provide reasonable revenue protection during extended restoration periods.

5.3.5 Policy and Research Integration

The sector-wide risk maturity gap identified in the perception analysis points to the need for institutional and policy reforms that elevate operational risk management to a first-class consideration in Nepal's hydropower regulatory and planning framework:

- Mandate multi-hazard operational risk assessments as a condition of PPA renewal or major plant upgrade approvals, requiring project developers to demonstrate that they have systematically identified, quantified, and developed mitigation plans for all significant hazard-component interactions. The framework developed in this study provides a replicable template for such assessments.
- Establish a national hydropower operational incident database, administered collaboratively by NEA, IPPAN, and the Department of Electricity Development, to systematically capture, classify, and analyze hazard-induced disruption data across all operational projects. This 'forensic learning' infrastructure would enable sector-wide improvement in risk modelling and mitigation design.
- Develop sector-specific insurance products through collaboration between IPPAN, insurance regulators, and reinsurance partners, addressing the unique risk profile of RoR hydropower, particularly the seasonal amplification of losses and the tail-risk from cascade hazard events, with appropriate premium structures and coverage terms.
- Integrate hydropower operational risk assessment into Nepal's national climate adaptation planning framework, recognizing that the resilience of the energy sector is a critical component of the country's overall climate adaptation strategy and that investment in hydropower risk reduction generates co-benefits for grid stability, energy security, and economic development.

Support academic research institutions in developing real-time sediment monitoring, early warning system design, and cascade hazard modelling capabilities specifically calibrated to Himalayan geomorphological conditions, building the technical capacity needed to support next-generation risk management practice in the sector.

REFERENCES

Alam, F., Alam, Q., Reza, S., Alam, S. K.-U., Saleque, K., & Chowdhury, H. (2017). A Review Of Hydropower Projects In Nepal. Energy Procedia .

Chen, H., Liang, Q., Zhao, J., & Maharjan, S. B. (2025). Assessing National Exposure To And Impact Of Glacial Lake Outburst Floods Considering Uncertainty Under Data Sparsity. Hydrology And Earth System Sciences.

Devi Prasadh, A. (2007). Risk Assessment And Management In Construction Projects. Chennai: Department Of Civil Engineering, College Of Engineering, Guindy Campus, Anna University.

Gurung, S. (2020). Risk Analysis For The Sustainable Hydropower Development In Nepal . International Journal Of Advanced Engineering, Sciences And Applications (Ijaesa) .

Huikku, J., Karjalainen, J., & Seppälä, T. (2026). Strategic Factors And The Use Of Risk Analysis Techniques In Strategic Investment Decisions. Accounting And Business Research , 463-491.

Icimod. (2011). Glacial Lakes And Glacial Lake Outburst Floods In Nepal. Kathmandu.

Independent Power Producers' Association. (2025). Ippan Silver Jubilee 2025 Report. Ippan, Nepal.

Ippc. (2023). Climate Chage Synthesis Report: Summary For Policymakers. Intergovernmental Panel On Climate Change.

Kadel, S., Chaudhary, S., & Khadka, S. S. (N.D.). Review On Assessing Climate-Change-Induced Risks To Run-Of-River Hydropower Infrastructure In Nepal. International Association Of Hydrological Sciences .

Khatri, D., & Pandey, V. P. (2021). Climate Change Induced Hydrological Alteration And Impact On Hydropower Production In Tamor River Basin, Nepal.

Khatri, D., & Pandey, V. P. (2021). Climate Change Induced Hydrological Alteration And Impact On Hydropower Production In Tamor River Basin, Nepal. Master's Thesis.

Kometa, S., Olomolaiye, P., & Harris, F. (1995). An Evaluation Of Clients' Needs And Responsibilities In The Construction Process. Engineering, Construction & Architectural Management , 2 (1), 7-76.

Kron, W. (2005). Flood Risk = Hazard • Values • Vulnerability. Water International , 30 .

Kron, W. (2005). Flood Risk = Hazard • Values • Vulnerability. Water International , 30.

Kucukali , S. (2011). Risk Assessment Of River-Type Hydropower Plants By Using Fuzzy Logic Approach. World Renewable Energy Congress .

Likert, R. (1932). A Technique For The Measurement Of Attitudes. Archives Of Psychology , 22 (140), 55.

Mammadova, K. M., & Agayev, I. (2025). Analysis Of Risks In Investment Projects. Economics Of The Transport Complex .

Meyer, V., Becker, N., Markantonis, V., Schwarze, R., Van Den Bergh, J., Bouwer, L., Et Al. (2023). Review Article: Assessing The Costs Of Natural Hazards-State Of The Art And Knowledge Gaps. Natural Hazards And Earth System Science , 13.

Mir, R., Jain, S., Ahmed, R., & Farooq, A. (2025). A Strategic Framework For Glacial Lake Outburst Flood (Glof) Risk Reduction In The Himalayas Under Climate Change. Discover Geoscience , 3.

Mulholland , B., & Christian, J. (1999). Risk Assessment In Construction Schedules. Journal Of Construction Engineering And Management , 8-15.

Nea. (2081). A Year In A Review-Fy 2023/24.

Nea. (2024). A Year In Review - Fiscal Year - 2023/2024. Kathmandu.

Ojha, R. N., Baral, S., & Mishra, B. K. (2025). A Comprehensive Risk Evaluation: A Case Study Of Super Madi Hydropower Project. Journal Of Engineering Issues And Solutions .

Regmi, S., & Dahal, R. K. (2024). Consequences Of Slope Instability And Existing Practices Of Mitigation In Hydropower Projects Of Nepal. Geoenvironmental Disasters .

Sah, R., Gautam, N., Pokharel, A., Gautam, B. K., & Silwal, B. (2025). Field Survey Findings Of Flood Impacts And Resilience Ofelectrical Systems In Nepalese Hydropower Plants. Journal Of Science And Engineering. Kathmandu.

Sah, R., Gautam, N., Pokharel, A., Gautam, B. K., & Silwal, B. (2025). Field Survey Findings Of Flood Impacts And Resilience Ofelectrical Systems In Nepalese Hydropower Plants. Journal Of Science And Engineering (Jsce).

Sati , V. P. (2025). Impact Of Climate Change In The Himalayan Region: Drivers, Implications, And Mitigations. Climate Change .

Sayers, P., Y, L., Galloway, G., Penning-Rowsell, E., Shen, F., Wen, K., Et Al. (2013). Flood Risk Management: A Strategic Approach. Paris: Unesco.

Shaktawat, A., & Vadhera, S. (2021). Risk Management Of Hydropower Projects For Sustainable Development: A Review. Environment, Development And Sustainability .

Shrestha, H. M. (1966). Cadastre Of Potential Water Power Resources Of Less Studied High Mountainous Regions, With Speical Reference To Nepal. Moscow: Moscow Power Institute, Ussr.

South Asia Subregional Economic Cooperation. (2025, July 20). Sasec.Asia. Retrieved 4 16, 2026, From Https://Www.Sasec.Asia/Index.Php?Page=News&Nid=1655&Url=Installed-Electricity-Capacity-Nepal-3878

Thapa, B., Shrestha, R., Dhakal, P., & Thapa, B. (2004). Sediment In Nepalese Hydropower Projects.

Timilsena , N. (2023). Bioengineering Techniques For Roadside Slope Stabilization In Nepal. International Journal Of Engineering And Science , 13 (1), 12-19.

Tripathi, P., & Shrestha, S. K. (2017). Risk Assessment Of Boot Hydropower Projects In Nepal Using Fuzzy Logic Approach. Journal Of Advanced College Of Engineering And Management .

United Nations. Sendai Framework For Disaster Risk Reduction 2015-2030.

Upadhayaya, R. P., & Baral, M. P. (2020). Trends Of Climate Change In Some Selected Districts Of Western Nepal. Janapriya Journal Of Interdisciplinary Studies .

Urja Khabar. (2025, May 29). Future Of Nepali Hydropower Amid Climate Change Challenges.

Wang, B.-W., He, Y., Wu, W.-H., & Teng, F. (2025). Quantifying Indirect Economic Losses From Extreme Events To Inform Global And Local Adaptation Strategies. Advances In Climate Change Research , 16, 674-687.

World Bank Group. (2021). Nepal Development Update, April 2021: Harnessing Export Potential For A Green, Inclusive, And Resilient Recovery.

Yu, J., Liu, X., Yu, Y., Li, H., Liu, P., Huang, K., Et Al. (2022). Research And Application Of High-Velocity Oxygen Fuel Coatings. Coatings , 12.

ANNEXES

Annex-I: Questionnaire

Loss Damage Analysis & Risk Mitigation Modelling of Operational Phase Hydropower due to Natural Calamities in Nepal

This survey collects technical and operational information regarding hydropower projects affected by natural hazards in Nepal. The responses will be used for academic research on hydropower operational risk, loss estimation, and mitigation modelling. All responses will remain confidential.

Instructions:

Please rate the following statements based on your experience.

Likert Scale Used:

Scale	Meaning
1	Very Low / Strongly Disagree
2	Low / Disagree
3	Moderate / Neutral
4	High / Agree
5	Very High / Strongly Agree

Section A: General Information of Hydropower Project:

1. Installed capacity of the plant (MW): _______
2. Type of hydropower plant: ________________
    - Run-of-River
    - Peaking Run-of-River
    - Storage
3. Design discharge (m^3/s): _______
4. Design head (m): _______

5. Type of turbine used: _____________
    - Pelton
    - Francis
    - Kaplan
    - Other
6. Number of turbine units: _____
7. Average annual energy generation (GWh): _______
8. Plant load factor (%): ______
9. Power Purchase Agreement (PPA) Details:
    - PPA Date (B.S./A.D.): ________________
    - Base Tariff Rate (Wet Season): NPR ______ / kWh
    - Base Tariff Rate (Dry Season): NPR _______ / kWh
    - Annual Escalation Rate (%): _______
    - Number of Escalations Completed: ________
10. Project Costing:
    - Total Commissioned Cost: NPR ________ Million
    - Debt-to-Equity Ratio: ________: ________

Section B: Respondent Information

1. Name: _____________________
2. Your Role: _________________
    - Operation Engineer
    - Maintenance Engineer
    - Plant Manager
    - Consultant

- ○ Project Engineer
- ○ Environmental Specialist
- ○ Other (Please Specify)

3. Years of Experience: _________
    - ○ <5
    - ○ 5:10
    - ○ 10:15
    - ○ >15

Section C: Natural Calamities Affecting Hydropower

Rate the severity of each natural disaster affecting plant operation.

Statement	**1**	**2**	**3**	**4**	**5**
Floods					
Landslides					
Sedimentation					
Debris flow					
Earthquakes					
Glacial Lake Outburst Flood (GLOF)					

Section D: Damage to Hydropower Components

Rate the vulnerability of the following components to disasters.

Statement	**1**	**2**	**3**	**4**	**5**

Intake structure					
Desander basin					
Penstock					
Turbine					
Generator					
Powerhouse					
Transmission line					

Section E: Impact of Natural Calamities on Hydropower Operation

1. Floods

Rate the impact of floods on hydropower project operation.

Statement	**1**	**2**	**3**	**4**	**5**
Flood events disrupt plant operation					
Flooding causes damage to intake structures					
Flood events increase sediment inflow to the plant					
Floods cause blockage of intake or desander basin					
Flood events lead to forced plant shutdown					
Flood protection structures are adequate					

Additional technical questions:

- Maximum flood discharge experienced since commissioning (m^3/s): ____________________
- Average downtime caused by flood events: _________________
- Are flood early warning systems available? (Yes/No): ______________

2. Landslides

Statement	1	2	3	4	5
Landslides affect access roads and plant infrastructure					
Landslides affect penstock alignment or stability					
Landslides cause sediment influx into waterways					
Landslides disrupt transmission lines					
Slope stabilization measures are effective					

Additional technical questions:

- Frequency of landslides near project area (No. of landslides Per Year): ______________
- Distance of landslide-prone slopes from major structures (Approx. Km): _____________
- Are slope stabilization measures implemented? (Yes/No): _______________

3.Sedimentation

Statement	1	2	3	4	5
Sediment load during monsoon significantly affects plant operation					
Sediment causes abrasion of turbine blades					
Sediment accumulation reduces hydraulic efficiency					
Sediment deposition affects intake operation					
Sediment management systems are effective					

Additional technical questions:

- Average sediment concentration during monsoon (ppm): ___________
- Desander efficiency (%): __________

- Frequency of turbine maintenance due to sediment abrasion: __________

4.Debris Flow

Statement	1	2	3	4	5
Debris flow blocks intake structures					
Debris flow damages diversion weirs					
Debris flow increases maintenance requirements					
Debris barriers are effective in preventing damage					
Debris flow causes plant shutdowns					

Additional technical questions:

- Is a debris barrier installed upstream of the intake? (Yes/No): ____
- Frequency of debris accumulation at intake: __________

5. Earthquakes

Statement	1	2	3	4	5
Seismic activity poses risk to hydropower structures					
Structural design meets seismic safety standards					
Earthquakes could cause misalignment of electro-mechanical equipment					
Emergency shutdown systems are adequate during seismic events					
Seismic monitoring systems are installed					

Additional technical questions:

- Seismic zone classification of project location: ___________
- Design peak ground acceleration used in design: ___________

6. Glacial Lake Outburst Flood (GLOF)

Statement	**1**	**2**	**3**	**4**	**5**
The hydropower project is vulnerable to upstream GLOF events					
GLOF events could damage diversion structures					
GLOF could cause extreme sediment and debris inflow					
Early warning systems exist for GLOF monitoring					
Current infrastructure can withstand extreme GLOF events					

Section F: Historical Hazard & Operational Impact

1. Significant Disaster Timeline:

Please identify major events that caused a shutdown since the plant's commissioning.

Year (B.S.)	Primary Hazard (e.g., Flood, Landslide)	Total Outage Duration (Days)	Primary Reason for Delay (e.g., Roadblock, Part Lead Time)

2. Cumulative Operational Losses:

- Estimated Total Generation Loss due to hazards in the last 5 years: ________ MWh.
- Estimated Total Financial Loss (Revenue + Repair) in the last 5 years: NPR ________ Million.

Estimated downtime after a disaster: ________

- <1 day
- 1:7 days
- 1:4 weeks
- 1 month

Section G: Financial Loss and Insurance

Statement	1	2	3	4	5
Natural disasters cause significant financial losses					
Revenue loss occurs due to forced outages					
Repair costs after disasters are high					
Insurance coverage is adequate for disaster damage					
Financial risk management strategies are effective					

- Claim Settlement Ratio: What percentage of total disaster repair costs was recovered from insurance in past events? ________ %
- Tariff Impact: Has the project ever requested a "Deemed Generation" payment or tariff adjustment due to a natural disaster? (Yes/No) ________

Section H: Risk Mitigation and Preparedness

Rate the effectiveness of the following mitigation measures.

Statement	1	2	3	4	5
Flood protection structures					
Sediment flushing systems					
Debris barriers					
Real-time monitoring systems					
Early warning systems					
Preventive maintenance programs					

Section I: Overall Risk Perception

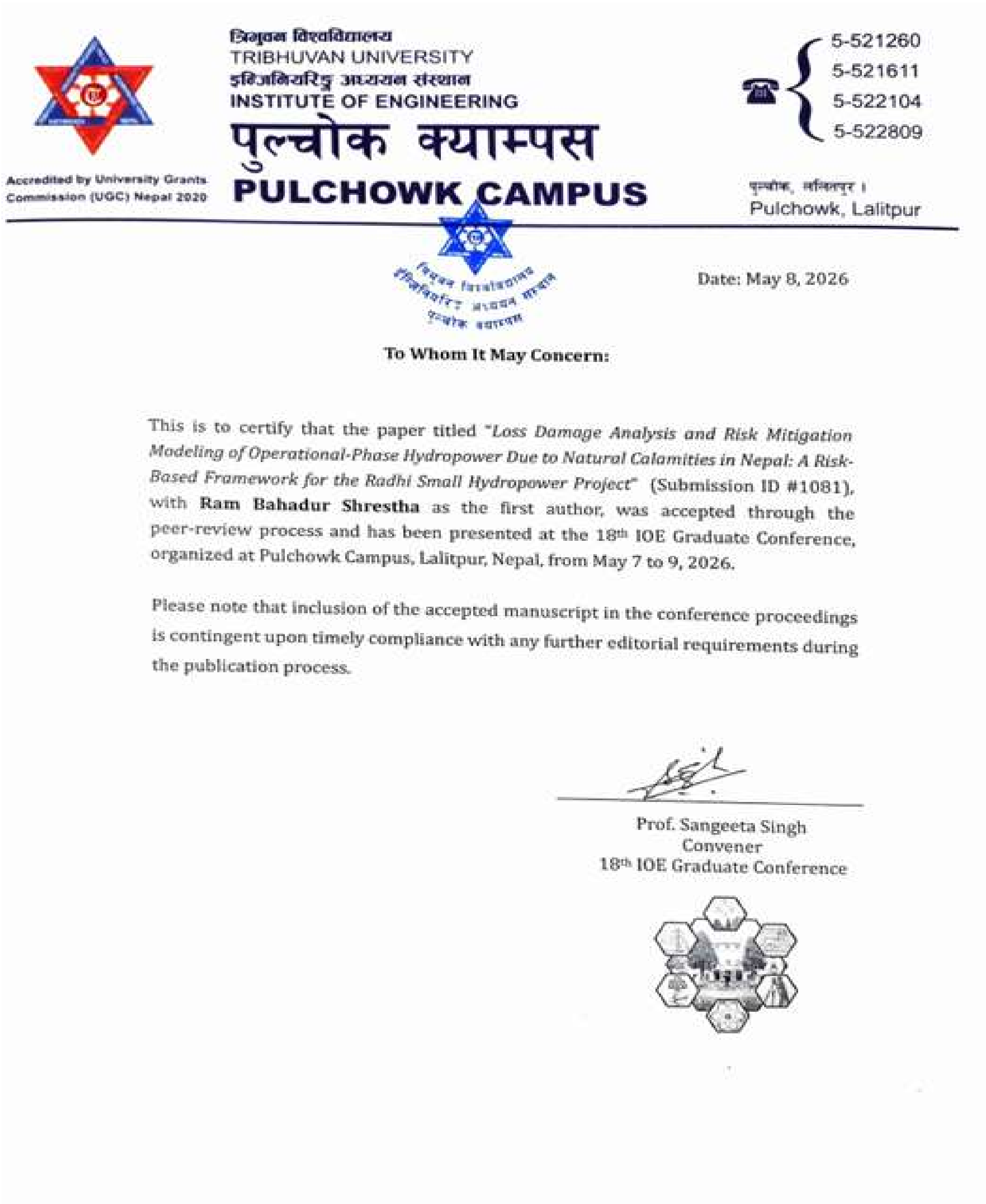
Statement	1	2	3	4	5
Hydropower plants in Nepal are highly vulnerable to natural disasters					
Current mitigation measures are sufficient					
Climate change will increase future hydropower risk					
Better risk modelling is necessary for plant operation					

Annex-II: Glossary of Technical Terms

Debris Flow	A debris flow (commonly called a mud slide) is a moving mass of loose mud, sand, soil, rock, water and air that travels down a slope under the influence of gravity.
Desander Basin (S-Trap)	A desander basin is the hydraulic structure of hydropower used to remove sand, abrasive sediment, and slit from the intake water. It is located between the intake structure and the penstock of hydropower.
Energy Loss	
Exposure (E)	In the tripartite risk model, the total economic value of assets and operational revenue subject to potential loss from hazard events.
GLOF	Glacial Lake Outburst Flood is a sudden, catastrophic release of water from a glacially dammed lake, typically triggered by dam failure through overtopping, seepage, or moraine collapse.
Hazard (H)	In the tripartite risk model, the spatial and temporal probability of a physical event (flood, landslide, earthquake, etc.) occurring with a specific intensity.
HVOF Coating	High-Velocity Oxygen Fuel coating is a thermal spray process used to apply wear-resistant metallic or ceramic coatings to turbine runner blades to protect against hydro-abrasive erosion.
Hydro-abrasive Erosion	Material removal from turbine surfaces caused by the impact of hard mineral particles (primarily quartz) carried in suspension in the water flowing through the turbine.
LDOF	Landslide Dam Outburst Flood is a flood event caused by the failure of a landslide dam that has impounded a river, releasing accumulated water and debris in a sudden surge.
Normalized Exposure (E_norm)	The composite exposure value (sum of asset replacement cost and annual energy revenue) divided by a reference threshold value (NPR 1,000 million in this study) to produce a dimensionless factor for use in the Risk calculation.

PPA	Power Purchase Agreement is a contract between an independent power producer and the electricity authority (NEA in Nepal) governing the terms and tariff rates for electricity purchase over a defined period.
Relative Importance Index (RII)	A quantitative metric derived from Likert-scale expert survey data, computed as $\Sigma W/(A\times N)$, where W is respondent ratings, A is the maximum rating, and N is total respondents. Values range from 0 to 1.
Run-of-River (RoR)	A type of hydropower project that generates electricity from the natural flow of a river without significant water storage, making generation highly dependent on natural discharge variability.
Tail Risk	In risk management, tail risk refers to the probability of rare, extreme events that lie in the far tails of a probability distribution, events that occur infrequently but cause disproportionately large losses when they do occur.
Vulnerability (V)	In the tripartite risk model, the predisposition of an infrastructure component to suffer functional failure or physical damage when subjected to a hazard of a given intensity.

Annex-III: IOE GC Acceptance Letter



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Pulchowk, Lalitpur

Date: May 8, 2026

To Whom It May Concern:

This is to certify that the paper titled "*Loss Damage Analysis and Risk Mitigation Modeling of Operational-Phase Hydropower Due to Natural Calamities in Nepal: A Risk-Based Framework for the Radhi Small Hydropower Project*" (Submission ID #1081), with **Ram Bahadur Shrestha** as the first author, was accepted through the peer-review process and has been presented at the 18th IOE Graduate Conference, organized at Pulchowk Campus, Lalitpur, Nepal, from May 7 to 9, 2026.

Please note that inclusion of the accepted manuscript in the conference proceedings is contingent upon timely compliance with any further editorial requirements during the publication process.

Prof. Sangeeta Singh
Convener
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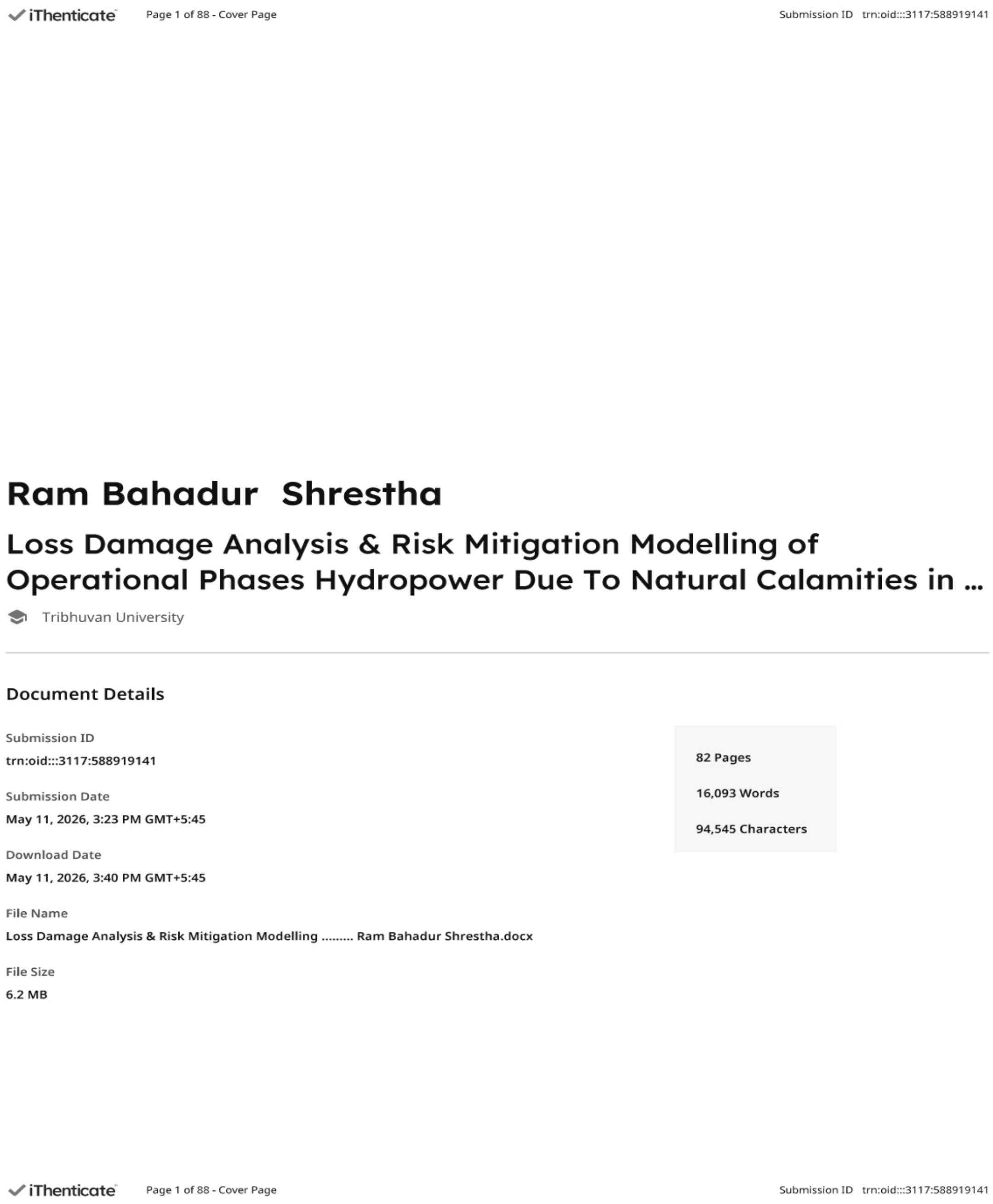
Annex-IV: Plagiarism Check



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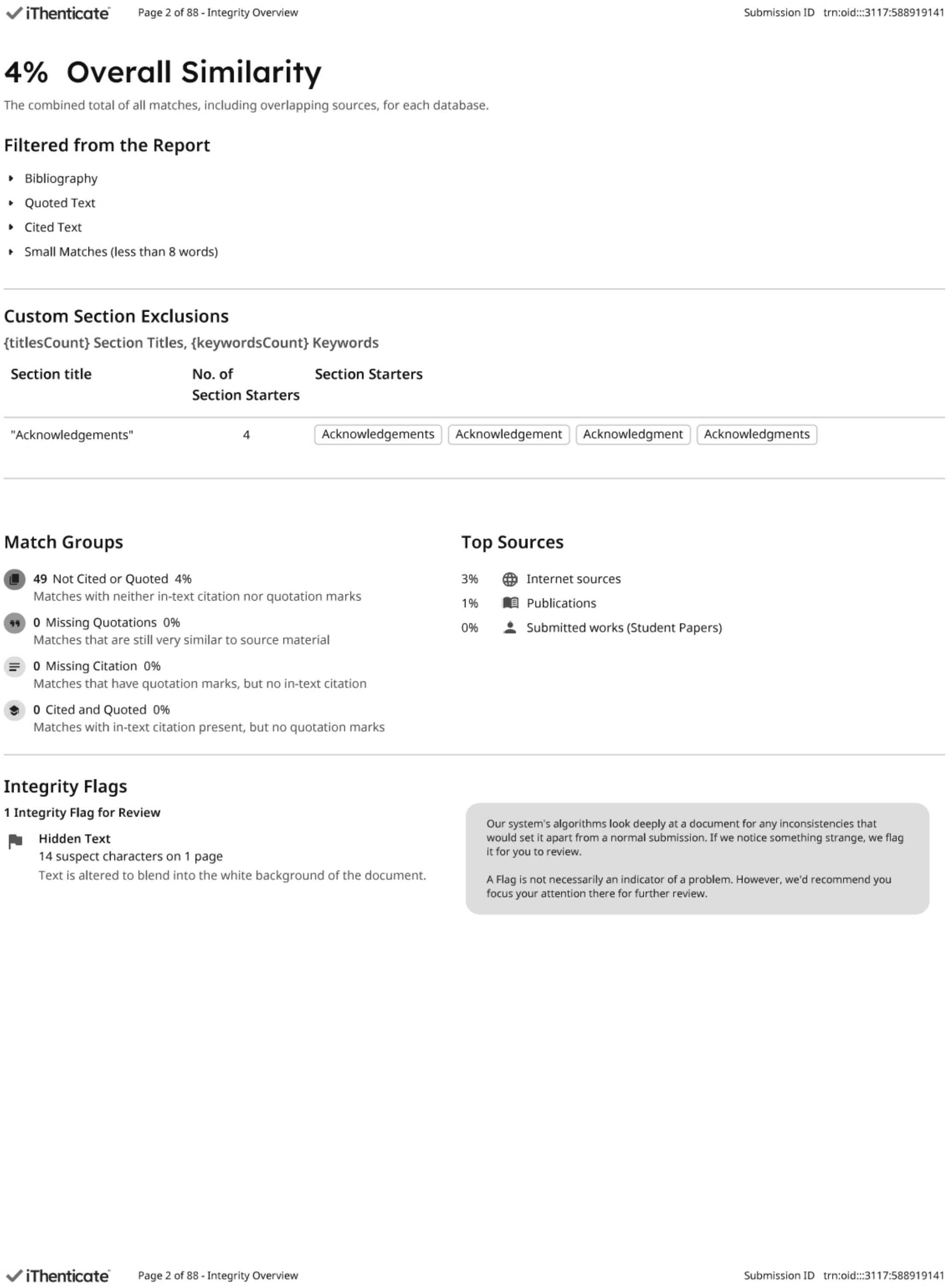

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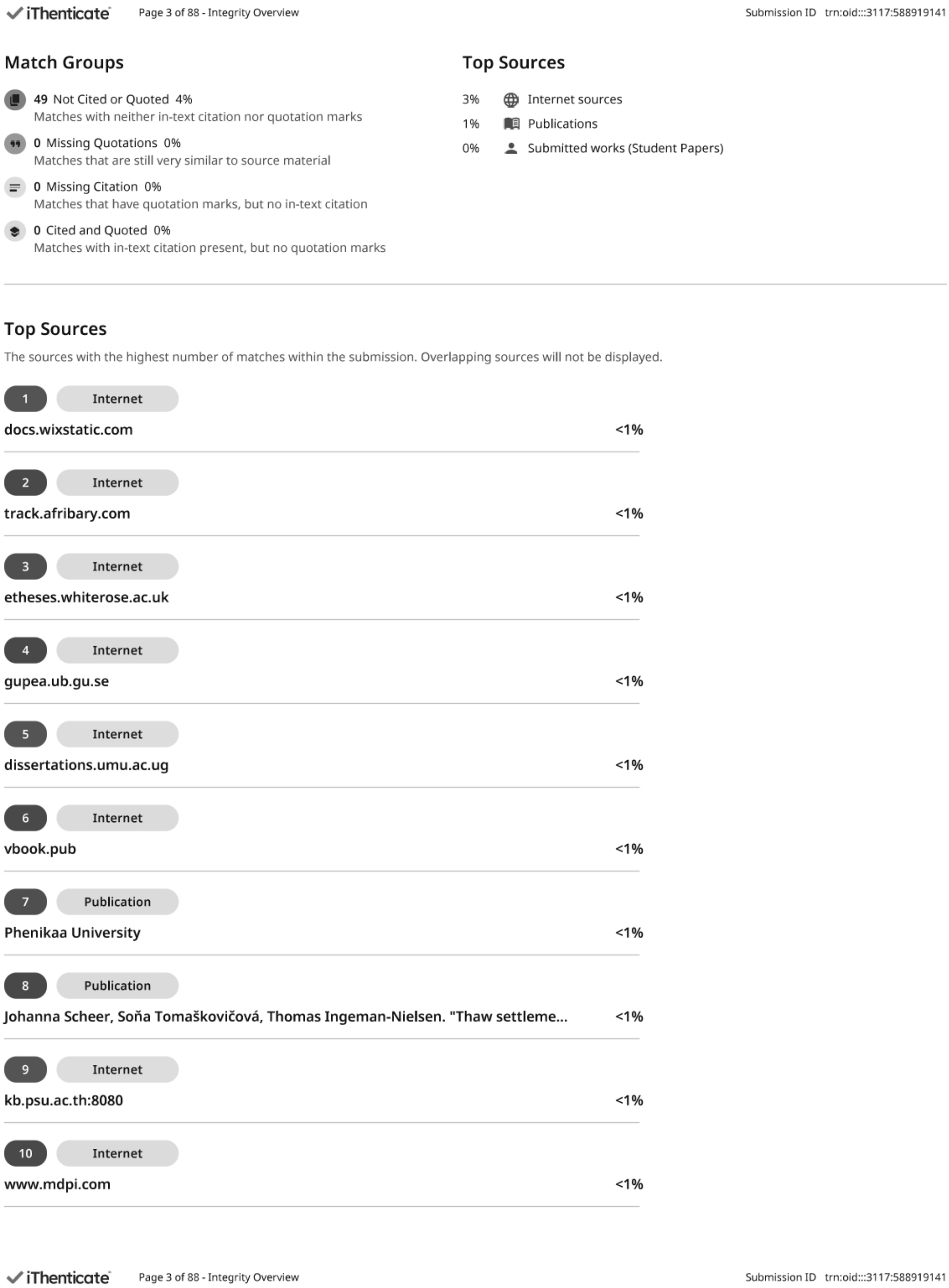

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