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FIELD SURVEY FINDINGS OF FLOOD IMPACTS AND RESILIENCE OF ELECTRICAL SYSTEMS IN NEPALESE HYDROPOWER PLANTS

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Abstract

Nepal's dependence on hydropower highlights the critical importance of ensuring the resilience of hydropower infrastructure amid increasing climate-induced disasters. This study investigates the impacts of flood events on the structural and electrical integrity of three types of hydropower plants in Nepal, run-of-river (RoR), peaking run-of-river (PRoR), and reservoir-based systems. Field observations were conducted at Trishuli, Kulekhani-I, and Mandu hydropower plants to assess flood-induced damage, system downtime, and operational vulnerabilities. Key aspects such as sediment accumulation, mechanical wear, switchyard exposure, and emergency response protocols were analyzed to understand each plant's capacity to withstand and recover from flood events. The findings reveal significant disparities in resilience based on plant design and location, with RoR plants demonstrating higher susceptibility to direct flood impacts. This study highlights the urgent need for improved flood forecasting, infrastructure upgrades, and adaptive operational strategies to bolster the long-term sustainability and reliability of Nepal's hydropower sector.

Keywords: Climate change, Electrical systems, Flood impact, PRoR, Reservoir hydropower, RoR, Structural damage, System vulnerability

1. Introduction

The cornerstone of clean energy generation, hydropower plants, play a critical role in meeting base as well as peak energy demand while contributing to grid stability, frequency and voltage regulation and in addition, facilitates the effective integration of renewable energy in the power system. Hydropower plants account for approximately 94.73% of total installed electricity generation capacity of Nepal (NEA, 2024).Therefore, Nepal relies predominantly on resilience of electrical systems in hydropower to maintain sustainability on the electricity generation market.

Nepal is ranked 69th among the countries most affected by extreme weather events in between the years 1993 and 2022 (Adil et al., 2025) despite only having contributed 0.051 percent (GoN, 2020) to the global emissions. The Ministry of Forest and Environment has highlighted increased glacial outbursts, floods and landslides as the consequences of climate change in Nepal (MoFE, 2021). Climate change has increased the frequency of heavy rainfall during monsoon resulting in more floods. Especially after the 2000s, the frequency of floods has increased by six times and the casualty rate has increased by four times than in the 1970s (Sharma et al., 2023). These after-effects of climate change have a severe impact in the hydropower plants in Nepal, mainly due to the topography of the plant locations. The flood of September 2024 caused damage in 11 operational hydropower projects with a total installed capacity of 625.96MW causing the loss of NPR 3 billions (NDRRMA, 2024).

Climate change has resulted in frequent unpredictable and extreme weather events like intense and frequent flooding. These events create severe risk for the electrical systems in hydropower plants. These risks include equipment failures, prolonged power outages, and operational disruptions. Even though the electrical systems are extremely important for power generation and grid stability, there is a limited understanding of how different types of hydropower plants respond to flood events and methods to improve the resilience of these plants. Standards and design practices used for designing these hydropower plants may not fully account for the continuously evolving nature of flood, especially in a diverse geography with

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dynamic hydrology like in Nepal. Hence, it has become imperative to observe, analyze and compare the impacts of floods on electrical infrastructure in different types of hydropower plants, for devising plans to make these systems more resilient accordingly.

The main objective of this study is to present observational findings of three hydropower plants focusing on investigating the effects of flooding on both electrical and mechanical equipment within these plants. Specifically, the study aims to analyze and compare the impacts of floods on the electrical infrastructure of different types of hydropower plants and to devise strategies for enhancing their resilience against such extreme weather events.

2. Area and Scope of the Study

This paper uses a multi-faceted approach to provide valuable insights into the vulnerabilities faced by hydropower infrastructure due to flooding, emphasizing the importance of resilience in maintaining energy generation capabilities in the face of climate change challenges. The scope of this study focuses on evaluating the impacts of flooding on electrical systems and structural resilience within three specific hydropower plants in Nepal: Trishuli, Kulekhani-I, and Mandu.

The study encompasses detailed field visits to the selected hydropower plants, enabling direct observation and assessment of flood impacts on both structural and electrical components. It aims to gather first-hand data regarding the physical state and operational disruption caused by the floods. The study distinguishes between run-of-river (RoR) and reservoir-based hydropower systems, examining how different designs and operational capacities respond to flooding. This comparative analysis aims to highlight discrepancies in resilience and operational effectiveness under extreme weather conditions.

The scope of the paper includes an examination of the operational downtime and generation losses experienced by each plant during flooding events. By analyzing the operational responses and capacity to recover, the study seeks to understand the implications for overall energy security. The study also assesses existing emergency response protocols and operational procedures during flood events. This analysis aims to identify strengths and weaknesses in current systems, providing insights for improving future emergency preparedness.

The paper will delve into the resilience of the electrical infrastructure associated with the hydropower plants. It will evaluate the impacts of flooding on electrical equipment, maintenance costs, and the potential for equipment failure due to environmental stresses. The broader implications of climate change on hydropower operations, particularly in a region like Nepal that is increasingly affected by extreme weather events has been recognized in this investigation. The findings aim to provide a contextual understanding of how these climatic factors exacerbate risks for hydropower facilities.

3. Methodology

Flood impact on electrical system resilience of hydropower plants can be observed by site visit of different hydropower plants that have been recently affected by flood and analyzed by the appropriate analytical approach and comparative analysis.

3.1. Site Visits

The details of the hydropower plants visited during the study have been presented in Table 1. Although Trishuli Hydropower Plant is planned as PRoR, it is currently operated as RoR plant.

3.2. Analytical Approach

Structural and electrical stresses on hydropower plants were assessed to analyze the impact of flooding on overall system vulnerability. Field observations were conducted at dam sites to identify structural damage, sediment buildup, and the presence of debris. All of these were found to reduce plant efficiency and increase both operational and maintenance demands. It was observed that debris and impurities passing through the penstock contributed to accelerated wear on turbines and generators, reducing the effective service life of electrical components and requiring more frequent maintenance interventions.

Flood-related downtime was recorded and analyzed in terms of its effect on power generation. The interruptions caused by these events led to noticeable reductions in energy output and increased strain on the electrical grid, highlighting the operational challenges during flood conditions. In addition, Observations of electrical machinery performance under stress conditions made after flood events provided insight into plant vulnerabilities. A comparative assessment was carried out across various types of hydropower plants, allowing for a clearer understanding of how different designs and site conditions influenced the plants' ability to endure flood impacts and maintain performance.

4. Observed Impact

4.1. Run-of-River Hydropower Plants

The observation focused on 4 major events like structural stress and damage, downtime and generation loss, substation and switchyard exposure, and emergency responses and protocol.

Structural stress and damage: The observations show that the major structural impact of flood is on the gates of the dam

Table 1. Details of three hydropower systems visited for study

Aspect	Kulekhani I HPP	Trishuli HPP	Mandu HPP
Type	Reservoir	PRoR	RoR
Head (m)	550	51.4	150
Capacity (MW)	60	24	22
Covered river basin	Bagmati	Trishuli	Bagmati
Catchment area (km2)	126	2600	180
Design discharge (m3/sec)	13.1	45.66	18
Annual energy (GWh)	211	304.78	120
Turbine Details			
Type	Vertical Shaft Pelton	Horizontal Shaft Francis	Vertical Shaft Francis
No. of units	2	7	2
Capacity(MW/unit)	31	3.62	11
Rated speed (rpm)	600	500	750
Discharge (m3/sec)	13.1	7.8	9
Generator Details			
Capacity(KVA)	35000	3889	13000
Power factor	0.85	0.9	0.85
Rated voltage (kV)	11	6.6	11
Frequency (Hz)	50	50	50
Transformer Details			
Type	3-phase	1-phase	3-phase
No. of units	2	6	2
Capacity (MVA)	35	5	13
Rated voltage (kV)	11/66	6.6/66	11/132

as the gates are the first section of the power plants which encounter the flood. The debris carried by the flood have severely damaged the dam gates requiring extensive repair works.

In case of Mandu HPP, the station itself has been severely damaged with the control room being completely swept away, as the power plant is right beside the river which has a bottleneck immediately downstream.

Downtime and generation loss: In case of Trishuli HPP due to the presence of excessive silts and debris in the flood water, the intake of the HPPs had been closed to prevent the equipment like turbines in the hydropower plant. However, the generator efficiency was not directly affected as the intake of the HPPs had been closed.

In the case of Mandu HPP, the turbine and generators were completely submerged in flood water destroying the whole system.

The Trishuli HPP was partially operated with the energy generation as shown in Figure 2 during the excessive flooding while Mandu HPP halted its production after the damage caused by the flood. But, as these two power stations are of small capacities, the impact to the central grid was not significant.

Substation and switchyard exposure: Although the hydropower stations are located on the banks of rivers, they tend to install the switchyard at a certain height from the river. It is the same for Trishuli HPP. So their substation and switchyard were not affected significantly. It was even more so due to the stop in power generation.

For Mandu HPP, the substation and switchyard had been installed right beside the Bagmati river, so they have been completely washed out with no component remaining intact.

Emergency responses and protocols: The hydropower plants train the personnel working in the plant to follow certain protocols and respond accordingly during natural disasters.

Based on these protocols, the HPPs had continuously monitored the weather forecast and water level in the rivers. When the water level reached a critical level they shut down all the operations of the plant. They opened the spillways according to the requirement to reduce the water pressure on the dam gates and intakes.

In case of Mandu HPP, as the flood water crossed the danger limit (at their measuring station in Chovar, Kathmandu), they evacuated the station preventing the loss of lives.

4.2. Reservoir Based Hydropower Plants

The observation focused on 4 major events like sediment accumulation, SCADA and operational delays, electrical infrastructure resilience, and emergency response protocol.

Sediment accumulation: Reservoir-based hydropower

Figure 1. Damaged gate of Trishuli HPP

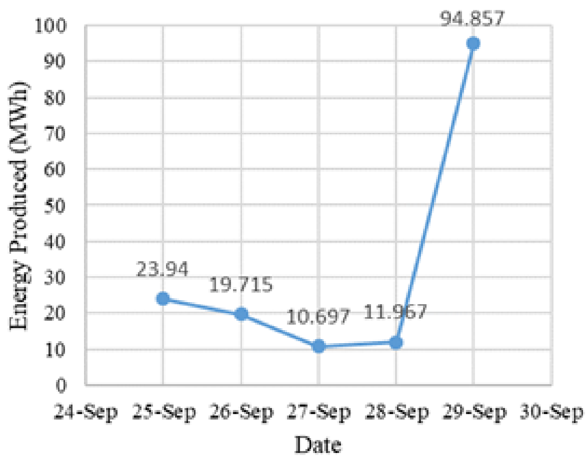

Figure 2. Energy production of Trishuli HPP

plants often contend with sediment accumulation as a significant challenge. This problem is more significant in flooded conditions. Sediments erode from the surrounding landscape and are deposited in the reservoir, leading to a reduction in storage capacity over time. The Kulekhani reservoir has faced the same problem due to the flood. The reservoir has lost over 25% of its total storage capacity in just 22 years of its operation (Sangroula, 2008). Although, there has been no detailed assessment after the flood, preliminary survey has shown that there has been a decrease in storage capacity due to the flood. This accumulation can impede water flow and decrease the efficiency of the turbines, ultimately impacting energy production capabilities.

SCADA and operational delays: The implementation of SCADA (Supervisory Control and Data Acquisition) systems in reservoir-based plants provides real time monitoring of systems including the water level in the reservoir. In case of Kulekhani dam, they are on manual monitoring and the SCADA system has not been implemented yet. After the brief interaction with the operator, it is suggested that during the peak flood, sudden rise in water level may occur that leads to operational delays. Since the spillway gate must be opened gradually, there must be some predicted data of water level which require proper operation of rain gauge around the catchment area and due to lack of appropriate amount of information and monitoring medium, operational delay has occurred.

Electrical infrastructure resilience: Electrical infrastructure resilience is a cornerstone of effective operation for reservoir-based hydropower plants. These systems are typically designed to cope with excess water through specific architectural features, such as elevated switchyards and encapsulated control systems that minimize flood risks which was the case in Kulekhani as well. The electrical infrastructure has been installed in such a way that the flood water could not affect it in any way.

Emergency response protocol: Being a storage type power plant, the generating unit of Kulekhani HPP was not affected directly by the flood, instead it was running at maximum capacity throughout the flood duration to release the water from the reservoir and prevent overflow.

The major area of focus of the hydropower during the flood was the water level of the reservoir. The plant operator continuously monitored the water level and opened the spillway gate when the discharge through the uncontrolled ogee spillway was not enough. Although this helped to save the reservoir, the water from spillways caused catastrophic damage in villages downstream.

5. Assessment of Plant Response and Resilience

This section analyzes the plant-specific responses and identifies key factors influencing the ability of electrical and structural systems to withstand and recover from flood-induced stress.

5.1. Electrical System Resilience

While all the types of hydropower plants are designed to deal with excess water in some form, their ability to control the operation of plants during floods depends upon the type of hydropower plant.

In a plant like Trishuli hydropower plant with less generation capacity whose small downtime does not have

Figure 3. Damage and reconstruction of Mandu HPP

significant effect on the grid, Operators may temporaryly shutdown the system to prevent the electromechanical machinery during peak floods. Although the electrical system has been isolated, the dam and gates are exposed to the flood directly and those parts of the plant are manually monitored and maintenance will be done after the flood settles down.

In reservoir-based hydropower plants like Kulekhani hydropower plant, control system, switchyard and other electrical equipment are generally indoor and isolated from the impact of flood. Mainly the stress due to flood occurs on the dam site of the plant. Proper spillway system has been adopted for the excess water to flow and to predict the operation of the spillway, the water level has been continuously monitored.

In run-of -river hydropower plants like Mandu hydropower, the whole plant system has been exposed to the flood and all other weather conditions. Plant response and resilience depend upon the location of the plant and enough diversion path for the flowing water. Floods have more impact on the ROR type hydropower plant and the system does not possess any protection against heavy flood conditions.

5.2. Key Resilience Factors

The key resilience factor against flood condition has been summarized in Table 2.

6. Discussion

6.1. Interpretation of Field Findings

In Nepal, the majority of hydropower plants—particularly RoR types, are situated along riverbanks, taking advantage of the country's steep topography and sufficient river systems. However, this geographical location also exposes these plants to a high risk of flooding and other water-related disasters. These disasters are exacerbated by the increasing frequency and intensity of extreme weather events driven by climate change, making hydropower infrastructure particularly vulnerable.

The proximity to rivers, while essential for energy generation, presents significant challenges in terms of structural safety and operational continuity. Flood events can cause severe damage to critical components, including intake structures, turbines, and transmission lines. Moreover, they pose a serious threat to human safety, especially to workers and communities living downstream or near the project sites. In extreme cases, the failure of hydropower facilities during floods can lead to cascading disasters, including widespread blackouts and loss of livelihoods. Given the high stakes involved, it is imperative that flood risk assessment and disaster resilience be central components in the design, planning, and operation of hydropower plants in Nepal. This includes integrating robust flood forecasting systems, designing infrastructure to withstand extreme hydrological events, and incorporating adaptive measures such as sediment management, reinforced embankments, and emergency response protocols. By addressing these risks comprehensively, Nepal can enhance the safety, sustainability, and long-term reliability of its hydropower sector, which remains a cornerstone of its renewable energy ambitions and economic development.

Table 2. Key flood resilience factors of different hydropower

HPP Type	Key flood resilience point
RoR	Floodwalls and levees around vital structures. High capacity spillways and bypass channels. Early warning system.
P-RoR	Moderate short-term flood regulation. Controlled spillway gates for proper flood routing. Real time monitoring of the system.
Storage	Large flood storage capacity. Flood forecasting and monitoring system. Controlled spillway gates.

6.2. Implications for Energy Security

In the short term, floodwaters can disrupt power generation by damaging critical components such as turbines, generators, substations, and control systems. This can lead to sudden shutdowns, causing grid instability and power outages, particularly in regions heavily reliant on hydropower. Additionally, flooding may damage transmission infrastructure, including power lines and transformers, further disrupting electricity delivery and increasing the risk of blackouts.

In the long term, repeated flooding accelerates siltation and the accumulation of debris in reservoirs and intake systems. This reduces storage capacity, clogs waterways, and impairs turbine performance, resulting in decreased generation efficiency and increased wear on mechanical parts. Persistent sediment buildup requires frequent maintenance and can ultimately shorten the operational lifespan of the facility. If these issues are not properly managed, the plant's generation capacity may decline over time, threatening its role in a stable, renewable energy mix and undermining national and regional energy security.

6.3. Broader Climate Change Impacts on Hydropower

Climate change greatly affects hydropower generation by changing precipitation patterns, increasing the frequency of extreme weather events, and causing glacier and snowmelt changes. These shifts lead to unpredictable river flows, seasonal water shortages, and rising intensity of floods, all of which compromise the reliability and efficiency of hydropower generation. In the long term, reduced water flow in rivers in some regions and increased siltation from intense rainfall may lower energy output and damage the infrastructure. Hence, climate change threatens the role of hydropower as a stable and sustainable energy source, demanding adaptive strategies in energy planning and water resource management.

7. Conclusion

In conclusion, while hydropower plants provide significant energy generation capabilities, they are not impervious to the challenges posed by sediment accumulation, operational delays, and extreme weather conditions. By focusing on infrastructure resilience, proactive sediment management, effective SCADA utilization, and comprehensive emergency response protocols, these plants can better navigate the complexities of an evolving climate and safeguard their operational integrity. Continuous investment in technology and infrastructure adaptation will be crucial for maintaining energy security in the face of climate-induced challenges. The major challenges that the hydropower sector of Nepal is facing while tackling the flood related damages are:

- Lack of updated flood risk models
- Limited infrastructure adaptation
- Financial constraints on retrofitting
- Environmental trade-offs (e.g. ecological disruption versus dam safety)

8. Acknowledgements

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