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RELIABILITY AND AVAILABILITY EVALUATION OF PEAKING RUN-OF-RIVER (PROR) HYDROPOWER PLANT OWNED BY NEA

BY

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CERTIFICATE OF APPROVAL

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ABSTRACT

Hydropower is the backbone of Nepal's energy sector and as of February 1, 2025, the installed capacity of hydropower plants in Nepal reached 3,255.806 MW. In this research, the availability and reliability of four Peaking Run-of-River (PRoR) hydropower plants owned by the Nepal Electricity Authority are evaluated: Kaligandaki "A" Hydropower Station (KGA), Middle Marsyangdi Hydropower Station (MMHPS), Marsyangdi Hydropower Station (MHPS) and Chameliya Hydropower Station (CHPS). Markov modeling techniques were utilized to analyze past historical operational data of five fiscal years (2076/77–2080/81) to identify major causes of failure, estimate downtime and propose optimization techniques.

Key reliability indices—Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), failure rates (λ), and repair rates (μ)—were computed to determine plant performance. The results present significant variation in the reliability of the plants examined, and faults in turbines and generators account for 47% and 20% of forced outages, respectively. KGA had the least reliability (99.36%) due to recurring generator and switchgear faults, while MHPS was suffering from aging plant issues, particularly increased shaft seal leakage, power transformer faults, TGB, LGB replacement and repair, while CHPS was suffering from repeated excitation system failure.

To address these issues, the following are proposed: conducting predictive maintenance activities, maintenance, and overhauling work of significant equipment as specified by OEMs, upgrading major components (turbine shaft seals, governor systems, control systems, and excitation systems), and maintaining spare part inventories. Additionally, employee training programs and knowledge transfer are recommended to enhance the operational efficiency of the hydropower plant. The study suggests proactive maintenance and technological upgradation in keeping Nepal's hydropower plants in good condition. One of the potential areas for research is embedding real-time monitoring systems, considering the cost-competitiveness of the modernization, and evaluating climate resilience to guarantee sustainable long-term supply.

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LIST OF ABBREVIATIONS

CHPS	Chameliya Hydropower Station
FY	Fiscal Year
GCB	Generator Circuit Breaker
KGA	KaligandakiHydropower Station
MHPS	Marsyangdi Hydropower Station
MIV	Main Inlet Valve
MMHPS	Middle Marsyangdi Hydropower Station
MTBF	Mean Time Between Failure
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
NEA	Nepal Electricity Authority
OEM	Original Equipment Manufacturer
PLC	Programmable Logic Controller
PRoR	Peaking Run-of-River
SCADA	Supervisory Control and Data Acquisition
TGB	Turbine Guide Bearing

CHAPTER ONE: INTRODUCTION

1.1 Background

Hydropower is the most reliable, cost-effective, and eco-friendly energy generation technique with the highest potential to replace conventional energy sources by harnessing the energy of flowing water. The installed capacity of hydropower plants in Nepal as of 1st February 2025 reached 3,255.806 MW [1], out of which 573.6 MW was contributed by the Nepal Electricity Authority (NEA), and that constitutes 17.54% of Nepal's hydropower generation. NEA is the only organization in Nepal that owns 13 RoR, 3 Storage-Cum-Cascade, and 4 PRoR hydropower plants to date. These hydropower plants play a crucial role in stabilizing the national grid. To have a stable and reliable power supply throughout the country, these power plants must be monitored and operated at optimal efficiency.

The Generation Directorate under NEA oversees the efficient operation and maintenance of 20 hydropower stations. The primary mandate of this Directorate is to maximize energy production by ensuring the optimal use of resources, periodic overhauling, minor to major maintenance, and manpower allocation. Among several hydropower plants owned by NEA, the following, as shown in Table 1.1, are the plants with a minimum installed capacity of 30 MW.

Table 1.1: Storage and PRoR Hydropower Plant Owned by NEA

S.No.	Hydropower Plant	Installed Capacity (MW)	Annual Designed Generation (GWh)	Number of Units	Type of Scheme
1	Kaligandaki ”A” Hydropower Station	144	842.57	3	PRoR
2	Middle Marsyangdi Hydropower Station	70	398	2	PRoR
3	Marsyangdi Hydropower Station	69	467.45	3	PRoR
4	Kulekhani-I Hydropower Station	60	165	2	Seasonal Storage
5	Upper Trishuli 3A Hydropower Station	60	489.76	2	RoR
6	Kulekhani-II Hydropower Station	32	104.6	2	Cascade
7	Chameliya Hydropower Station	30	184.2	2	PRoR

In Nepal for Fiscal Year (F.Y.) 2080/81, the annual system energy demand was 14,624 GWh, while the total annual energy generation from these seven hydropower plants amounts to 2441.7 GWh, which constitutes 16.7%. Hydropower plays a important role in the generation of electricity in the nation, and among these hydropower plants, PRoR plants contribute significantly to grid reliability and stability with energy security during peak demand. Thus, only the remaining 4 PRoR hydropower plants-Kaligandaki "A" Hydropower Station (KGA), Middle Marsyangdi Hydropower Station (MMHPS), Marsyangdi Hydropower Station (MHPS) and Chameliya Hydropower Station (CHPS) were included in the study. These four hydropower plants in F.Y. 2080/81 in total generated 1,862.773 GWh annually, which is equivalent to 12.74% of the total demand [2]. This justifies the importance of optimization in operation and maintenance to guarantee efficiency, reliability and availability for these plants.

The reliability and availability of power plants are vital components for judging the performance, strengths and weaknesses of plants and their constituent units. Reliability is the probability of a device or system performing its intended function adequately for the period intended under the operating conditions required. However, this definition of reliability applies to a particular kind of performance, where a device is considered successful if it operates without failure during its intended period of service.

The potential for maintenance after failures and continuous service after repair is not considered. However, there exists a class of equipment and systems (e.g., generators) which is repaired upon failure, then it continues service and is to continue doing so forever. Therefore, it is evident that the reliability of such a device must be described by a measure other than the one given above. One index of reliability in such situations is the availability. The availability of a repairable device is the fraction of time in the long run, that is in or available for service [3, 4]. Reliability evaluation can primarily be conducted using two techniques: analytical and simulation methods. Analytical techniques such as network analysis and Markov modeling utilize mathematical models to represent the network and derive reliability indices through mathematical solutions [5, 6].

1.2 Problem Statement

Nepal relies heavily on hydropower for power generation and its contribution is increasing very rapidly and therefore the stability and reliability of the power supply have become a big concern. PRoR hydropower plants play an important role in maintaining grid stability and energy security, particularly during peak demand periods. However, certain units of the NEA's PRoR plants have experienced extended outages, which have raised questions regarding their reliability. For instance, KGA unit 1 was halted for 413 hours due to a stator fault of the generator during F.Y. 2079/80, CHPS unit 1 had a 230-hour shutdown due to an excitation fault during F.Y. 2076/77, and MHPS had long downtime due to Turbine component issues. These are just a few examples of major forced shutdowns, with other factors likely contributing to outages as well. These long periods of downtime can create gaps in reliability and availability, potentially threatening grid stability during the crucial 4–6 hour daily peak demand period, even though PRoR plants account for 12.74% of Nepal's annual energy generation.

Currently, NEA's maintenance policy is mostly reactive and schedule-based, which leads to unplanned energy shortages resulting the need for costly energy imports. About 70% of forced outages in hydropower plants are caused by turbine and generator failures while the rest are due to issues with the excitation system, governor system, switchgear and auxiliary components. Thus, it becomes necessary to analyze the reliability and availability of NEA-owned PRoR hydropower plants to improve maintenance practices, prioritize repairs, and develop more effective strategies for reducing downtime and ensuring a more reliable energy supply.

1.3 Objectives

- The main objective of this study is to assess availability and reliability of PRoR hydropower plants owned by NEA to enhance the operational efficiency and sustainability of these plants.

- To achieve the main objective, key reliability indices such as MTBF, MTTR, failure rates(λ) and repair rates(μ) were calculated using the Markov modeling technique.

- The study identifies key causes of outages, including scheduled & forced outages and evaluates their impact on plant performance.

- The findings will contribute to the long-term sustainability of hydropower, enhancing grid stability and energy security in Nepal.

1.4 Limitation

- This study is limited to NEA-owned four PRoR hydropower plants- Kaligandaki "A" Hydropower Station, Middle Marsyangdi Hydropower Station, Marsyangdi Hydropower Station and Chameliya Hydropower Station, excluding other types of hydropower plants or privately owned stations.

- Analysis is carried out based on past operational records from F.Y. 2076/77 to 2080/81.

- Cause identification of outages are limited to:

  – Scheduled outage

  – Generator issues

  – Excitation system issues

  – Turbine issues

  – Governor system issues

  – Switchgear issues

  – Auxiliary system issues

  – Force majeure events

1.5 Thesis Organization

The dissertation is organized into five chapters. This section enlists a brief outline of each chapter and its contents.

- Chapter 1 gives brief introduction of the dissertation. The problem statement is described followed by the objectives, scope of works and limitation of the thesis.

- Chapter 2 explores the necessary literature review done for this dissertation.

- Chapter 3 describes the research methodology followed for this dissertation.

- Chapter 4 discusses and performs the analysis of the obtained results.

- Chapter 5 concludes the thesis work.

Finally, this thesis will end with a list of references and the relevant appendices.

CHAPTER TWO: LITERATURE REVIEW

This chapter provides a comprehensive literature review for the dissertation. It explains the fundamental principles of reliability and availability evaluation methods of hydropower plants, analysis of critical failures and make recommendations for their improvement.

2.1 Introduction

A hydropower plant is a power plant that generates power using the energy of flowing water. Nepal is the second largest and richest country in the world with abundant water source availability. Thus, Hydropower is a crucial component of Nepal's electricity generation system, playing a significant role in ensuring energy security and grid stability. Nowadays, energy mixing in Nepal is increasing to maintain reliability and stability of the national grid. Energy generated by PRoR hydropower plants is also a way of mixing energy in the national grid. Hence, out of the different types of sources available in Nepal, PRoR plants are particularly important in meeting peak energy demands. Thus, measuring the availability and reliability of these plants is very important in optimizing their operation and minimizing downtime.

Reliability is the probability that a hydropower plant will run without breakdown for a specified period of time under normal operating conditions. Availability, on the other hand is the proportion of time the plant runs or could run. Considerable work has been done in reliability and availability analysis of hydropower plants using statistical models, particularly Markov modeling techniques & Simulation techniques. This section reviews key literature on the subject, focusing on past research methodologies, findings and their implications for PRoR plants.

2.2 Reliability and Availability

The reliability of hydropower plants is the ability of the plant and its components to operate continuously without failure. These metrics are critical to ensure a consistent supply of electricity and a decrease in economic loss due to unexpected outages.

A reliable and highly available hydropower system contributes to energy security, which reduces dependency on backup power sources and enhances the sustainable supply of electricity. Maintenance schedules, equipment quality, and operating efficiency are the major determinants influencing reliability and availability.

2.2.1 Method for Evaluating Reliability and Availability

Mainly, the reliability evaluation can be carried out by two techniques: analytical and simulation. Numerous studies have been conducted to evaluate the reliability and availability of hydropower plants, and the generally used methods for their evaluation are listed below:

- **Analytical Techniques:** These involve mathematical models such as Markov chains, network analysis and failure rate modeling [6, 3].

- **Simulation Method:** Monte Carlo simulations estimate the reliability indices by simulating the actual process and random behavior of the system [5].

- **Historical Data Analysis:** Real-time and historical operational data are analyzed to determine failure trends, outage causes, and maintenance effectiveness [4, 7].

2.3 Monte Carlo Simulation in Reliability and Availability Analysis

Monte Carlo simulation is a computational algorithm that utilizes random sampling and statistical modeling methods to simulate the behavior of systems under uncertain conditions. The method is very effective for evaluating the reliability and availability of power plants, complex systems, etc., as it can include many factors, such as equipment failure rates, maintenance and operation schedules.

In [8], the Monte Carlo simulation-based method for estimating the reliability of structural systems was presented. Monte Carlo simulation method provides good estimates for the system failure probability with reduced computational cost. Pertaining to reference [9], the recently developed subset simulation and line sampling techniques are considered for improving the Monte Carlo simulation efficiency in the estimation of system failure probability. Whereas, the paper [10] aimed to discuss the possibilities of the use of Markov matrix-based Monte-Carlo Simulation of maintenance processes. The Monte Carlo simulation method can be used for the assessment of the requested number for spare part availability and maintenance cost of a technical system operation depending on required estimating uncertainty. The applicability of [11] is shown by the analysis of a 50MW, two-unit Hydroelectric Power Plant. The methodology is generally applicable and may be used to support the identification of a robust maintenance strategy for many engineering systems, including Nuclear Power Plants. Monte Carlo simulations require a large amount of computing time and are not used extensively if alternative analytical methods are available [5].

2.4 Markov Modeling in Reliability Analysis

Markov modeling is a must-used method for analyzing the reliability and availability of hydropower plants. It involves defining different operational states of the system and modeling the transitions between these states on the basis of failure and repair rates.

2.4.1 Key Studies on Markov Modeling in Hydropower

The author of [6] established the fundamental concepts of reliability evaluation in power systems, providing mathematical frameworks for reliability assessment. Major studies were done for the reliability evaluation of different systems, components, works, etc., using the concept established by this. Whereas, [7] applied Markov modeling method for reliability and availability evaluation of Sunkoshi Hydropower Station. The study concluded that scheduled maintenance significantly affected the availability of the station.

The paper [12] evaluated the reliability and availability of PATHRI & CHILLA Hydro Power Station (India) by using the Markov Model and they highlighted the importance of preventive maintenance done in hydropower plants. While, [13] has used frequency and duration (F&D) methods alongside Markov modeling to assess the reliability of the Kainji Hydro-Electric Power Station in Nigeria and concluded that the generating units at Kainji hydropower stations have not been adequately maintained leading to frequent and delayed forced outage indicating unreliable performance of the individual units and the entire station.

The researcher behind [14] applied Markov modeling techniques to the Dokan hydropower station, identifying key factors affecting its availability and reliability. They have highlighted that in the maintenance program, the skills of engineers and technicians play an important role in improving the performance of the units for increasing the availability and reliability of the units and the power plant. System reliability evaluation of Dadin Kowa hydropower plant was done in [15] where two methods were adopted and compared; Markov model and Energy index of reliability in the reliability evaluation and concluded that plant is reliable but daily seasonal and annual energy management system is recommended to enhance availability.

For systems with a manageable number of states, Markov models are fast and exact. Monte Carlo requires many iterations and can be computationally expensive for the same systems. These studies highlight the effectiveness of Markov modeling in predicting failure probabilities and optimizing maintenance schedules in hydropower plants and power systems. This improves reliability, reduces downtime and improves cost efficiency in engineering applications, ensuring sustainable energy generation and efficient asset management for long-term operational performance and stability.

2.5 Previous Studies on Hydropower Reliability

2.5.1 International Research

Several global studies have extensively analyzed hydropower plant reliability and availability by evaluating performance, failure patterns and maintenance strategies for operational efficiency improvements. The academic behind [4] analyzed the availability of the Balimela Hydro Electric Power Station using Markovian techniques. From the study, the failures that causes the maximum unit downtime was thrust bearing overheat and apart from this, the rest of the failures that occur on a daily basis were excitation and governer system faults. Although these faults do not always cause downtime, they cause interruptions in the continuity of the service. Whereas [3] introduced reliability evaluation methods for large electric power systems, which have since been applied in hydroelectric stations worldwide. Meanwhile, [13] has used frequency and duration (F&D) methods alongside Markov modeling to assess the reliability of the Kainji Hydro-Electric Power Station in Nigeria.

The researcher of [14] applied Markov modeling techniques to evaluate energy not generated, reliability, and availability of Dokan hydropower station, while [15] adopted two methods and compared; Markov model and Energy index of reliability in the reliability evaluation. Reliability indices of the Generation system were evaluated by using a radial basis function neural network in [16] and results obtained indicate that the proposed radial basis function neural network approach is a promising tool for evaluation of generation system reliability indices.

2.5.2 Research in Nepal

Limited research has been conducted on the reliability and availability evaluation of hydropower in Nepal. Though there have been some studies to evaluate the performance of existing hydropower plants, comprehensive evaluations with the purpose of system reliability, availability and operational efficiency are still limited, hindering development in optimizing this sector.

Different outage occurred in power plant in between F.Y. 2007/10 to F.Y. 2013/14 was analyzed for reliability and availability evaluation of Sunkoshi hydropower station using Markov method and concluded that plant is reliable with each of its unit being reliable and having the reliability index of more than 99% during the study period in all the units [7]. Reliability-based maintenance studies were done in [17] and made recommendations to install a redundant system of controllers for each unit. Risk rating for Risk-Based maintenance was done in [18] Risk through the Analytical Hieratical Process and Fault Tree Analysis and Rating through Failure Mode and Effects Analysis.

2.6 Factors Affecting Reliability and Availability of Hydropower Plant

The reliability and availability of hydropower plants depend on various factors, including water flow, maintenance, environmental conditions, weather patterns, and operational efficiency.

- **Scheduled Outages:**
  These are planned maintenance activities done on a schedule, such as preventive maintenance work, spiral casing/penstock inspection, system outage, transmission line maintenance, load dispatch center instruction, social issues, etc., that are essential for long-term plant health, so they reduce short-term unavailability.

- **Generator Failures:**
  Issues related to Generator Circuit Breakers (GCB), controllers, sensors, metering equipment, etc., that can lead to unexpected shutdowns affecting availability and reliability.

- **Excitation System Issues:**
  Common failures include rectifier bridge circuit faults, excitation transformer malfunctions, slip ring-carbon brush wear, etc., that lead to reduced efficiency and unplanned downtime.

- **Turbine Issues:**
  Guide vane failures, shaft seal leakage, bearing, Main Inlet Valve (MIV), bushes, link mechanical wear and tear, etc., are frequent causes of forced outages in hydropower plants.

- **Governor Issues:**
  Problems in oil pressure units, lubrication systems, servo motors, different sensors, etc., can impact the smooth operation of turbines and generators.

- **Auxiliary System Issues:**
  The cooling water system, MIV/Guide vane lubricating system, power supply system, braking/jacking, firefighting system, drainage/dewatering system, etc., may cause the shutdown of units.

2.7 Critical Failure Cause and Trend Analysis

Hydropower plants are complex systems and are susceptible to various kinds of failures due to hydro-mechanical, electro-mechanical, and environmental factors. Identifying and analyzing the critical failure causes is essential for improving the reliability of plants, minimizing their downtime, and optimizing maintenance strategies. The [19] examines the effect of critical failure modes on the reliability of the Effluent Treatment and Injection plant of an oil field. The essential equipment of the plant is identified, which, upon failure, could result in downtime of the facility. Based on the field data and OREDA database, probable failure rates in each critical mode and mean active repair time are developed with the help of Reliability Block Diagrams using the BLOCKSIM™ tool. Using the Monte Carlo approach, the performance of the system is analyzed in the critical failure modes over the lifetime. The author of [20] has investigated the statistical relationships among different critical failures (factors) and their associated causes (cause of failures), which occurred due to material deficiency, production organization, and planning. A real business case is presented, and the results that cause significant failure are illustrated. This study enables the creation of an intelligent predictive failure control system that can be integrated with production devices to create an ambient intelligence environment and thus will provide a solution for a smart manufacturing process of the future.

The [21] investigates Dynamic Environmental Flows assessment and shows the extent to which the choice and method of aggregation of different indicators impacts the Frontier of Pareto efficient solutions. While [22] presents the possibilities of using the Pareto method in evaluating the effectiveness of machine production processes, the paper deals with the production process of material cutting using progressive technology and subsequent evaluation of its effectiveness and quality. In [23], the authors demonstrate the issues with the help of a real-life case study in a service scenario and suggest the appropriate remedial measures for effectively separating the ‘vital few’ causes from the ‘trivial or useful many’ causes to enhance the discriminating power of the Pareto graph. However, the challenge is the identification of the correlation between error types, for which the authors suggest carrying out cluster analysis and its visual representation through the use of dendrograms.

As [24] the Pareto distribution and Pareto analysis are efficient tools that could be used to help company management to analyze the defects data and diagnose all the causes and causes of the biggest defect (dielectric defect) to determine and take any necessary corrective actions that will minimize the defective products. The article [25] presents a general classification of quality management tools applied in different industry branches. From among these tools, the authors have chosen a Pareto chart to present an analysis of the mining machines participating in the mining process. The analysis covers mining machines such as a road header, chain conveyor, belt conveyor, crusher, and a support.

2.8 Research Gap and Contribution

Despite much research on hydropower plant reliability worldwide, there have been few studies that focus on PRoR plant performance and reliability in Nepal. This gap in the literature is significant because PRoR plants, which operate primarily during periods of peak demand, have unique challenges that distinguish them from other types of hydropower plants. These Nepal power plants, which are mostly owned by NEA, are a valuable part of the country's power generation assets. However, their reliability and efficiency of operation are comparatively less known, opening up avenues for potential inefficiencies and increased risks of unscheduled outages.

This study aims to fill this gap by focusing specifically on NEA-owned PRoR hydropower plants and applying advanced techniques to understand their operational challenges in greater detail. The objectives of this study are as follows:

- **Applying Markov Modeling to Assess Reliability:**
  The study will utilize Markov modeling a robust stochastic process, to model the reliability of NEA-owned PRoR plants. This will allow the examination of plant performance in terms of the probabilistic transition between different states of operation.

- **Identifying Major Failure and Outage Causes:**
  A key component of the research entails the identification and examination of the primary causes of failure that influence the plants. These may include mechanical failures, e.g., turbine, shaft seal, thrust bearing, turbine guide bearing etc. or electrical faults, e.g., generator failure, switchgear, controllers etc.. Moreover, operational problems, e.g., inadequate maintenance techniques or equipment wear, will be taken into consideration as well. Through the identification of specific outage causes and failure causes, the study will be in a position to provide informative data regarding

weaknesses of PRoR plants and areas of importance that should be addressed in order to increase reliability.

- **Developing Optimized Maintenance Strategies:**
  Based on the findings of the Markov modeling and failure mode analysis, the study will suggest maintenance strategies that are optimized based on the specific needs of PRoR plants. The strategies will be predictive maintenance practices, which will aim to minimize unscheduled downtime and maximize the overall plant availability. The objective is to improve plant performance, reduce operating costs and extend the lifespan of the equipment while making the plants capable of meeting peak demand efficiently.

By accomplishing these objectives, this study will do much in increasing the operational efficiency and reliability of PRoR hydropower plants in Nepal. The study, apart from filling the existing gap in the literature, will also offer practical solutions to the existing problems in the hydropower sector in the country. Ultimately, the research aims to construct a whole system of improving the long-term performance and sustainability of hydropower plants in Nepal to offer a more stable source of energy to meet the country's growing demand.

CHAPTER THREE: METHODOLOGY

This study evaluates the reliability and availability of NEA-owned PRoR hydropower plants. The approach uses historical operating records, statistical modeling and the Markov state modeling method to obtain results.

3.1 Approach

To gain a comprehensive understanding of the availability and reliability of hydropower plants, a literature review was conducted. A detailed analysis was carried out for the major hydropower plants of NEA based on their structure, components and operational characteristics. The past performance data in terms of operating records and outage records due to major equipment such as turbines, generators, transformers, auxiliaries, etc., were collected from selected hydropower plants.

Using the collected data, various reliability indices, failure rates, and repair rates were calculated. To determine the overall reliability and availability of the hydropower plants, an initial evaluation was conducted at the unit level using the Markov modeling technique.

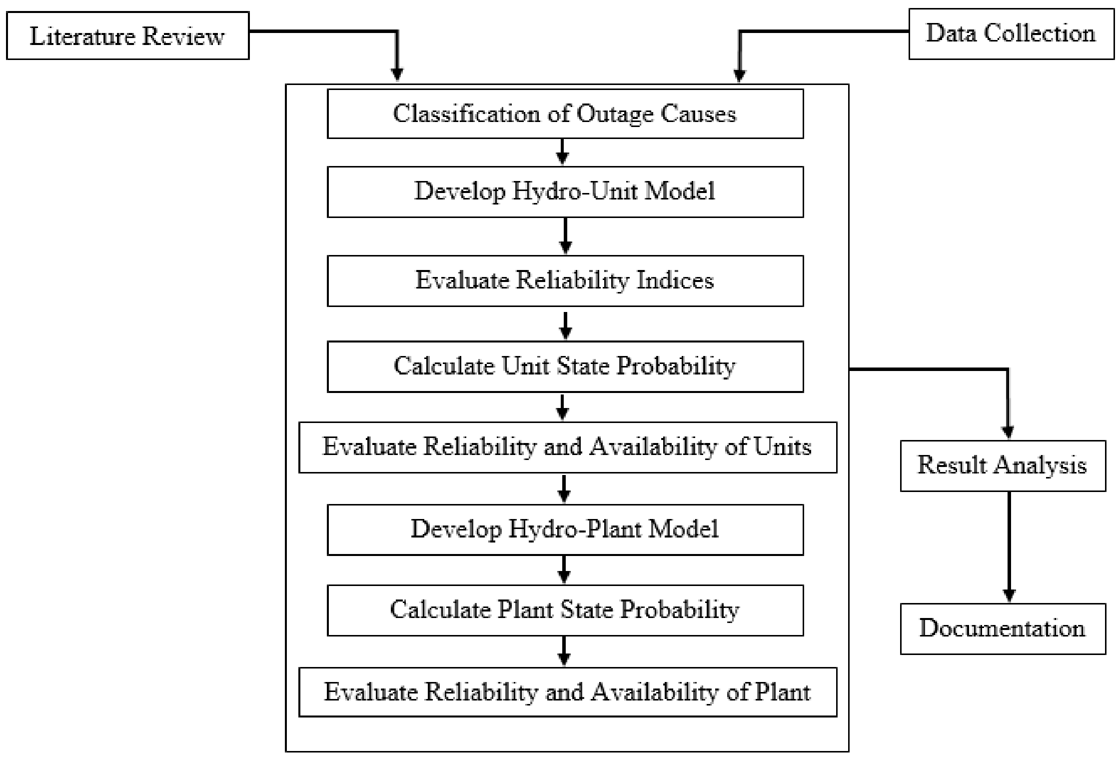


Figure 3.1: Methodology Approach

Initially, a hydro-unit model was developed in which a Unit State Probability Table was obtained based on failure rates and repair rates. Subsequently, a hydro-plant model was developed to yield a Plant State Probability Table. Finally, the reliability and availability of all plants were determined. The overall methodology followed in this dissertation is illustrated in Figure 3.1.

3.2 Data Collection

The study considers the 4 PRoR hydropower plants (Kaligandaki "A" Hydropower Station, Middle Marsyangdi Hydropower Station, Marsyangdi Hydropower Station, and Chameliya Hydropower Station). Data from fiscal years 2076/77 to 2080/81 was analyzed for forced outage records, scheduled maintenance logs and operational status.

The objective of this study is to provide an integrated performance assessment of NEA-owned PRoR hydropower plants, considering a systematic approach for reliability assessment to evaluate their performance under various operating conditions. The most significant reliability indices to be considered are MTBF, MTTR, MTTF, failure rate (λ), and repair rate (μ), which will be determined by analytical techniques.

3.3 Modeling

The system was modeled by defining the Markov states. To derive the Markov model of Hydro-Unit or Plant, the states can be classified into up-state and down-state as shown in Figure 3.2 [12]. The system is said to be in the up-state if plant or units are in operating state, and the system is said to be in down-state if plant or units are in non-operating condition due to forced or scheduled outages. The outage can be further classified into ideal outage, schedule outage, and forced outage. If the hydropower plant was non-operational due to less demand in the national grid or insufficient flow in the river, then it can be called an ideal outage.

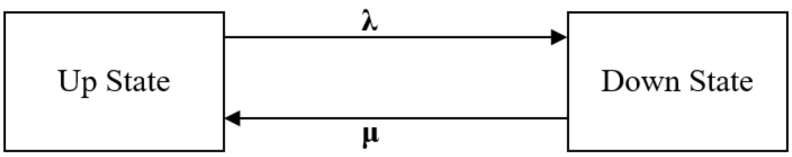


Figure 3.2: Two-State Model

If the hydropower plant was non-operational due to the unanticipated breakdown of a unit or machine, then it is called a forced outage. A scheduled outage means the shutdown of a generating unit for inspection or maintenance according to an advance schedule.

To develop the Markov model for the generating units, it is assumed that the failure and repair rates are exponentially distributed. There is no transition between scheduled and forced outages. The unit, after repairing, immediately returns to the up-state. From this, a developed Markov model is obtained as follows, known as the three-state Markov model as shown in Figure 3.3 [12].

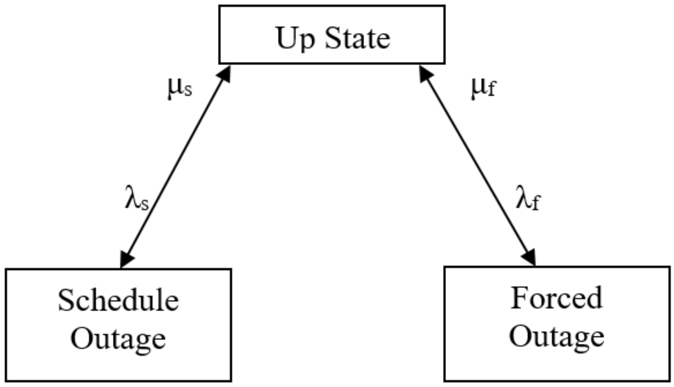


Figure 3.3: Three-State Model

3.3.1 Modeling of Hydro-Unit

A hydro-unit model of each unit of all plants was developed by defining eight Markov states based on the collected data and considering various types of failure observed in these plants and their units. Reliability indices were then calculated for each state, and the failure rate & repair rate were used to determine state probabilities as shown in Table 3.1 [15]. These probabilities were ultimately used to calculate units overall availability and reliability. The categorization of Hydro-Unit events can be classified as follows:

1. **Scheduled outage:** Preventive maintenance work, spiral casing/penstock inspection, system outage, transmission line maintenance, load dispatch center instruction, social issues, etc.

2. **Generator failure:** GCB, controllers, different associated sensors, metering equipment, current transformer, potential transformer, etc.

3. **Excitation system failure:** Rectifier bridge circuit, cooling system, transformer, slip ring-carbon brushes, etc.

4. **Turbine failure:** Turbine, shaft seal, bearings, MIV, guide vane, bushes, link, draft tube, etc.

Table 3.1: Unit State Probability

State Number	State Probability	
0	$\mu_1\mu_2\mu_3\mu_4\mu_5\mu_6\mu_7\mu_8/D$	d_0/D
1	$\lambda_1\mu_2\mu_3\mu_4\mu_5\mu_6\mu_7\mu_8/D$	d_1/D
2	$\mu_1\lambda_2\mu_3\mu_4\mu_5\mu_6\mu_7\mu_8/D$	d_2/D
3	$\mu_1\mu_2\lambda_3\mu_4\mu_5\mu_6\mu_7\mu_8/D$	d_3/D
4	$\mu_1\mu_2\mu_3\lambda_4\mu_5\mu_6\mu_7\mu_8/D$	d_4/D
5	$\mu_1\mu_2\mu_3\mu_4\lambda_5\mu_6\mu_7\mu_8/D$	d_5/D
6	$\mu_1\mu_2\mu_3\mu_4\mu_5\lambda_6\mu_7\mu_8/D$	d_6/D
7	$\mu_1\mu_2\mu_3\mu_4\mu_5\mu_6\lambda_7\mu_8/D$	d_7/D
8	$\mu_1\mu_2\mu_3\mu_4\mu_5\mu_6\mu_7\lambda_8/D$	d_8/D
Where $D = d_0 + d_1 + d_2 + d_3 + d_4 + d_5 + d_6 + d_7 + d_8$		

5. **Governor system failure:** Oil pressure unit, servo motors, different sensors, lubrication system, etc.

6. **Switchgear failure:** Main unit transformer, low voltage/ high voltage circuit breaker, power cable, bus-bar, disconnecting switches, etc.

7. **Auxiliary system failure:** Cooling water system, MIV/Guide vane lubricating system, power supply system, braking/jacking, firefighting system, drainage/dewatering system, etc.

8. **Force majeure:** Structural damage, flood etc.

The more developed hydro-unit model, after defining different states, is shown in Figure 3.4 [12].

Total outage time and number of faults that occurred for different failure conditions from the data collected will be utilized to calculate different reliability indices using the following formula [4]:

$$\textit{Mean time between fault (MTBF)} = \frac{\textit{Observed time}}{N} \tag{3.1}$$

$$\textit{Mean time to repair (MTTR)} = \frac{FOH}{N} \tag{3.2}$$

$$\textit{Mean time to failure (MTTF)} = MTBF - MTTR \tag{3.3}$$

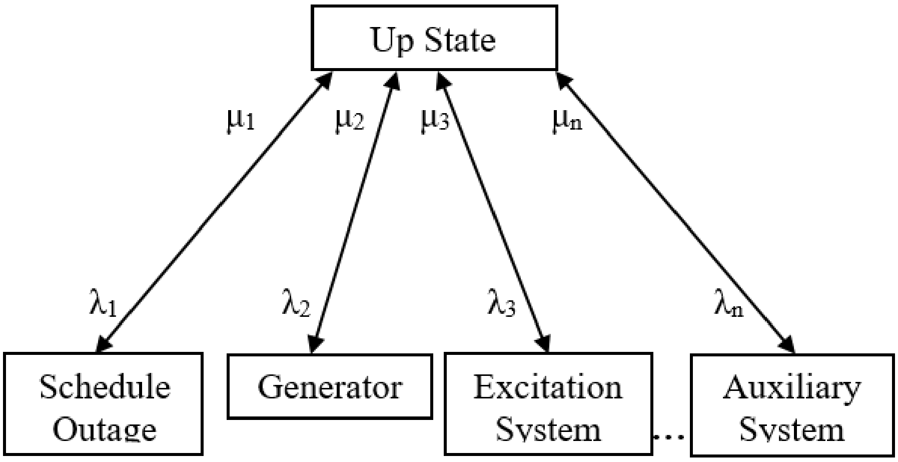


Figure 3.4: Developed Hydro-Unit Model

$$\textit{Repair rate } (\mu) = \frac{1}{MTTR} \tag{3.4}$$

$$\textit{Failure rate } (\lambda) = \frac{1}{MTTF} \tag{3.5}$$

Where,
Numbers of failure (N) = Number of times a unit experiencing downtime.
Force Outage Hours (FOH) = Time in hours during which a units or major equipment is down due to their failure.

Collected data will be analyzed using statistical methods to derive reliability functions for each unit. According to the definition of reliability, reliability is considered as the probability of the unit operating without unit failure [4]. States 0 and 1 are the states that are the probability of operating units without failure. Thus, the reliability of the unit is:

$$Reliability(R) = P_0 + P_1 \tag{3.6}$$

Availability considers the time when the unit is operating in normal condition, i.e. the availability is the probability of unit in up-state [4].

$$Availability(A) = P_0 \tag{3.7}$$

3.3.2 Modeling of Hydro-Plant

The hydropower plant chosen for study consists of two types: Type 1, consisting of 2 units (MMHPS and CHPS) and Type 2, consisting of 3 units (KGA and MHPS). The number of failure rates and repair rates of all units for one year are taken to determine the plant's availability and reliability. The transition rate matrix and state probabilities are determined in the same ways as for unit modeling. The maximum number of components is 2 for the hydropower plant, so the maximum number of states is calculated using the following formula [14]:

$$\text{Maximum number of states for plants} = 2^n \tag{3.8}$$

where,
n = Number of Units
At least one unit must be operating for the plant to be available. For a Type-1 plant, 1 out of 2 units and for a Type-2 plant, 2 out of 3 units must be operating to determine the reliability of the plant.

Type 1 plant modeling: For the modeling of plants having two units, i.e., MMHPS and CHPS, both units should be studied together. Thus, the maximum number of states is 4. The probability of a state is calculated using the following formulas [14]:

$$P_1 = \prod_{k=1}^{4} \frac{\mu_k}{\lambda_k + \mu_k} \tag{3.9}$$

$$P_4 = \prod_{k=1}^{4} \frac{\lambda_k}{\lambda_i + \mu_k} \tag{3.10}$$

$$Reliability(R) = \sum_{k=1}^{3} P_k \tag{3.11}$$

$$Availability(A) = \sum_{k=1}^{3} P_k \tag{3.12}$$

Type 2 plant modeling: For modeling plants having three units, i.e., KGA and MHPS, all units should be studied together. Thus, the maximum number of states is 8. The probability of state is calculated using the following formula [14]:

$$P_1 = \prod_{k=1}^{8} \frac{\mu_k}{\lambda_k + \mu_k} \tag{3.13}$$

$$P_8 = \prod_{k=1}^{8} \frac{\lambda_k}{\lambda_k + \mu_k} \tag{3.14}$$

$$Reliability(R) = P_1 + P_2 + P_3 + P_5 \tag{3.15}$$

$$Availability(A) = \sum_{k=1}^{7} P_k \tag{3.16}$$

3.4 Critical Failure Cause and Trend Analysis

After evaluating the reliability and availability of four PRoR hydropower plants, the trends in faults affecting the hydropower units were analyzed. The trend analysis revealed how faults impact the reliability of the units. Additionally, the critical failure causes impacting the plant were examined using the Pareto principle, which states that approximately 80% of the consequences result from 20% of the causes. Based on this principle, the most problematic systems of the units were identified, and based on this, a maintenance plan to enhance unit performance was developed. To determine the critical failure causes, the total outage hours for each unit during one fiscal year were calculated. The percentage of each failure cause was then calculated, and the failure causes were arranged in descending order. The top failure causes, which cumulatively account for 80% of the total downtime, were identified as the critical cause of failure that accounts for the majority of the unit's downtime.

3.5 Tools and Software

This section lists the tools and software used in this dissertation.

3.5.1 Microsoft Office

Microsoft Office comprises a suite of software applications created by Microsoft including a word processing program (Word), a spreadsheet application (Excel) and a presentation software (PowerPoint), among other tools. In this dissertation, Word is utilized for initial report drafting, while Excel is employed for storing the historic records of plant extracted.

3.5.2 Project Jupyter

Project Jupyter is a set of tools designed to develop open-source software and services for interactive computing across multiple programming languages. Within Project Jupyter, "Jupyter Notebook" can refer to two different concepts: the user-facing application used to edit code and text or the underlying file format, which is interoperable across various implementations. Jupyter Notebook is a web-based interactive computational environment that allows the creation of notebook documents. In this dissertation Jupyter Notebook is used to model the Markov method for performing analytical analysis and critical failure & outage trend analysis.

3.5.3 Overleaf

Overleaf is an innovative online platform and LaTeX editor designed specifically for academics, researchers, and professionals involved in scientific writing and publishing. Overleaf provides a collaborative environment where users can create, edit and manage LaTeX documents seamlessly, without the need for local LaTeX installations or complex setup. It offers LaTeX templates from various reputable journals. In this dissertation, overleaf is used for preparing the reports.

CHAPTER FOUR: RESULTS AND DISCUSSION

This chapter presents the results and discussion obtained through the process of data collection and analysis following the methodology described in Chapter 3.

The primary objective is to determine the reliability measures MTBF, MTTR, MTTF, failure rate and repair rate from data collected. These measures then have been used in calculating the state probabilities table of all the units of KGA, MMHPS, MHPS, and CHPS from which unit reliability and availability were obtained. Thereafter, the analysis also gives an overview of the availability and reliability of all four hydropower plants for the time period between F.Y. 2076/77 to 2080/81. These results are essential for understanding the operational performance status of the plant over the specified period of time.

4.1 Kaligandaki "A" Hydropower Station

The reliability and availability of KGA for F.Y. 2076/77 to 2080/81 of all three units and plants are presented in Table 4.1. Figures 4.1 and 4.2 depict the graphical representation of all units and plants, respectively.

- The overall availability and reliability of all three units of KGA were found to be low.
- **F.Y. 2076/77:** The availability of unit 1 and unit 3 found declined because both units were shutdown for scheduled maintenance work and issues; unit 1 for 789.23 hours and unit 2 for 740.05 hours. These works include unit overhauling and maintenance work, intake gate backwash, desander and reservoir flushing work, etc. Also, the reliability and availability of unit 2 dropped because of repeated forced shutdowns caused by faults in the control logic system, rotor faults, and subsequent repairs. Also, unit 2 suffered a 224-hour shutdown due to control system upgradation work, which has lowered its availability. During this F.Y., the plant was under a complete shutdown for different maintenance work for 70.25 hours. These are the major causes that have led to KGA's lower reliability for this F.Y..
- **F.Y. 2077/78:** After the modernization of the control system of all three units during F.Y. 2076/77 and 2077/78, the plant's reliability and availability have shown noticeable improvement, ensuring more stable operations and reduced unplanned

shutdowns. But the availability of unit 2 dropped because this unit was shutdown for 623.55 hours for unit overhauling work.

- **F.Y. 2079/80:** Unit 1 experienced a forced outage of 412.37 hours due to the stator earth fault and a further 16 hours of shutdown due to the excitation faults, which affected its reliability. Also, this unit was shutdown for 303 hours for unit overhauling work, and all these cumulatively reduced the availability to a significant degree. Unit 2 also experienced a forced outage of 75.52 hours due to the rotor earth fault and cooling system issues. Meanwhile, unit 3 was shutdown for 494.63 hours for unit overhauling work and also had experienced a forced outage of 54.78 hours due to the Buchholz relay failure in the power transformer with additional shutdown time for its repair. All these cumulatively led to the decreased reliability of the plant for this F.Y..

Table 4.1: Availability and Reliability of KGA Over Five Fiscal Years

F.Y.	Unit 1		Unit 2		Unit 3		Plant	
	A	R	A	R	A	R	A	R
2076/77	0.9026	0.9962	0.9627	0.9729	0.9005	0.9920	0.99969	0.98543
2077/78	0.9902	0.9921	0.9129	0.9934	0.9869	0.9909	0.99989	0.99801
2078/79	0.9909	0.9944	0.9969	0.9985	0.9955	0.9989	0.99989	0.99792
2079/80	0.9001	0.9362	0.9668	0.9693	0.9298	0.9920	0.99977	0.98789
2080/81	0.9879	0.9977	0.9405	0.9983	0.9888	0.9986	0.99989	0.99857

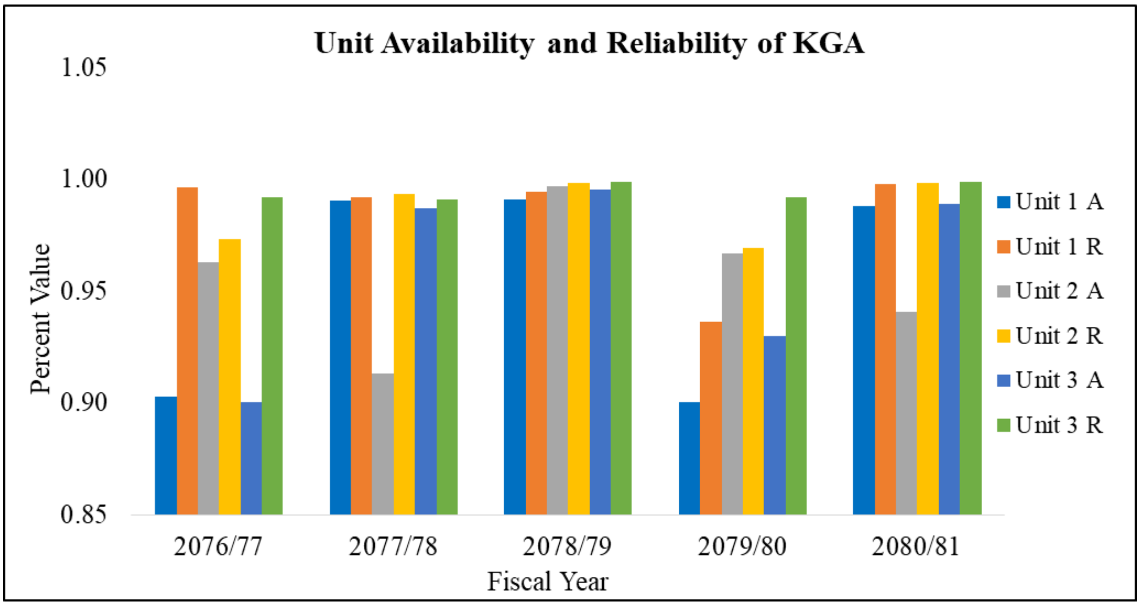


Figure 4.1: Unit Availability and Reliability of KGA

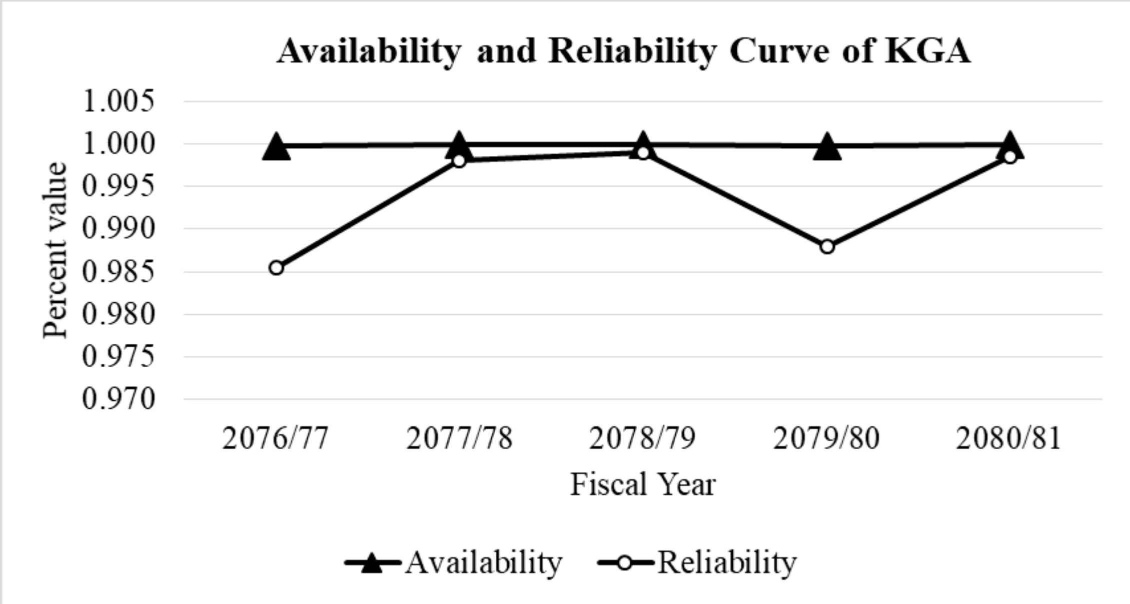


Figure 4.2: Plant Availability and Reliability of KGA

- In overall, for every F.Y. excluding planned ones, the major causes of forced shutdown of units were found to be maintenance of generators, auxiliary systems, controllers, GCB and power transformer.

4.1.1 Unit-Wise Critical Failure Cause and Trend Analysis

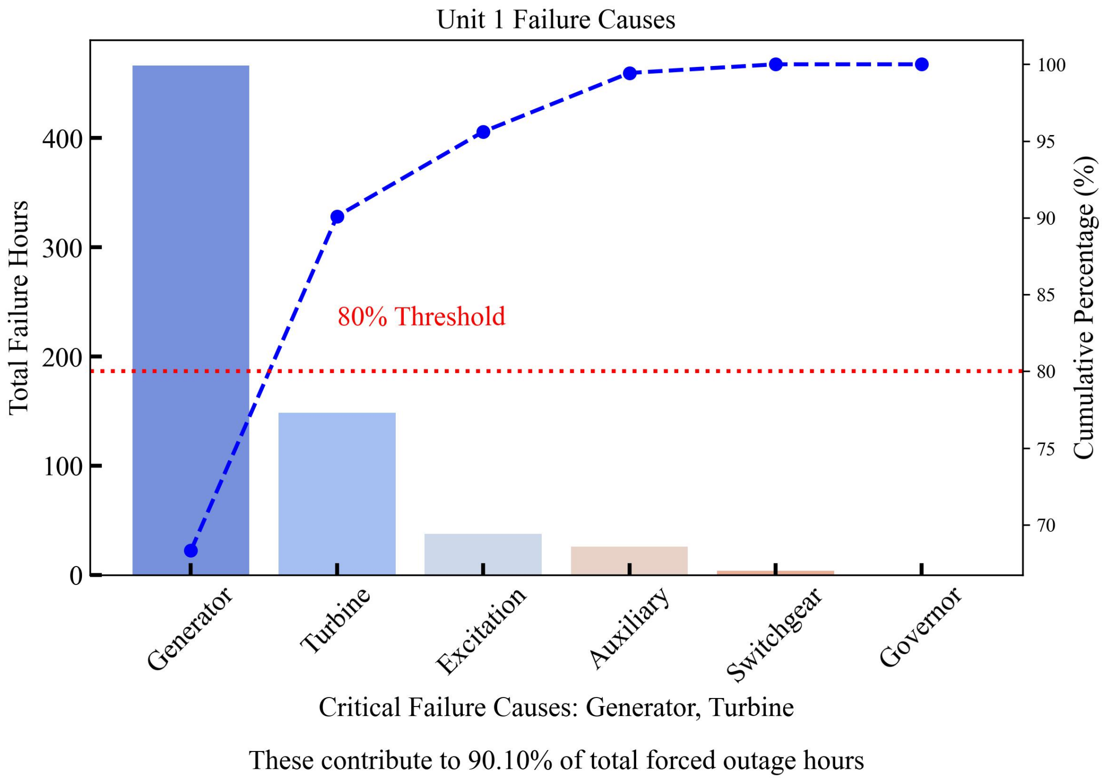
The unit-wise trend analysis for every F.Y. considered is illustrated in Figure 4.4. From this analysis, it can be concluded that the performance of unit 1 was low compared to other units. The Pareto analysis chart of all three units is presented in Figure 4.3, and the most critical failure causes for these units are given below:

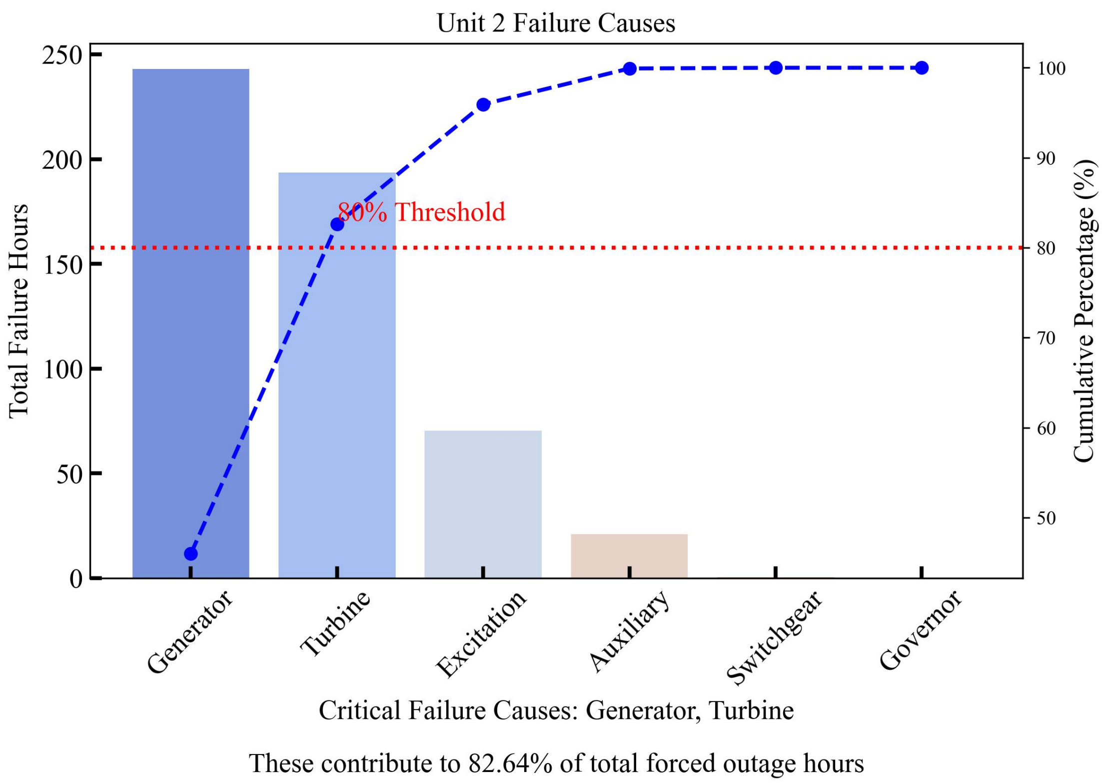
- **Unit 1:** Generator and Turbine which contribute to 90.101% of total forced outage hours.

- **Unit 2:** Generator and Turbine which contribute to 82.64% of total forced outage hours.

- **Unit 3:** Switchgear and Generator which contribute to 82.27% of total forced outage hours.

This analysis depicted that generator, turbine, and switchgear failures were the main causes of forced shutdowns in KGA. The generator of KGA was manufactured by Toshiba Japan and as per Original Equipment Manufacturer (OEM) recommendations, these generators require overhauling after every eight years. However, due to a lack of skilled personnel


Unit 1 Failure Causes
Total Failure Hours
0
100
200
300
400
Cumulative Percentage (%)
70
75
80
85
90
95
100
80% Threshold
Generator
Turbine
Excitation
Auxiliary
Switchgear
Governor
Critical Failure Causes: Generator, Turbine
These contribute to 90.10% of total forced outage hours


Unit 2 Failure Causes
Total Failure Hours
0
50
100
150
200
250
Cumulative Percentage (%)
50
60
70
80
90
100
80% Threshold
Generator
Turbine
Excitation
Auxiliary
Switchgear
Governor
Critical Failure Causes: Generator, Turbine
These contribute to 82.64% of total forced outage hours

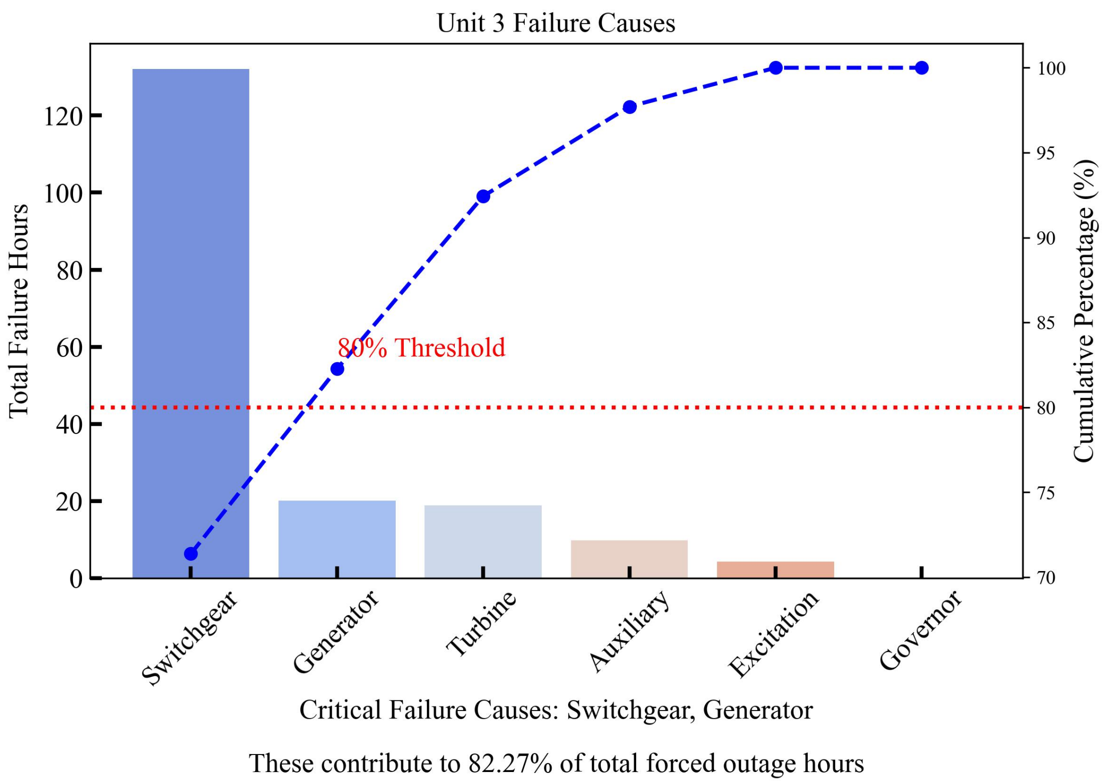


Figure 4.3: Causes of Critical Failure at KGA

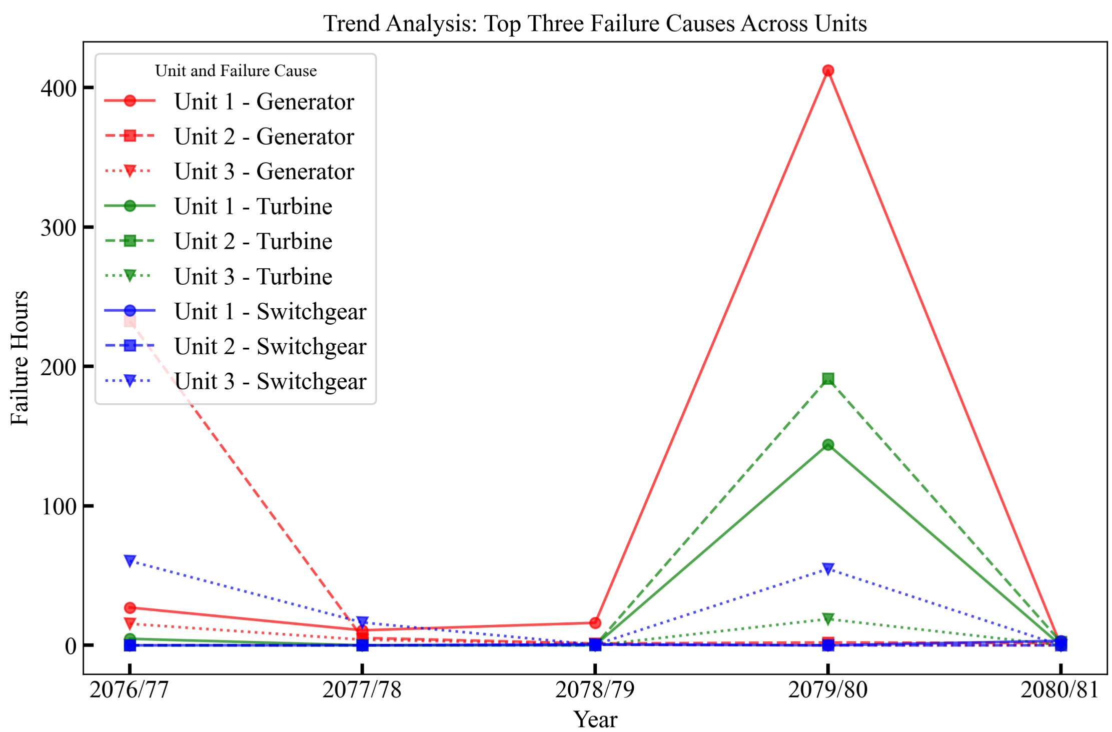


Figure 4.4: Trend Analysis Chart for KGA

and the energy crisis in Nepal, this overhauling work was not performed. As a result, unit 1 (from 3/8/2080 to 3/25/2080) experienced consecutive forced outages due to generator failures and were restored through their repair work. In order to prevent repetitions of these issues, the generators of all three units must be overhauled altogether in order to ensure reliability and stability in operation. Additionally, condition monitoring of power transformers and other high-voltage equipment is crucial in order to monitor their health, enabling quick repairs and replacements in order to reduce forced outages.

4.2 Middle Marsyangdi Hydropower Station

The reliability and availability of MMHPS for F.Y. 2076/77 to 2080/81 for both units and plants are presented in Table 4.2. Figures 4.5 and 4.6 depict the graphical representation of all units and plants, respectively.

Table 4.2: Availability and Reliability of MMHPS Over Five Fiscal Years

F.Y.	Unit 1		Unit 2		Plant	
	A	R	A	R	A	R
2076/77	0.9895	0.9930	0.9430	0.9948	0.99942	0.99942
2077/78	0.9940	0.9966	0.9950	0.9976	0.99989	0.99989
2078/79	0.9557	0.9912	0.9920	0.9943	0.99965	0.99965
2079/80	0.9915	0.9978	0.9259	0.9942	0.99940	0.99940
2080/81	0.9493	0.9987	0.9889	0.9982	0.99946	0.99946

- The overall availability and reliability of MMHPS remained above 99%, demonstrating strong power generation performance.

- **F.Y. 2076/77:** Availability and reliability of the plant were found to have declined because both units were shutdown for scheduled maintenance work and issues; unit 1 for 30.15 hours and unit 2 for 433.42 hours. These works include unit overhauling & maintenance work and reservoir flushing work, etc. Also, unit 1 was forced to shut down for 37 hours due to a fault in the braking system and burning of the 11 kV power cable. Unit 2 was forced to shut down for 28 hours due to a fault in the inverter, controller system, water leakage from the shaft seal and SS-cone.

- **F.Y. 2078/79:** The availability and reliability of the plant appeared to be reduced because unit 1 and unit 2 were forced to shut down for 52.05 hours due to failures in the firefighting and closed-circuit cooling water systems. Additional issues included leakage of water from the wicket gate, head cover, balancing pipe, and cooler. Also, the availability of unit 1 was found to be reduced due to a shutdown for overhauling work, which lasted for 282.72 hours.

- **F.Y. 2079/80:** The availability and reliability of the plant were found dropped as unit 1 was forced to shutdown for 18.37 hours for the repair and replacement of the 132 kV transmission line jumper at tower no. 1, as well as fault diagnosis and repair of the SCADA system's PLC. Meanwhile, unit 2 was shutdown for 44.95 hours due to a failure in the cooling water system. Also, the availability of unit 2 was found to be reduced due to a shutdown for overhauling work, which lasted for 507.5 hours.

- In general, for every F.Y., excluding planned outages, the major causes of forced shutdowns of units were found to be maintenance of the cooling water system, GCB and issues related to controllers & carbon brush replacements.

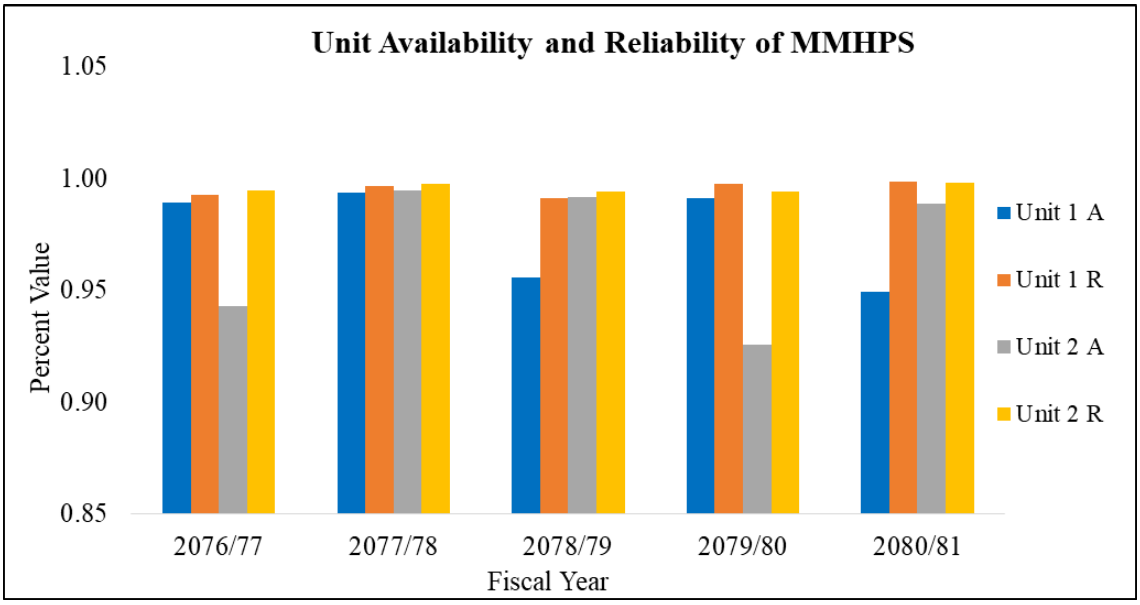


Figure 4.5: Unit Availability and Reliability of MMHPS

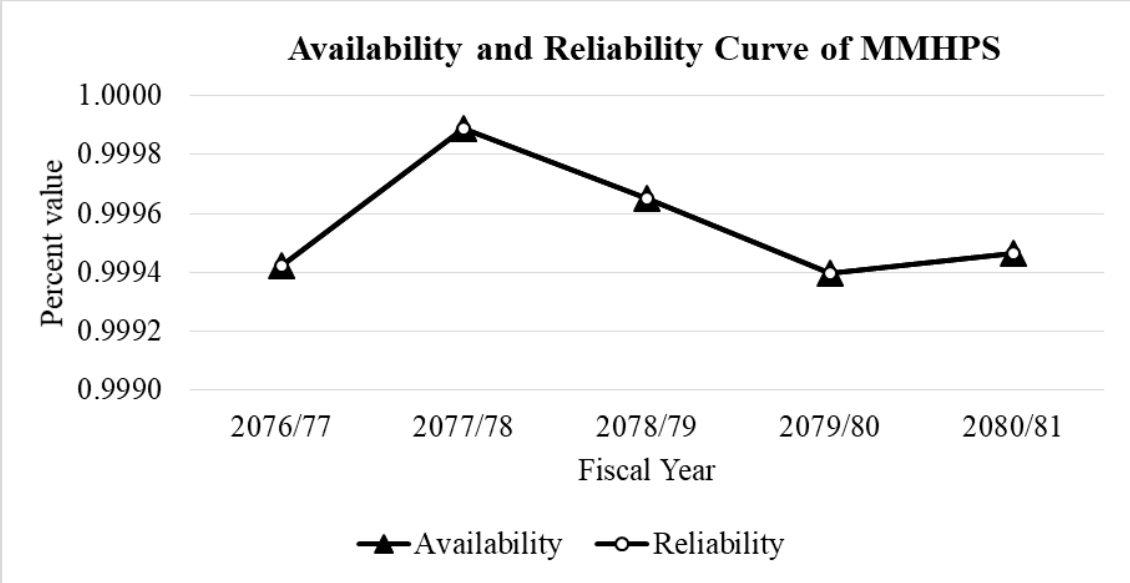


Figure 4.6: Plant Availability and Reliability of MMHPS

4.2.1 Unit-Wise Critical Failure Cause and Trend Analysis

The unit-wise trend analysis for every F.Y. considered is illustrated in Figure 4.8. From this analysis, it can be concluded that the performance of unit 2 was low compared to unit 2. The Pareto analysis chart for both units is presented in Figure 4.7, and the most critical failure causes for these units are given below:

- **Unit 1:** Turbine, switchgear, auxiliary and generator which contribute to 88.76% of total forced outage hours.

- **Unit 2:** Auxiliary, turbine and switchgear which contribute to 90.97% of total forced outage hours.

For MMHPS, it can be concluded that scheduled outages were the key cause for most of the shutdowns, while forced outages were minimal. Some of the forced outages appear to be caused by electronics equipment failure: controllers, power converters, sensors, etc. The forced shutdown can elevate if the maintenance team were not properly trained to identify faults and also, if the plant fails to maintain adequate supply of spare parts. Therefore, to maintain good reliability and availability of the plants, periodic condition monitoring of all hydro-mechanical and electro-mechanical equipment should be done, continuous staff training should be provided, and adequate spare parts stock should be maintained for immediate replacement.

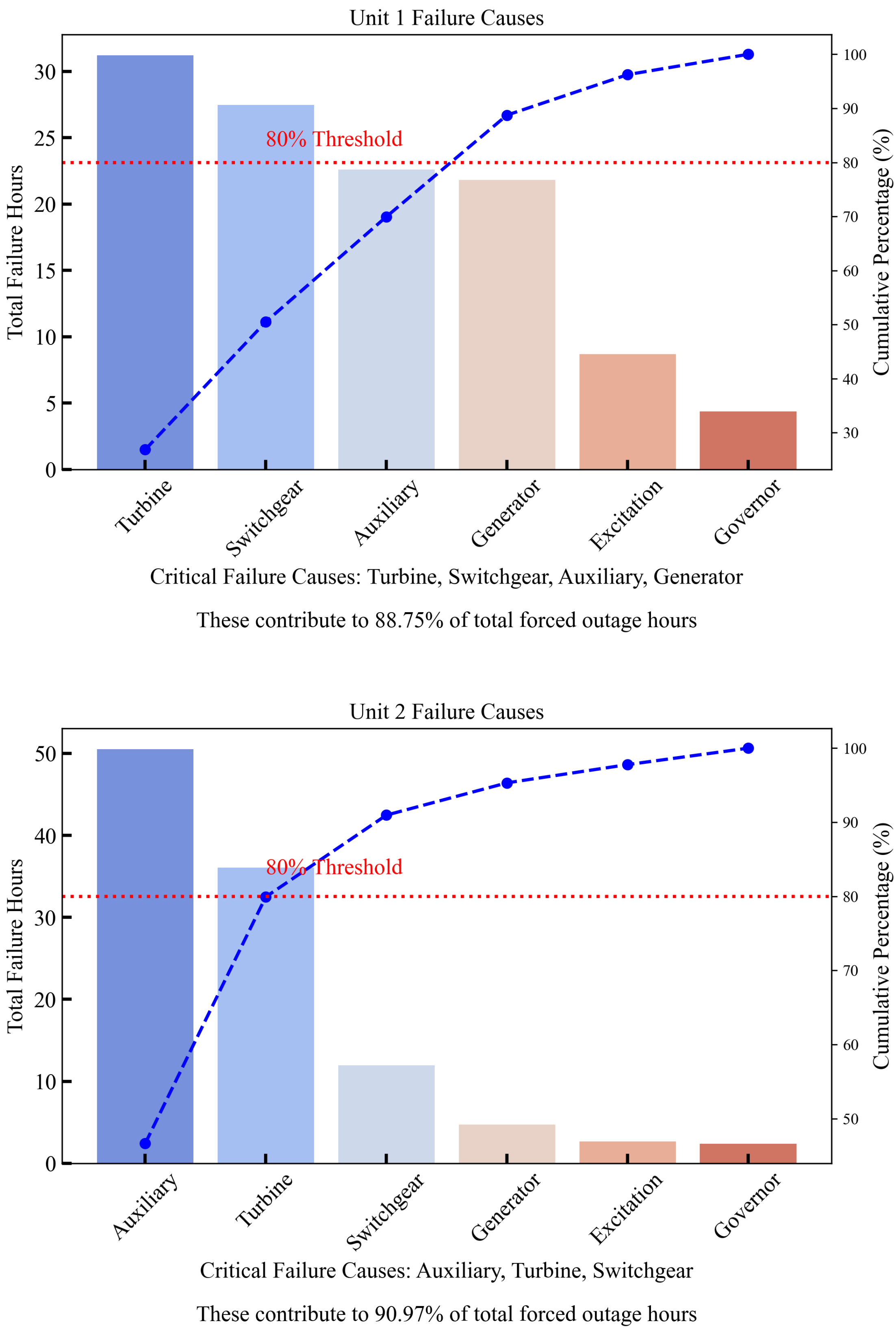


Figure 4.7: Causes of Critical Failure at MMHPS

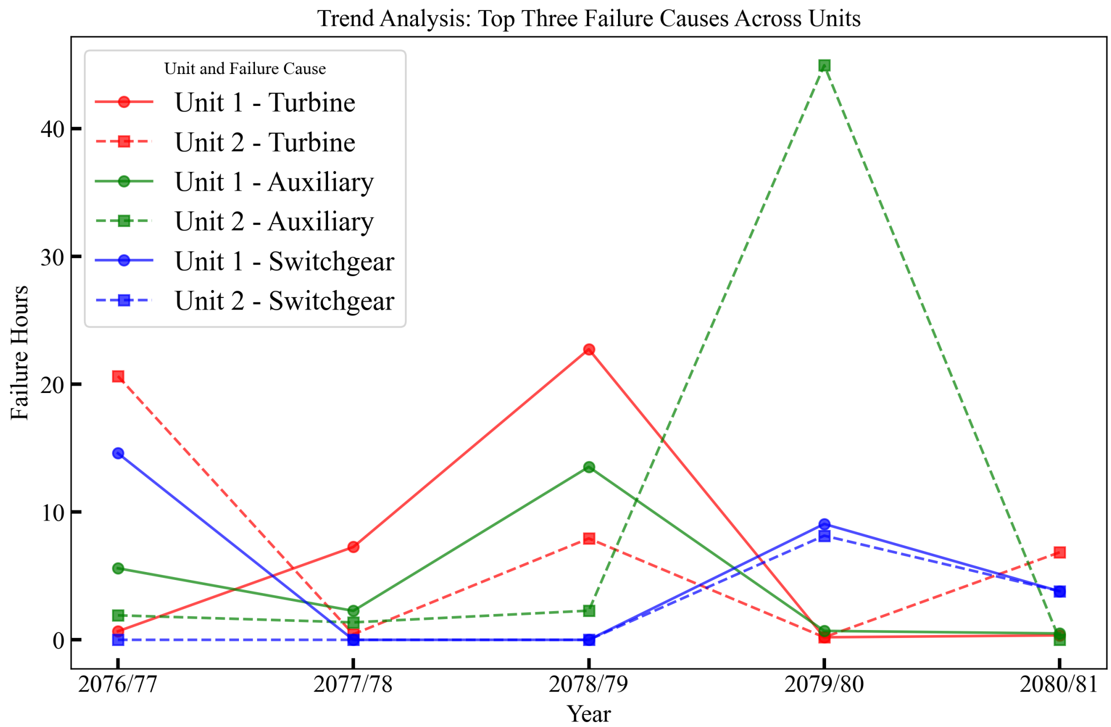


Figure 4.8: Trend Analysis Chart for MMHPS

4.3 Marsyangdi Hydropower Station

The reliability and availability of MHPS for F.Y. 2076/77 to 2080/81 of all three units and plants are presented in Table 4.3. Figures 4.9 and 4.10 depict the graphical representation of all units and plants, respectively.

Table 4.3: Availability and Reliability of MHPS Over Five Fiscal Years

F.Y.	Unit 1		Unit 2		Unit 3		Plant	
	A	R	A	R	A	R	A	R
2076/77	0.9824	0.9968	0.9678	0.9851	0.9248	0.9918	0.99989	0.99591
2077/78	0.9098	0.9680	0.9546	0.9705	0.9774	0.9936	0.99989	0.99297
2078/79	0.9600	0.9714	0.9437	0.9861	0.9625	0.9739	0.99991	0.99425
2079/80	0.9795	0.9881	0.9917	0.9988	0.9378	0.9968	0.99981	0.99815
2080/81	0.9556	0.9989	0.9867	0.9934	0.9931	0.9998	0.99978	0.99905

- The overall availability and reliability of all three units of MHPS were found dropped.

- The primary reason for this lower performance is that MHPS has been in operation since F.Y. 2046/47, making it the oldest among the four hydropower plants taken into consideration.

- Major contributing factors to the lower performance comprise mechanical equipment issues such as problems with the shaft seal, turbine & associated components, subsequent malfunction in the power transformer, and cooling systems.

- **F.Y. 2076/77:** The availability of unit 3 was low due to 416 hours shutdown for overhauling work and also was halted for 76.5 hours due to different issues such as generator thrust bearing, shaft seal, turbine guide bearing, etc. repair and replacement work. Similarly, unit 2 was forced to shutdown for 132.75 hours for slip ring machining and the repair & replacement of the shaft seal, TGB and other components.

- **F.Y. 2077/78:** The reliability and availability of units 1 and 2 were notably low. Unit 1 suffered compelled termination of 291 hours for shaft alignment work, replacement of the shaft seal, and maintenance of 11 kV power cable, in addition to a 330.233 hours shutdown for unit overhauling work. Similarly, unit 2 was inoperative for 263.3 hours due to cooling water system maintenance, shaft seal and governor maintenance, and replacement work.

- **F.Y. 2078/79:** The reliability and availability of all three units were low due to a complete plant shutdown for 84.933 hours to resolve water leakage from the MIV. Unit 2 was shutdown for unit overhauling work that lasted 344.5 hours. In addition to this, all three units in total were halted for 359.52 hours, and major reasons for the shutdown of units were turbine and governor-related issues, failures of 11 kV power cable, and problems with the power transformer and cooling system. These problems exerted a significant impact on the plant's operational performance during this F.Y..

- **F.Y. 2079/80:** Unit 1 faced multiple times in total of 95.8 hours forced shutdown for maintenance and changing of shaft seal which is the major causes for reduction in availability and reliability of unit 1. Also, unit 3 was shutdown for unit overhauling work for 427.9 hours, which is the major cause for the reduction in the availability of unit 3.

- **F.Y. 2080/81:** The availability of unit 1 was low because this unit was shutdown for 305.32 hours for unit overhauling work.

- In general, for every F.Y. excluding planned ones, major causes of forced shutdown of units are found to be maintenance of shaft seal, guide vane, coolers, transformer, and carbon brush replacements.

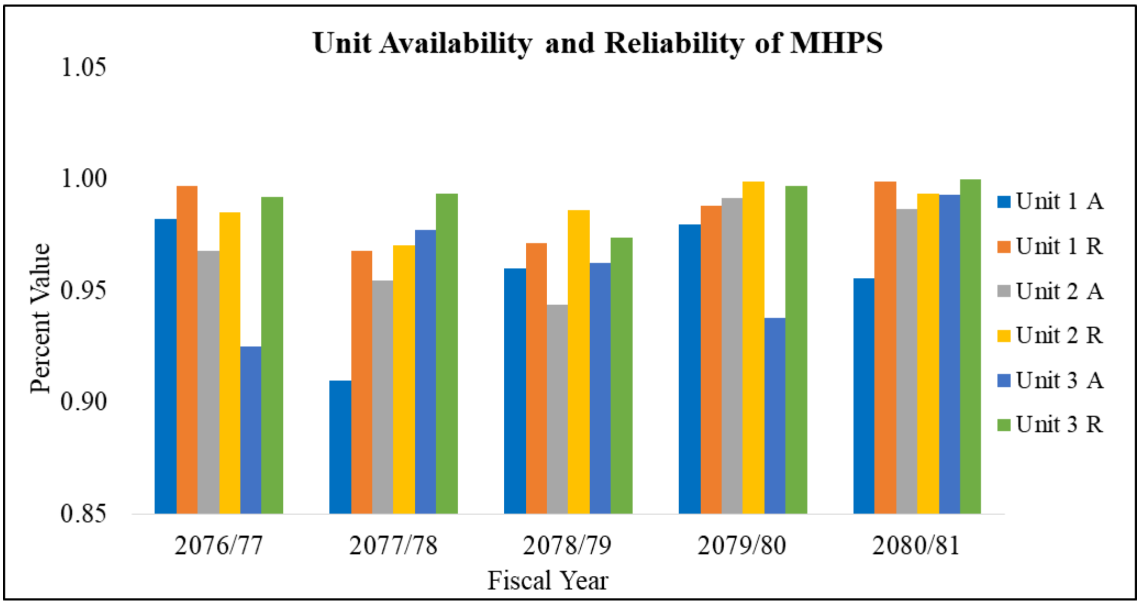


Figure 4.9: Unit Availability and Reliability of MHPS

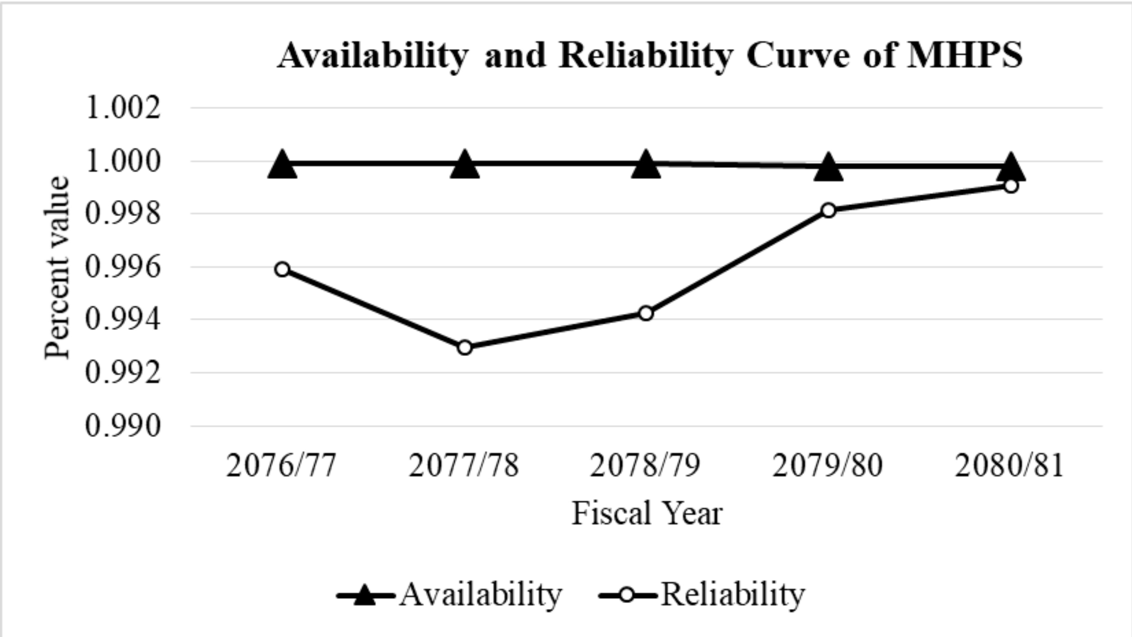


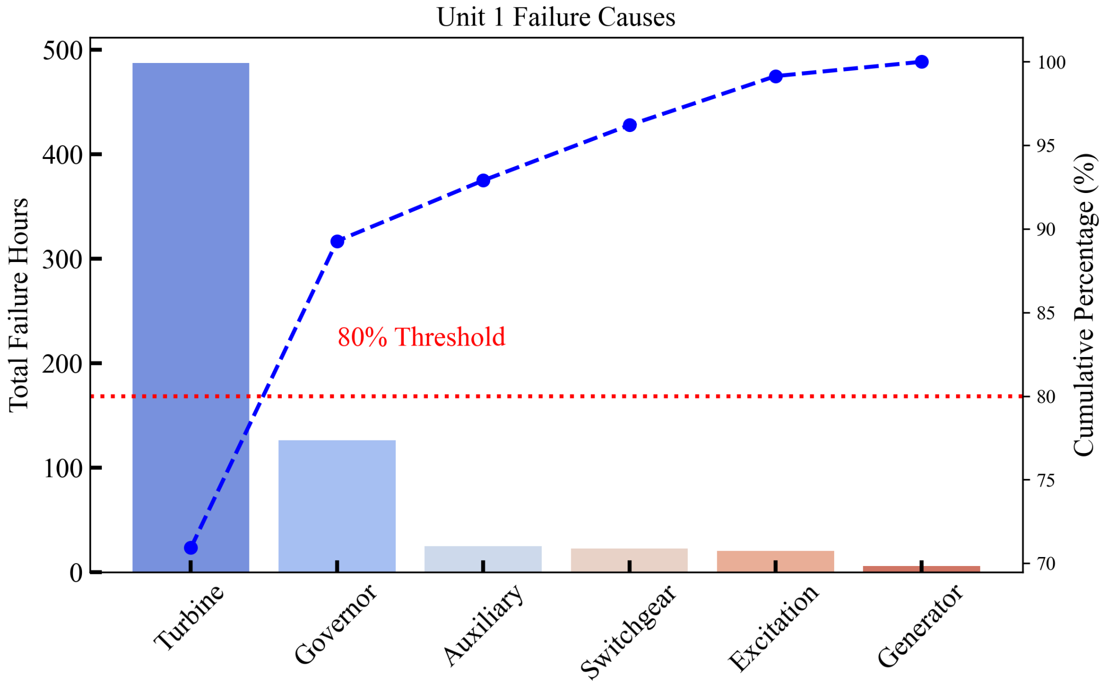
Figure 4.10: Plant Availability and Reliability of MHPS

4.3.1 Unit-Wise Critical Failure Cause and Trend Analysis

The unit-wise trend analysis for every F.Y. considered is illustrated in Figure 4.12. From this analysis, it can be concluded that the performance of unit 1 was low compared to other units. The Pareto analysis chart of all three units is presented in Figure 4.11, and the most critical failure causes for these units are given below:

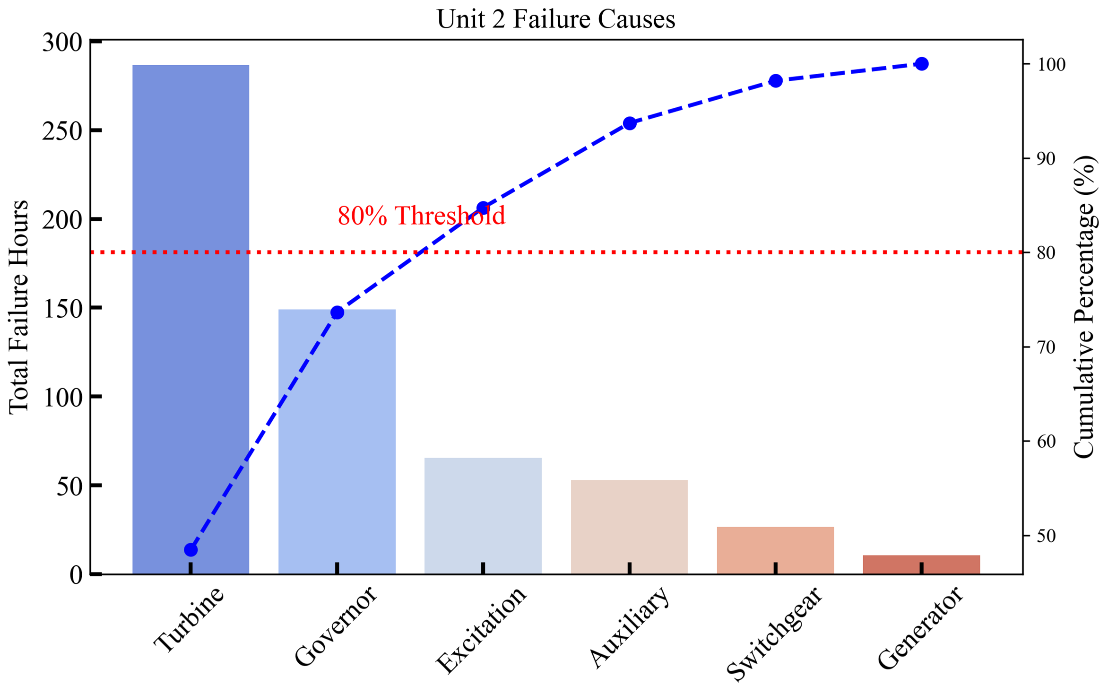
- **Unit 1:** Turbine and governor which contribute to 89.27% of total forced outage hours.
- **Unit 2:** Turbine, governor and excitation system which contribute to 84.75% of total forced outage hours.
- **Unit 3:** Turbine and governor which contribute to 85.11% of total forced outage hours.

The discussion above shows that turbine and governor issues were the main grounds for forced shutdowns in MHPS. The primary issue related to outages due to turbine system failure was shaft seal replacement. According to the OEM (Voith), the shaft seal should last at least 3 years, but problems with it have been appearing more frequently in recent years. To prevent this, the plant should use shaft seals with the material composition recommended by the OEM. Additionally, governor-related issues have significantly decreased after the governor system replacement. Thus, condition monitoring of generators, power transformers, and other high-voltage equipment is essential to assess their health so that timely repairs and replacements can be done to minimize forced outages.



Critical Failure Causes: Turbine, Governor

These contribute to 89.27% of total forced outage hours



Critical Failure Causes: Turbine, Governor, Excitation

These contribute to 84.75% of total forced outage hours

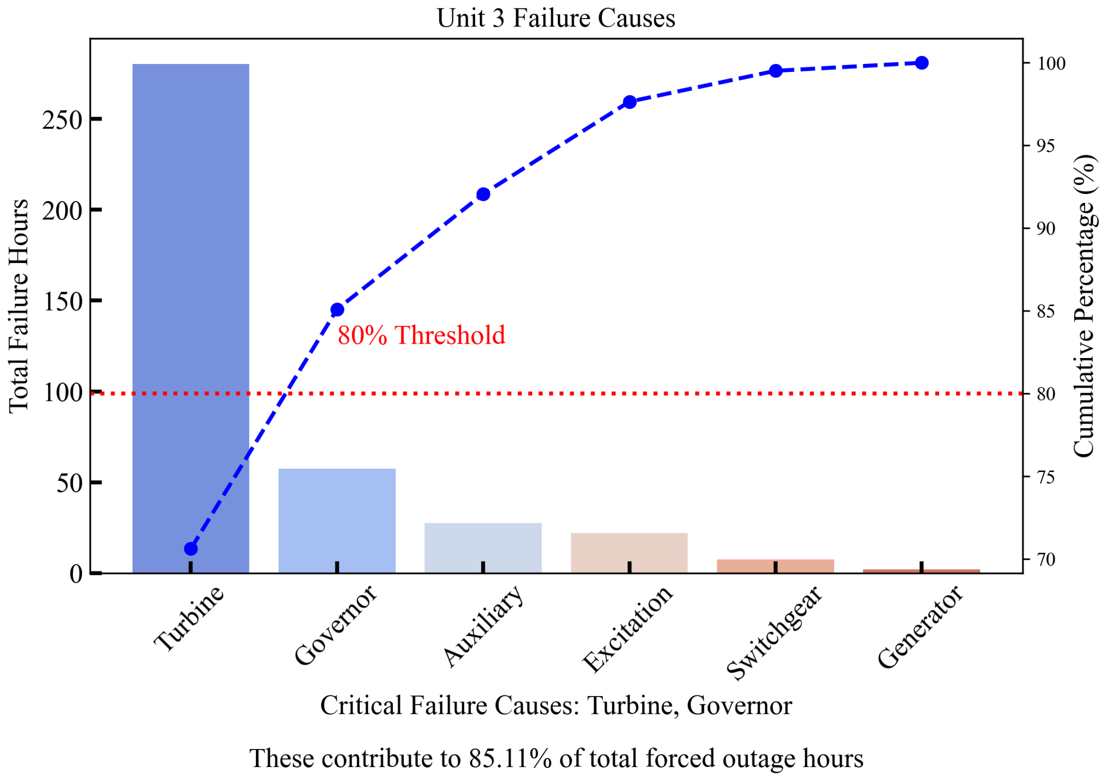


Figure 4.11: Causes of Critical Failure at MHPS

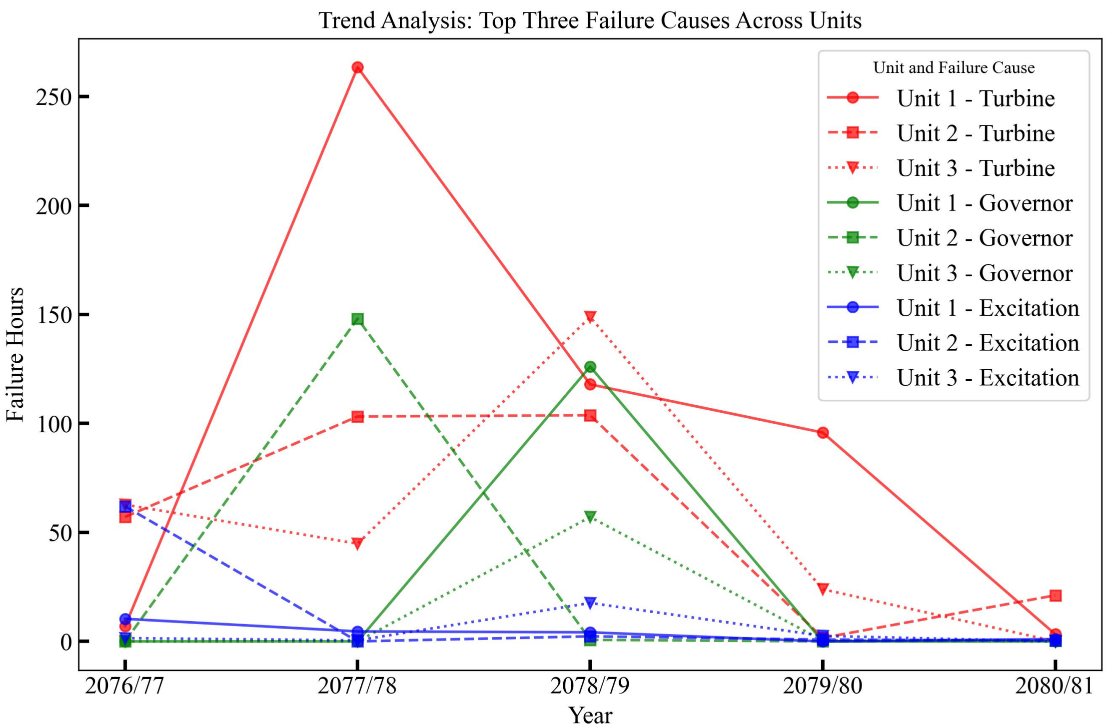


Figure 4.12: Trend Analysis Chart for MHPS

4.4 Chameliya Hydropower Station

The reliability and availability of CHPS for F.Y. 2076/77 to 2080/81 for both units and plants are presented in Table 4.4. Figure 4.13 and 4.14 depict the graphical representation of all units and plants, respectively.

- **F.Y. 2076/77:** The reliability and availability of the plant were found to have declined because unit 1 and unit 2 were halted for 229.2 hours and 38.6 hours, respectively, due to a fault in their excitation transformer. Similarly, unit 1 was forced to shutdown for 120.8 hours due to issues of turbine runaway speed and 70.55 hours due to machine vibration.

- **F.Y. 2078/79:** The reliability and availability of the plant was found to be affected because unit 1 was forced to shutdown for 48.5 hours due to the burning of flashing diode. The availability of both units during this F.Y. was found reduced because unit 1 was shutdown for 672 hours and unit 2 for 587 hours for unit overhauling work.

- In general, for every F.Y. excluding planned outage, major causes of forced shutdown of units are found to be maintenance of the shaft seal, pressure balancing pipe, auxiliary system, replacement of different sensors, TGB, and pressure relief valve.

Table 4.4: Availability and Reliability of CHPS Over Five Fiscal Years

F.Y.	Unit 1		Unit 2		Plant	
	A	R	A	R	A	R
2076/77	0.9354	0.9403	0.9764	0.9822	0.99841	0.99841
2077/78	0.9917	0.9969	0.9928	0.9981	0.99984	0.99984
2078/79	0.9100	0.9931	0.9216	0.9935	0.99369	0.99369
2079/80	0.9802	0.9869	0.9929	0.9997	0.99986	0.99986
2080/81	0.9825	0.9882	0.9833	0.9891	0.99971	0.99971

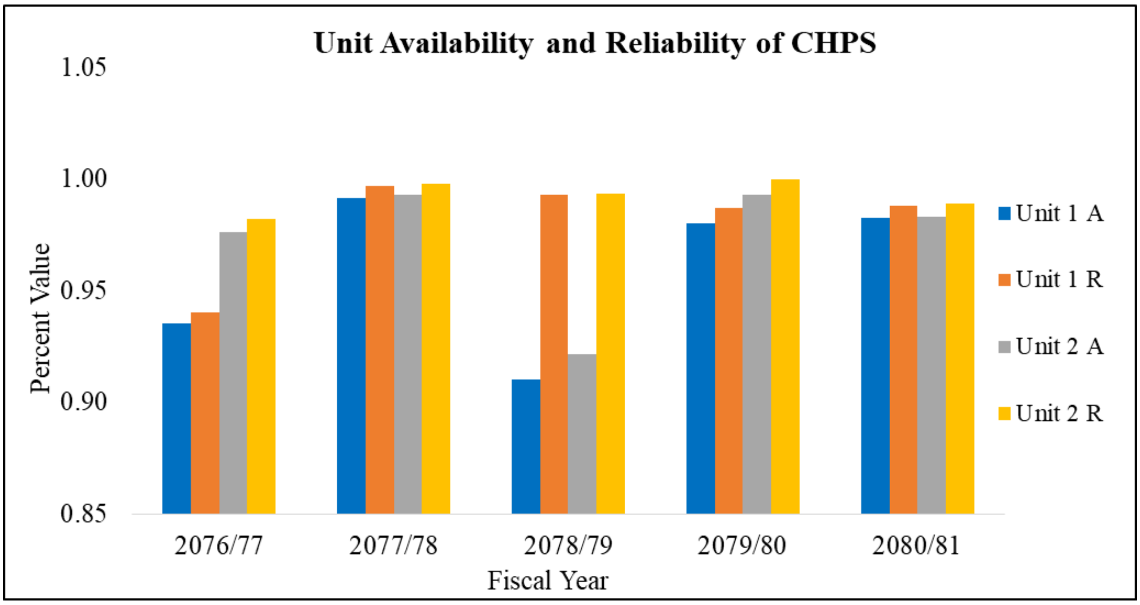


Figure 4.13: Unit Availability and Reliability of CHPS

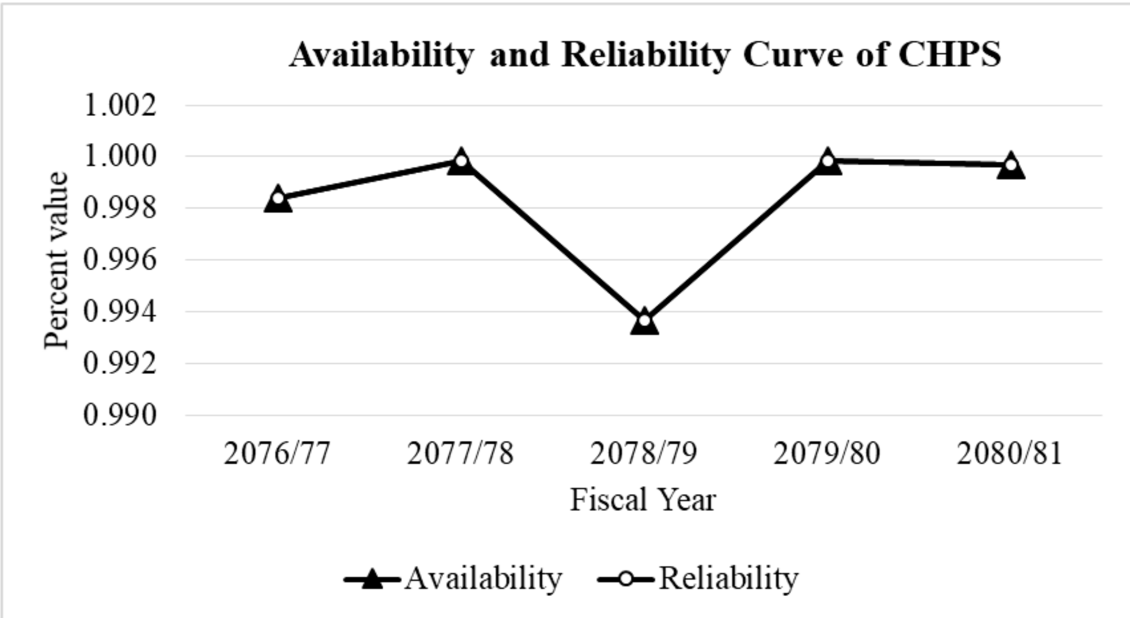


Figure 4.14: Plant Availability and Reliability of CHPS

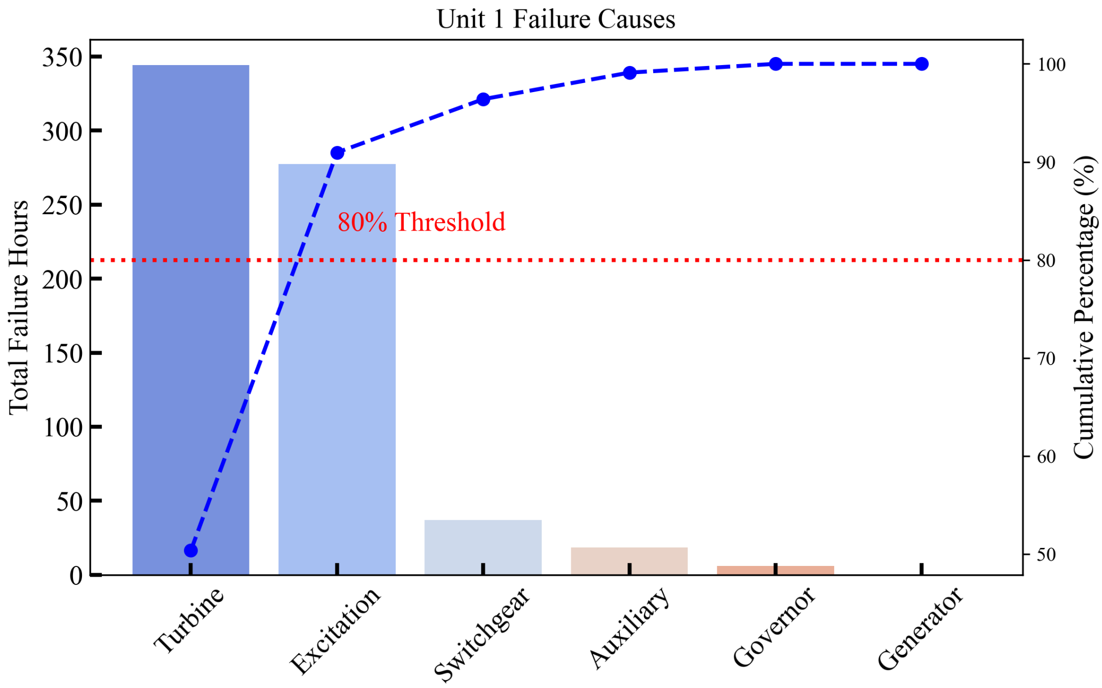
4.4.1 Unit-Wise Critical Failure Cause and Trend Analysis

The unit-wise trend analysis for every F.Y. considered is illustrated in Figure 4.16. From this analysis, it can be concluded that the performance of unit 1 was low compared to unit 2. The Pareto analysis chart of both units is presented in Figure 4.15, and the most critical failure causes for these units are given below:

- **Unit 1:** Turbine and excitation system which contribute to 90.97% of total forced outage hours.

- **Unit 2:** Turbine, excitation and switchgear system which contribute to 87.162% of total forced outage hours.

As a relatively new plant compared to others, the discussion above indicates that turbine and excitation issues are the primary factors contributing to forced shutdowns in CHPS. The failure of the excitation transformer caused excitation-related faults and after its replacement, these issues were reduced significantly. Turbine-related problems were happening frequently due to issues with the pressure-balancing pipe and turbine guide bearing. Thus, to minimize forced downtime, the plant needs to perform regular monitoring and maintenance of these components. Additionally, consistent condition monitoring of generators, turbines, power transformers, and other high-voltage equipment is essential to assess their health, enabling timely repairs and replacements to reduce forced outages.



Critical Failure Causes: Turbine, Excitation

These contribute to 90.97% of total forced outage hours

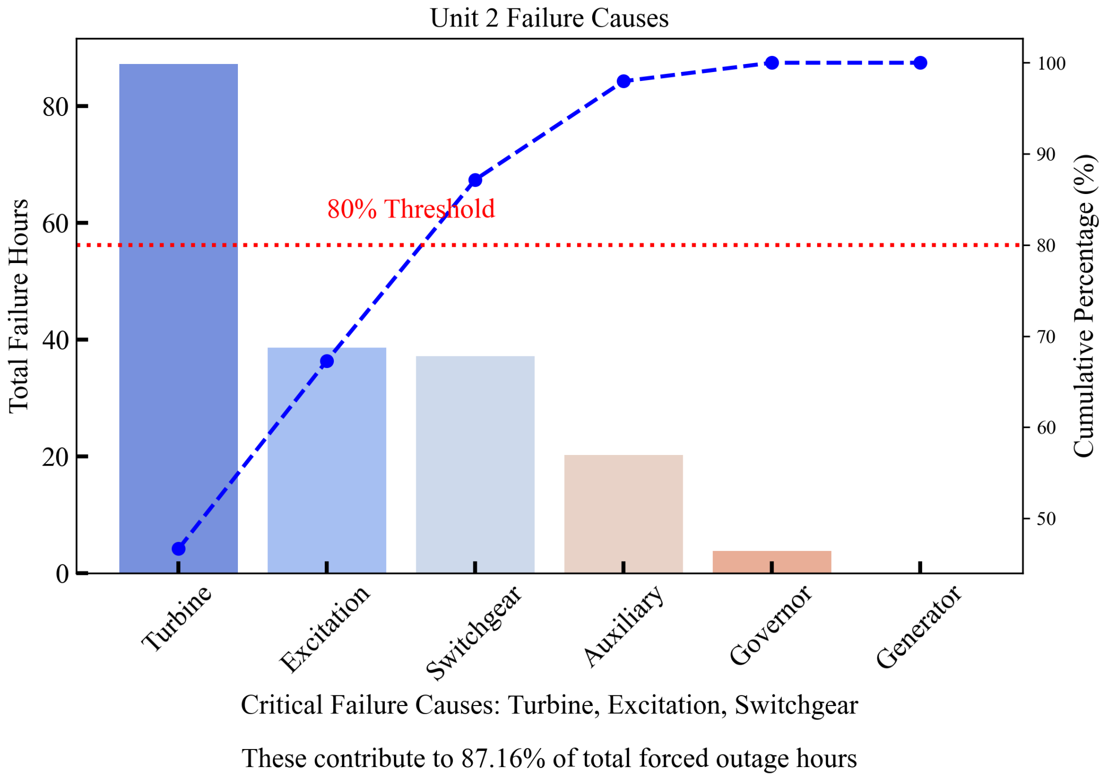


Figure 4.15: Causes of Critical Failure at CHPS

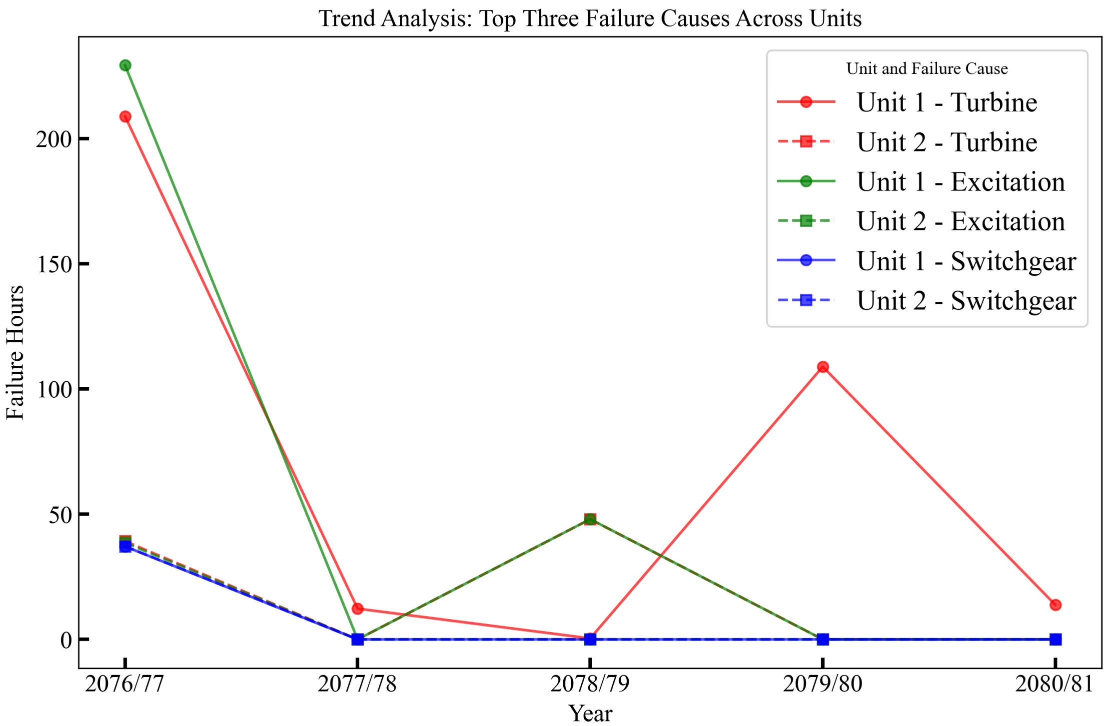


Figure 4.16: Trend Analysis Chart for CHPS

CHAPTER FIVE:CONCLUSION

This thesis conducted a comprehensive reliability and availability assessment of four Peaking Run-of-River hydropower plants owned by the Nepal Electricity Authority:

- Kaligandaki “A” Hydropower Station (KGA)– 144 MW
- Middle Marsyangdi Hydropower Station (MMHPS)–70 MW
- Marsyangdi Hydropower Station (MHPS)–69 MW
- Chameliya Hydropower Station (CHPS)–30 MW

The study analyzed the historical operational data of the past five F.Y. (2076/77 to 2080/81) using Markov modeling to determine key reliability indices, including MTBF, MTTR, failure rates and repair rates. Below is a structured conclusion covering findings, recommendations and future work.

5.1 Key Finding

The findings indicate that the availability and reliability of these hydropower stations varied throughout the years, with some of the units experiencing high forced outages due to faults in generators, maintenance of turbine, excitation system and auxiliary system failures.

5.1.1 Reliability and Availability Performance

- Kaligandaki ”A” Hydropower Station has lowest reliability but shows improved reliability and availability after up-gradation work of control system, but generator, turbine and switchgear failures remained key concerns. The primary cause of outages at KGA was the burning of stator slots.
- Middle Marsyangdi Hydropower Station showed high and uniform reliability, with minimal forced outages and efficient maintenance practices.
- The reliability of Marsyangdi Hydropower Station is also low among the studied plants, and the main grounds for this are its aging factor, turbine malfunctions and frequent shaft seal problems.

- Chameliya Hydropower Station, being one of the newer plants among the studied plants, has problems related to turbine and excitation issues requiring long maintenance hours.

Table 5.1: Hydropower Plant Performance Data

Hydropower Plant	Avg. Availability (%)	Avg. Reliability (%)	Key Factors Affecting Reliability
Kaligandaki “A” Hydropower Station	99.98	99.36	Generator issues (52%), turbine issues (26%)
Middle Marsyangdi Hydropower Station	99.96	99.96	Minimal forced outages, auxiliary system issues
Marsyangdi Hydropower Station	99.98	99.61	Aging equipment, turbine issues (63%)
Chameliya Hydropower Station	99.83	99.83	Turbine issues (50%), excitation system issues (36%)

5.1.2 Critical Failure Analysis

Thus, Table 5.2 indicates that the maintenance of turbines accounted for most of the plant outages, followed by the generator system. Excitation system problems came third, followed by governor failures, switchgear failures, and lastly, maintenance of auxiliary system, which had the least impact. The historical records indicate that while scheduled outages were managed in a planned manner, unscheduled outages due to equipment failures had a significant impact on plant availability and reliability.

- 80% of forced outages were caused by turbine, generator and excitation system failures.

- Scheduled maintenance accounted for significant but predictable downtime.

Table 5.2: Failure Causes and Their Impact on Hydropower Plants

Failure Cause	% of Total Forced Outages	Affected Plants	Recommended Action
Turbine Issues	46%	MHPS, KGA, CHPS	Overhauling, predictive maintenance & use of OEM recommended parts
Generator Issues	19%	KGA, MHPS	Generator overhauling & predictive maintenance
Excitation Issues	13%	CHPS, KGA, MHPS, MMHPS	Condition monitoring based maintenance
Governor Issues	8%	MHPS, CHPS, MMHPS	Condition monitoring based maintenance
Switchgear Issues	7%	KGA, CHPS, MHPS, MMHPS	Condition monitoring based maintenance & predictive maintenance
Auxiliary Issues	7%	MMHPS, MHPS	Condition monitoring based maintenance of cooling system

5.2 Recommendations

The study emphasizes the need to optimize planned maintenance to minimize forced shutdowns. While the overall availability and reliability of all four plants exceed 99%, the reliability and availability of individual units fluctuate between 90% and 99% due to equipment or system failures. Given that the primary purpose of the PRoR hydropower plant is to meet peak energy demand, the following measures are recommended to enhance the reliability, availability and operational efficiency of NEA's PRoR hydropower plants:

Table 5.3: Maintenance Optimization Strategies

Strategy	Implementation	Expected Benefit
Predictive Maintenance	Deploy IoT sensors for vibration, temperature and oil condition monitoring	Early fault detection, reduced unplanned outages
OEM-Recommended Overhauls	Follow OEM-recommended service intervals for hydro-mechanical and electro-mechanical equipment	Extended equipment lifespan with fewer breakdowns
Spare Parts Inventory	Maintain critical spares (shaft seals, carbon brushes, sensors, controllers, etc.)	Faster repairs and minimized downtime

Table 5.4: Equipment Upgrades and their Impact

Component	Upgrade Needed	Impact
Turbine Shaft Seals	Replace with high-durability materials	Reduce leakage-related shutdowns (MHPS)
Control System	Upgrade to modern PLC-based system for better control & monitoring	Enhance the efficiency of the hydropower plant and reduce operational delays (MHPS, CHPS)

- **Workforce Development**
  Training Programs: Enhance technical skills of technical manpower in fault diagnosis, repair techniques, and condition monitoring.
  Knowledge Transfer: Document best practices to mitigate reliance on experienced personnel.

This study provides a data-driven strategy for improving the performance of Nepal's PROR hydropower plants. By implementation of predictive maintenance, machinery upgrades and employee training strategies, NEA would be able to prevent forced outages by a significant extent and enhance grid stability. Subsequent studies would be required to focus on real-time monitoring systems and climate adaptation strategies for the long-term sustainability of hydropower plants.

These findings and recommendations aim to support Nepal's energy security goals while optimizing the operational efficiency of its hydropower infrastructure.

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APPENDIX A: AGGREGATE DOWNTIME DUE TO SHUTDOWN

Total Outage Duration of Generating Units Across Five Consecutive Fiscal Years

Basic Events	Unit No.	Down Time (hrs.) due to Forced Shutdown			
		KGA	MMHPS	MHPS	CHPS
Schedule	Unit 1	1210.52	823.78	1163.63	877.97
	Unit 2	1262.02	1119.38	772.83	798.28
	Unit 3	1406.00	-	1344.87	-
Generator	Unit 1	466.35	21.83	5.90	0.00
	Unit 2	243.02	4.48	10.67	0.00
	Unit 3	20.15	-	1.93	-
Excitation	Unit 1	37.60	8.70	20.15	277.20
	Unit 2	70.28	2.67	65.57	38.60
	Unit 3	4.23	-	22.13	-
Turbine	Unit 1	148.67	31.22	487.23	344.18
	Unit 2	193.62	36.05	286.70	87.22
	Unit 3	18.82	-	280.23	-
Governor	Unit 1	0.00	4.37	126.05	6.10
	Unit 2	0.00	2.40	149.07	3.78
	Unit 3	0.00	-	57.45	-
Switchgear	Unit 1	3.83	27.47	22.73	37.12
	Unit 2	0.42	11.95	26.52	37.15
	Unit 3	132.08	-	7.40	-
Auxiliary	Unit 1	26.13	22.60	24.93	18.50
	Unit 2	21.05	50.65	53.02	20.22
	Unit 3	9.77	-	27.63	-
Force Majeure	Unit 1	65.48	87.13	0.00	162.28
	Unit 2	65.48	81.43	0.00	148.07
	Unit 3	69.45	-	0.00	-

APPENDIX B: STATE PROBABILITY TABLE

KALIGANDAKI "A" HYDROPOWER STATION

Unit/Plant	Events	State No.	State Probability for F.Y.				
			2076/77	2077/78	2078/79	2079/80	2080/81
Unit 1	Upstate	0	0.902585	0.990206	0.990894	0.897810	0.987905
	Schedule	1	0.093598	0.001899	0.003530	0.053838	0.009821
	Generator	2	0.002810	0.001220	0.001830	0.046656	0.000000
	Excitation	3	0.000000	0.000000	0.002459	0.001642	0.000000
	Turbine	4	0.000481	0.000000	0.000000	0.000000	0.000000
	Switchgear	6	0.000000	0.000000	0.000070	0.000000	0.000363
	Auxiliary	7	0.000526	0.000356	0.001217	0.000053	0.000749
	Force Majeure	8	0.000000	0.006319	0.000000	0.000000	0.001162
Unit 2	Upstate	0	0.962710	0.912943	0.996933	0.966593	0.940545
	Schedule	1	0.010232	0.080424	0.001524	0.024737	0.057792
	Generator	2	0.027014	0.000555	0.000150	0.000226	0.000170
	Excitation	3	0.000044	0.000212	0.000232	0.007322	0.000048
	Turbine	4	0.000000	0.000000	0.000000	0.000000	0.000258
	Switchgear	6	0.000000	0.000000	0.000047	0.000000	0.000000
	Auxiliary	7	0.000000	0.000040	0.001114	0.001123	0.000081
	Force Majeure	8	0.000000	0.005826	0.000000	0.000000	0.001107
Unit 3	Upstate	0	0.900450	0.986940	0.995529	0.929449	0.988763
	Schedule	1	0.091537	0.003924	0.003389	0.063838	0.009796
	Generator	2	0.001594	0.000457	0.000074	0.000000	0.000000
	Excitation	3	0.000000	0.000058	0.000334	0.000053	0.000032
	Turbine	4	0.000000	0.000000	0.000000	0.000691	0.000000
	Switchgear	6	0.006308	0.001849	0.000049	0.005886	0.000000
	Auxiliary	7	0.000111	0.000474	0.000421	0.000083	0.000000
	Force Majeure	8	0.000000	0.006298	0.000205	0.000000	0.001409
Plant	1		0.993713	0.997485	0.998322	0.996284	0.996524
	2		0.001958	0.000552	0.000379	0.000469	0.000734
	3		0.000708	0.000730	0.000342	0.002195	0.000718
	4		0.000001	0.000000	0.000000	0.000001	0.000001
	5		0.003611	0.001231	0.000957	0.001048	0.002020
	6		0.000007	0.000001	0.000000	0.000000	0.000001
	7		0.000003	0.000001	0.000000	0.000002	0.000001
	8		0.000000	0.000000	0.000000	0.000000	0.000000

MIDDLE MARSYANGDI HYDROPOWER STATION

Unit/Plant	Events	State No.	State Probability for F.Y.				
			2076/77	2077/78	2078/79	2079/80	2080/81
Unit 1	Upstate	0	0.941614	0.957368	0.955729	0.991457	0.949337
	Schedule	1	0.051704	0.002507	0.035443	0.006380	0.049382
	Generator	2	0.001537	0.000166	0.000490	0.000168	0.000011
	Excitation	3	0.000203	0.000000	0.000000	0.000773	0.000000
	Turbine	4	0.000072	0.000898	0.002493	0.000023	0.000000
	Governor	5	0.000000	0.000204	0.000000	0.000011	0.000181
	Switchgear	6	0.001575	0.000000	0.000000	0.001028	0.000078
	Auxiliary	7	0.000603	0.000248	0.001481	0.000079	0.000054
	Force Majeure	8	0.002694	0.038610	0.004364	0.000081	0.000957
Unit 2	Upstate	0	0.991118	0.958331	0.992038	0.925936	0.988891
	Schedule	1	0.003435	0.002509	0.002243	0.068245	0.009285
	Generator	2	0.000349	0.000000	0.000096	0.000048	0.000011
	Excitation	3	0.000000	0.000292	0.000000	0.000000	0.000000
	Turbine	4	0.002346	0.000055	0.000900	0.000021	0.000735
	Governor	5	0.000260	0.000000	0.000000	0.000011	0.000000
	Switchgear	6	0.000000	0.000000	0.000000	0.000863	0.000081
	Auxiliary	7	0.000217	0.000164	0.000259	0.004801	0.000000
	Force Majeure	8	0.002275	0.038649	0.004464	0.000076	0.000997
Plant	1		0.998711	0.999343	0.998210	0.999799	0.999674
	2		0.000471	0.000177	0.000349	0.000098	0.000168
	3		0.000818	0.000480	0.001440	0.000103	0.000158
	4		0.000000	0.000000	0.000001	0.000000	0.000000

MARSYANGDI HYDROPOWER STATION

Unit/Plant	Events	State No.	State Probability for F.Y.				
			2076/77	2077/78	2078/79	2079/80	2080/81
Unit 1	Upstate	0	0.982361	0.909751	0.960027	0.979536	0.955623
	Schedule	1	0.014469	0.058274	0.011422	0.008590	0.043256
	Generator	2	0.000101	0.000189	0.000349	0.000000	0.000000
	Excitation	3	0.001163	0.000476	0.000457	0.000000	0.000115
	Turbine	4	0.000781	0.029097	0.013276	0.010950	0.000358
	Governor	5	0.000000	0.000000	0.014223	0.000000	0.000000
	Switchgear	6	0.000470	0.001825	0.000000	0.000117	0.000000
	Auxiliary	7	0.000655	0.000388	0.000245	0.000806	0.000648
	Force Majeure	8	0.000000	0.000000	0.000000	0.000000	0.000000
Unit 2	Upstate	0	0.967812	0.954650	0.943710	0.991724	0.986733
	Schedule	1	0.017338	0.015823	0.042371	0.007075	0.006654
	Generator	2	0.000433	0.000349	0.000000	0.000402	0.000000
	Excitation	3	0.006942	0.000000	0.000252	0.000096	0.000049
	Turbine	4	0.006388	0.011512	0.011444	0.000185	0.002392
	Governor	5	0.000000	0.016699	0.000077	0.000000	0.000034
	Switchgear	6	0.000033	0.000688	0.001858	0.000310	0.000000
	Auxiliary	7	0.001054	0.000280	0.000287	0.000208	0.004138
	Force Majeure	8	0.000000	0.000000	0.000000	0.000000	0.000000
Plant	1		0.997103	0.994387	0.996387	0.997788	0.996588
	2		0.000403	0.001139	0.001719	0.000426	0.002149
	3		0.001166	0.002040	0.000940	0.000498	0.000310
	4		0.000000	0.000002	0.000002	0.000000	0.000001
	5		0.001326	0.002423	0.000951	0.001287	0.000951
	6		0.000001	0.000003	0.000002	0.000001	0.000002
	7		0.000002	0.000005	0.000001	0.000001	0.000000
	8		0.000000	0.000000	0.000000	0.000000	0.000000

CHAMELIYA HYDROPOWER STATION

Unit/Plant	Events	State No.	State Probability for F.Y.				
			2076/77	**2077/78**	**2078/79**	**2079/80**	**2080/81**
Unit 1	Upstate	0	0.935361	0.991695	0.909994	0.980210	0.982455
	Schedule	1	0.004975	0.005211	0.083090	0.006721	0.005755
	Generator	2	-	-	-	-	-
	Excitation	3	0.025825	0.000000	0.005042	0.000000	0.000000
	Turbine	4	0.023411	0.001394	0.000042	0.012494	0.001554
	Governor	5	0.000000	0.000134	0.000000	0.000551	0.000000
	Switchgear	6	0.003997	0.000000	0.000000	0.000000	0.000000
	Auxiliary	7	0.000588	0.000302	0.000461	0.000024	0.000638
	Force Majeure	8	0.005843	0.001264	0.001372	0.000000	0.009597
Unit 2	Upstate	0	0.976371	0.992845	0.921582	0.992909	0.983309
	Schedule	1	0.005799	0.005217	0.071922	0.006808	0.005760
	Generator	2	-	-	-	-	-
	Excitation	3	0.004341	0.000000	0.000000	0.000000	0.000000
	Turbine	4	0.004410	0.000000	0.005106	0.000000	0.000000
	Governor	5	0.000422	0.000000	0.000000	0.000000	0.000000
	Switchgear	6	0.004176	0.000000	0.000000	0.000000	0.000000
	Auxiliary	7	0.000000	0.000673	0.000000	0.000284	0.001326
	Force Majeure	8	0.004480	0.001265	0.001389	0.000000	0.009606
Plant	1		0.992188	0.996993	0.993590	0.996723	0.992353
	2		0.002829	0.001971	0.006105	0.002823	0.004196
	3		0.004969	0.001034	0.000303	0.000453	0.003436
	4		0.000014	0.000002	0.000002	0.000001	0.000015

APPENDIX C: PUBLICATION

Conference paper

Notifications ×

[IOEGC16] Editor Decision

2025-03-29 07:20 AM

Bipin Silwal:

We are pleased to inform you that your manuscript titled "Reliability and Availability Evaluation of Peaking Run of River (PRoR) Hydropower Plant Owned by NEA" submitted to 16th IOE Graduate Conference is **Accepted** for presentation in the Conference as well as inclusion in the Peer-Reviewed Proceedings. Please note that inclusion in hard copy proceedings is contingent upon your timely response to further edits, if any, during the publication process.

Reviewer's Comments:

With Warm Regards,
IOEGC-16 Editorial Team

Reliability and Availability Evaluation of Peaking Run of River (PRoR) Hydropower Plant Owned by NEA

Bipin Silwal [a], *Basanta Kumar Gautam* [b]

Abstract:

Hydropower plant is highly important in Nepal's electricity generation, that plays a vital role for grid stability and energy security. This paper conducts a systematic evaluation of Nepal Electricity Authority (NEA)-owned peaking run-of-river (PRoR) hydropower plants in terms of their availability, reliability and efficiency of operation. Using historical operational data from Fiscal Years 2076/77 to 2080/81, key reliability indices such as Mean Time Between Failures, Mean Time to Repair, Repair Rates and Failure Rates were determined through statistical data and reliability and availability was determined using Markov state modeling approaches. The study identifies major outage causes, categorizing them into scheduled maintenance, generator failures, turbine issues, switchgear failures and auxiliary system malfunctions. The results indicate that NEA's PRoR plants maintain reliability and availability levels above 98%, with scheduled outages being the primary contributors to reduced availability. Findings highlight the importance of optimized maintenance strategies to minimize forced outages and enhance plant performance. The study's insights contribute to improved hydropower management practices, ensuring long-term sustainability and operational efficiency.

Keywords:

Hydropower, Peaking Run-of-River (PRoR) Plants, Reliability and Availability Evaluation, Markov Modeling.

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IOE Graduate Conference
[Placeholder for Publication Information]

Reliability and Availability Evaluation of Peaking Run of River (PRoR) Hydropower Plant Owned by NEA

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Keywords
Hydropower, Peaking Run-of-River (PRoR) Plants, Reliability and Availability Evaluation, Markov Modeling.

1. INTRODUCTION

Hydropower is the most reliable, cost-effective and environmentally clean forms of energy generation techniques with the highest potential to replace conventional energy sources by harnessing the energy of flowing water. Nepal's power generation largely depends on electricity produced by hydropower plants. As of 1st February 2025, the total installed capacity of hydropower in Nepal reached 3,255.806 MW, as per Department of Electricity Development (DoED). Whereas, 573.6 MW is contributed by NEA, which is equivalent to 17.54% of the hydropower generation. NEA is the only institution in Nepal that owned 13 RoR, 3 Storage-Cum-Cascade and 4 PRoR hydropower plants to date and these hydropower plants play a vital role in stabilizing the national grid. To ensure a reliable and stable power supply throughout the nation, these plants must be operated in an optimized manner.

The Generation Directorate under NEA oversees the efficient operation and maintenance of 20 hydropower stations. Primary responsibility of Generation Directorate is to maximize energy generation through optimal resource utilization, periodic overhauling, minor to major maintenance and manpower allocation. Among several hydropower plant owned by NEA the following as shown in Table 1 are PRoR and the storage-cum-cascade plant with installed capacity greater than 30 MW.

In Nepal for F.Y. 2080/81, the annual system energy demand was 14,624 GWh, while the total annual energy generation from these six hydropower plants amounts to 2,015 GWh which is 13.78%. Since the forced outage of 2 storage-cum-cascade hydropower plants is zero, thus only the remaining 4 PRoR hydropower plants- Kaligandaki "A" Hydropower Station (KGA), Middle Marsyangdi Hydropower Station (MMHPS), Marsyangdi Hydropower Station (MHPS) and Chameliya Hydropower Station (CHPS) were considered for study. These 4 hydropower plants in F.Y. 2080/81 in total generated 1,862.773 GWh annually which is equivalent to 12.74% of the total demand [1] . This thus, justifies the importance of optimization in operation and maintenance to guarantee reliability and availability for these plants.

Table 1: Storage and PRoR Hydropower Plant Owned by NEA

S.No.	Name of Hydropower Plant & (No. of Units)	Installed Capacity (MW)	Annual Designed Generation (GWh)	Type of Scheme
1	Kaligandaki "A" Hydropower Station (3)	144	842.57	PRoR (6 hrs. daily peaking)
2	Middle Marsyangdi Hydropower Station (2)	70	398	PRoR (5 hrs. daily peaking)
3	Marsyangdi Hydropower Station (3)	69	467.45	PRoR (4 hrs. daily peaking)
4	Kulekhani-I Hydropower Station (2)	60	165	Seasonal Storage
5	Kulekhani-II Hydropower Station (2)	32	104.6	Cascade
6	Chameliya Hydropower Station (2)	30	184.2	PRoR (4 hrs. daily peaking)

1.1 Reliability and Availability

The reliability and availability studies are one of the vital components for assessing the performance, strengths and weaknesses of power plants and their constituent units. Reliability is the probability of a device or system performing its intended function adequately for the period of time intended, under the operating conditions required. But this definition of reliability is applicable to a particular kind of performance, where a device is successful if it has not failed during its intended time of service.

The possibility of repairs after failures and of continued service after repairs is not considered. However, there is a class of devices and systems (e.g. generators) which undergoes repair when failed, then returns to service and is expected to function in this manner indefinitely. Hence, it is clear that the reliability of such a device needs to be expressed by a measure different from the one defined above. An index of reliability in such cases is the availability. The availability of a repairable device is defined as the proportion of time, in the long run, that is in or ready for service [2, 3]. Reliability evaluation can primarily be conducted using two techniques: analytical and simulation methods. Analytical techniques, such as network analysis and Markov modeling, utilize mathematical models to represent the network and derive reliability indices through mathematical solutions [4].

1.2 Research Background

Previous studies on the reliability of hydropower plants have employed analytical and simulation-based approaches to assess the performance of plants. Researchers have employed statistical methods, including Markov modeling, to evaluate key reliability indices. Markov modeling technique was used to evaluate the reliability and availability of Sunkoshi Hydropower Station and concluded that availability was below 90% and reliability was above 99% for F.Y. 2009/10 to F.Y. 2012/13 for all 3 units [5]. Similarly, Markov modeling technique was used for the evaluation of availability and reliability of units and plant of Balimela Hydro Electric Power Station [3], PATHRI and CHILLA Hydro Power Station [6]. The overall reliability of Kainji Hydro-Electric Power Station is evaluated using lump-ability (convolution) of the generation and load models, using frequency and duration (F&D) approach [7]. Similarly, Reliability, availability and energy not generated of Dokan Hydropower Station was evaluated using a Markov modeling technique and main causes of outage were determined [8]. The studies on various hydroelectric power plants have highlighted the significance of predictive maintenance and optimized operation strategies. These studies indicate that scheduled outages have the maximum impact on availability, whereas forced outages are mainly caused by turbine, generator and auxiliary system failures. On the basis of these studies, Markov modeling techniques have been used in this study to evaluate reliability and availability of NEA owned PRoR hydropower plants with a view to enhancing operational efficiency and sustainability.

2. METHODOLOGY

The purpose of this study is to discuss a comprehensive performance analysis of NEA-owned PRoR hydropower plants, considering a structured approach to reliability assessment in order to evaluate their performance under various operational conditions. The Key reliability indices to be considered are MTBF, MTTR, MTTF, failure rate (λ) and repair rate (μ) which will be determined through analytical techniques.

The reliability and availability of 4 PRoR hydropower plants KGA, MMHPS, MHPS and CHPS along with their individual units were calculated using operational data from F.Y. 2076/77 to F.Y. 2080/81. The system was modeled by defining the Markov states technique. To derive Markov model of Hydro-Unit or Plant, the states can be classified into up-state and down-state as shown in Figure 1. The system is said to be in the up-state if it is in operating state and system is said to be in down-state if plant or units are in non-operating condition due to forced or schedule outages. The outage can be further classified into ideal outage, schedule outage and forced outage. If the hydropower plant was in non-operational state due to less demand in national grid or has insufficient flow in the river then it can be called as ideal outage. If the hydropower plant was non-operational due to unanticipated breakdown of unit or machine then it can be called as forced outage. Schedule outage means the shutdown of a generating unit for inspection or maintenance according to an advance schedule.

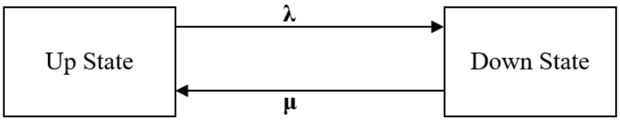

Figure 1: Two-State Model

Where, λ is the failure rate and μ is the repair rate. To develop the Markov model for the generating units, it is assumed that the failure and repair rates are exponentially distributed. There is no transition between scheduled and forced outages. The unit after repairing immediately returns to the up-state. From this a developed Markov model is obtained as follows, known as the three-state Markov model as shown in Figure 2.

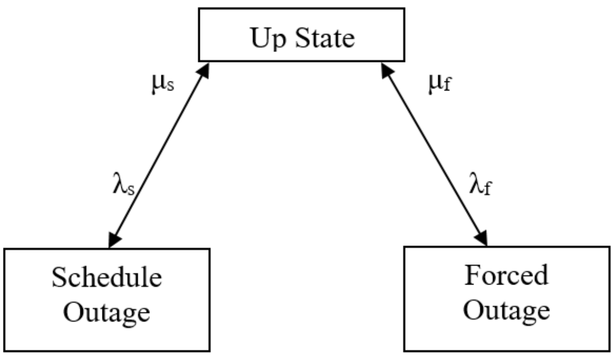

Figure 2: Three-State Model

3. MODELING

3.1 Modeling of Hydro-Unit

Hydro-Unit model of each unit of all plants was developed by defining eight Markov states based on the collected data and considering various types of failure observed in these plants and their units. Reliability indices were then calculated for each state, and the failure rate (λ) & repair rate (μ) were used to determine state probabilities as shown in Table 2.

Table 2: Unit State Probability

State Number	State Probability	
0	$\mu_1\mu_2\mu_3\mu_4\mu_5\mu_6\mu_7\mu_8/D$	d_0/D
1	$\lambda_1\mu_2\mu_3\mu_4\mu_5\mu_6\mu_7\mu_8/D$	d_1/D
2	$\mu_1\lambda_2\mu_3\mu_4\mu_5\mu_6\mu_7\mu_8/D$	d_2/D
3	$\mu_1\mu_2\lambda_3\mu_4\mu_5\mu_6\mu_7\mu_8/D$	d_3/D
4	$\mu_1\mu_2\mu_3\lambda_4\mu_5\mu_6\mu_7\mu_8/D$	d_4/D
5	$\mu_1\mu_2\mu_3\mu_4\lambda_5\mu_6\mu_7\mu_8/D$	d_5/D
6	$\mu_1\mu_2\mu_3\mu_4\mu_5\lambda_6\mu_7\mu_8/D$	d_6/D
7	$\mu_1\mu_2\mu_3\mu_4\mu_5\mu_6\lambda_7\mu_8/D$	d_7/D
8	$\mu_1\mu_2\mu_3\mu_4\mu_5\mu_6\mu_7\lambda_8/D$	d_8/D
Where $D = d_0 + d_1 + d_2 + d_3 + d_4 + d_5 + d_6 + d_7 + d_8$		

These probabilities were ultimately used to calculate the overall reliability and availability of the units. The categorization of Hydro-Unit events can be classified as follows:

1. **Scheduled outage:** Preventive maintenance work, spiral casing/penstock inspection, system outage, transmission line maintenance, load dispatch centre instruction, social issues etc.
2. **Generator failure:** Generator circuit breaker (GCB), controllers, different associated sensors, metering equipment, CT, PT etc.
3. **Excitation system failure:** Rectifier bridge circuit, cooling system, transformer, slip ring-carbon brushes etc.
4. **Turbine failure:** Turbine, shaft seal, bearings, MIV, guide vane, bushes, link, draft tube etc.
5. **Governor system failure:** Oil pressure unit, servo motors, different sensors, lubrication system etc.
6. **Switchgear failure:** Main unit transformer, LV/HV CB, power cable, bus-bar, disconnecting switches etc.
7. **Auxiliary system failure:** Cooling water system, MIV/Guide vane lubricating system,

power supply system, braking/jacking, firefighting system, drainage/dewatering system etc.

8. **Force majeure:** Structural damage, flood, landslide, earthquake, drought etc.

The more developed Hydro-Unit model after defining different states is shown in Figure 3.

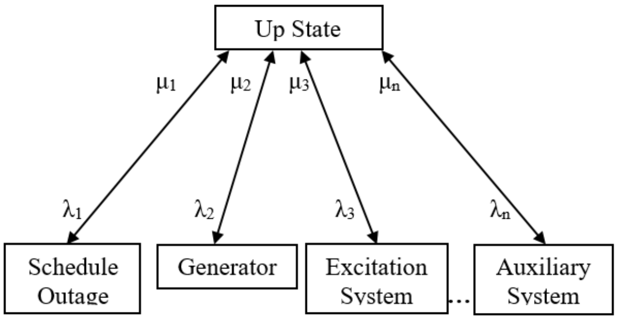

Figure 3: Developed Hydro-Unit Model

Total outage time and number of faults that occurred for different failure conditions from the data collected will be utilized to calculate different reliability indices using following formula:

$$Meantimetorepair(MTTR) = \frac{FOH}{N} \quad (1)$$

$$Meantimebetweenfault(MTBF) = \frac{Observedtime}{N} \quad (2)$$

$$Meantimetofailure(MTTF) = MTBF - MTTR \quad (3)$$

$$\text{Repair rate } (\mu) = \frac{1}{MTTR} \quad (4)$$

$$\text{Failure rate } (\lambda) = \frac{1}{MTTF} \quad (5)$$

where,

Number of failures (N) = Number of times a unit experiences outage.
Forced Outage Hours (FOH) = Time in hours during which a unit or major equipment is unavailable due to their failure.
Service Hours (SH) = Total number of hours the unit was actually operated with breakers closed to the station.

Collected data will be analyzed using statistical methods to derive reliability functions for each units. According to the definition of reliability, the reliability is considered as the probability of the unit operating without unit failure. State 0 and 1 are the states that are without failure. Thus reliability of the unit is:

$$Reliability_(R) = P_0 + P_1 \quad (6)$$

Availability considers the probability of the unit in operating state that is in state 0.

$$Availability_(A) = P_0 \quad (7)$$

3.2 Modeling of Hydro-Plant

The hydropower plant chosen for study consists of two type: Type 1 consisting of 2 units (MMHPS and CHPS) and Type 2 consisting of 3 units (KGA and MHPS). The number of failure rates and repair rates of all units for one year are taken to determine the plant availability and reliability. The transition rate matrix and state probabilities are determined by the same ways as for unit modeling. Maximum number of component is 2 for hydropower plant so, the maximum number of states is calculated using formula:

$$\text{Maximum number of states for plants} = 2^n \quad (8)$$

where, **n** = Number of Units
At least one unit must be in operating state for plant to be available. For Type-1 plant, 1 out of 2 units and for Type-2 plant, 2 out of 3 units must be in operating state to determine reliability of plant.

Type 1 plant modeling : For modeling of plants having two units i.e., MMHPS and CHPS both units should be studied together. Thus, maximum number of states is 4. The probability of state is calculated using formula:

$$P_1 = \prod_{i=1}^{4} \frac{\mu_i}{\lambda_i + \mu_i} \quad (9)$$

$$P_4 = \prod_{i=1}^{4} \frac{\lambda_i}{\lambda_i + \mu_i} \quad (10)$$

Type 2 plant modeling : For modeling of plants having three units i.e., KGA and MHPS all units should be studied together. Thus, maximum number of states is 8. The probability of state is calculated using formula:

$$P_1 = \prod_{i=1}^{8} \frac{\mu_i}{\lambda_i + \mu_i} \quad (11)$$

$$P_8 = \prod_{i=1}^{8} \frac{\lambda_i}{\lambda_i + \mu_i} \quad (12)$$

4. RESULT AND DISCUSSION

From the collected data, the key reliability metrics MTBF, MTTR, MTTF, failure rate and repair rate were calculated. These metrics have been further used to estimate state probabilities for individual units. The unit state probability table of MHPS for F.Y. 2080/81 is shown in Table 3.

Table 3: MHPS Unit State Probability

Unit	State Number	Events	State Probability
1	0	Upstate	0.955623
	1	Schedule	0.043256
	3	Excitation	0.000115
	4	Turbine	0.000358
	7	Auxiliary	0.000648
2	0	Upstate	0.986733
	1	Schedule	0.006654
	3	Excitation	0.000049
	4	Turbine	0.002392
	5	Governor	0.000034
	7	Auxiliary	0.004138
3	0	Upstate	0.993054
	1	Schedule	0.006696
	7	Auxiliary	0.000250

Scheduled outages will generally be defined in the annual outage schedule or planned in the design stage of the hydropower plant, so they do not directly affect the reliability of the units. However, they do reduce the availability of the units. The availability and reliability table of KGA, MMHPS, MHPS and CHPS for F.Y. 2076/77 to 2080/81 of all their Units are shown in Table 4, Table 5, Table 6 and Table 7.

Table 4: KGA Unit Availability and Reliability

F.Y.	Unit 1		Unit 2		Unit 3	
	A	R	A	R	A	R
2076/77	0.9026	0.9962	0.9627	0.9729	0.9005	0.9920
2077/78	0.9902	0.9921	0.9129	0.9934	0.9869	0.9909
2078/79	0.9909	0.9944	0.9969	0.9985	0.9955	0.9989
2079/80	0.9001	0.9362	0.9668	0.9693	0.9298	0.9920
2080/81	0.9879	0.9977	0.9405	0.9983	0.9888	0.9986

Table 5: MMHPS Unit Availability and Reliability

F.Y.	Unit 1		Unit 2	
	A	R	A	R
2076/77	0.9895	0.9930	0.9430	0.9948
2077/78	0.9940	0.9966	0.9950	0.9976
2078/79	0.9557	0.9912	0.9920	0.9943
2079/80	0.9915	0.9978	0.9259	0.9942
2080/81	0.9493	0.9987	0.9889	0.9982

Table 6: MHPS Unit Availability and Reliability

Fiscal Year	Unit 1		Unit 2		Unit 3	
	A	R	A	R	A	R
2076/77	0.9824	0.9968	0.9678	0.9851	0.9248	0.9918
2077/78	0.9098	0.9680	0.9546	0.9705	0.9774	0.9936
2078/79	0.9600	0.9714	0.9437	0.9861	0.9625	0.9739
2079/80	0.9795	0.9881	0.9917	0.9988	0.9378	0.9968
2080/81	0.9556	0.9989	0.9867	0.9934	0.9931	0.9998

Table 7: CHPS Unit Availability and Reliability

F.Y.	Unit 1		Unit 2	
	A	R	A	R
2076/77	0.9354	0.9403	0.9764	0.9822
2077/78	0.9917	0.9969	0.9928	0.9981
2078/79	0.9100	0.9931	0.9216	0.9935
2079/80	0.9802	0.9869	0.9929	0.9997
2080/81	0.9825	0.9882	0.9833	0.9891

The probability of plant state for MHPS for fiscal year 2080/81 is presented in Table 8. The reliability (R) and availability (A) of the KGA and MHPS hydropower plants for the fiscal years 2076/77 to 2080/81 are presented in Table 9, with their graphical representation shown in Figure 4 and Figure 5.

Table 8: MHPS Plant State Probability

State No.	Plant State Probability
1	0.9380587056
2	0.0065218471
3	0.0126526367
4	0.0000879674
5	0.0418200937
6	0.0002907539
7	0.0005640739
8	0.0000039217

Table 9: Availability and Reliability of KGA and MHPS

Fiscal Year	KGA		MHPS	
	A	R	A	R
2076/77	0.99969	0.98543	0.99989	0.99591
2077/78	0.99989	0.99801	0.99989	0.99297
2078/79	0.99989	0.99792	0.99991	0.99425
2079/80	0.99977	0.98789	0.99981	0.99815
2080/81	0.99989	0.99857	0.99978	0.99905

Similarly, the reliability and availability of the MMHPS and CHPS hydropower plants for F.Y.

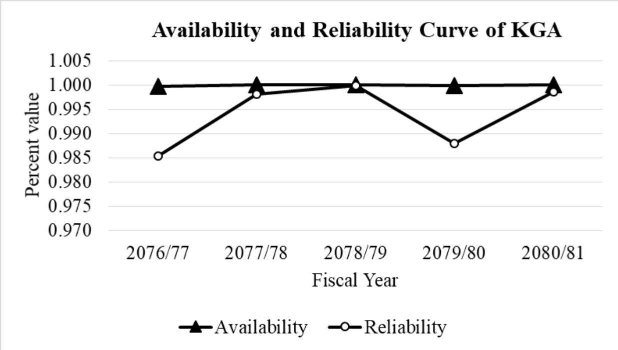

Figure 4: Availability and Reliability of KGA for F.Y. 2076/77 to 2080/81

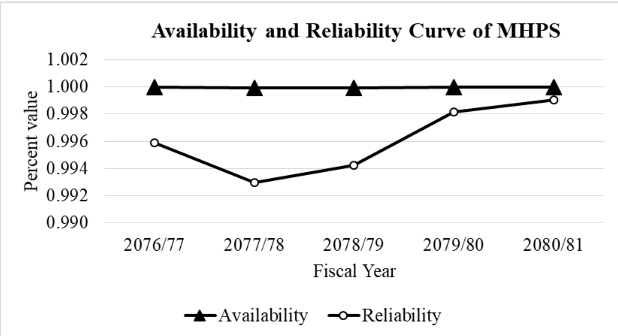

Figure 5: Availability and Reliability of MHPS for F.Y. 2076/77 to 2080/81

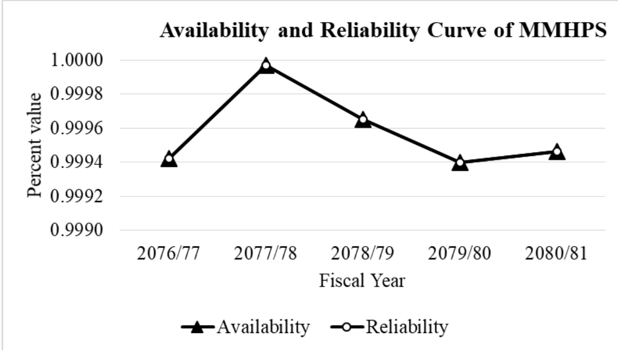

Figure 6: Availability and Reliability of MMHPS for F.Y. 2076/77 to 2080/81

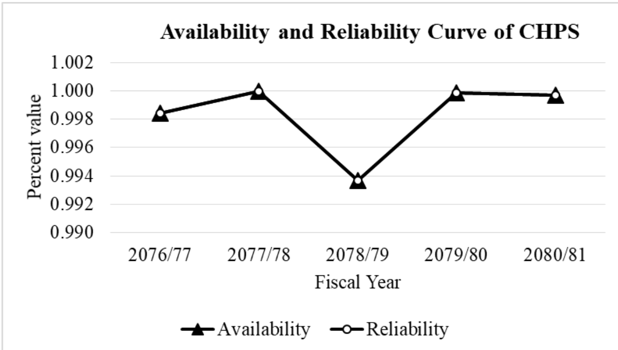

Figure 7: Availability and Reliability of CHPS for F.Y. 2076/77 to 2080/81

2076/77 to 2080/81 are presented in Table 10, with their graphical representation shown in Figure 6 and Figure 7.

Table 10: Availability and Reliability of MMHPS and CHPS

Fiscal Year	MMHPS		CHPS	
	A	R	A	R
2076/77	0.99942	0.99942	0.99841	0.99841
2077/78	0.99989	0.99989	0.99984	0.99984
2078/79	0.99965	0.99965	0.99369	0.99369
2079/80	0.99940	0.99940	0.99986	0.99986
2080/81	0.99946	0.99946	0.99971	0.99971

Scheduled outages were identified as the major cause of most outages in all plants based on the analysis of operational data across various fiscal years. The reliability observed for the studied PRoR hydropower plants remained above 98%, whereas availability of theses plants were above 99% which is regarded as good performance. Key finding obtained from research are:

1. **Kaligandaki "A" Hydropower Station (KGA)**
   - In F.Y. 2076/77, reliability was found to be reduced because units were forced to shut down for 347.07 hours due to a control logic circuit problem and burning of the transformer bushing of unit-3 power transformer.
   - After the up gradation of the control circuit in F.Y. 2076/77 and 2077/78, the reliability and availability of the plant was found improved.
   - In F.Y. 2079/80, reliability was reduced because unit 1 was forced to shut down for 412.37 hours due to the stator earth fault and further of 16 hours shutdown due to the excitation faults, which affected its reliability and availability to a significant degree. Unit 2 also had experienced a forced outage of 75.52 hours due to the rotor earth fault and cooling system issues. Meanwhile, Unit 3 had experienced a forced outage of 54.78 hours due to the Buchholz relay failure in the power transformer, with additional shutdown time for its repair.
   - In overall, for every F.Y. excluding planned ones the major causes of forced shutdown of units were found to be maintenance of

generators, auxiliary systems, controllers, GCB and power transformer.

2. **Middle Marsyangdi Hydropower Station (MMHPS)**

    - In F.Y. 2076/77, availability and reliability were found to have decreased because unit 1 was forced to shut down for 37 hours due to a fault in the braking system and burning of the 11 kV power cable. unit 2 was forced to shut down for 28 hours due to a fault in the inverter, controller system, water leakage from the shaft seal and SS-cone.
    - In F.Y. 2078/79, availability and reliability of the plant appeared to be reduced because Unit 1 and Unit 2 were forced to shut down for 130.52 hours in total due to failures in the firefighting and closed-circuit cooling water systems. Additional issues included leakage of water from the wicket gate, head cover, balancing pipe, and cooler.
    - In F.Y. 2079/80, availability and reliability of the plant appeared to be reduced because Unit 1 was forced to shutdown for 44.95 hours due to faults in cooling water system.
    - In general, for every F.Y. excluding planned ones the major causes of forced shutdown of units were found to be maintenance of the pressure balancing pipe, GCB, auxiliary system, controllers and carbon brush replacements.

3. **Marsyangdi Hydropower Station (MHPS)**

    - In F.Y. 2077/78, reliability was found to decrease because unit 1 was forced to shutdown for 291 hours for shaft alignment arrangement work, replacement of shaft seal and maintenance of 11 kV power cable. Similarly, units 2 and 3 were forced to shutdown for 321 hours for cooling water system maintenance, shaft seal maintenance and replacement work.
    - Similarly, the reliability of plant during F.Y. 2078/79 was low due to a complete plant shutdown for 84.933 hours to resolve water leakage from the Main Inlet Valve (MIV). In addition to this, all three units were forced to shutdown for 359.52 hours and major reasons for the shutdown of units were turbine and governor-related issues, failures of 11 kV power cable and problems with the power transformer and cooling system.
    - In general, for every F.Y. excluding planned ones major causes of forced shutdown of units are found to be maintenance of shaft seal, guide vane, coolers, transformer and carbon brush replacements.

4. **Chameliya Hydropower Station (CHPS)**

    - In F.Y. 2076/77, reliability and availability of the plant were found reduced because unit 1 was forced to shutdown for 229.2 hours due to fault in B-phase of excitation transformer and unit 2 was forced shutdown for 38.6 hours due to fault in its excitation transformer. Similarly, unit 1 was forced to shutdown for 120.8 hours due to issues of turbine run away speed and 70.55 hours due to machine vibration.
    - In F.Y. 2078/79, reliability of the plant was found affected because unit 1 was forced to shutdown for 48.5 hours due to burning of flashing diode.
    - In general, for every F.Y. excluding planned ones major causes of forced shutdown of units are found to be maintenance of shaft seal, pressure balancing pipe, auxiliary system, replacement of different sensors, TGB and PRV.

5. CONCLUSION

Despite the considerable body of research focused on hydropower system reliability worldwide, there is a limited studies specifically addressing the availability and reliability of PRoR hydropower plants in Nepal. Since PRoR plants, which operate primarily during peak demand times, face unique challenges that differ from those encountered by other types of hydropower plants. These plants in Nepal, many of which are owned by NEA, are vital to the country's power generation infrastructure. However, their reliability and operational efficiency remain under-explored, leading to potential inefficiencies and increased risks of unscheduled outages. In overall the total outage hours based on basic events of studied hydropower plant from F.Y. 2076/77 to F.Y. 2080/81 was shown in table 11.

Thus, the results discussed above indicate that the overall availability and reliability of all four PRoR

Table 11: Total Outage due to Forced Shutdown of Units over 5 Years

Basic Events	Unit No.	Down Time (hrs.) due to Forced Shutdown			
		KGA	MMHPS	MHPS	CHPS
Generator	Unit 1	466.35	21.83	5.90	0.00
	Unit 2	243.02	4.48	10.67	0.00
	Unit 3	20.15	0.00	1.93	0.00
Excitation	Unit 1	37.60	8.70	20.15	277.20
	Unit 2	70.28	2.67	65.57	38.60
	Unit 3	4.23	0.00	22.13	0.00
Turbine	Unit 1	4.67	31.80	487.23	344.18
	Unit 2	2.40	35.77	286.70	87.22
	Unit 3	6.50	0.00	280.23	0.00
Governor	Unit 1	0.00	3.63	126.05	6.10
	Unit 2	0.00	2.40	149.07	3.78
	Unit 3	0.00	0.00	57.45	0.00
Switchgear	Unit 1	3.83	24.38	22.73	37.12
	Unit 2	0.42	8.87	26.52	37.15
	Unit 3	132.08	0.00	7.40	0.00
Auxiliary	Unit 1	26.13	22.60	24.93	18.50
	Unit 2	21.05	50.65	53.02	20.22
	Unit 3	9.77	0.00	27.63	0.00
Force Majeure	Unit 1	65.48	87.13	0.00	162.28
	Unit 2	65.48	81.43	0.00	148.07
	Unit 3	69.45	0.00	0.00	0.00

plants exceed 99% and 98%, respectively. However, some individual units within these plants exhibited availability and reliability as low as 90%. This shortfall of units could impact the plant's ability to supply energy during peak energy demand. Table 11 indicates that the maintenance of turbines accounted for most of the plant outages, followed by the generator system. Excitation system problems came third, followed by governor failures, switchgear failures and lastly, maintenance of auxiliary system, which had the least impact. The historic records indicate that while scheduled outages were managed in a planned manner, unscheduled outages due to equipment failures had a significant impact on unit availability and reliability. According to Tables 9 and 10, MMHPS is the most reliable plant, followed by CHPS, MHPS and KGA.

Thus, regular condition monitoring, up-gradation and overhauling works of all the major hydro-mechanical and electro-mechanical equipment should be done as per recommended by the OEM. Also, enhancing workforce training to reduce fault detection and response times, along with maintaining a stock of spare parts, will help reduce repair delays and minimize downtime.

Acknowledgments

This work was supported by the Kaligandaki ”A” Hydropower Station, Middle Marsyangdi Hydropower Station, Marsyangdi Hydropower Station and Chameliya Hydropower Station, all of which fall under the Large Generation Operation and Maintenance Department of the Nepal Electricity Authority (NEA), located in Durbarmarg, Kathmandu. This department oversees the operation and maintenance of the large hydropower plants owned by NEA.

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