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Integrated Planning and Simulation of Multipurpose Reservoir Operation for Basin-Wide Energy Maximization: Exploring the Case of Kaligandaki River Basin in Nepal

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Abstract

The Kaligandaki River, a significant tributary in Nepal, is central to various proposed projects for reservoirs and inter-basin transfers, primarily aimed for hydropower generation. These projects have been planned and studied separately without observing the impact of individual projects on each other. To achieve efficient reservoir operation, it is crucial to incorporate key elements such as water resource management, hydropower considerations, and the integration of reservoir projects, supported by simulation techniques. This research undertakes to achieve shared benefits regarding the relationship of the three reservoir projects i.e. Kaligandaki Storage Hydroelectric Project, Adhikhola Storage Hydroelectric Project, Lower Badigad Storage Hydroelectric Project and an inter-basin transfer project i.e. Kaligandaki Diversion Multipurpose Project lying in the study area. HEC-ResSim software has been employed to simulate hydropower under different project development scenarios. The simulation model was applied to operate reservoirs as per the rule curve taken. For each of the three reservoir projects, a reservoir operation rule curve is proposed which assures the maximum annual energy and dry energy productions with the best reservoir performance indicators. The integrated operation of these projects aims to maximize energy generation and fulfill the diversion requirements of the Kaligandaki Diversion Multipurpose Project by ensuring that upstream reservoirs adhere to specified rule curves. The system of three planned reservoirs and an inter-basin transfer project of the Kaligandaki River basin has the ability to produce a dry firm power of 466.8 MW. The system has the capacity to produce an average total annual energy output of 8752 GWh per year, along with a dry energy output of 3322.4 GWh/year. Results show that undertaking these projects entirely will produce higher benefits in terms of energy generation rather than planning these projects independently.

Keywords

HEC-ResSim, Rule Curve, Reservoir Operation, Performance Indicators

1. Introduction

Dams and storage reservoirs are the central components of large water resources systems. They are acknowledged as among the most effective infrastructure elements within the framework of integrated water resources management [1]. They have the capacity to store surplus water during high-flow periods for utilization during periods of low-flow [2]. They provide hydraulic head and storage for hydropower generation but also serve as seasonal storage capacity for multiple purposes [3] for instance irrigation, water resources supply, flood control, etc. [4] Many developing countries have organized Integrated Water Resource Management (IWRM) as an analytical concept for their nationwide water policy and have commenced on the transboundary river basin planning. The IWRM approach is widely recognized as the most scientifically rigorous and comprehensive method for ensuring effective management of water resources [5].

Nepal is one of the richest countries in water resources, featuring a network of 6000 rivers, a mean annual runoff spanning 224 km^2, and an impressive per capita water availability of 9000 m^3. However, Nepal's hydrology is predominantly influenced by the monsoon, with a significant 85% of the annual rainfall concentrated between June to September. The extensive temporal and spatial fluctuations in rainfall and runoff create the problem of surplus water during the monsoon season and scarcity during the dry period [5]. Due to the limited water resources in winter, the problem of water resource scarcity has escalated. The firm power of the run-off river projects available in winter is only about 20% of the installed capacity [6] which creates problems in fulfilling the energy balance between supply and demand. Various research endeavors have been undertaken to identify prospective projects for optimal allocation of available resources [7]. When projects are examined, planned, and designed independently, discords may arise during their operation within the river basin, resulting in the inability to achieve maximum benefit. Therefore, it is crucial to conduct project studies and planning within the context of the river basin, taking into account the interrelationships between projects. This approach aims to maximize the overall benefits derived from the basin as a whole, rather than solely focusing on individual projects [8].

Optimal water usage is becoming essential in order to maximize the benefit of the available water resources. The various methods can be applied to make decision in order to plan and manage the reservoir for its effective operation. Simulation serves as a modeling method to understand the dynamics of a system on a computer, typically represented by a mathematical or algebraic description encompassing all system properties. Applying simulation to reservoir operation and project relationships on a basin-wide scale aids in optimal utilization of water resources within the basin. This optimization ensures fulfillment of various requirements, including technical, economic, social, environmental, and other constraints in the basin [9]. There are various tools available such as HEC-ResSim, Mike Basin, WASP, etc. which perform simulation under varying input scenarios.

HEC-ResSim was developed with the aim of assisting engineers and planners in the comprehensive study of water resources for the purpose of planning and forecasting reservoir behavior. The model exhibits goals and limitations while operating reservoir through an innovative structure of rule-based logic meticulously designed to accurately depict the decision-making protocol [10].

The performance of the simulated result can be analyzed based on the different performance indicator criteria, including reliability, resiliency, and vulnerability [11]. Reliability denotes the likelihood of a system maintaining a suitable condition, essentially representing the inverse of the probability of failure or risk. However, as both reliability and risk fail to capture the extremity and potential consequences of the system during failure, additional criteria like resiliency and vulnerability must be considered. Resiliency reflects a system's capacity to rebound or recover swiftly following a failure, crucial for mitigating the potential impact of prolonged failure events on a project. On the other hand, vulnerability assesses the probable magnitude of failure if it occurs. It is noteworthy that endeavors to enhance reliability may inadvertently elevate the system's susceptibility to a potentially expensive failure [11]. These three criteria collectively provide an effective framework to describe the frequency, duration, and severity of potential failures within a system.

In this research, the HEC-ResSim model serves as a pivotal mechanism for strategically planning the operation of three reservoirs and a diversion project within the Kaligandaki River basin. It is also attempted to perform a user-defined rule-oriented simulation technique to analyze new circumstances built on Kaligandaki Storage Project, Adhikhola Storage Project, and Lower Badigad Storage Project for the effective hydropower production with an acceptable reliability of meeting release requirements from Kaligandaki Diversion Multipurpose Project for various purposes.

2. Methodology

2.1 Overview of the study area

Kaligandaki is one of Nepal's major rivers that flows from the northern reaches of the high Himalayas to the southern Terai plains of Nepal, where it eventually merges with the Ganges River in India. The Kaligandaki River originates at the Nhubine Himal Glacier in Nepal's Mustang region, standing at an elevation of 6268 m [12]. Notably, the Kaligandaki River forms a large portion of water as it is the largest tributary of the Gandaki River system. The energy output obtained through the development of reservoir projects in Kaligandaki Basin can have a significant impact on the overall energy generation of the country. So, the Kaligandaki River Basin has been selected for this study due to its suitable features that can provide shared benefits among stakeholders.

This research undertakes the three envisioned storage hydropower projects i.e. Kaligandaki Storage Hydroelectric Project, Adhikhola Storage Hydroelectric Project, and Lower Badigad Storage Hydroelectric Project, and an inter-basin transfer project i.e. Kaligandaki Diversion Multipurpose Project situated within its scope. The proposed Kaligandaki Multipurpose Storage Hydropower project lies between the latitudes 28° 16' 32" N to 28° 09' 25" N and the longitudes 83° 42' 32" E to 83° 36' 11" E. The inundation area of the project covers the Parbat, Baglung, and Gulmi districts [13]. The proposed Adhikhola Storage Hydropower Project is in the Syangja district. The project boundary lies between latitudes 27° 55' 00" N to 27° 59' 00" N and longitudes 83° 35' 00" E to 83° 45' 00" E [6]. Similarly, the proposed Lower Badigad Storage Hydropower Project is in the Gulmi district of the Lumbini Province of Nepal. The project boundary lies between latitudes 27° 57' 00" N to 28° 11' 00" N and longitudes 83° 16" 00" E to 83° 29' 25" E [14]. Kaligandaki Tinau Diversion Multipurpose Project (KTDMP), an inter-basin and inter-provincial project, seeks to transfer water from the Kaligandaki River (Gandaki Basin) to the Tinau River Basin. It is situated in the districts of Palpa, Syangja, and Rupandehi in Nepal. The proposed project boundary is located between latitude and longitude of 27° 41' 33" to 27° 54' 28" N and 83° 25' 54" to 83° 39' 35" E respectively. The study area experiences a tropical monsoon climate characterized by two distinct seasons: a wet season and a dry season. The average

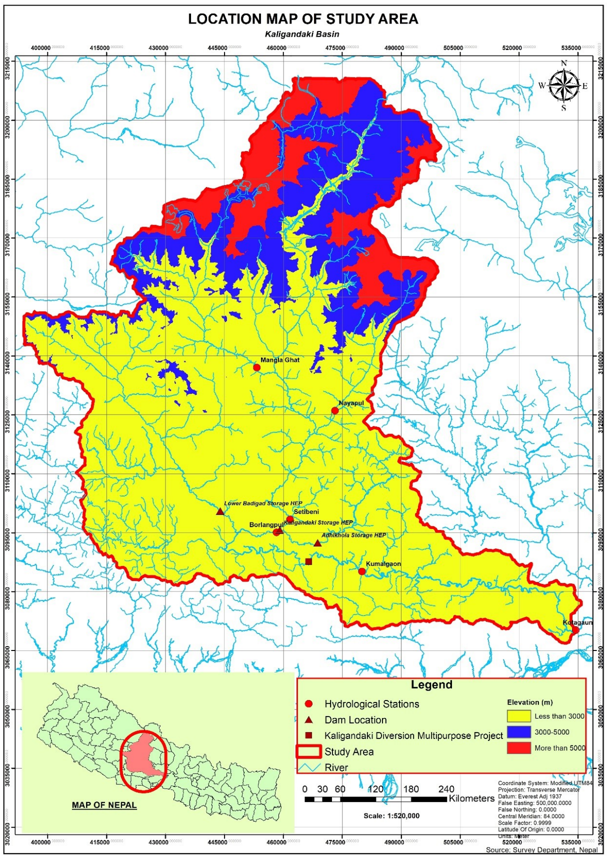

Figure 1: Location map of the study area

annual precipitation in the study region varies between 1,100 mm and 1,800 mm. The monthly temperature typically ranges from a maximum of 28 ºC to a minimum of 13 ºC. Relative humidity ranges from 41-82% [15].

The primary objective of this research project is to maximize energy extraction from the Kaligandaki basin by employing specifically chosen rule curves for each reservoir, ensuring fulfillment of performance indicator criteria.

2.2 Methodical approach

The reservoir simulation model necessitates comprehensive input data, including hydrological time series data, as well as physical and operational information for dams and reservoirs. The hydrological data for stations numbered 406.5, 404.7, 415.1, and 419.1 in proximity to the proposed dam sites were sourced from the Department of Hydrology and Meteorology (DHM) for the period spanning from 1996 to 2018. Any gaps in the hydrological data were addressed through the application of regression analysis techniques. A simple CAR hydrological method has been applied for these hydrological stations to better correlate the time series data. The model was calibrated and validated to enhance accuracy and reliability, improving the model performance parameters such as Root Mean Square Error (RMSE), Nash-Sutcliffe Efficiency (NSE), and R-squared. Then, the HEC-ResSim model was set up and the simulation was carried out for each alternative trial case of each scenario. The result of each simulation was further analyzed to find the total annual average energy, average dry energy, and dry energy's contribution to annual energy expressed in percentage. Now, based on dry energy generation, reservoir performance indicators i.e. reliability, resiliency, and vulnerability were determined for each alternative trial of simulation. Finally, the selection of the best reservoir operation rule curve will be done based on maximum energy generation and respective performance indicator criteria.

2.3 HEC-ResSim approach

HEC-ResSim simulation software comprises three distinct components: the watershed configuration, the reservoir network, and the simulation process [10]. Within the watershed setup module, users generate schematic representations of the physical components integral to the project. In the network module, we outline the configurations of river reaches, junctions, and reservoirs, detailing their respective properties and assigning a range of input feature data. Subsequently, within the simulation module, the model is executed for the specified duration, exploring a predetermined set of alternatives. Following the assignment of all input parameters, the optimal alternative is identified for effective reservoir operation.

2.4 Reservoir Operation Rules

Reservoir operation rules serve as a structured framework for determining the optimal release of storage in the next time step, informed by the current reservoir status, and typically guide discharge decisions [10]. A coordinated operation rule is employed to regulate reservoir discharge, aiming to maximize dry energy and total energy output while adhering to acceptable performance indicators. Various simulation trials, each governed by distinct operation policies defined by buffer levels, are conducted. The operation policy aligning with the defined objective is subsequently chosen. The buffer level, in this context, signifies a predetermined water elevation in the reservoir to be sustained during the specific time of year (month). Discharge release occurs up to full capacity when the elevation surpasses the buffer level and ceases when it falls below it.

2.5 Simulation scenarios

This paper examines the simulation of two scenarios for three reservoir projects, Kaligandaki, Adhikhola, and Lower Badigad, and one diversion project, KTDMP within the scope of Kaligandaki River.

Scenario 1:
All three planned storage projects were operated mainly to obtain maximum energy generation from the system and KTDMP was operated to divert constant design flow of $82\,m^3/s$.

Scenario 2:
Two planned storage projects were operated mainly to obtain maximum energy generation and KTDMP was managed to divert a constant design flow rate of $82\,m^3/s$.

2.6 Performance Evaluation

The simulation results are assessed through specific performance indicators. In addition to emphasizing energy generation objectives, this study integrates three key indicators: reliability, vulnerability, and resiliency.

Reliability, in this context, is quantified as the ratio of the number of data points in a satisfactory state (those equal to or greater than a specified threshold X^T) to the total number of data points in the time series (n). Considering satisfactory values in the time series X_t, comprised of n values, as those meeting or exceeding a specified threshold X^T, then [16]

$$\text{Reliability (R)} = \frac{\text{No. of time periods such that } X_t \leq X^T}{n} \quad (1)$$

Where,

X_t = specific value in the time series at time t
X^T = threshold value

Vulnerability quantifies the magnitude of disparities between the threshold value and unsatisfactory values, and can be computed as follows: [16]

$$\text{Vulnerability (V)} = \frac{[\text{Sum of positive values of}(X_t - X^T)]}{\text{No. of times an unsatisfactory value occurred}} \quad (2)$$

Resiliency is quantified as the likelihood that when in an unsatisfactory state, the subsequent state will be satisfactory. It represents the probability of obtaining a satisfactory value in time period t+1 following an unsatisfactory value in any time period t and can be computed as: [16]

$$\text{Resiliency } (Re) = \frac{\begin{bmatrix}\text{No. of times a satisfactory value follows} \\ \text{an unsatisfactory value}\end{bmatrix}}{\text{No. of times an unsatisfactory value occurred}} \quad (3)$$

3. Results and Discussion

3.1 Individual Project Energy Production

Kaligandaki Storage Project

Four distinct trial operating rule policies, depicted in Figure 2, were employed to determine the optimal reservoir rule curve. Among these, trial 4 is chosen for the reservoir's operation. Operating under this policy, the reservoir is expected to generate an annual energy output of 4825.586 GWh/year, with a dry energy contribution of 1731.067 GWh/year. The plant is anticipated to produce 220 MW of firm power, ensuring 95% reliability during the dry season.

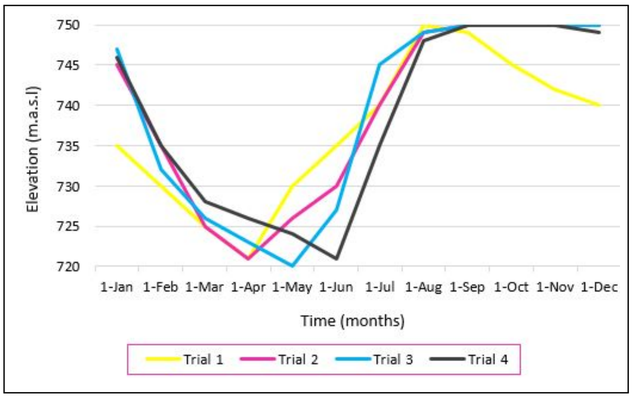

Figure 2: Alternative operation rule curves used for Kaligandaki reservoir

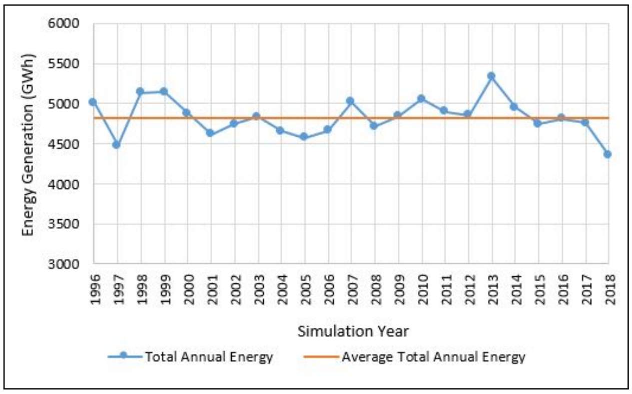

Figure 3: Energy generation trend over simulation years in Kaligandaki storage project

Adhikhola Storage Project

Likewise, Figure 4 illustrates four distinct reservoir operation rules for the Adhikhola reservoir. Among the options, the trial 4 reservoir operation policy emerged as the most effective, generating a maximum average annual energy of 955.61 GWh/year, with 426.74 GWh/year attributed to dry energy. This policy yields 38 MW of dependable power during dry conditions, achieving power reliability of 93.44%.

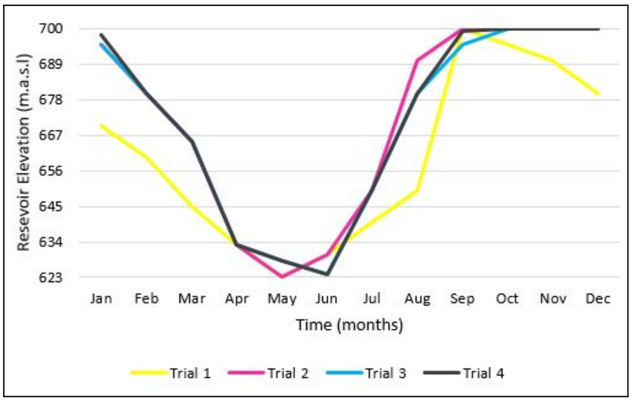

Figure 4: Alternative operation rule curves used for Adhikhola reservoir

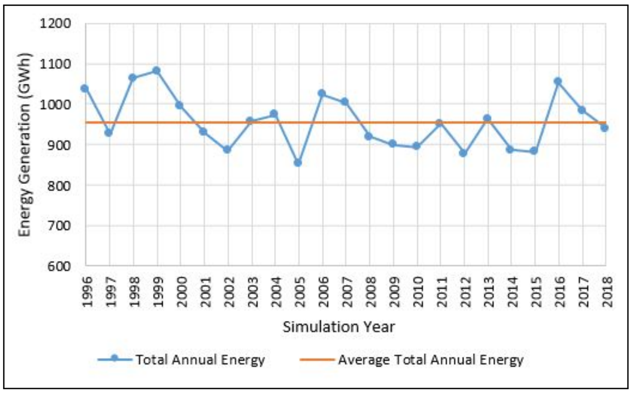

Figure 5: Energy generation trend over simulation years in Adhikhola storage project

Lower Badigad Storage Project

Similarly, Figure 6 illustrates four distinct reservoir operation rules for Lower Badigad. The trial 4 reservoir operation policy, as an alternative, resulted in the maximum average annual energy output of 1842.23 GWh/year, with 600.367 GWh/year attributed to dry energy. This policy delivers 80 MW of reliable power during dry conditions, with power reliability rate of 96%.

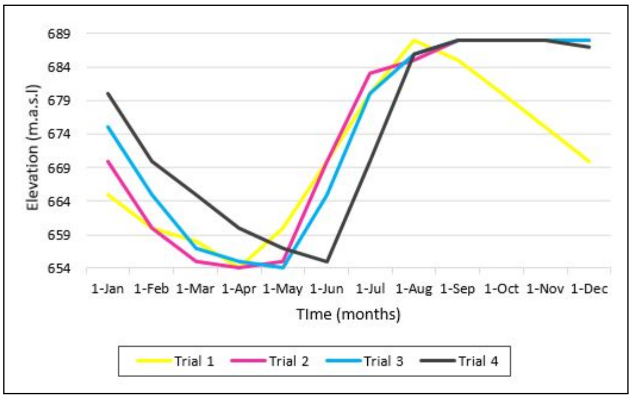

Figure 6: Alternative operation rule curves used for Lower Badigad reservoir

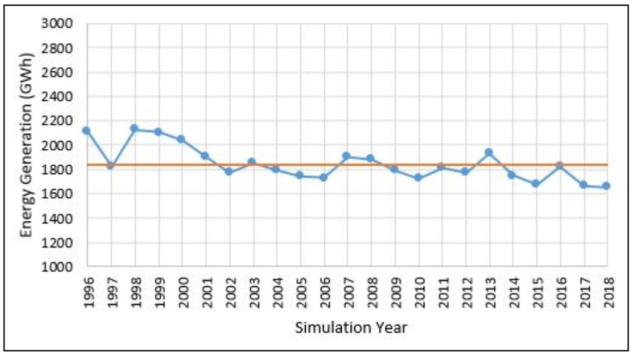

Figure 7: Energy generation trend over simulation years in Lower Badigad storage project

Kaligandaki Diversion Multipurpose Project

A constant of 82 m³/s diversion flow all- round the year is assured for Kaligandaki Diversion Multipurpose Project in both scenarios. KTDMP has the capacity of producing total annual energy of 1128.6 GWh and 128.8 MW of firm power in both scenarios.

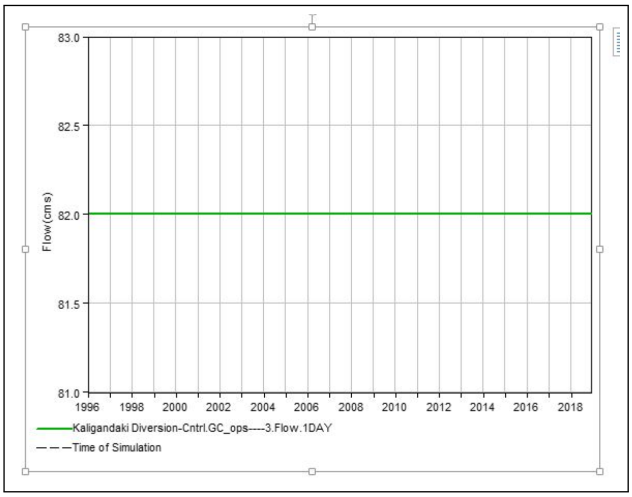

Figure 8: Curve showing constant diversion from KTDMP

3.2 System energy comparison in each scenario

3.2.1 Comparison of System Energy in Scenario 1

In scenario 1 operation, the system yields an average annual energy output of 8752.0 GWh, with 3322.4 GWh attributed to dry energy.

Table 1: Comparison of System Energy in Scenario 1

Project		Kaligandaki Storage HEP	Adhikhola Storage HEP	Lower Badigad Storage HEP	KTDMP	Total
Firm Power (MW)		220	38	80	128.8	466.8
Energy (GWh)	Total	4825.6	955.6	1842.2	1128.6	8752.0
	Dry	1731.1	426.7	600.4	564.3	3322.4
	Wet	3094.5	528.9	1241.9	564.3	5429.6
Dry percent		0.4	0.4	0.3	0.5	
PI from Dry Period Firm Power (%)	Reliability	96.0	93.4	96.0	100	
	Vulnerability	3.8	32.2	8.3	-	
	Resiliency	3.0	9.5	3.6	-	

3.2.2 Comparison of System Energy in Scenario 2

Similarly, when the system operates in scenario 2, the optimum energy generation and the performance indicators criteria in case 1, case 2, and case 3 are shown in Table 2, Table 3 and Table 4 respectively. Case 2 of scenario 2 can generate the maximum total energy of 7796.4 GWh/year. The maximum firm power produced from this case is 428.8 MW and the dry energy contribution is 2895.7 GWh/year.

Table 2: Comparison of System Energy in Case 1 of Scenario 2

Project		Kaligandaki Storage HEP	Adhi khola Storage HEP	KTDMP	Total
Firm Power (MW)		220	38	128.8	386.8
Energy (GWh)	Total	4825.6	955.6	1128.6	6909.8
	Dry	1731.1	426.7	564.3	2722.1
	Wet	3094.5	528.9	564.3	4187.7
Dry Percent		0.4	0.4	0.5	
PI from Dry Period Firm Power (%)	Reliability	96.0	93.4	100	
	Vulnerability	3.8	32.2	-	
	Resiliency	3.0	9.5	-	

Table 3: Comparison of System Energy in Case 2 of Scenario 2

Project		Kaligandaki Storage HEP	Lower Badigad Storage HEP	KTDMP	Total
Firm Power (MW)		220	80	128.8	428.8
Energy (GWh)	Total	4825.6	1842.2	1128.6	7796.4
	Dry	1731.1	600.4	564.3	2895.7
	Wet	3094.5	1241.9	564.3	4900.7
Dry percent		0.4	0.3	0.5	
PI from Dry Period Firm Power (%)	Reliability	96.0	96.0	100	
	Vulnerability	3.8	8.3	-	
	Resiliency	3.0	3.6	-	

Table 4: Comparison of System Energy in Case 3 of Scenario 2

Project		Adhi khola Storage HEP	Lower Badigad Storage HEP	KTDMP	Total
Firm Power (MW)		38	80	128.8	246.8
Energy (GWh)	Total	955.6	1842.2	1128.6	3926.4
	Dry	426.7	600.4	564.3	1591.4
	Wet	528.9	1241.9	564.3	2335.1
Dry percent		0.4	0.3	0.5	
PI from Dry Period Firm Power(%)	Reliability	93.4	96.0	100	
	Vulnerability	32.2	8.3	-	
	Resiliency	9.5	3.6	-	

4. Conclusions

This study conducted a simulation of the three proposed reservoir projects and an inter-basin transfer project within the Kaligandaki Basin to assess the benefit (energy generation) of the system. Based on the simulation findings, the aggregate of the average total annual energy under the optimal operation rule in trial 4 was determined as 8752.0 GWh/year, encompassing 3322.4 GWh/year of dry energy. In contrast to the findings in existing literature, the energy generation results derived from the Kaligandaki Tinau Diversion Multipurpose

Project closely align with the predictions outlined in the feasibility report of KTDMP. However, it is noteworthy that both the total energy generation and dry energy generation outcomes from the reservoir projects surpass the values anticipated in the individual project feasibility reports.

This study has succeeded in generating the maximum annual energy of the planned reservoir while fulfilling the design discharge of $82\,m^3/s$ as the constant diversion requirement of KTDMP. The maximum energy generation helps to select the best reservoir operation rules (policy). The findings indicate that employing the reservoir operation rule curve, which sustains the full supply level elevation at the start of December, yields higher quantities of both dry energy and total annual energy. Moreover, the criteria for performance evaluation including reliability, resiliency, and vulnerability were well within the acceptable range.

Therefore, while the commissioning of an individual project is anticipated, a comprehensive analysis of identified projects within a basin should be conducted in an integrated manner for effective reservoir operation. It was especially aimed to encourage constituents and decision-makers to engage actively in decision-making processes concerning projects within the Kaligandaki basin. Future research should integrate a climate impact assessment into basin project analyses, ensuring sustainable planning by understanding climate change effects on water resources and energy generation. This approach enhances the adaptability and long-term success of proposed projects within evolving climatic patterns.

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