TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS

THESIS NO: M-177-MSESPM-2019-2023

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

by

Anusha Shrestha

A THESIS
SUBMITTED TO THE DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ENERGY SYSTEMS PLANNING AND MANAGEMENT

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
LALITPUR, NEPAL

OCTOBER, 2023

COPYRIGHT

The author has agreed that the library, Department of Mechanical and Aerospace Engineering, Pulchowk Campus, Institute of Engineering may make this thesis freely available for inspection. Moreover, the author has agreed that permission for extensive copying of this thesis for scholarly purposes may be granted by the professor(s) who supervised the work recorded herein or, in their absence, by the Head of the Department wherein the thesis was done. It is understood that recognition will be given to the author of this thesis and the Department of Mechanical and Aerospace Engineering, Pulchowk Campus, Institute of Engineering for any use of the material of this thesis. Copying or publication or the other use of this thesis for financial gain without the approval of the Department of Mechanical and Aerospace Engineering, Pulchowk Campus, Institute of Engineering, and the author's written permission is prohibited.

Request for permission to copy or to make any other use of the material in this thesis in whole or in part should be addressed to:

Head
Department of Mechanical and Aerospace Engineering
Pulchowk Campus, Institute of Engineering
Lalitpur, Nepal

TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS
DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis entitled **"Integrated Planning and Simulation of Multipurpose Reservoir Operation for Basin-Wide Energy Maximization: Exploring the Case of Kaligandaki River Basin in Nepal"** submitted by Anusha Shrestha in partial fulfillment of the requirements for the degree of Master of Science in Energy Systems Planning and Management.

Supervisor, Associate Prof. Dr. Nawraj Bhattarai
Department of Mechanical and Aerospace Engineering

Supervisor, Assistant Prof. Laxman Motra
Deputy Head
Department of Mechanical and Aerospace Engineering

External Examiner, Yogendra Dev Bhatta
Senior Civil Engineer
Urja Developers

Committee Chairperson, Dr. Sudip Bhattrai
Head
Department of Mechanical and Aerospace Engineering

Date: October 08, 2023

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, proposed reservoir operation rule curve assures the maximum annual average energy and the 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, by maintaining a constant diversion rate of $82 m^3/s$ through the Kaligandaki diversion throughout the year. Results show that undertaking these projects entirely will produce higher benefits in terms of energy generation than planning these projects independently.

K*eywords: Reservoir Simulation, HEC-ResSim, Rule Curve, Reservoir Operation, Performance Indicators*

ACKNOWLEDGEMENT

The author would like to express her sincere appreciation to Prof. Laxman Motra, without whom the completion of this thesis work wouldn’t have been possible. His invaluable guidance, insightful suggestions, and unwavering support have been the main driving force behind the success of this project.

The author also extends her special thanks to Prof. Dr. Nawraj Bhattarai for his invaluable guidance and suggestions, which were crucial in the successful completion of this work.

Furthermore, the author expresses her gratitude to Er. Manoj Bista for his continuous support, assistance, and guidance throughout the thesis period.

Moreover, the author would like to express her gratitude to all the faculty members of the Department of Mechanical and Aerospace Engineering, Pulchowk Campus, Institute of Engineering, including Prof. Sanjay Neupane and Prof. Aayush Bhattarai, for their invaluable assistance during the study program.

Last but not least, the author would like to express her deep gratitude to her parents for their never-ending love and unwavering trust, which have been a constant source of inspiration for her to pursue higher studies.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CAR	Catchment Area Ratio
DHM	Department of Hydrology and Meteorology
DOED	Department of Electricity Development
DSS	Data Storage System
GON	Government of Nepal
H-A-V	Height – Area – Volume
HEC-ResSim	Hydrological Engineering Center- Reservoir Simulation Model
HEP	Hydroelectric Project
IMP	Irrigation Master Plan
IWRM	Integrated Water Resource and Management
JICA	Japanese International Corporation Agency
KTDMP	Kaligandaki Tinau Diversion Multipurpose Project
MCM	Million Cubic Meter
M.O.W.L	Minimum Operating Water Level
NEA	Nepal Electricity Authority
NSE	Nash-Sutcliffe Efficiency
OP	Operating Policy
RMSE	Root Mean Square Error

CHAPTER ONE: INTRODUCTION

1.1. Background

Hydropower utilizes the energy of water, stored in dams and flowing in rivers, to create electricity through hydropower plants. This form of renewable energy plays a significant role in global electricity production and has been instrumental in the development of the electric power industry, from small to large-scale hydroelectric power developments. Hydropower has been a driving force in promoting economic growth and improving the quality of life in many countries. Hydropower emerges as a pivotal solution to meet the escalating global need for clean, reliable, and cost-effective energy.

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 (Anand, Ashvani Kumar Gosain, & Rakesh Khosa, 2018). They have the capacity to store surplus water during high-flow periods for utilization during periods of low flow (Loucs & Beek, 2005). They provide hydraulic head and storage for hydropower generation but also serve as seasonal (or over-year) storage capacity for multiple purposes (Goor, 2010) for instance irrigation, water resources supply, flood control, etc. (Yoshioka, 2020)

The numerous objectives of reservoirs and dams are often conflicting, especially during extreme hydrological conditions. Until the 90’s, many reservoirs were managed independently, usually with a single objective (usually hydropower generation or seasonal storage for irrigation). Nowadays, IWRM calls for new methodologies to manage and operate water resources systems in order to maximize benefit from the entire hydro-system (river basin) in an equitable and sustainable manner (Goor, 2010). 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 (Suhardiman, Clement, & Bharati, Integrated water resources management in Nepal: key stakeholders' perceptions and lessons learned, 2015).

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 decisions in order to plan and manage the reservoir for its effective operation. 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.

Simulation serves as a modeling method to replicate a system's behavior on a computer, wherein the system's features are predominantly captured through a mathematical or algebraic description (Yeh, 1985). The purpose of reservoir simulation is to understand the system's response to input conditions, and the complexity intensifies when modeling and managing multipurpose reservoirs, involving aspects such as river flow modeling, reservoir storage, and the distribution of water through hydropower plants and other outlets groups (Theobald, 2014). 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 (Joan D. Klipsch, 2010). 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 (Joan D. Klipsch, 2010). The performance of the simulated result can be analyzed based on the different performance indicator criteria, including reliability, resiliency, and vulnerability (Tsuyoshi Hashimoto, 1982). 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 the 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.

1.2. Problem Statement

Nepal is one of the most water-abundant countries in the world, with 6000 rivers, a total mean annual runoff of 224 km^3 and per capita water availability of 9000 m^3 (Suhardiman, Integrated water resources management in Nepal; key stakeholders' perceptions and lessons learned, 2015). Annual average precipitation and hydrological data published by the DHM shows that Nepal has an abundant amount of freshwater available contributed by the Bay of Bengal and Arabian Sea by the process of the hydrological cycle.

However, Nepal's hydrology is predominantly influenced by the monsoon, with a significant 85% of the annual rainfall concentrated within the months of June to September. The extensive temporal and spatial fluctuations in rainfall and runoff create problems of surplus water during the monsoon season and scarcity during the dry period (Suhardiman, Integrated water resources management in Nepal; key stakeholders' perceptions and lessons learned, 2015). 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 (NEA, 2021) 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 (JICA, 2014). This enhances the development of storage projects at the earliest.

This paper deals with the utilization of three storage projects in the upstream of the Kaligandaki basin as studied by the GON for optimal hydropower generation that can fulfill the diversion requirement of KTDMP as well with acceptable reliability. An important improvement is to transfer water between the different uses of the reservoir system by adopting operational rules. Determining the optimal operational rules for multi-purpose reservoirs serving various purposes such as irrigation, hydropower, flood control, etc. is a challenging task as it can bring environmental, social, and other conflicts. That's why an efficient and effective operation of the reservoir is needed for the development of the country in the agricultural as well as power sector.

1.3. Research Objectives

1. 3. 1 Main Objective

The main objective of this thesis is to investigate opportunities for integrating Multipurpose Reservoir Operations to maximize energy derived from the basin.

1. 3. 2 Specific Objectives

The specific objectives of the study are:

- To maximize the total energy generation output from the system while meeting irrigation water requirements.
- To recommend the best operation rule curve for each planned reservoir to operate based on maximizing energy generation.
- To satisfy the selected Performance Indicators (PI) criteria based on the maximum energy generation.

1.4. Scope of Study

The main scope of my work will be as follows:

- Review of past studies reports conducted on Kaligandaki River Basin.
- Collection of hydrological data of different stations, reservoir data, etc.
- Application of the CAR method to calculate the discharges at the required control points.
- HEC-ResSim Model set up.
- Simulate different scenarios and select the best reservoir rule curves.
- Result data interpretation and discussion.

1.5. Limitations

The limitation of this study is as follows:

i. Secondary data have been used for the simulation of the Kaligandaki River basin.

ii. Project parameters for the simulation purposes have been taken from the report of respective projects.

CHAPTER TWO: LITERATURE REVIEW

2.1 Overview of Previous Studies

2.1.1 Discharge Estimation

Many water management approaches require stream flow data that can be obtained through hydrological stations of the particular area. For sites where no streamflow data were collected or for stream flow-gaging stations for periods when the gauge was not operational (Emerson, Vecchi, & Dahl, 2005), we consider it as an ungauged basin (SIVAPALAN, et al., 2010). The International Association for the Hydrological Science took the initiative to enroll the scientific community aiming to advance the understanding and prediction capability of hydrologic parameters in the case of ungauged basins. Traditional stream flow transfer techniques can be used to get flow values at an ungauged site. Standardizing flows by drainage area, standardizing flows by mean flows, standardizing with the maintenance of variance extension (MOVE), and the usage of the FDC are the four basic types of flow transfer strategies (SAKA & BABACAN, 2019).

Catchment area ratio (CAR) is one of the most common methods, since it requires no additional information other than the stream flow at an index site and the catchment areas of the index and ungauged sites, making it the simplest method available (Farmer, 2012). For any given month of two sites X and Y:

$$\frac{Q_y}{A_y} = \frac{Q_x}{A_x}$$

Where, site X is considered the gauged site and site Y is the ungauged site with monthly stream flow Q and catchment area A (Farmer, 2012).

The CAR method is also one of the linear equations, and this can be simply represented as

$$Y = BX$$

Assuming Y is Qy, and X is Qx. B can be written as

$$B = \left(\frac{A_y}{A_x}\right)$$

All discharge transfer methods require strongly correlated data between the discharge and drainage areas, demonstrating that places with similar hydrologic features have similar discharge transferring characteristics.

Model Performance Evaluation

Some quantitative information is required to measure model performance to calibrate and validate the models for evaluating the accuracy of the model and take better decisions. Stream flow data is commonly used to evaluate the performance of hydrological models. The assessment of model performance is based on various factors such as the water balance closure of the watershed, the overall shape of the time series of discharge, the total accumulated volumes, and statistical performance indices including, (Nash & Sutcliffe, 1970) root mean square error (RMSE), modeling efficiency (EF), and goodness of fit (R2) (Golmohammadi et al., 2014).

The RMSE quantifies how well a linear regression model fits the dataset. A perfect match between observed and predicted values is indicated by an RMSE value of 0 (zero). As the RMSE value increases, the match between observed and predicted values becomes poorer. RMSE values that are less than half the standard deviation of the observed data can be considered low, which suggests a good model prediction. The Nash–Sutcliffe efficiency (NSE) indicates how well model simulation predicts outcome variables. The NSE value has a range from $-\infty$ to 1. A score of 1 indicates a perfect match between predicted and observed values. A score between 0.0 and 1.0 is considered acceptable, while a score less than 0.0 shows that the simulated value is worse than the mean observed value, indicating unsatisfactory performance. The coefficient of determination (R2) indicates how well the predictor variables can explain the variation in the response variable. The R-squared value represents the degree to which the model explains the variance in the measured data, ranging from 0 to 1. Higher values indicate less error variance. A value of R-squared greater than 0.5 is generally considered acceptable. (Santhi et al., 2012).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}}$$

$$NSE = \frac{\sum_{i=1}^{n} (O_i - \overline{O})^2 - \sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2}$$

$$R^2 = \left[\frac{\sum_{i=1}^{n} (O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \overline{O})^2} \sqrt{\sum_{i=1}^{n} (P_i - \overline{P})^2}} \right] 0 \leq R^2 \leq 1$$

Since these model performance evaluations are used extensively, the use of these parameters are reliable to check the model performance.

2. 1. 2 Reservoir Operation

The Water management approach assesses the current state of the water resources and the conflicts and priorities over their use for effective reservoir operation to extract maximum benefit from limited resources (Loucs & Beek, 2005). The operation of the proposed largest individual dams and cascade dams has an impact on flow patterns and energy production. The effect of irrigation water demand, land use change, and climate change on hydropower should be considered for improving dam operation and should be the subject of future research to manage risks and maximize basin benefits (Piman, 2016). The challenge of the hydropower generation problem can be improved by improving the individual reservoir operation to an integrated operation system (Theobald, 2014). Water resource system studies have been created throughout the previous few decades, and they include a variety of analytical approaches such as simulation and optimization algorithms (Wurbs, 1993; Fayaed, 2013; Rani and Moreira, 2010). Simulations track the flow of water through a system, while optimization programs look for the best operating policy to meet a predefined goal. In designing a highly efficient as well as effective dam and reservoir operational system, reservoir simulation constitutes one of the most important steps to be considered (Fayaed, 2013).

2. 1. 3 Reservoir Simulation Tools

In practice, simulation models are still the most commonly used tool for river basin planning and management research (Bosona and Gebresenbet, 2010; Singh and Singal, 2017; Jahandideh-Tehrani et al., 2014). Water resource development agencies tasked with the planning, construction, and operation of reservoirs have consistently relied on simulation models for numerous years. The following is a list and description of a few:

The HEC-5 software, accessible at http://www.hec.usace.army.mil/, simulates the consecutive functioning of a multi-purpose reservoir system using input sequences of unregulated stream flows and reservoir evaporation rates. The software uses a configurable time interval to gather data on reservoirs. During normal or low flow periods, monthly or weekly data can be combined with daily or hourly data during flood events. HEC-5 allows users to specify operational principles such as reservoir storage zones, diversion and minimum in-stream flow targets, and permissible flood flow (Bonner, 1980).

Acres International designed the Acres Reservoir Simulation Program (ARSP) for the examination of operational strategies pertaining to a versatile system encompassing water supply, hydropower, and flood control in Ontario, Canada (Bosona & Gebresenbet, 2010). The program is based on network flow programming, which models multi-reservoir systems. The program assigns upper and lower limits, as well as cost functions, to network flow paths based on user input. Water demands are prioritized to determine operating policies. The ARSP is a useful tool for decision-making related to water resource management (Wurbs, Dissemination of generalized water resources models in the United States., 1998).

The US Army Corps of Engineers Hydrologic Engineering Center developed a reservoir simulation model called HEC-ResSim. This model is used to help engineers and planners predict how reservoir systems behave during water management studies. It also assists reservoir operators in planning releases in real-time for day-to-day and emergency operations (HEC, 2021).

In simulating a complex system based on user-defined constraints, HEC-ResSim has an advantage over other simulation tools. Therefore, this study utilizes HEC-ResSim as the preferred simulation tool.

2. 1. 4 HEC-ResSim Model Description

Man-made reservoirs of substantial size are established and maintained for a variety of purposes. Those responsible for their operation must concurrently address a range of needs, encompassing flood control, power generation, recreational activities within the reservoir area, downstream environmental well-being, as well as ensuring the safety and structural integrity of the dam (Loucks et al., 2013). Each of these requirements places restrictions on both the storage and discharge of water from the reservoir, often resulting in conflicting requirements and limits. Setting a reservoir release schedule that serves the reservoir's purpose, fits operating limitations, and is physically feasible is a difficult process, hence engineers have developed reservoir simulation models to aid in the development of release schedules (Wurbs, Reservoir System Simulation and Optimization Models., 1993).

The HEC-ResSim model is designed to incorporate the actual decision-making process that reservoir operators must use to meet operating criteria for electricity generation, flood management, and environmental release, using an original rule-based approach (Theobald, 2014). The software simulates the physical dynamics of reservoir systems by integrating hydraulic calculations for controlled flow through structures with hydrologic routing to replicate the delay and moderation of flows across segments of streams. It expresses operational objectives and restrictions through a proprietary rule-based logic system specifically designed to mirror the decision-making process for reservoir operation (Babazadeh et al., 2007).

HEC-ResSim provides access to various sorts of data within a watershed through three sets of functions known as modules i.e. watershed setup, reservoir network, and simulation. Each module is designed with a unique purpose and features a set of functions that users can access through menus, toolbars, and schematic elements

- **Watershed Setup**

The main purpose of the Watershed Setup module is to establish a uniform structure for creating and defining watersheds across various modeling applications. In the watershed, one can encompass a range of elements such as streams, projects (like reservoirs), computation sites, impact areas, time-series locations, and hydrologic and hydraulic data points specific to a particular region. When configured, all of these details combine to form the system's watershed framework (Olani, 2006).

- **Reservoir Network**

After the completion of the watershed establishment, the next phase of development is the Reservoir Network. The primary objective of the Reservoir Network Module is to separate the construction of the reservoir model from the output analysis. The Reservoir Network module allows users to create a schematic representation of the river system, determine the physical and operational characteristics of the reservoir model, and generate alternative options for evaluation (HEC, 2021). The Reservoir Network is constructed on the foundation of the Watershed Setup Module's configurations, which serve as a guide.

The physical and operational data for reservoirs include the specification of withdrawal priority among various needs, as well as the definition of extraction for different reservoir storage levels, such as whether the level of the reservoir is in the flood, conservation, or dead storage zone. Every network element’s data is integrated after the schematic is finalized. For multipurpose projects, environmental releases (if any), irrigation, and power are usually given higher priority; spillways are given the lowest priority in all circumstances. This module includes routing and losses accounting properties in the reservoir systems, where the routing connects one reservoir to the next. Detailed river physical data is required to calculate routing and seepage losses between reservoirs. Time-series mapping is utilized to generate options for the Reservoir Network, operation set(s), beginning conditions, and assignment of DSS pathname (Olani, 2006). HEC-ResSim can represent four different types of network components: junctions, routing reaches, diversions, and reservoirs. The design of each component is optimized to ensure physical accuracy while maintaining computational efficiency.

- **Simulation Procedure and Results**

The Simulation module's goal is to keep output analysis independent from the model construction process. The Simulation module is employed to set up the simulation after finalizing the reservoir model and defining the alternatives. (HEC, 2021). The Simulation module is where computations are done and the outcomes are shown.

It was necessary to indicate a simulation time frame, a computational interval, and the parameters to be explored during the development of the simulation model. The temporal boundaries for the given instance were the simulation's start, lookback, and end times. A lookback time is an estimate of the time needed to bring the reservoir's storage to full level. Then, within the RSS folder of the watershed, ResSim generates a directory structure that depicts the "simulation." A copy of the watershed will be included in this "simulation" tree, containing only the files required by the designated alternatives. Concurrently, a Decision Support System (DSS) file named simulation.dss is generated throughout the simulation, progressively accumulating all DSS records delineating the input and output for the selected choices (HEC, 2021). The use of this method has made file handling and computing easy and managed.

2. 1. 5 Reservoir Operation Rules

Rules for reservoir operation offer a structured approach to managing storage, prescribing the appropriate water release for the next time step based on the reservoir's current status (HEC, 2021). The formulation of "a collection of operation (or regulation or release) processes, regulations, schedules, policies, or plans that best achieve a set of objectives" is required for reservoir management (Wurbs, Reservoir System Simulation, and Optimization Models., 1993). Reservoir operational rules usually guide release decisions. Allocation of storage capacity and water discharges occurs among reservoirs and various uses during distinct periods as integral components of operational decisions.

Operating rules define optimal pool levels or zones, and delineate actions to be taken if reservoir storage diverges from these specified levels or zones, encompassing a diverse array of regulatory policies presently employed (Ahn et al., 2012). In Figure 2.1, the division of reservoir storage capacity into various zones or pools is depicted, encompassing inactive, conservation, flood control, and surcharge zones. When the modeler hasn't set a rule, the "Guide Curve" figure specifies the reservoir level at which the model tries to retain the water surface. To keep that storage level, a guide curve operation monitors release.

HEC-ResSim requires that a reservoir maintains a designated target elevation (HEC, 2021). The guide curve serves as the representation of the reservoir's targeted elevation over time, functioning as the delineation between the upper section (referred to as the flood-control pool) and the lower zones (typically known as the conservation pool) (HEC, 2021). The decision logic of HEC-ResSim commences and concludes at the guide curve. In instances where the reservoir elevation surpasses the guide curve ("in flood control"), the objective is to release more water than received; conversely, when the reservoir elevation falls below the guide curve ("in conservation"), the goal is to release less water than received (Ahn et al., 2012).

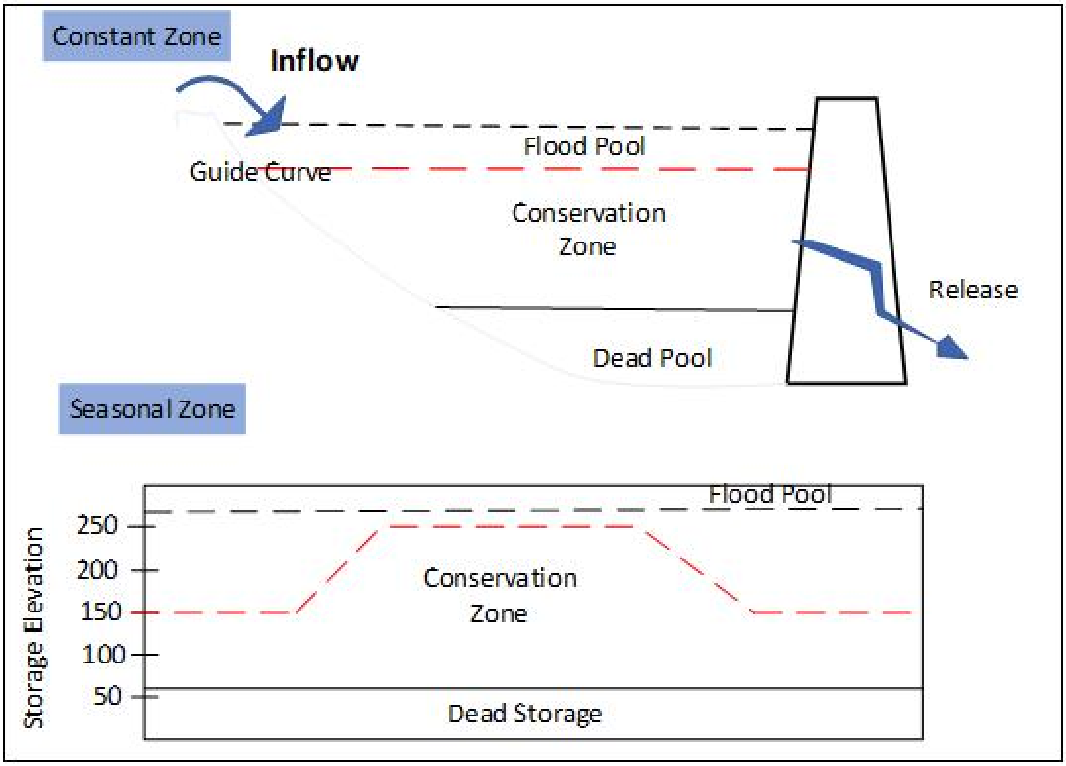


Figure 2.1: Reservoir Operation Policy and Rule Curve for Constant and Seasonal Zone

The reservoir faces challenges in attaining the goal of returning the pool to its guide curve height due to the presence of numerous limitations and physical constraints. In the absence of any guidelines, the reservoir's only limitation would be the physical capacity of the outflows to reach and maintain the guide curve elevation (Klipsch et al., 2021). The rules governing reservoir operations are generally categorized into four groups: pool rules, dam and outlet group rules, power plant rules, and pump works rules (HEC, 2021). This study establishes a variable zone, referred to as the buffer level, and introduces a trial operating policy that creates a variable zone curve in the reservoir over time.

2. 1. 6 Performance Indicators

Water resource systems provide economic, environmental, and ecological benefits through functions such as water supply, flood prevention, hydropower generation, navigation, recreation, waste reduction, and transportation (Loucks &Beek, 2017). Performance criteria serve as a rational approach to evaluate the effectiveness of a management policy or strategy, providing insight into how a reservoir behaves. Different criteria can be used to assess and compare system performance.

Statistical Performance Criteria

Reliability

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 (Loucks & Beek, 2017)

$$Reliability\ [Re] = \frac{[number\ of\ time\ periods\ t\ such\ that\ X_t \geq\ X^T]}{n}$$

Where,

X_t = specific value in the time series at time t

X^T = threshold value

Reliability denotes the likelihood of a system maintaining a suitable condition, essentially representing the inverse of 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. It is noteworthy that endeavors to enhance reliability may inadvertently elevate the system's susceptibility to a potentially expensive failure (Loucks &Beek, 2017).

Vulnerability

Vulnerability assesses the probable magnitude of failure if it occurs. It quantifies the magnitude of disparities between the threshold value and unsatisfactory values and can be computed as follows: (Loucks & Beek, 2017)

$$Vulnerability\ [V] = \frac{[sum\ of\ positive\ values\ of\ (X^T -\ X_t)]}{[number\ of\ times\ an\ unsatisfactory\ value\ occurred]}$$

Resiliency

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. 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 t+1 following an unsatisfactory value in any time period t and can be computed as: (Loucks & Beek, 2017)

$$Resiliency[Re] = \frac{[number\ of\ times\ a\ satisfactory\ value\ follows\ an\ unsatisfactory\ value\ ]}{[number\ of\ times\ an\ unsatisfactory\ value\ occurred]}$$

These three parameters serve as the key elements for understanding the reservoir's performance in any given simulation trial. The selection of the most appropriate operation rule curve for reservoir operation is based on both energy and performance criteria. With each simulation output, these parameters are meticulously calculated to know how the reservoir behaves under the user-defined simulation case.

2. 2 Research Gap

Several numbers of researches have been conducted for the development of the storage type hydroelectric power projects in the Kaligandaki river basin (JICA, 2014; DOED, 2022; DWRI, 2019; NEA, 2021; WECS, 2021). Hydrological analysis using sophisticated tools incorporating climate change provides additional information for decision-making on the formulation of operation policy based on given constraints (Lauri et al., 2012; Li et al., 2010; Yun et al., 2020; Ngo et al., 2018; Ahmadianfar and Zamani, 2020). Certain changes have been brought at times in the identified planned projects to incorporate the contemporary issues and norms of integrated water resource management (WECS, 2021).

Nationwide Master Plan Study on Storage-type Hydroelectric Power Development in Nepal was prepared by the JICA (2014) aiming to prepare storage-type hydroelectric power development for domestic demand in Nepal. The Integrated Water Resource Management Plan has focused on Kaligandaki basin's hydropower generation, irrigation, inter-basin development schemes, and flood control and navigation. The above study identified the various storage HEP planned on the Kaligandaki basin. Kaligadaki storage HEP, Lower Badigad storage HEP and Adhikhola storage HEP are few among them. NEA has performed the feasibility study of the Adhikhola storage project which analyzed many feasible solutions and proposed a dam at Galyang Bazar. Likewise, the study of the Lower Badigad storage project performed by DOED has analyzed many feasible solutions and proposed a dam at Gulmi.

More studies of projects have been conducted on isolation but lack study on an integrated approach at the river basin level assessing the benefit of hydropower production and irrigation. 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.

CHAPTER THREE: STUDY AREA AND DATA COLLECTION

3. 1 Physical Feature

3.1.1 General

The Gandaki River, which runs from north to south in the central Himalayan region, is integral to the region's sustenance by providing vital resources for agriculture, culture, and hydropower. It extends from China in the north, through Nepal, to India in the south, and is bounded by the Karnali basin to the west and the Koshi basin to the east (ICIMOD, 2017, p. 34). The Gandaki River, also known as the Narayani or the Gandak, has seven major tributaries which are Kali Gandaki, Seti Gandaki, Madi, Marsyangdi, Daraudi, Budhi Gandaki, and Trishuli. Kaligandaki River is the largest tributary of Gandaki River which drains 11,600km^2 and is 316 km long (Ministry of Irrigation, 2011). The energy output obtained through the development of reservoir projects in Kaligandaki Basin can provide 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.

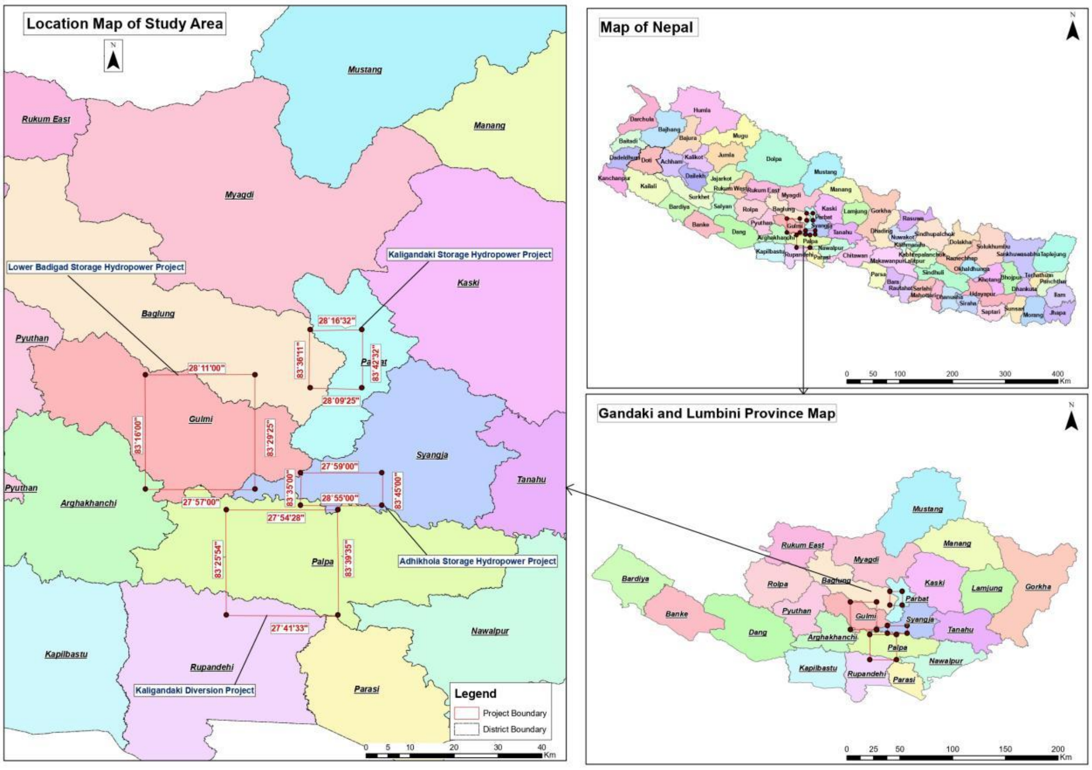


Figure 3.1: Map of study area showing boundary of planned projects

- **Reservoir Projects**

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. The suggested headworks location is situated approximately 2 kilometers upstream from the convergence point of the Seti River and Kaligandaki River, commonly referred to as Setibeni. Setibeni is positioned 6 kilometers away from the headworks of the Kaligandaki A Hydropower Project (DOED, 2021). The planned 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. The dam site is at Motichaur village, Kaligandaki Rural Municipality (Adhikhola). The powerhouse site is at Galyang Municipality, Ward No. 3 (Kaligandaki River) (Authority, 2021). 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. The dam site is about 600m from the roadhead (Shantipur highway). Similarly, the powerhouse site is located at the Rudra Beni Bazar (DEVELOPMENT, 2022).

- **Inter-basin transfer project**

Kaligandaki-Tinau Diversion Multipurpose Project (KTDMP), an inter-basin and inter-provincial project seeks to transfer water from Kaligandaki River Basin to Tinau River Basin. (Sanstha, 2021). 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. Kaligandaki Tinau Diversion Multipurpose Project (KTDMP), located in Palpa, Syangja, and Rupandehi districts, is a multipurpose project with the primary aim of irrigating the cultivated areas of Rupendehi and Kapilvastu Districts in Lumbini province by diverting water from Kaligandaki River to Tinau River. The hydropower development along the diversion route is the secondary outcome of this project.

The headwork for the project is proposed at Pipaldanda, Ward No. 3 of Rambha Rural Municipality, Palpa district. The proposed barrage axis is located 2.2km downstream from the Ramdi Bridge along the Siddhartha Highway with an intake and surface settling basin on the right bank of the Kaligandaki River. From the settling basin, discharge is conveyed through a 27km long and 6.5m dia. tunnel up to the surge shaft. The diameter of the proposed surge shaft is 26 m and the height of the surge shaft is 92.47 m. The discharge is conveyed from the surge shaft via. 450 m long penstock pipe of 6.4 m dia. steel up to the Powerhouse. The optimum design discharge for the diversion has been calculated as 82 m^3/s considering the water availability in Kaligandaki and Tinau Rivers (DWRI, 2019).

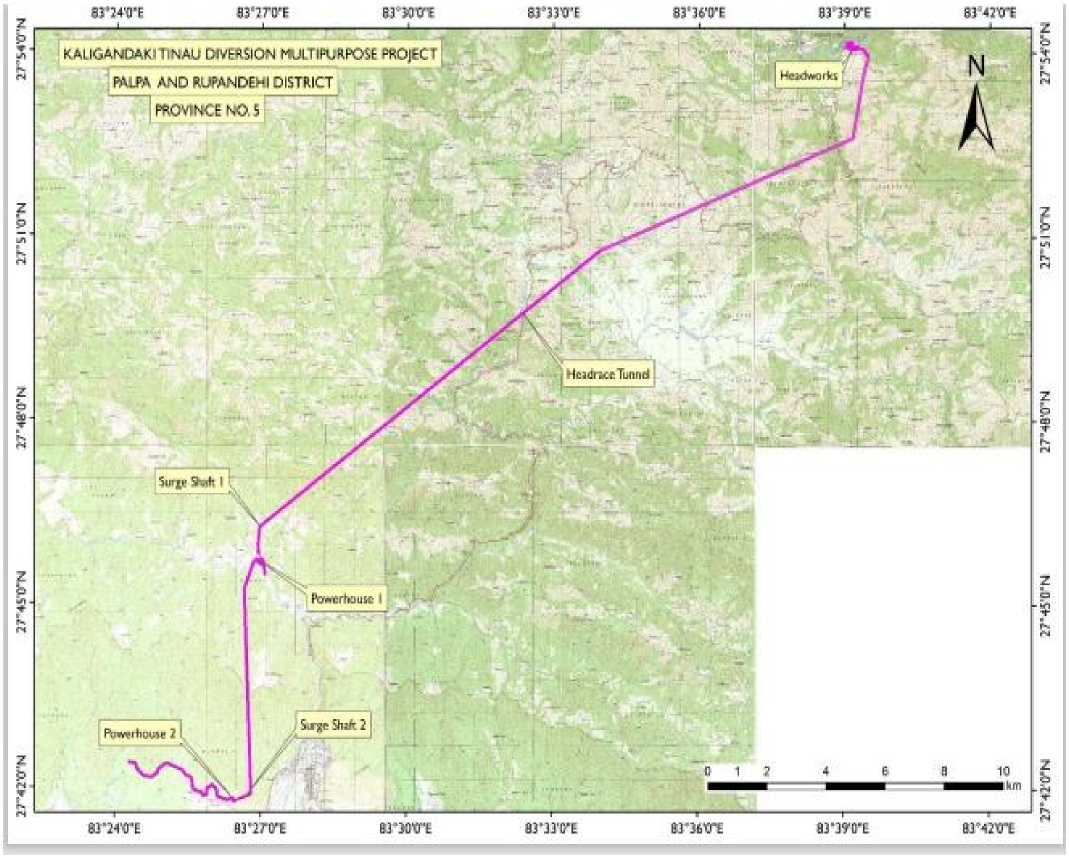


Figure 3.2: Layout of Kaligandaki Tinau Diversion Multipurpose Project

Source: https://dwri.gov.np/files/report/20210709080705.pdf

The Kaligandaki-Tinau Diversion Multipurpose Project is a runoff river type project comprised of two major components:

A) Development of Irrigation and

(B) Development of Hydropower

A short description of each component is briefed here under.

Component-A: Development of Irrigation

The component A of this project is focused on the development of the year-round irrigation facility for Rupandehi and Kapilvastu Districts. The proposed command area includes five existing irrigation systems (Banganga, Char Tapaha, Sorah Chattis Kulo, Marchawar, and Nepal Gandak) with a combined area of more than 62,000 ha which would benefit from the development (DWRI, Irrigation Master Plan, 2019). The command area is divided into Eastern and Western Command areas taking Tinau River as a reference. The main food crops of both command areas are paddy, maize, and wheat for the cropping pattern. The main cash crops are potatoes and vegetables due to higher return of yield and less water requirement respectively.

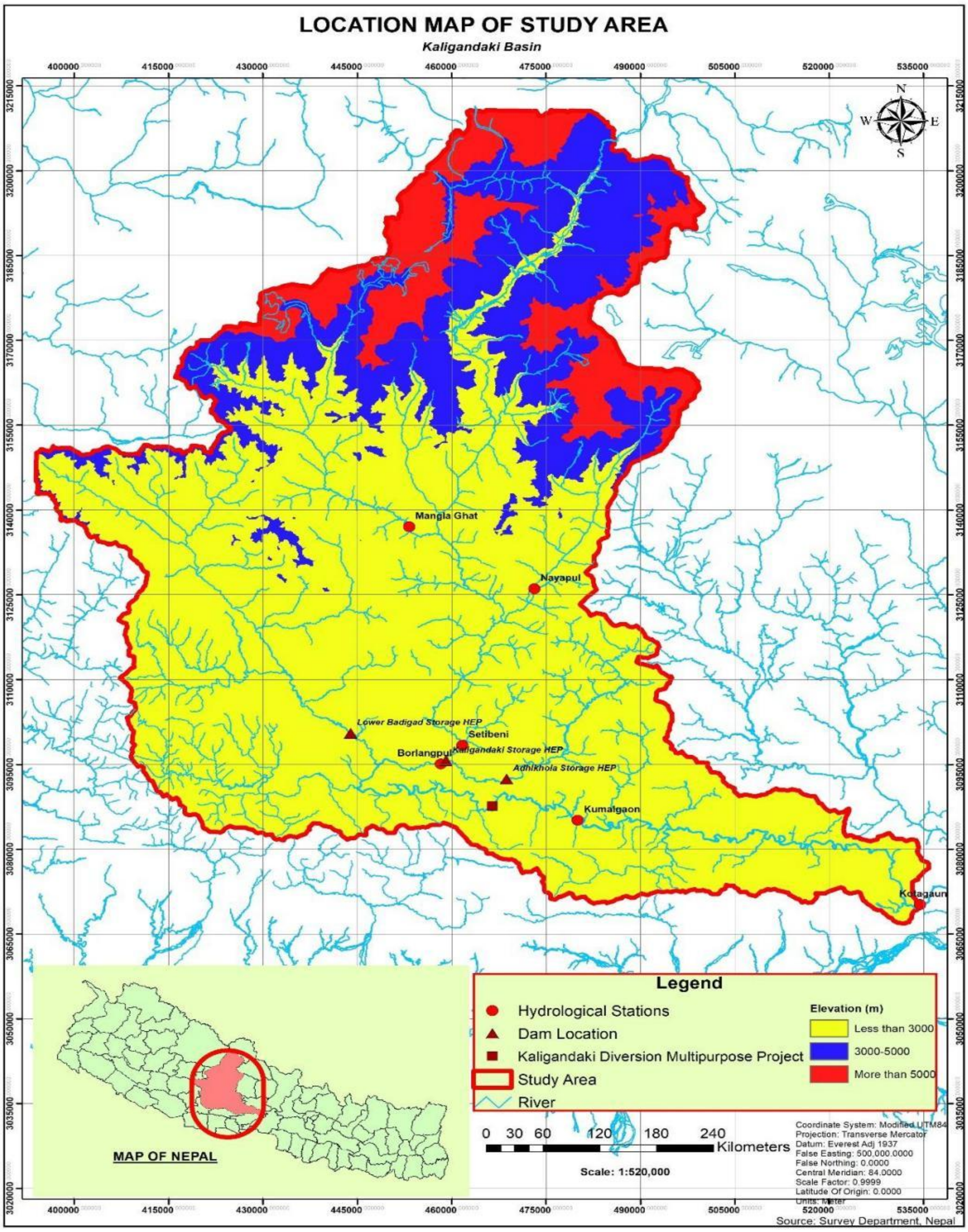
Table 3.1: Irrigation Component of KTDMP

S.N	Features	Eastern Command Area	Western Command Area	Remarks
1	Location	Eastern side of Tinau River and 3km offset area west of Tinau River	Lies 3km west of Tinau River	
2	District	Rupendehi	Rupendehi and Kapilvastu	
3	Net irrigable command area (ha)			Total
	Dry season	24,191	74,410	98,601
	Wet season	13,534	61,834	75,368
4	Supply of irrigation water	Water released from powerhouse I into Tinau River	Water released from tailrace of powerhouse II	

Source: (Sanstha, 2021)

Component-B: Development of Hydropower

The component B of this project is targeted to development of hydropower in route to irrigation project downstream with the storage of Kaligandaki River water at dam site in Palpa District. KTDMP considers two powerhouses. The first one is proposed at Dovan Gau, Dovan Khola, Ward No. 3 of Tinau Rural Municipality. The second powerhouse will operate as a cascade of the first powerhouse and is located at Belbas of Butwal Sub-metropolitan city ward No.13, Rupendehi district. According to the feasibility study, the installed capacity of the project is 104 MW and the available net head is 182m. (Limited H.-C. E., 2019).



Source: Survey Department, Nepal

Figure 3.3: Location map of the study area

There are different projects identified, planned, or being studied in the Kaligandaki basin. Kaligandaki Storage Project, Adhikhola Storage Project, and Lower Badigad Storage Project are the major storage projects in the upstream region of the KTDMP

(Sanstha, 2021). These planned storage projects are responsible for regulating the flow in the Kaligandaki Tinau Diversion Multipurpose Project. 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.

3.1.2 Climate

Broadly, the Kaligandaki basin can be divided into three climatic zones:

- A cold temperate zone up to 3000m;
- An alpine zone between 3000m and 4500m and
- A tundra zone above 4500m.

The study area experiences a tropical monsoon climate characterized by two distinct seasons: a wet season and a dry season. The wet season starts from June and ends in September while the dry season continues from October to May. The rainfall occurs mainly during the wet season, which is caused by the aerographic effect of the Himalayan topography. The average annual precipitation in the study region varies between 1,100 mm and 1,800 mm. The hottest months are May and June while the coldest months are December and January. The monthly temperature typically ranges from a maximum of 28 ºC to a minimum of 13 ºC. Relative humidity ranges from 41-82% (DWRI, 2011).

3.1.3 River Course in the Study Area

Kaligandaki is one of Nepal’s major rivers that run from north to south in the higher Himalayan region, flows eastwardly through the lesser (or lower) Himalayan region, enters the Terai plains of Nepal, and ultimately joins the Ganges River in India. In the upper reaches, Kaligandaki is called Muktinath Khola. It flows in the southwest direction till Kalapani in Mustang District when it takes a turn towards the southeast. It passes through deep gorges in this region and the deepest is 5,488 m between Dhaulagiri and Anapurna peaks. It again flows southwest till its confluence with Myagdi Khola in the Baglung district when it flows towards the southeast. It meets Modi Khola which lies in Kushma in the Parbat district and starts flowing due southwest. Near its confluence with Badigad and Ridi Khola around Ridibazar, it makes an O-bend and flows due east till Arauli in Tanahu district when it makes an S-bend and joins the Narayani River at Devghat in Chitwan. It is then called the Narayani River. The Narayani River flows towards the southwest from Devghat and turns to the south near Tamaspur in Nawalparasi district before it goes to India. It joins the Ganges in India and is known as the Gandak River in the Indian Territory (Ministry of Irrigation, 2011).

Kaligandaki Tinau Diversion Multipurpose Project intends to divert the surplus water from the Kaligandaki basin (surplus basin) to the Tinau basin (deficit basin). Banganga, Tinau and Rohini are the major rivers in Kapilvastu and Rupandehi districts. The proposed command area encompasses Banaganga River on the west, Tinau River in the middle, and Rohini River on the east.

3. 2 Data Collection

Data used in this study are obtained from secondary sources. Monthly hydrological time series data of the hydrological station lying in the study area are obtained from the Department of Hydrology and Meteorology (DHM). The physical and operational policy required for setting up a HEC-ResSim model was obtained from the Department of Electricity Development (DOED), Nepal Electricity Authority (NEA), and Water and Energy Commission Secretariat (WECS) projects' report.

3. 2. 1 Hydrologic Data

Simulation in ResSim was carried out using the monthly hydrological time series data recorded in the nearby Hydrological stations of the project sites. The location of the hydrological stations, their basin area, and the period of data availability of each of the stations are tabulated.

Table 3.2: Hydrological Station in the Study Area and Data Availability

St. No.	**Name of River**	**Location**	**Latitude (d/m/s)**	**Longitude (d/m/s)**	**Elevation (m)**	**Basin Area (km^2)**	**Data Availability**	
							From	**To**
406.5	Modikhola	Nayapul	28 15 15	83 43 27	701	601	1976	2015
410	Kali Gandaki	Setibeni	28 00 14	83 36 31	546	6630	1964	1995
415	Adhikhola	Andhimuhan	27 58 28	83 35 58	543	476	1964	1991
415.1	Adhikhola	Borlangpul	27 58 27	83 34 26	749	195	2000	2019
419.1	Kali Gandaki	Ansing	27 53 05	83 47 42	351	10020	1996	2019
404.7	Mayagdikhola	Mangla Ghat	28 21 10	83 31 16	914	1112	1976	2019

Data Quality Assessment of the station

- Infilling of missing data

In this study, simulation is carried out from 1996 to 2018 using monthly hydrological time series data obtained from the DHM. DHM data for some months were missing for each hydrological station. So, filling up the missing data is carried out using correlation analysis. Table 3.3 shows the duration of data available for each hydrological station and the number of missing monthly data are given.

Table 3.3: Months of Unmeasured Monthly Data

St. No	Location	Data Used		No. of months missing data
		From	To	
406.5	Nayapul	1976	2015	102
410	Setibeni	1964	1995	5
415	Andhimuhan	1964	1991	0
415.1	Borlangpul	2000	2019	5
419.1	Ansing	1996	2019	3
404.7	Mangla Ghat	1976	2019	74

Station 419.1 and station 415.1 are similar in hydrological conditions and when the correlation between them was carried out for the monthly hydrological time series data of 1996-2018, as shown in Figure 3.4, the correlation coefficient is up to 0.9188.

Therefore, according to the flow of the 415.1 station, the following equation is adopted to calculate the average monthly flow that is not measured in that station.

$$y = 0.0083x^{1.2336}$$

Where, y = the average monthly flow of station 415.1 (m^3/s)

x = the average monthly flow of station 419.1 (m^3/s)

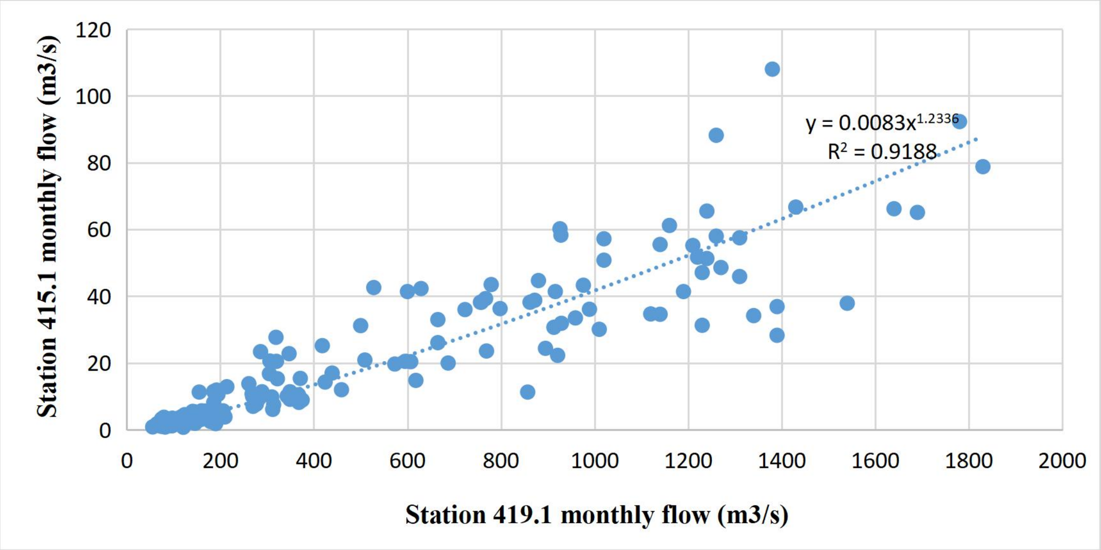


Figure 3.4: Relation between Average Monthly Flow of Station 419.1 and 415.1

For station 404.7, as shown in Figure 3.5, the following equation is adopted to calculate the average monthly flow that is not measured in that station.

$$y = 0.2082x^{0.9769}$$

Where, y = the average monthly flow of station 404.7 (m^3/s)

x = the average monthly flow of station 419.1 (m^3/s)

The correlation coefficient for station 419.1 and station 404.7 was measured to be 0.9003.

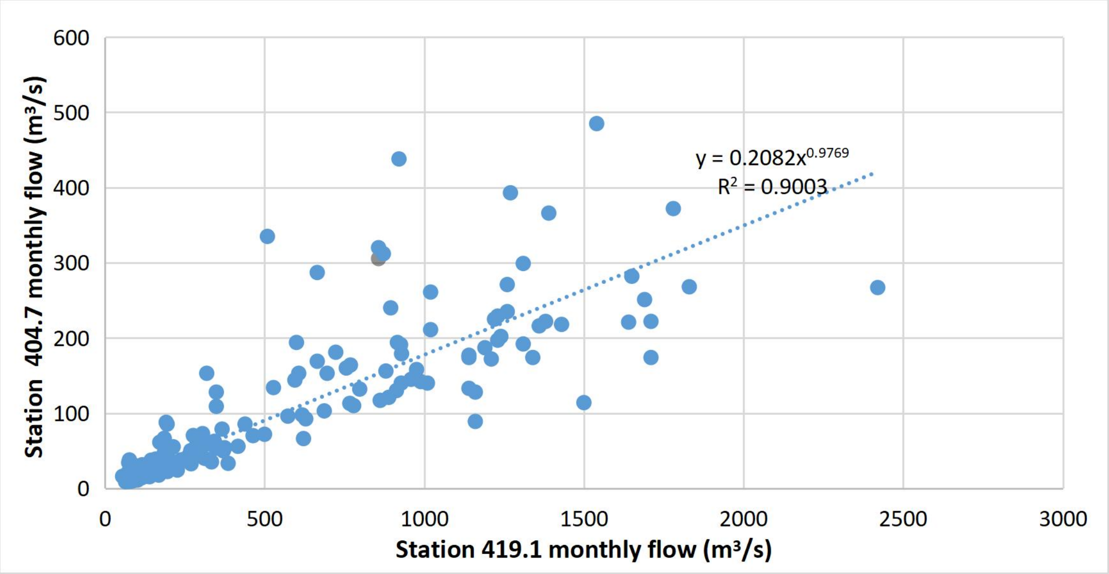


Figure 3.5: Relation of Average Monthly Flow of Station 419.1 and 404.7

The correlation coefficient of 0.9517 is obtained for station 419.1 and station 406.5. For station 406.5, as shown in Figure 3.6, the following equation is adopted to calculate the average monthly flow that is not measured in that station.

$$y = 0.1054x^{1.0292}$$

Where, y = the average monthly flow of station 406.5 (m^3/s)

x = the average monthly flow of station 419.1 (m^3/s)

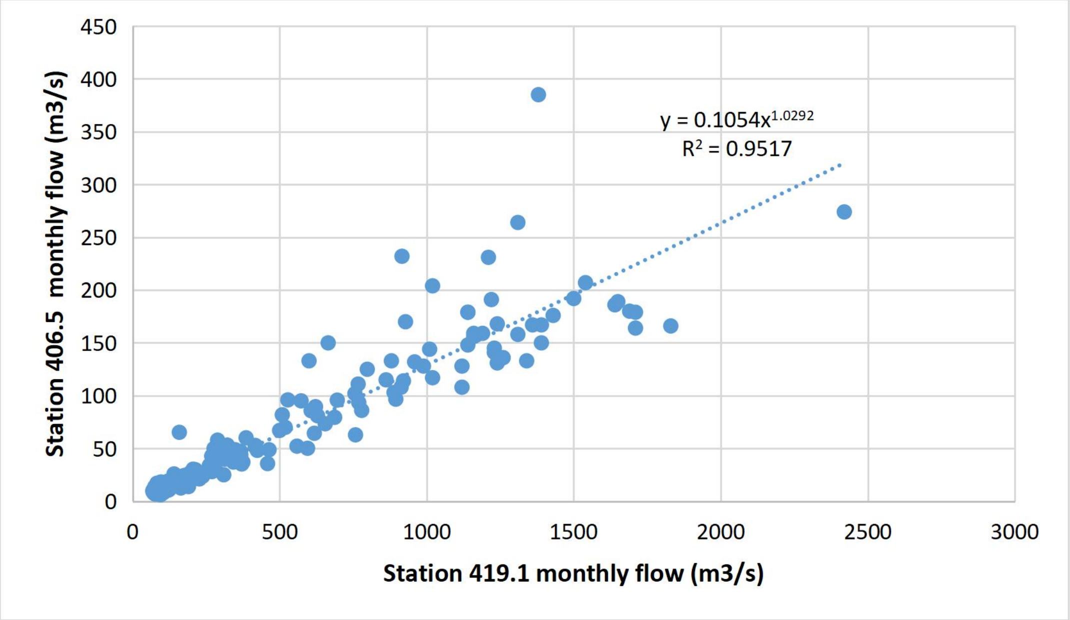


Figure 3.6: Relation of Average Monthly flow of Station 419.1 and 406.5

- Monthly observed graph of the Station from 1996 to 2018

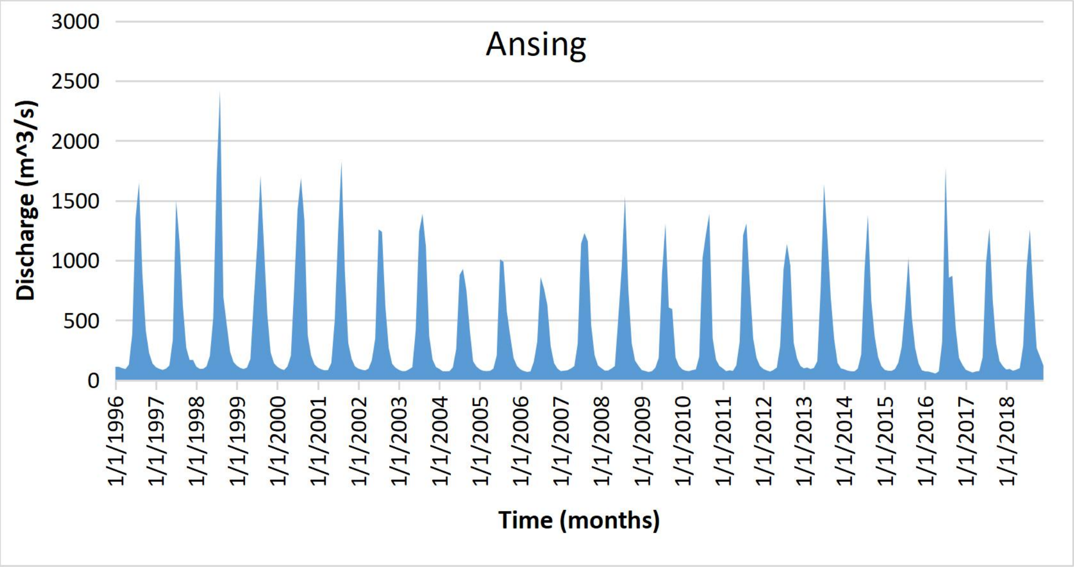


Figure 3.7: Monthly observed graph for Station 419.1

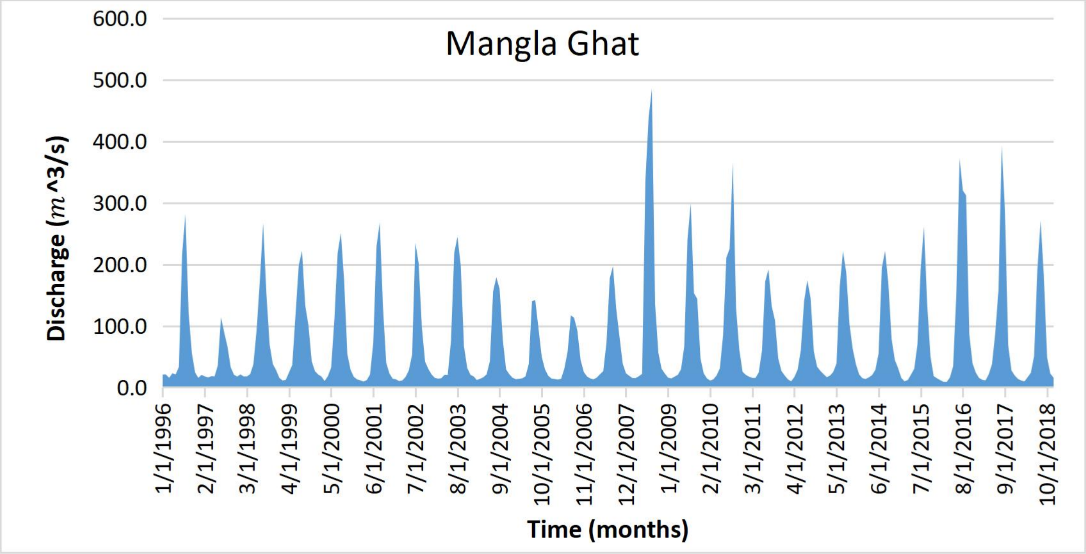


Figure 3.8: Monthly observed graph for Station 404.7

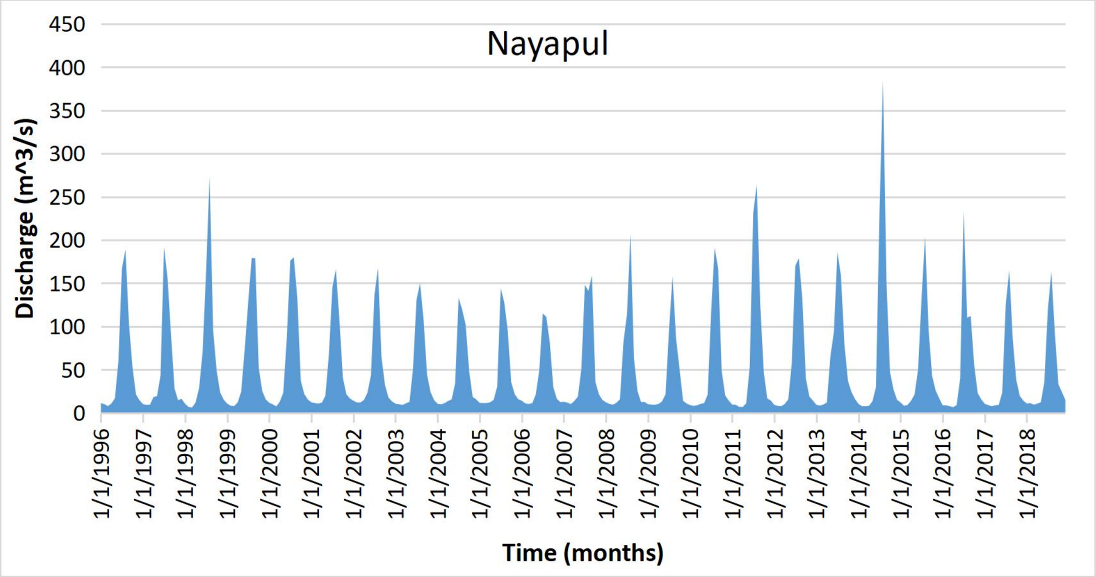


Figure 3.9: Monthly observed graph for Station 406.5

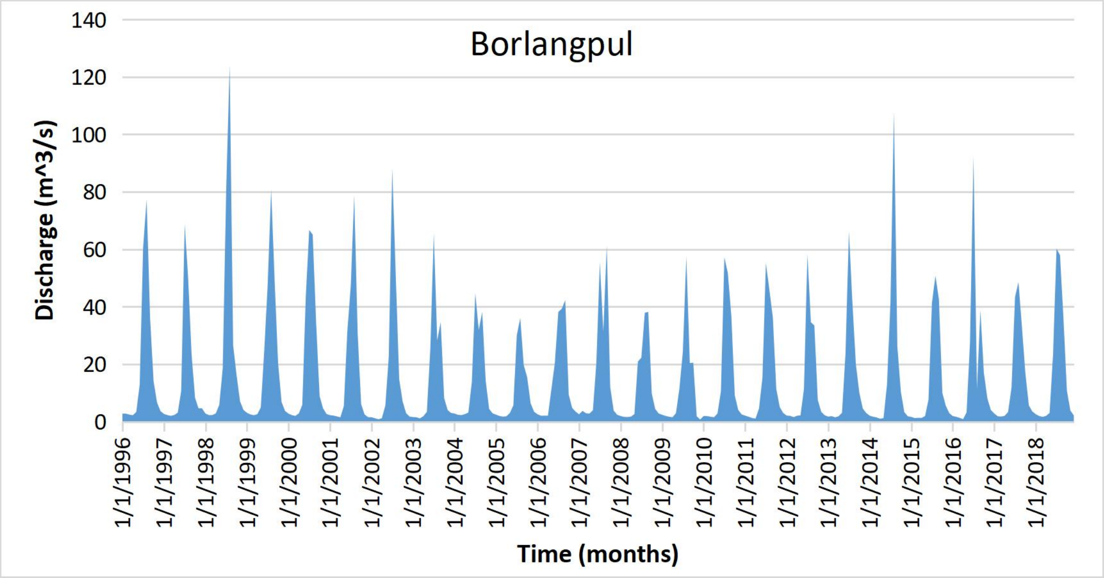


Figure 3.10: Monthly observed graph for Station 415.1

- Cumulative discharge graph of the Station

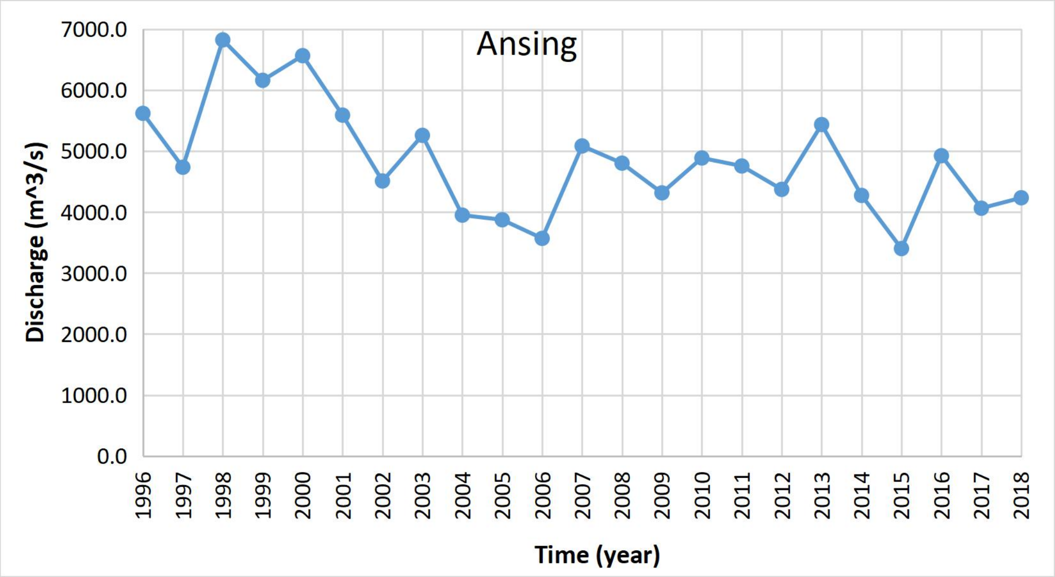


Figure 3.11: Cumulative discharge graph for Station 419.1

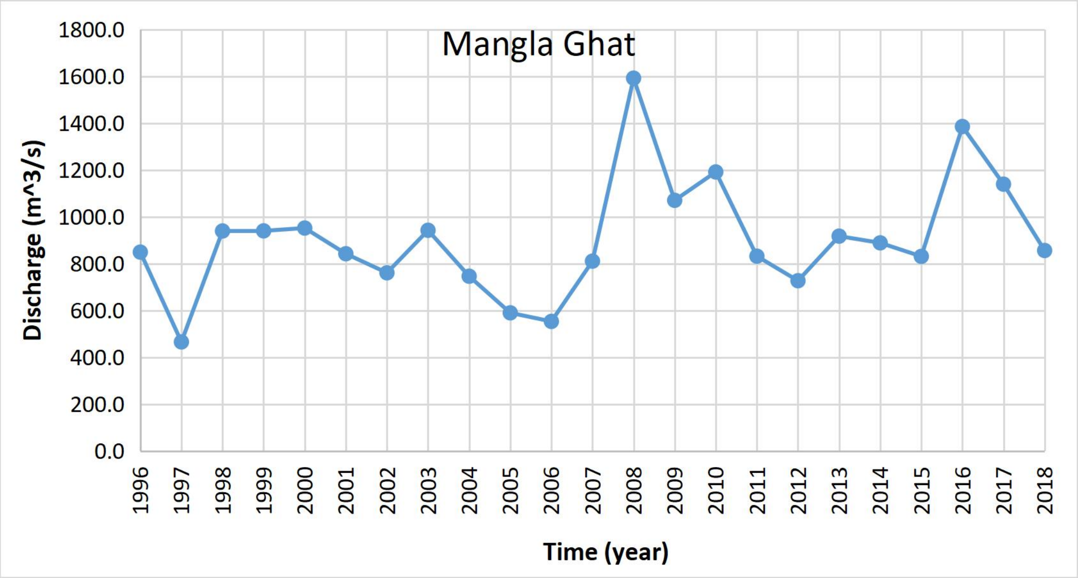


Figure 3.12: Cumulative discharge graph for Station 404.7

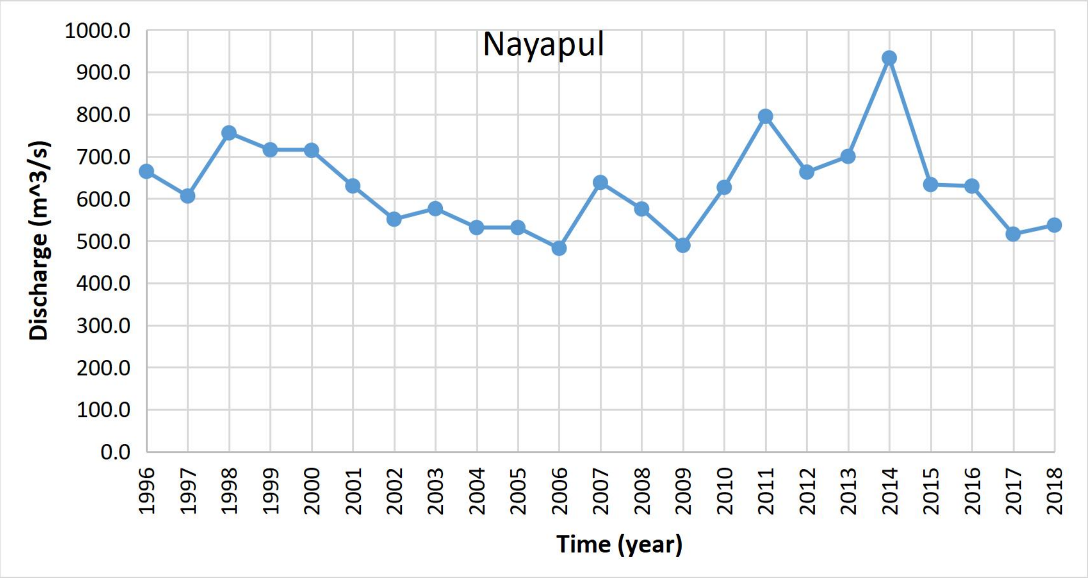


Figure 3.13: Cumulative discharge graph for Station 406.5

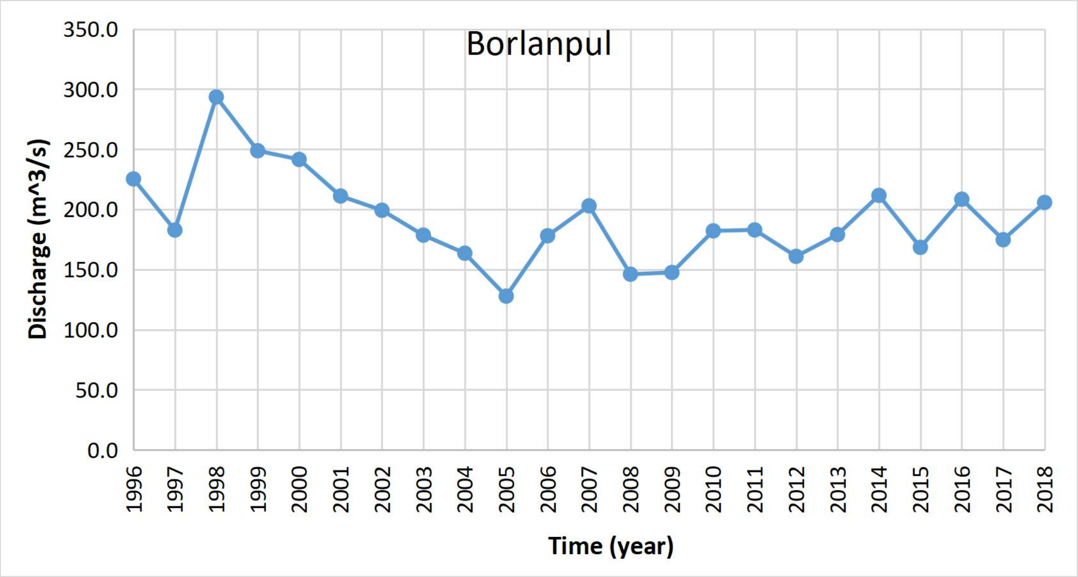


Figure 3.14: Cumulative discharge graph for Station 415.1

To get the precise result, the correlation of the station is done using the Catchment Area Ratio to enhance the model performance indexes.

The following equation is used to correlate the two stations.

$$Q_y = \left(\frac{A_y}{A_x}\right) Q_x$$

Where,

Qy = streamflow at an ungauged site;

Qx = streamflow at a gauged site;

Ay = drainage area of ungauged site;

Ax = drainage area of gauged site.

Similarly, in our study area, Kaligandaki River is a gauged catchment. So, the discharge in the intake area at Ramdi (diversion point) was derived using CAR with Kaligandaki Gauging station in Ansing.

The model was calibrated and validated with the recorded hydrological data of the stations. Analysis duration is selected yearly because the number of data for analysis might fall short for another period of analysis and this might not set a good relationship between the model and observed data. Also, the yearly analysis of the data has shown an acceptable range of model performance indexes.

The CAR relationship has been established between different hydrological stations as shown in Table 3.4. All the indexes, i.e. RMSE, NSE, and R2 in both calibration and validation are within the acceptable range which shows that there exists a strong correlation between the data of these stations.

Table 3.4: CAR Relationship Developed between Different Hydrological Station

S.N	**Analysis Duration**	**Relationship**	**Model Performance Evaluation (Calibration)**			**Model Performance Evaluation (Validation)**		
			RMSE	NSE	R2	RMSE	NSE	R2
1	Yearly	Ansing and Manglaghat	64.35	0.53	0.86	27.95	0.74	0.999
2	Yearly	Ansing and Nayapul	48.44	0.42	0.93	39.95	0.498	0.999
3	Yearly	Ansing and Borlangpul	15.16	0.44	0.92	18..68	0.51	0.996

A plot of calibration for the Borlangpul station is shown in Figure 3.15. The graph shows a good relationship between the observed and simulated data.

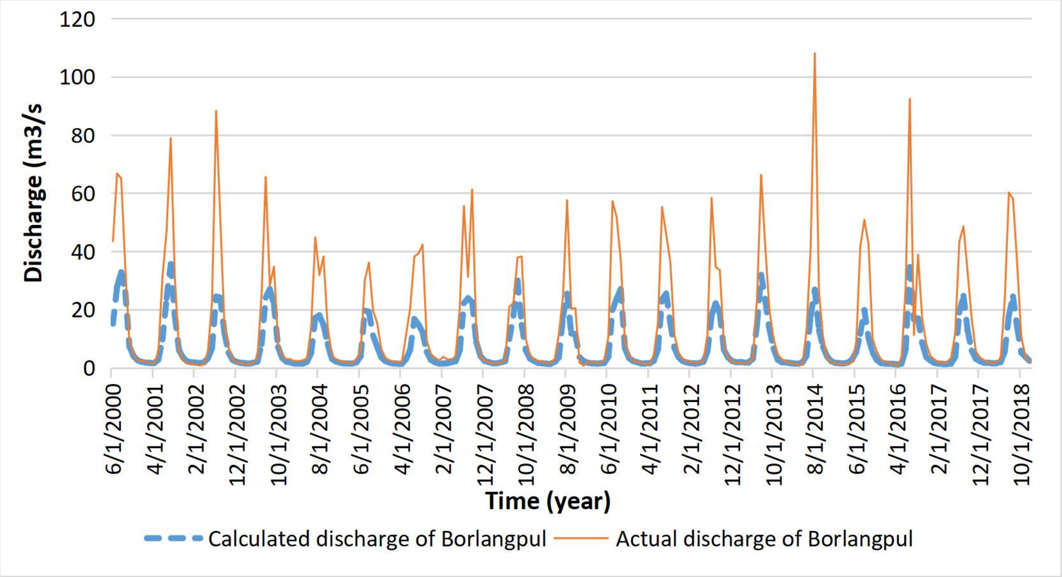


Figure 3.15: Simple CAR calibration graph in Borlangpul Station

Similarly, the validation graph of Borlangpul station is shown in Figure 3.16. The model tends to underestimate the flow during the wet season, however, the model has predicted the close values during the dry period.

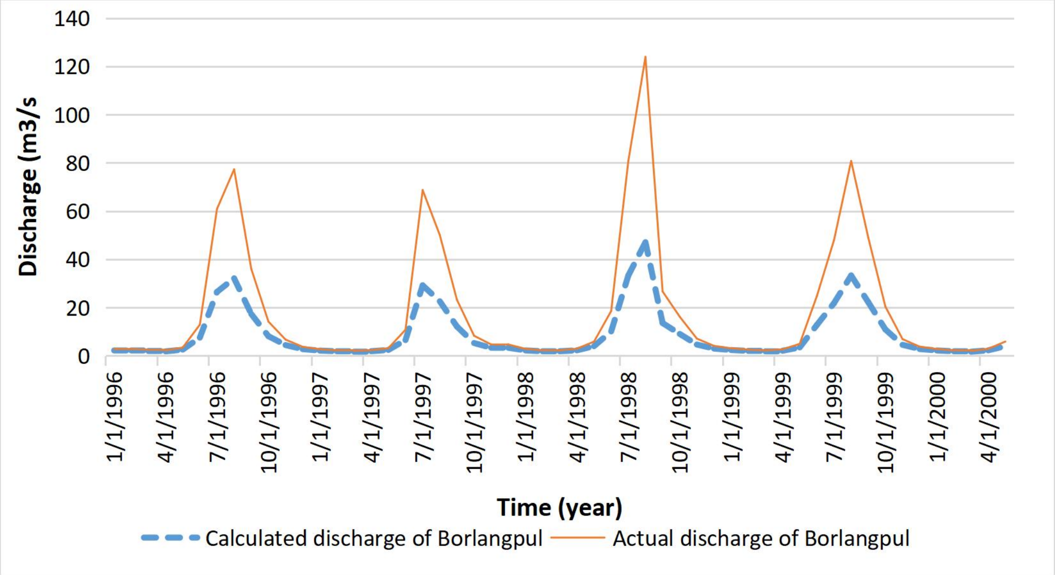


Figure 3.16: Simple CAR validation graph in Borlangpul Station

In a similar manner, a calibration and validation graph for the Nayapul station is shown in Figure 3.17 and Figure 3.18 respectively.

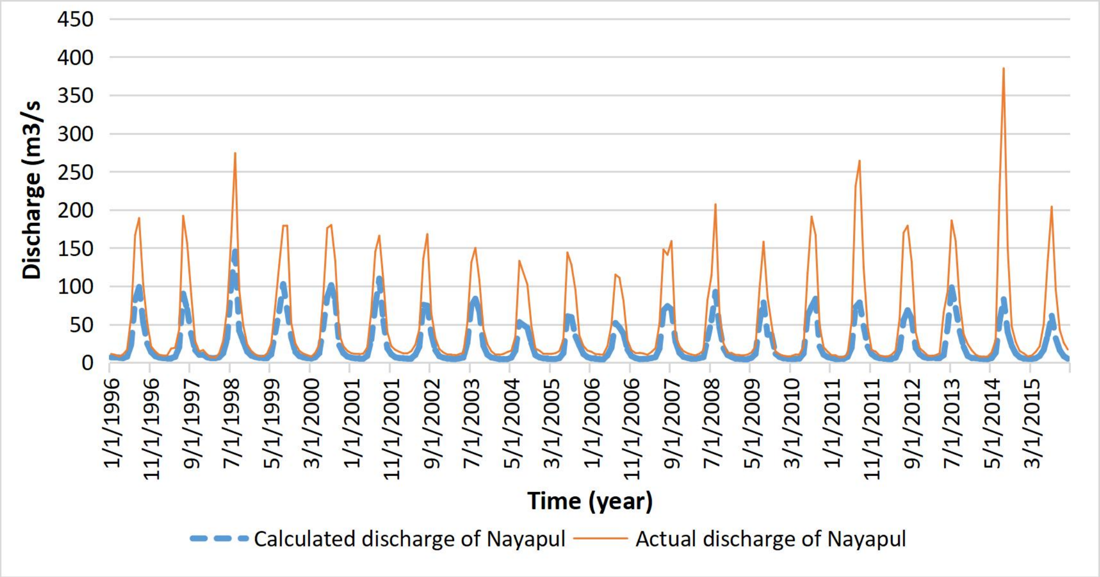


Figure 3.17: Simple CAR calibration graph in Nayapul Station

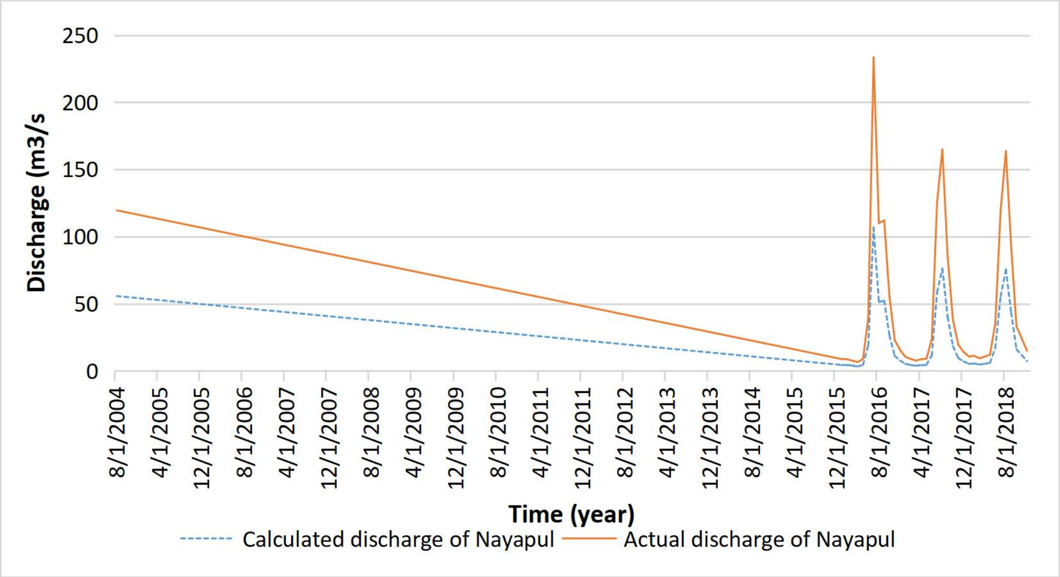


Figure 3.18: Simple CAR validation graph in Nayapul station

Similarly, the calibration and validation graph for Manglaghat station are shown in Figure 3.19 and Figure 3.20 respectively.

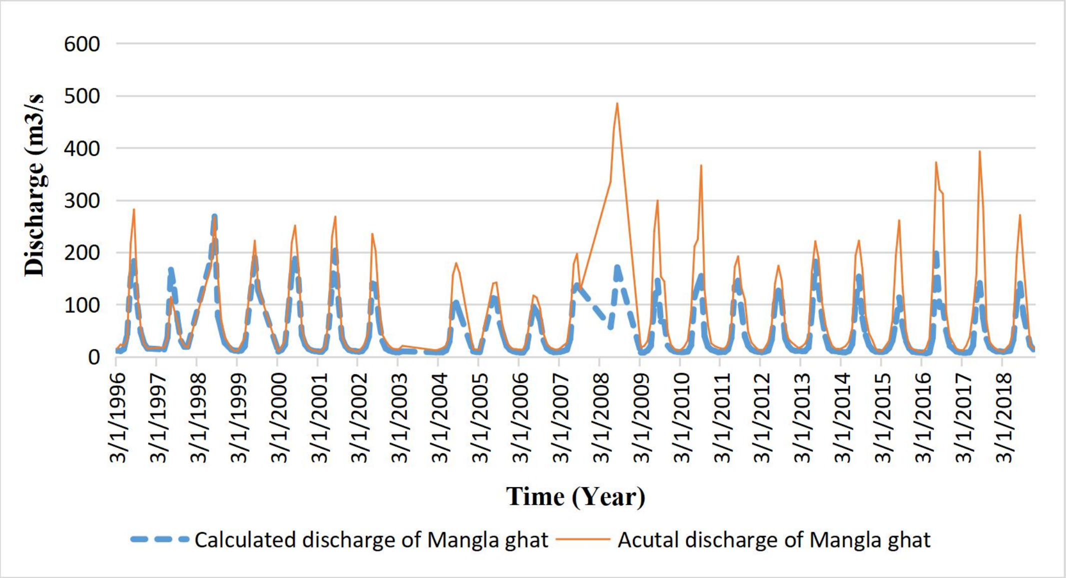


Figure 3.19: Simple CAR calibration graph in Manglaghat station

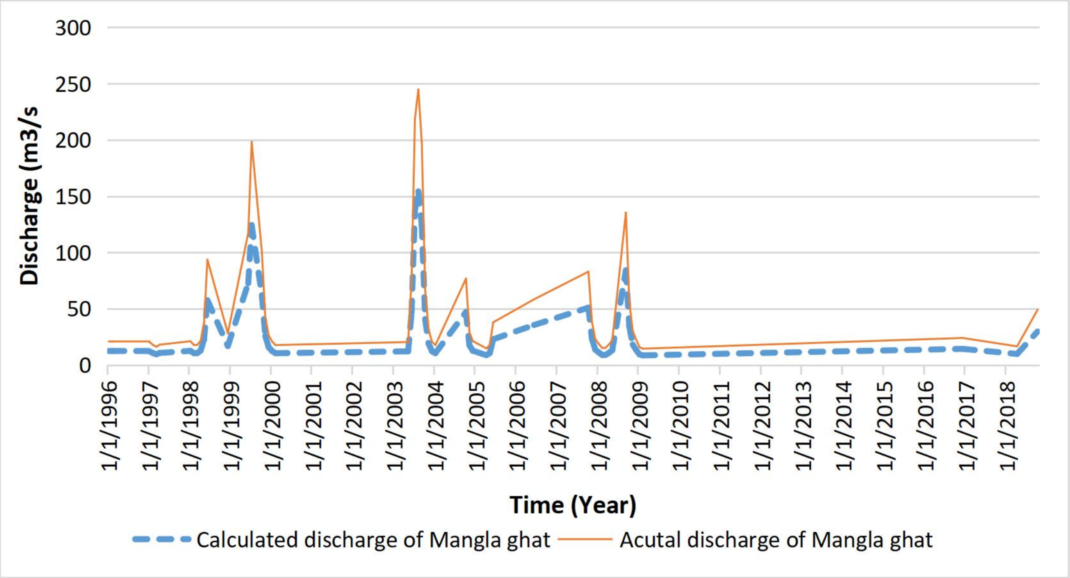


Figure 3.20: Simple CAR validation graph in Manglaghat station

3. 2. 2 Reservoir System Data

HEC-ResSim demands reservoirs' different zone data, H-A-V data, dam data, etc. Along with these physical data, it requires other operational rules and their priority, constraints, etc. to simulate for flood control, hydropower generation, or to regulate release to different other sectors.

Some of the data that were used to calibrate the ResSim model to simulate hydropower energy production are described in the following section.

Physical Data

HEC-ResSim demands an extensive amount of reservoir and dam physical data to properly calibrate the simulation model. The accuracy of energy generation predicted by the model is directly linked to the precision of the physical input data assigned to the model. The source of the physical data used in this study is from the recent project reports prepared by the Government of Nepal's authentic offices, the Nepal Electricity Authority (NEA), and the Department of Electricity Development (DOED) on respective projects. Physical data of the reservoir used in the ResSim model is given in Table 3.5.

Table 3.5: Physical Data of the Project Components

S.N	Dam Features	Kaligandaki storage project	Lower Badigad storage project	Adhikhola storage project
1	Location	Parbat and Baglung	Gulmi	Syangja
2	Installed Capacity (MW)	844	380.3	180
3	Minimum Water Level (m.a.s.l)	720	654	623
4	Full Supply Level (m.a.s.l)	750	688	700
5	Tail Water Level (m.a.s.l)	533	475	371.4
6	Design Discharge (m3/s)	479.88	232.6	73
7	Catchment Area (km2)	6706	2050	475
8	Gross Storage Capacity (MCM)	2043	995.9	401.1
9	Net Storage Capacity (MCM)	552.7	505.5	341.42
10	Dead Storage (MCM)	410.11	64.15	60
11	Height of Dam (m)	220	191	167
12	Type of Dam (m)	Concrete Gravity Dam	Concrete Face Rockfill Dam	Concrete Face Rockfill Dam

Source: https://jvs-nwp.org.np/wp-content/uploads/2022/01/kaligandaki-tinau_final-report.pdf

The Height-Area-Volume (HAV) data used for the three reservoir projects i.e. Kaligandaki reservoir, Adhikhola reservoir, and Lower Badigad reservoir are shown in the figure below.

i. Kaligandaki storage project

A rockfill dam of height 220 m is proposed for the Kaligandaki reservoir. The reservoir has a gross capacity of 2043 MCM and a live storage capacity of 552.7 MCM. The net operating head is taken as 206.15 m.

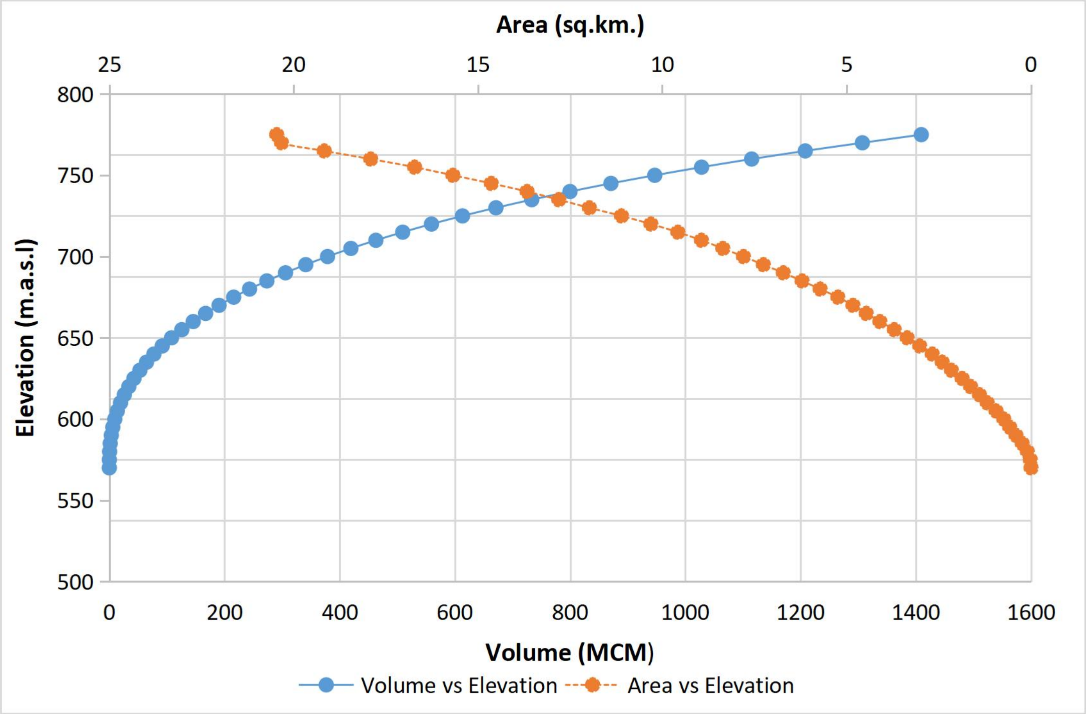


Figure 3.21: Reservoir H-A-V curve of Kaligandaki Reservoir

ii. Adhikhola storage project

A concrete face rockfill dam of height 167 m is proposed for the Adhikhola reservoir. The reservoir has a gross capacity of 401.0 MCM and a live storage capacity of 341.42 MCM.

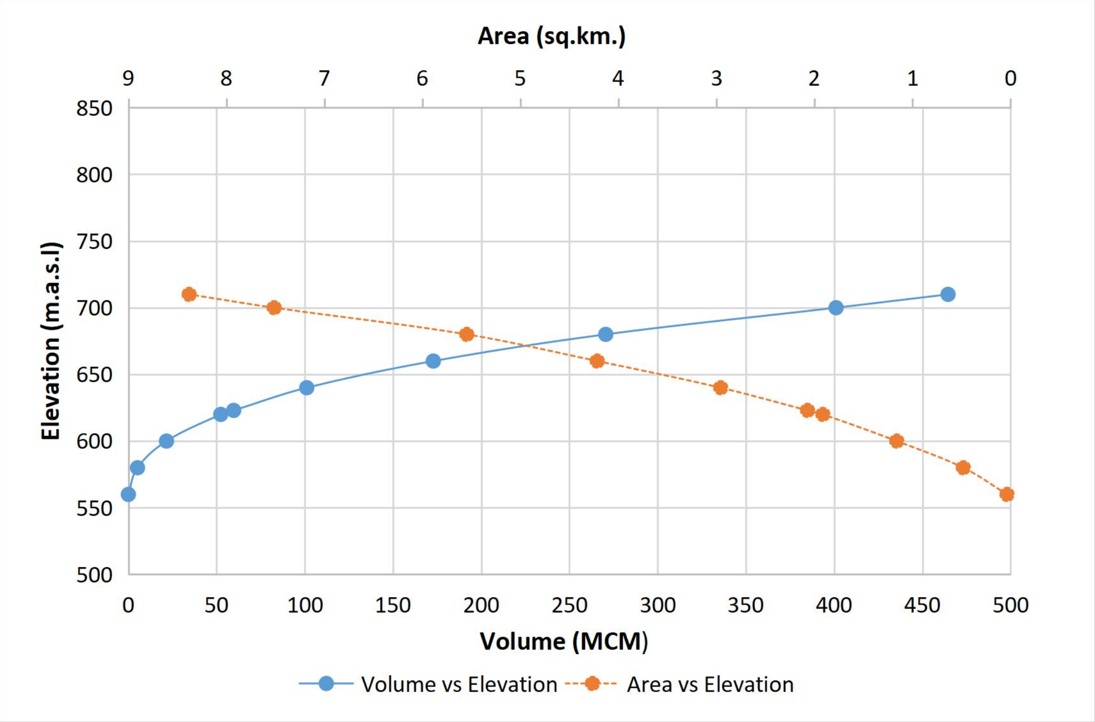


Figure 3.22: Reservoir H-A-V curve of Adhikhola Reservoir

iii. Lower Badigad storage project

A rockfill dam of height 191m is proposed for the Lower Badigad reservoir. The reservoir has a gross capacity of 995.9 MCM and a live storage capacity of 505.5 MCM. The net operating head is taken as 192.5 m.

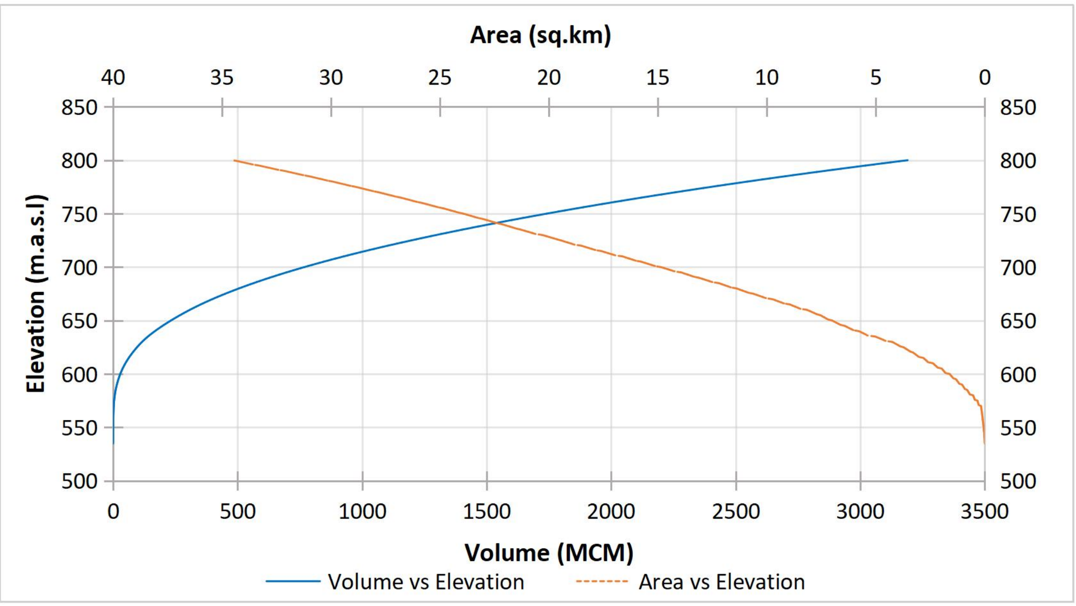


Figure 3.23: Reservoir H-A-V curve of Lower Badigad Reservoir

CHAPTER FOUR: METHODOLOGY

4.1 Methodology Framework

The study primarily focuses on integrating the planned reservoirs and inter-basin transfer projects to assess the interrelationship of one project with another. The hydrological time series from 1996-2018 is obtained from the DHM and missing values are filled up using regressions analysis of similar hydrological stations. A simple CAR hydrological method is applied for these hydrological stations to better correlate the time series data improving the model performance parameters. Then, the HEC-ResSim model is set up and the simulation is carried out for each trial case of each scenario. The result of each simulation is further analyzed to find the total annual average energy, average dry energy, and dry energy's contribution to annual energy expressed in percentage. Now, using the above results, reservoir performance indicators i.e. reliability, resiliency, and vulnerability for the result of each trial of simulation, are calculated. At last, the selection of the best reservoir operation rule curve will be done based on energy and performance indicator criteria.

A sequential flow of work that was carried out to get into the predefined objectives is shown in the schematic diagram Figure 4.1. The methodological flowchart can be studied under the five sub-topics of Data collection and preparation, HEC-ResSim Model Setup, Simulation of different Scenarios, Reservoir Performance Evaluation, and Result data interpretation. Calibration of the HEC-ResSim model will be carried out using the processed hydrological data, physical and operational data of dams and reservoirs, alternative generations, etc. Then, the scenarios for the simulations will be defined in such a way that will help in achieving the objectives of this study.

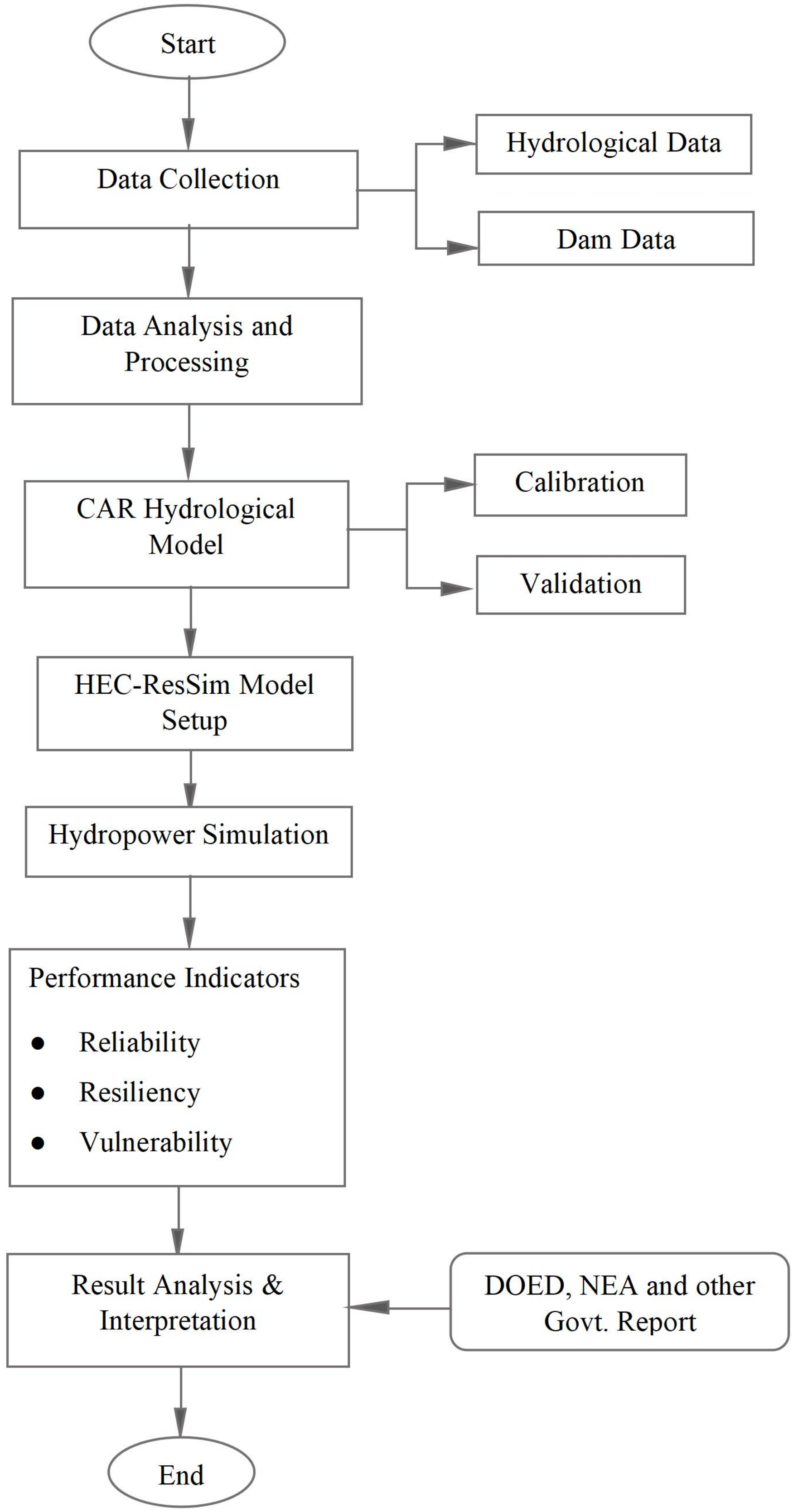


Figure 4.1: Methodological Flowchart of Study

4.2 Set up HEC-ResSim Model

HEC-ResSim software has been used to simulate hydropower production and inter-basin transfer in the Kaligandaki basin under two scenarios. Three basic sections of HEC-ResSim i.e. watershed setup module, reservoir network module, and simulation module are used to achieve the optimum result. The basic modeling features available in each module are depicted in Figure 4.2.

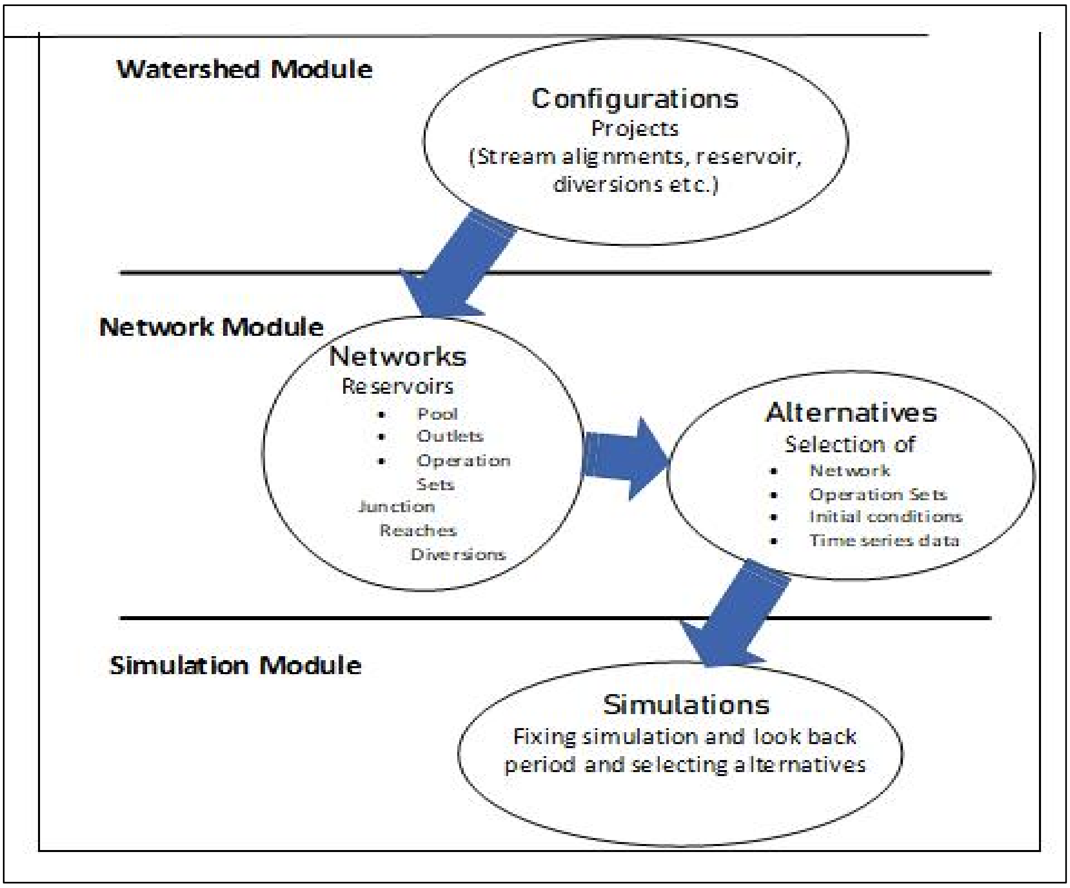


Figure 4.2: Modelling Feature Available in HEC-ResSim

4.2.1 Watershed Setup Module

To accomplish the primary goal of the study, integration of all the scheduled reservoir projects and the inter-basin transfer project will be done while setting up a ResSim model. All three reservoir projects and an inter-basin transfer project were modeled in a single model and are interlinked by the river reaches (Stream), junctions, and diversions.

4.2.2 Reservoir Network Module

In this module, all available reservoir systems and basic diversions were introduced and connected via routing reach elements, utilizing configurations defined in the watershed setup module as a template. We proceeded by analyzing the reservoir systems' physical and operational data, utilizing the reservoir system data. The final step before concluding this module is to establish options that define the reservoir network, operating arrangements, initial conditions, and DSS pathname assignments (mapping time-series data).

Data Storage System (HEC-DSS)

This is a tool in ResSim that is primarily used to store and retrieve time series data. The inflows to each reservoir, as well as any other time-series data defined during the setup of alternatives or scenarios, come from this database.

i. Scenario Setting (Defining alternatives)

This research 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 which is listed below:

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

b) Scenario 2: Two planned storage projects were operated at the same time mainly to obtain maximum energy generation from the system and KTDMP was operated to divert a constant design flow of $82m^3/s$.

A brief discussion of these two scenarios is described below:

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

Figure 4.3 represents the HEC-ResSim setup for Scenario 1. In Scenario 1, the model contains three reservoir projects i.e. Kaligandaki Reservoir, Adhikhola Reservoir, and Lower Badigad Reservoir. The inflow of Mayagdi Khola and Modi Khola is accumulated in Junction 19 which reaches to CP30 assessing the inflow of Kaligandaki reservoir. Similarly, the inflow of Adhikhola accesses the discharge of the Adhikhola reservoir. The inflow of the Lower Badigad reservoir is determined using CAR considering Ansing as the gauged site. The discharge from Kaligandaki, Adhikhola, and Lower Badigad reservoirs are accumulated on Junction 13 which reaches to Junction 14 fulfilling the Kaligandaki Diversion requirement.

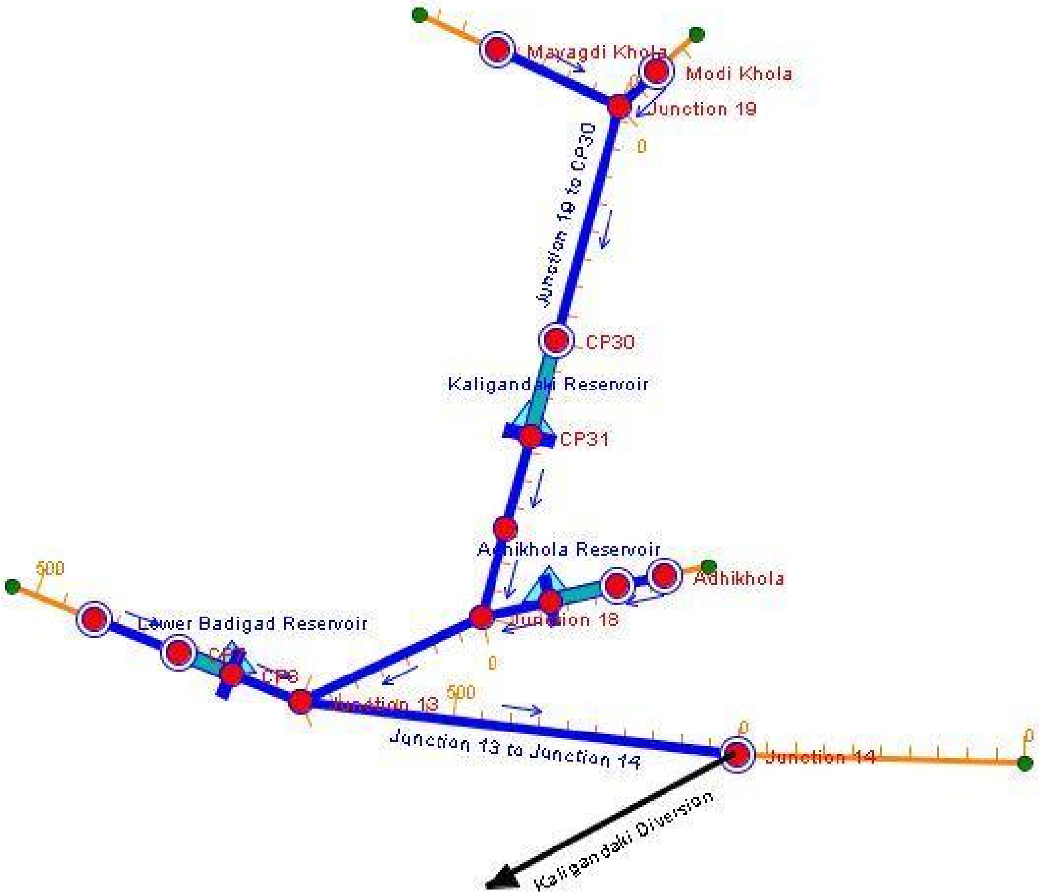


Figure 4.3: HEC-ResSim model set up for Scenario 1

Each reservoir was simulated for the four different trials. From each trial, the obtained time series energy output data was used to calculate the total annual energy generation, dry energy generation, dry energy percent, and firm power capacity. Now, these calculated energies were further analyzed to find the Performance Indicators of the reservoir for dry period firm power.

Therefore, scenario 1 will run the simulation for

=3(reservoirs) × 4(number of trials for each reservoir) + Kaligandaki Diversion

=13 trials

For all 13 trials total energy, dry period energy, dry energy percent, firm power capacity, and PI of reservoir reliability, vulnerability, and resiliency was computed.

b) Scenario 2: Two planned storage projects were operated at the same time mainly to obtain maximum energy generation from the system and KTDMP was operated to divert the constant design flow of 82 m^3/s.

Case 1: Both Kaligandaki Reservoir and Adhikhola Reservoir will run at an instant

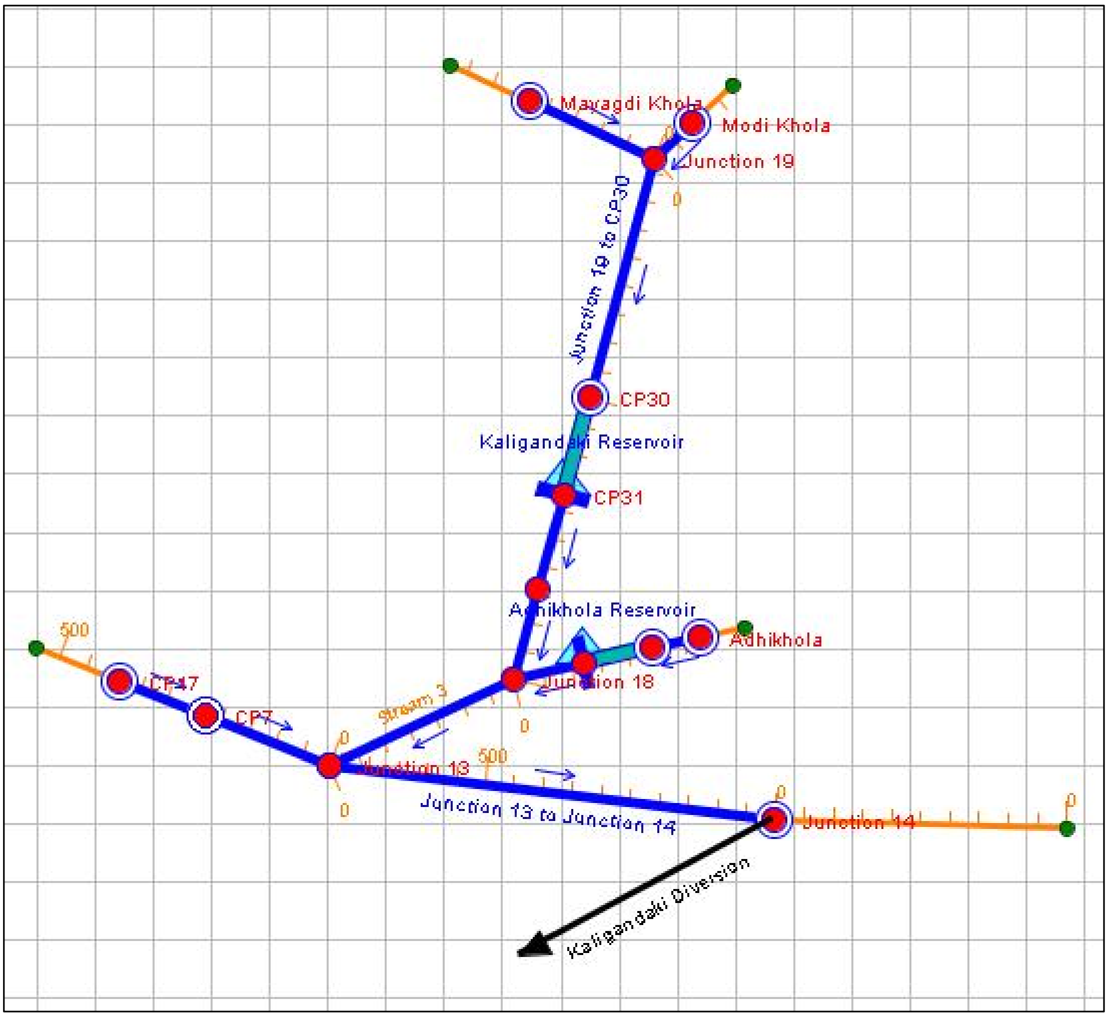


Figure 4.4: HEC-ResSim model set up for Case 1

Case 2: Both Kaligandaki Reservoir and Lower Badigad Reservoir will run at an instant

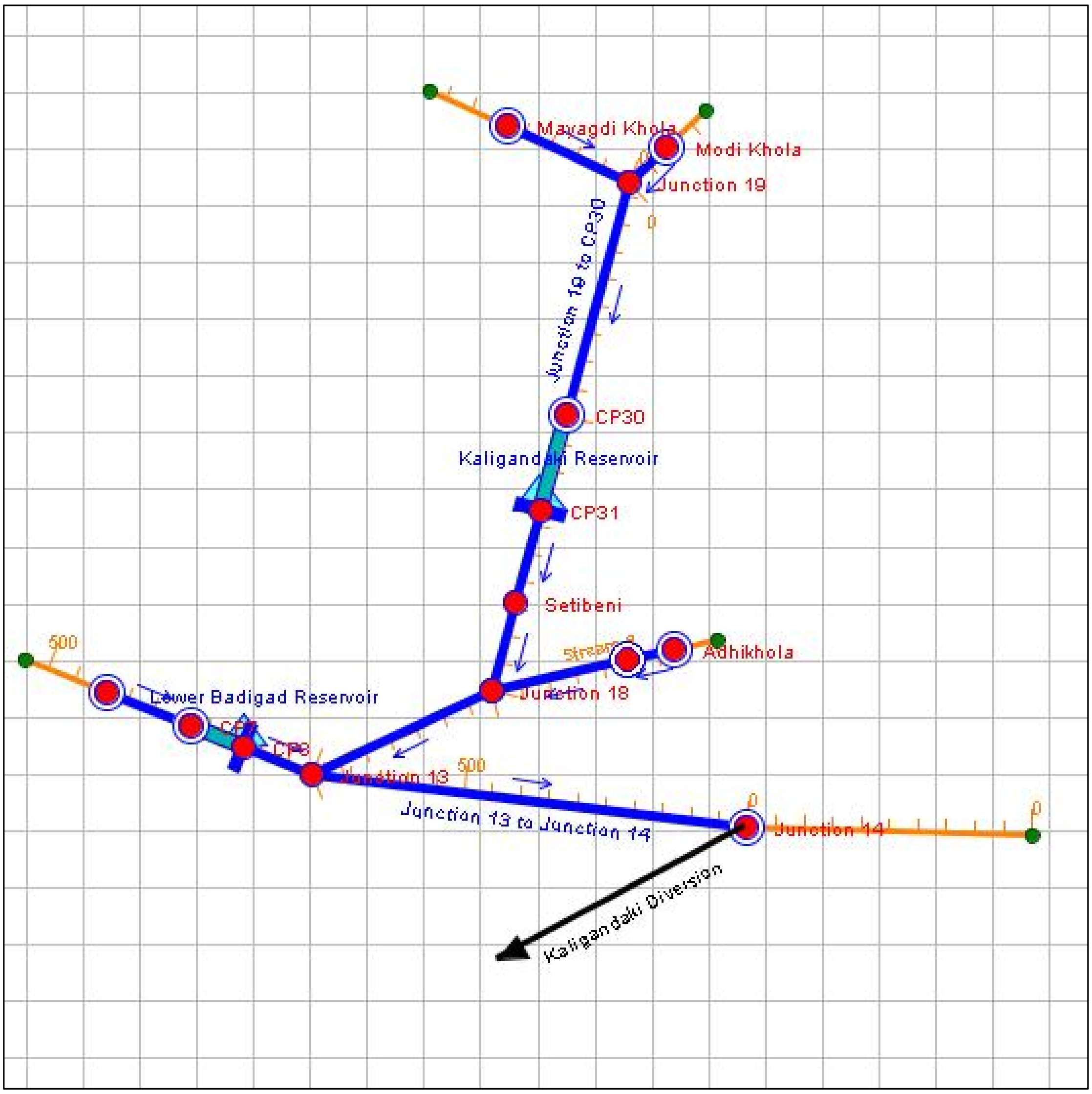


Figure 4.5: HEC-ResSim model set up for Case 2

Case 3: Both Adhikhola Reservoir and Lower Badigad Reservoir will run at an instant

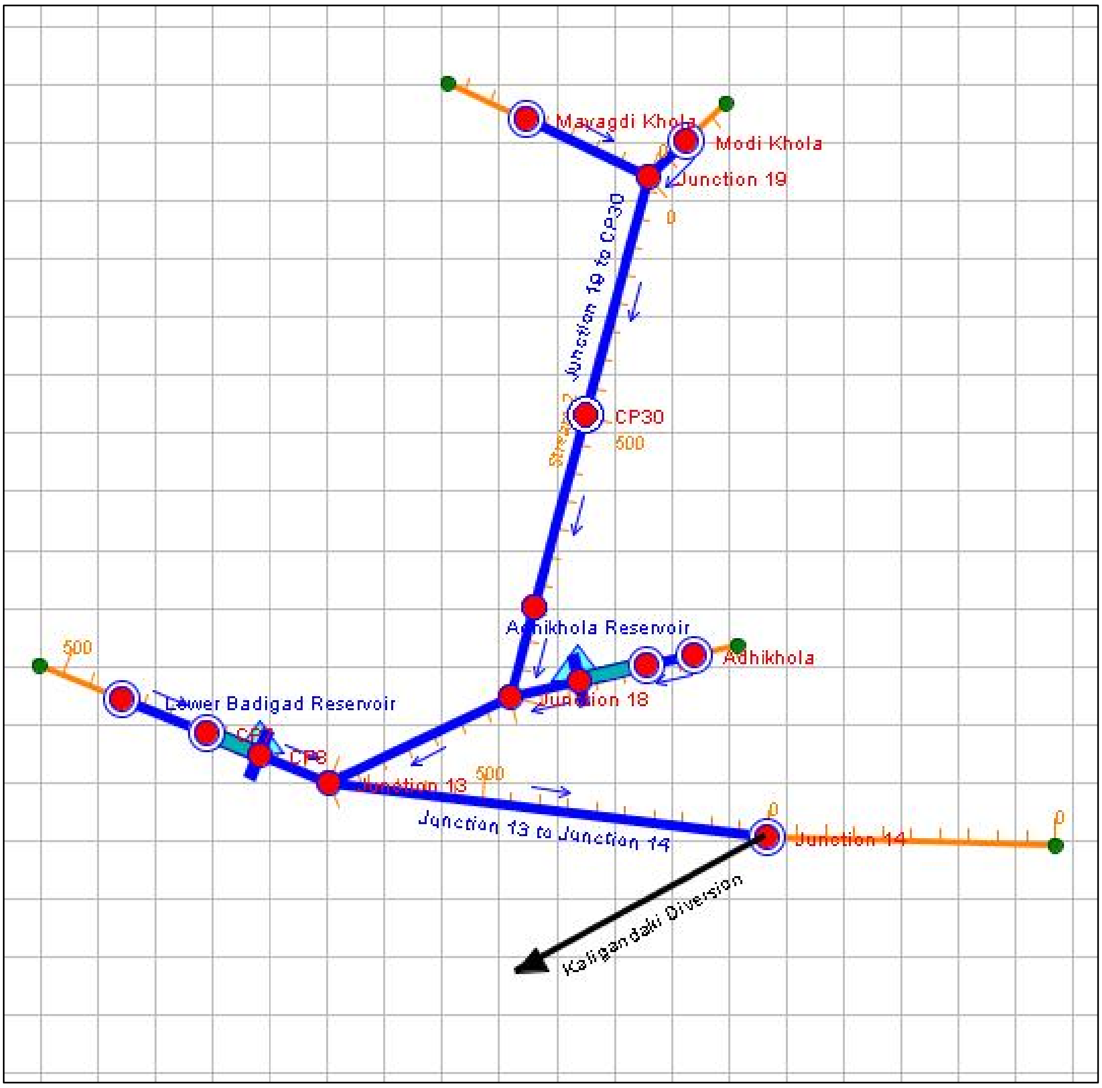


Figure 4.6: HEC ResSim model set up for Case 3

Therefore, Scenario 2 conducted altogether 27 trials, and each trial has the information of total energy, dry period energy, dry energy percent, firm power capacity, and PI of reservoirs reliability, resilience, and vulnerability.

Therefore, the total number of simulations from both scenarios

= 13 + 27

= 40 simulations have been carried out in this study.

4.2.3 Simulation Module

Once the reservoir model was completed and the alternatives were defined, the simulation module was used to configure the simulation. The simulation was carried out for 23 years (1996-2018) of monthly flow time series of hydrological data. Here the simulation and lookback time window was specified; alternatives and computational intervals were selected. In this study, the lookback or initial condition for all reservoirs has been defined at the spillway level, so that a shorter lookback time is needed. Calculations are executed, and outcomes are observed within the simulation module.

4.3 Reservoir Operation Policy

Taking the head effect into account changes the reservoir operating policies which in turn impact not only the production of energy but also the availability of water in the system (Goor, 2010).

I. Reservoir Operational Rule

All the trial rule curves used in this study follow these two fundamental reservoir operational rules:

i. Fulfill the required water demand for hydropower as long as the reservoir level is above the Minimum Normal Water Level;

ii. Excess inflows (when inflows are larger than the required water for hydropower) are stored in the reservoir till the water level reaches the Maximum Normal Water Level, and then are discharged through turbines and then spillways.

II. Reservoir Operation Logic

The reservoir operation logic is defined in accordance to the season which is described as:

- **Dry season:** The river inflows are smaller than the water demand for hydropower. The water demand for hydropower is satisfied by reservoir storage provided that the reservoir level is above the Minimum Normal Water Level. As a consequence, the reservoir level decreases continuously. The water demand for hydropower increases and thus the hydropower release increases continuously during this period. This is to compensate for the decrease of the reservoir level and thus the decrease of the head. To generate the same power, the volume of water to be passed through the turbines has to be increased.

- **Wet Season, beginning of the monsoon:** At the beginning of the wet season, the reservoir is empty. The turbine discharge is smaller than the inflowing discharge therefore, the reservoir level is increasing. The Maximum Normal Water Level is reached between the end of July and the beginning of August.
- **Wet Season:** The river inflows are larger than the water demand for hydropower. The water demand for hydropower is 100% satisfied by the inflows. The excess water is released downstream by the spillway.
- **Wet Season, end of the monsoon:** The river inflows are decreasing therefore the turbine discharge is decreased in order to maintain the reservoir at the Maximum Normal Water Level at the end of the wet season. This operational rule allows obtaining the maximum energy production during the dry season.

An illustration of a reservoir operation rule curve is presented in Figure 4.7, which follows all the rules described above. The top graph shows the reservoir pool elevation with respect to the simulation time. Operation rule curve, as indicated by the green line in the graph, elevation fluctuates only in between the reservoir Full Supply Level (F.S.L) and Minimum Water Level (M.W.L). The next graph is the plot between the flow and the simulation time. The black line indicates the inflow curve while the green line indicates the outflow from the reservoir.

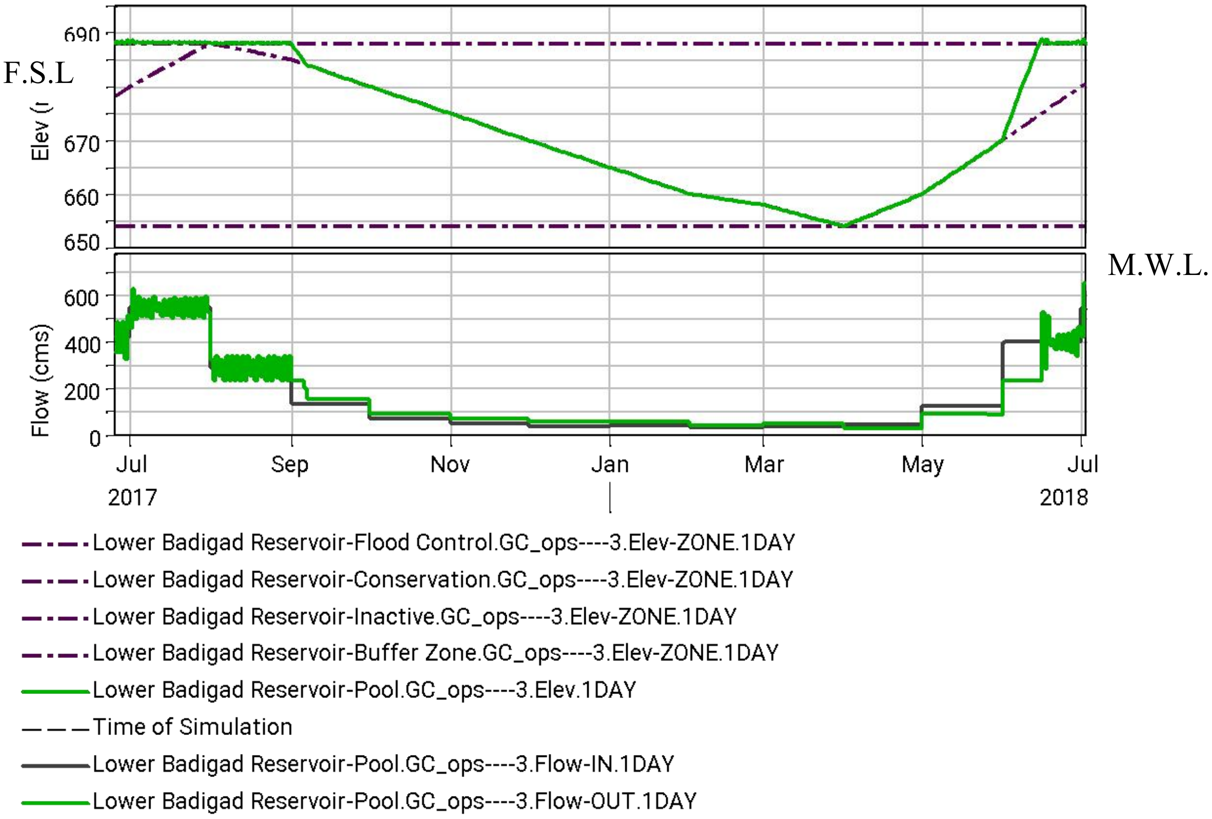


Figure 4.7: A Sample Reservoir Operation Rule of Lower Badigad Reservoir

The criteria adopted for the optimization of the selected Operation Policy are the maximization of average annual and average dry season energy production, the maximization of the Firm Power in the dry season and the maximization of Reservoir Performance Indicators.

4.4 Reservoir Performance Evaluation

The reservoirs' performances have been evaluated using the three performance indicators criteria viz. Reliability, Vulnerability, and Resilience as defined by Loucks and Beek (2017). Performance indicator parameters, in addition to energy criteria, are crucial factors for determining the most suitable reservoir operation rule from among the trial rule curves. Therefore, these indicators are calculated for each simulation output in both scenarios.

CHAPTER FIVE: RESULTS AND DISCUSSION

5.1 General

The main objective of the study was to integrate the planned reservoir and inter-basin transfer project in a single model to achieve the maximum benefit from the system. Projects are interlinked while modeling and simulations are carried out in an integrated system.

The HEC-ResSim model has been taken using hydrological time series data for 1996-2018. Buffer level elevation has been changed for each trial of reservoir operation policy in each reservoir. The buffer level is set as the guide curve for the ResSim, which guides the reservoir to attain the predefined pool elevation of buffer level in each time step by regulating the release. Environment release is given the highest priority followed by irrigation, hydropower release, and spillway. These rules can be seen in the following graphs and tables in this section.

The detailed analysis of every reservoir project and inter-basin transfer project is discussed hereafter. The result from the best trial operation policies is only described in the subsequent topic and the energy generation capacity.

5.2 Individual Project Energy Production

i. Kaligandaki Storage Project

Four different trial operating rule policies, as shown in Figure 5.1, were used to find the most suitable reservoir operation rule curve that provides the maximum average annual energy and dry energy with the best reservoir performance criteria. The reservoir operating policy of Trail 4 generated the maximum average annual energy and dry energy with satisfactory performance criteria. Therefore, the Trial 4 operating policy is selected to set as a reservoir operation rule curve for the Kaligandaki project.

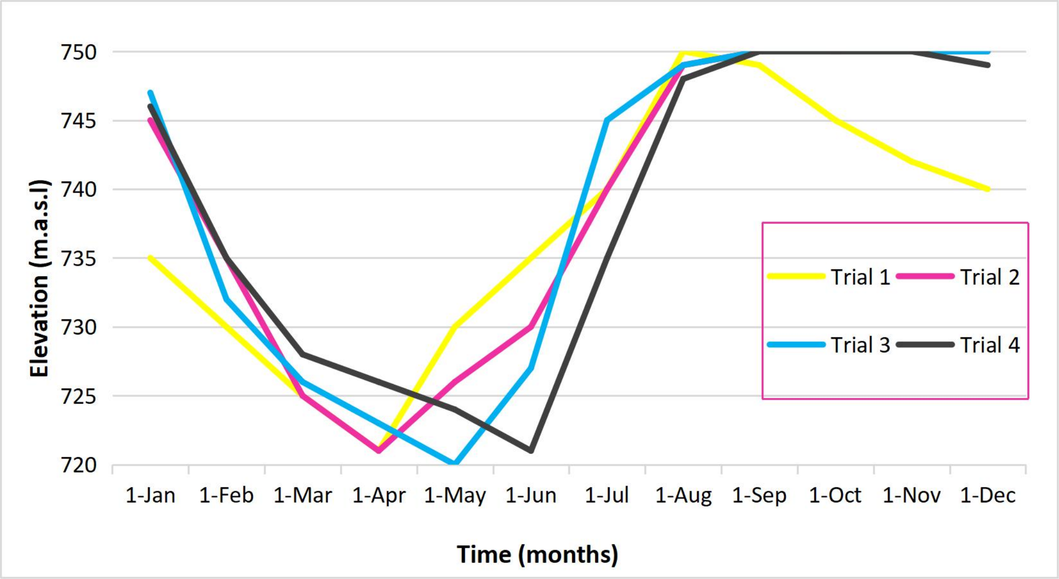


Figure 5.1: Alternative Operation Rule Curves Used for Kaligandaki Reservoir

While operating the Kaligandaki hydropower with reservoir operation policy as per Trail 4, the model simulated the inflow-outflow graph as shown in Figure 5.2.

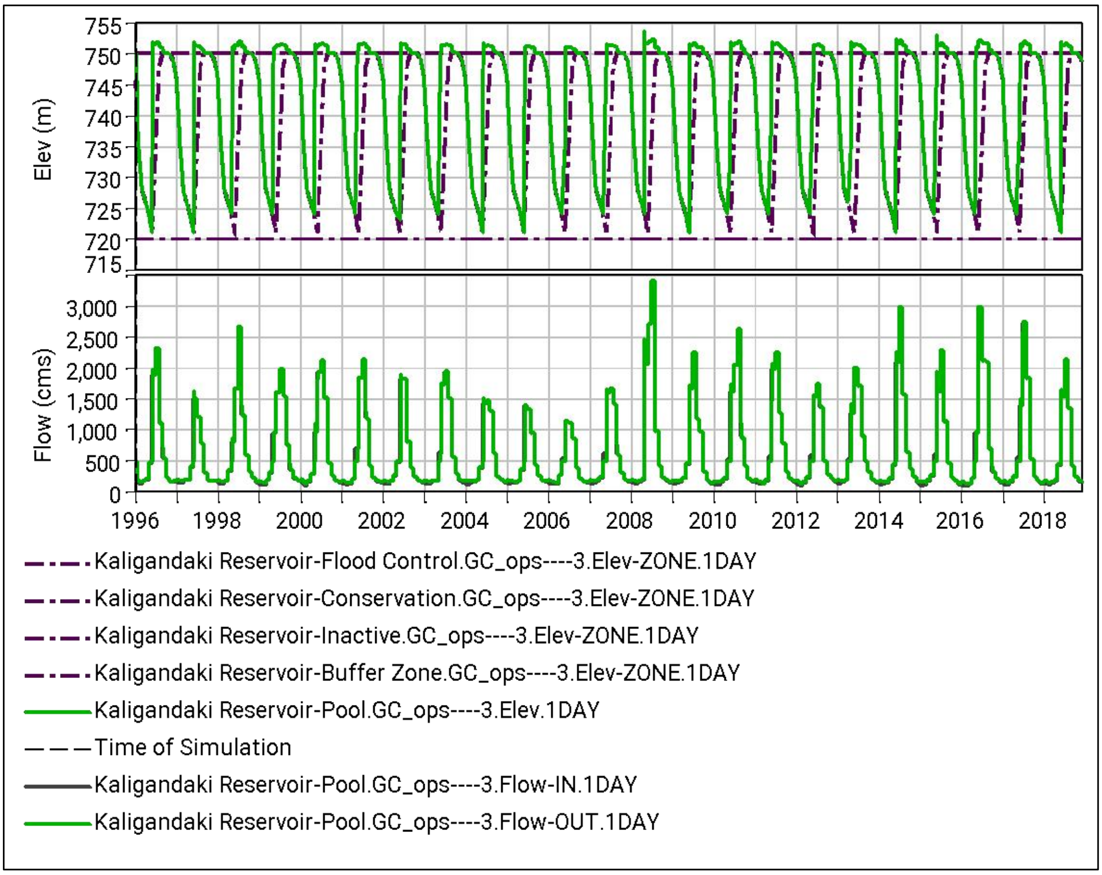


Figure 5.2: Inflow-Outflow Curve of Kaligandaki Project

Similarly, trail 4 reservoir operating policy generated the annual average energy of 4825.586 GWh and dry energy of 1731.067 GWh which is illustrated in Figure 5.3 and Figure 5.4 respectively.

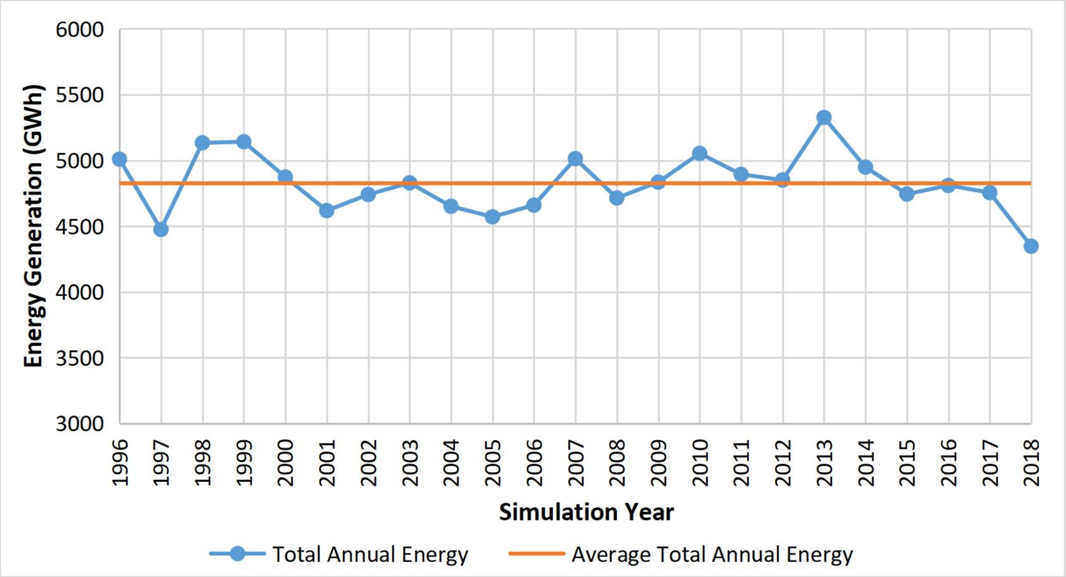


Figure 5.3: Energy generation trend over simulation years in Kaligandaki storage project

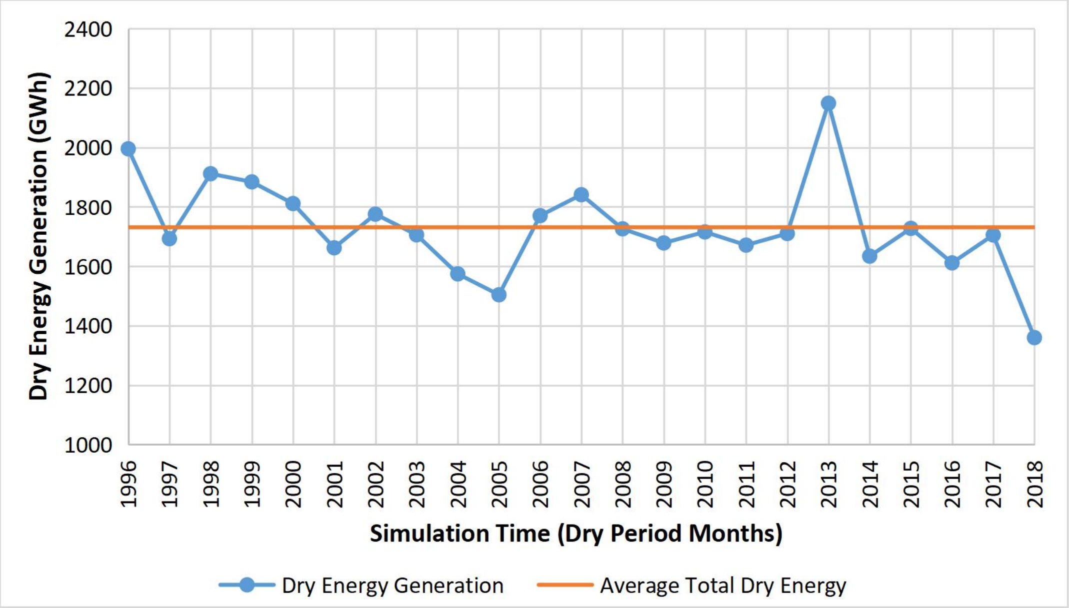


Figure 5.4: Dry Period Energy Generation of Kaligandaki Reservoir

The Performance Indicator (PI) criteria analyzed in this study is only for the dry period firm power. Trial 4 operating policy has the capacity of generating 220MW of firm power during dry period with 95.51 % dry period firm power reliability. The reservoir has a very low vulnerability of 3.7% and a low resiliency of 2.9%. The dry period firm power of Kaligandaki reservoir as per trial 4 operating rule policy is shown in Figure 5.5.

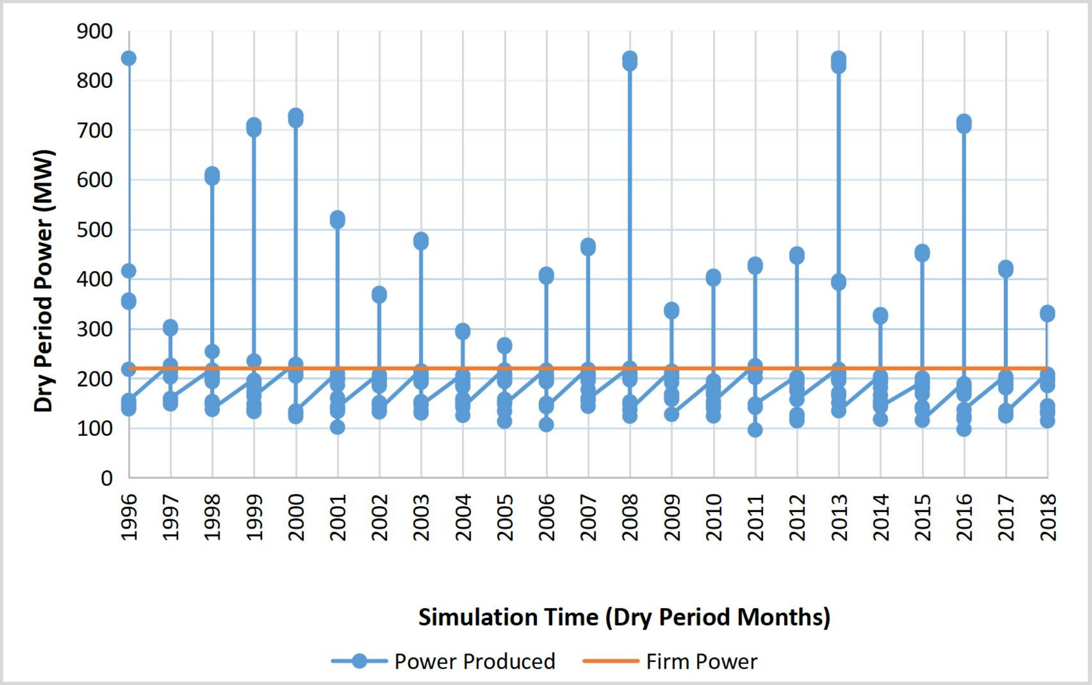


Figure 5.5: Dry Period Firm Power of Kaligandaki Reservoir

In both scenarios, Trial 4 obtains the optimum result in terms of energy and performance indicators. As trial 4 OP generates the maximum annual and dry energy with the best performance indicators, trial 4 OP is selected as a reservoir operation rule for Kaligandaki reservoir in both scenarios.

ii. Adhikhola Storage Project

In the same manner, four different trial reservoir operating policies were used in the Adhikhola reservoir as shown in Figure 5.6. In the case of Adhikhola reservoir, the reservoir operating policy of trial 4 is selected to set the reservoir operation rule policy because it produces the maximum average annual energy and dry energy. While operating the Adhikhola reservoir with reservoir operation policy as per Trail 4, the model simulated the inflow-outflow graph as shown in Figure 5.7.

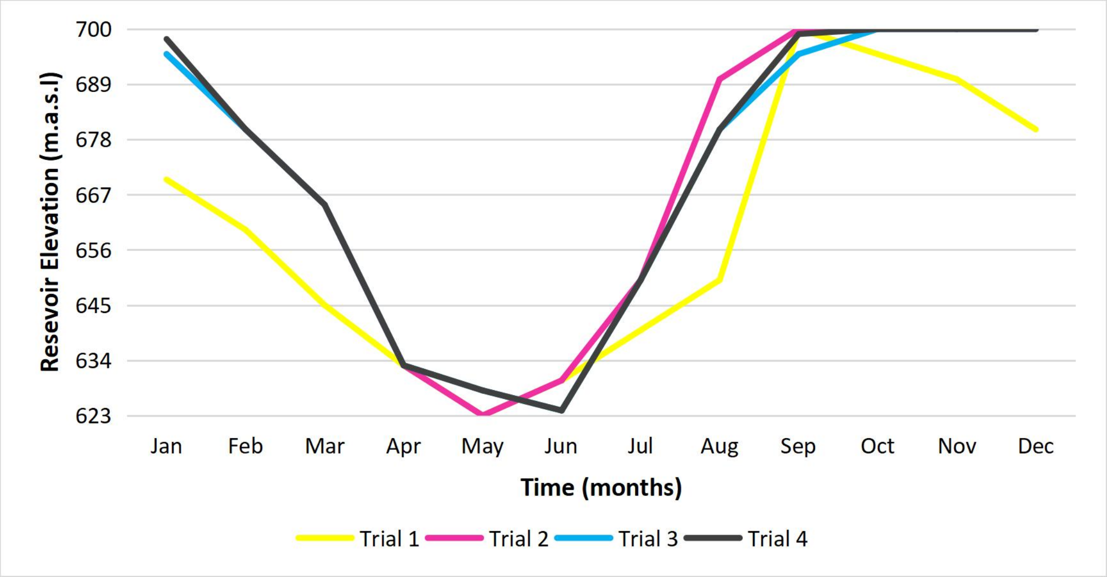


Figure 5.6: Alternative Operation Rule Curves used for Adhikhola Reservoir

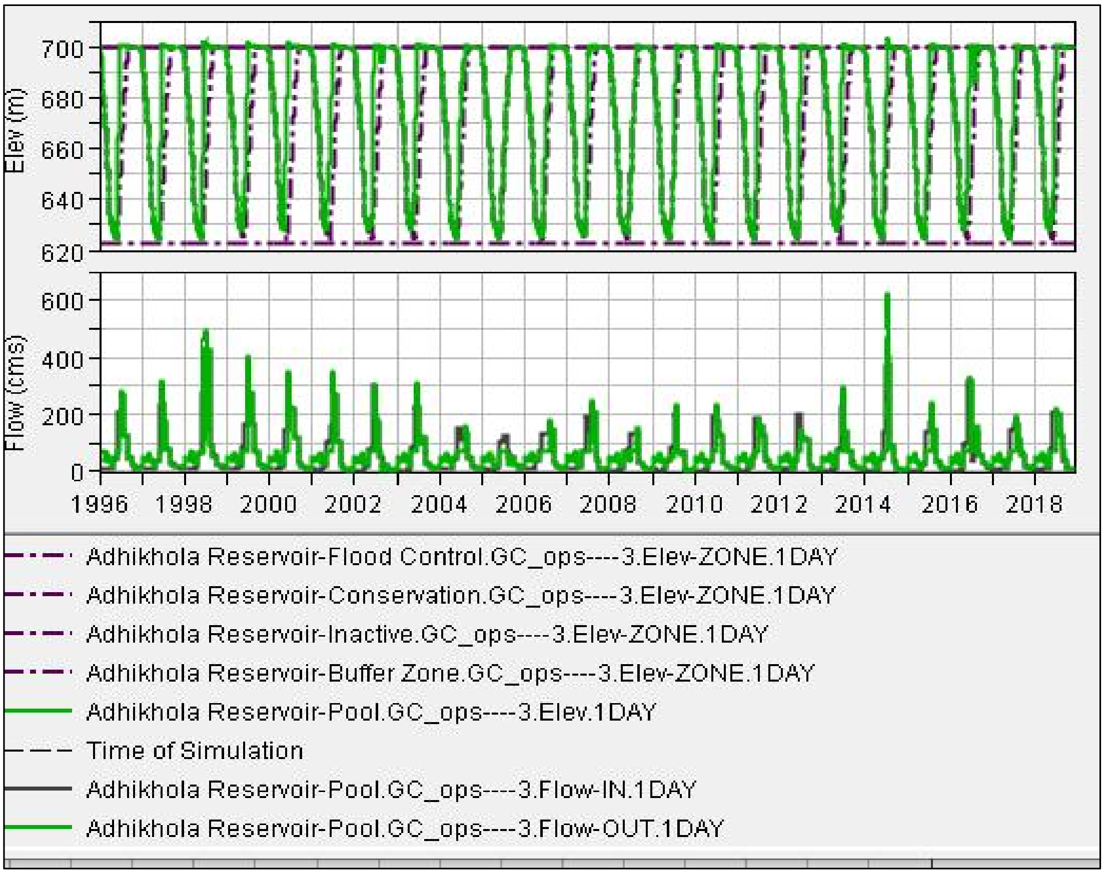


Figure 5.7: Inflow-Outflow Curve of Adhikhola Project

Trail 4 generated the maximum average annual energy as 955.61 GWh and dry energy as 426.74 GWh as shown in Figure 5.8 and Figure 5.9 respectively.

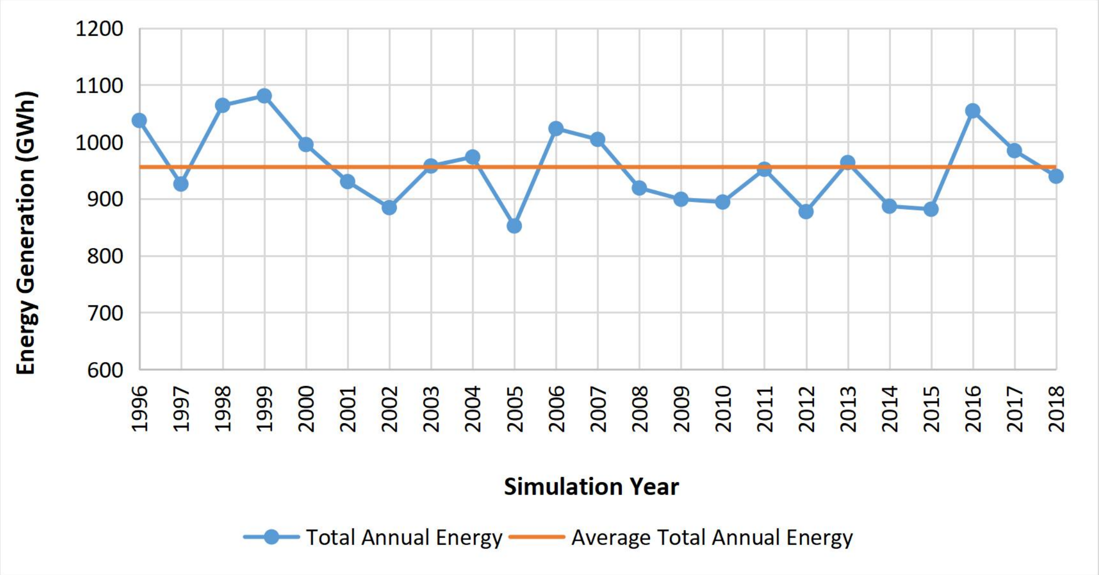


Figure 5.8: Energy generation trend over simulation years in Adhikhola storage project

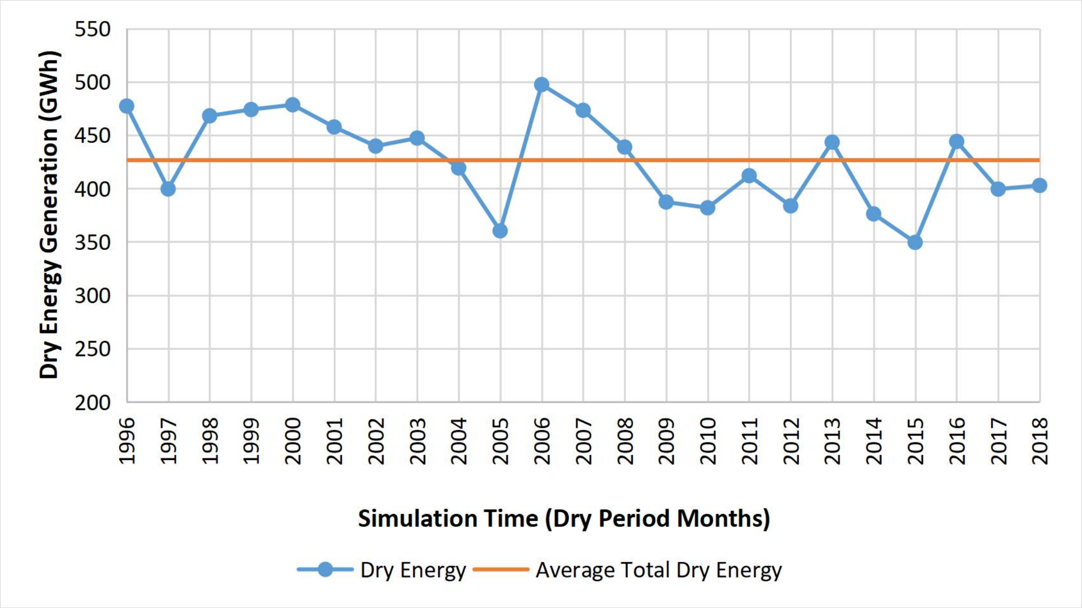


Figure 5.9: Dry Period Energy Generation of Adhikhola Reservoir

Trial 4 has a capacity of generating 38 MW of firm power during the dry period with 93.44% of dry period firm power reliability. The reservoir has a high vulnerability of

32.1% and resiliency of 9.5%. The dry period firm power graph of the Adhikhola reservoir as per trial 4 operating rule policy is shown in Figure 5.10.

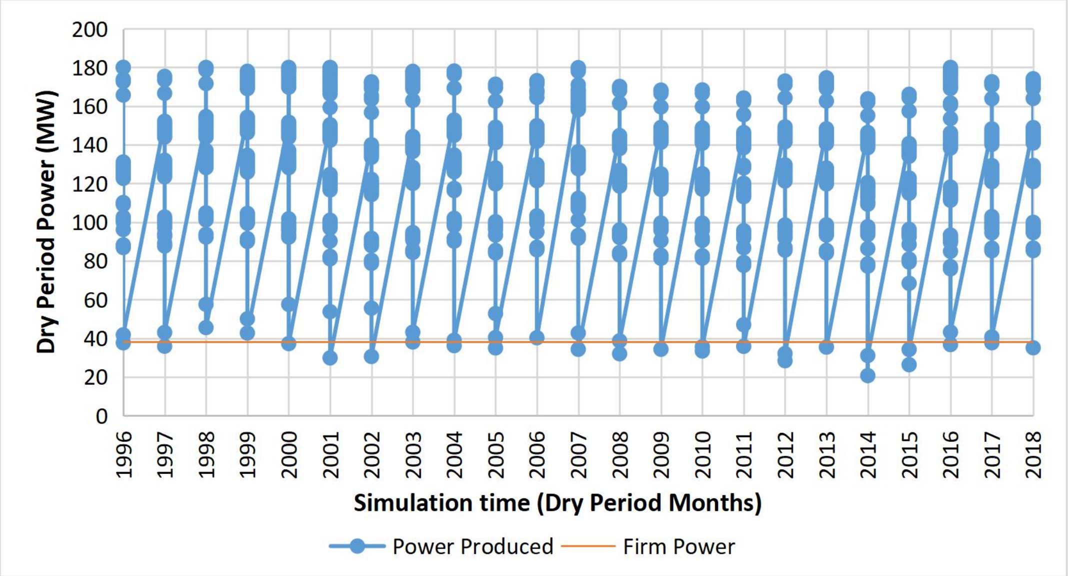


Figure 5.10: Dry Period Firm Power of Adhikhola Reservoir

In both scenarios, Trial 4 obtains the optimum result in terms of energy and performance indicators. As trial 4 OP generates the maximum annual and dry energy with the best performance indicators, trial 4 OP is selected as a reservoir operation rule for the Adhikhola reservoir in both scenarios.

iii. Lower Badigad Project

Four different trial operating rule policies, as shown in Figure 5.11 were used to find the most suitable reservoir operation rule curve that provides the maximum average annual energy and dry energy with the best reservoir performance criteria. The trial 4 operating policy has generated the maximum annual average energy and dry energy with the best performance indicators. Therefore, the Trial 4 operating policy is selected to set as a reservoir operation rule curve for the Lower Badigad project.

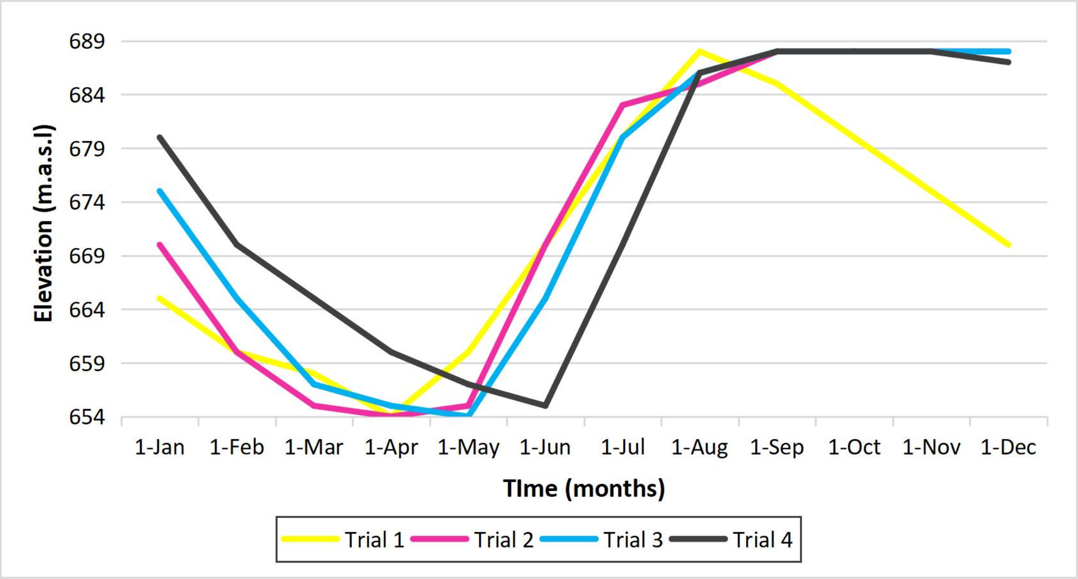


Figure 5.11: Alternative Operation Rule Curves Used for Lower Badigad Reservoir

In Figure 5.12, the inflow and outflow graph of the same trial operating condition is shown.

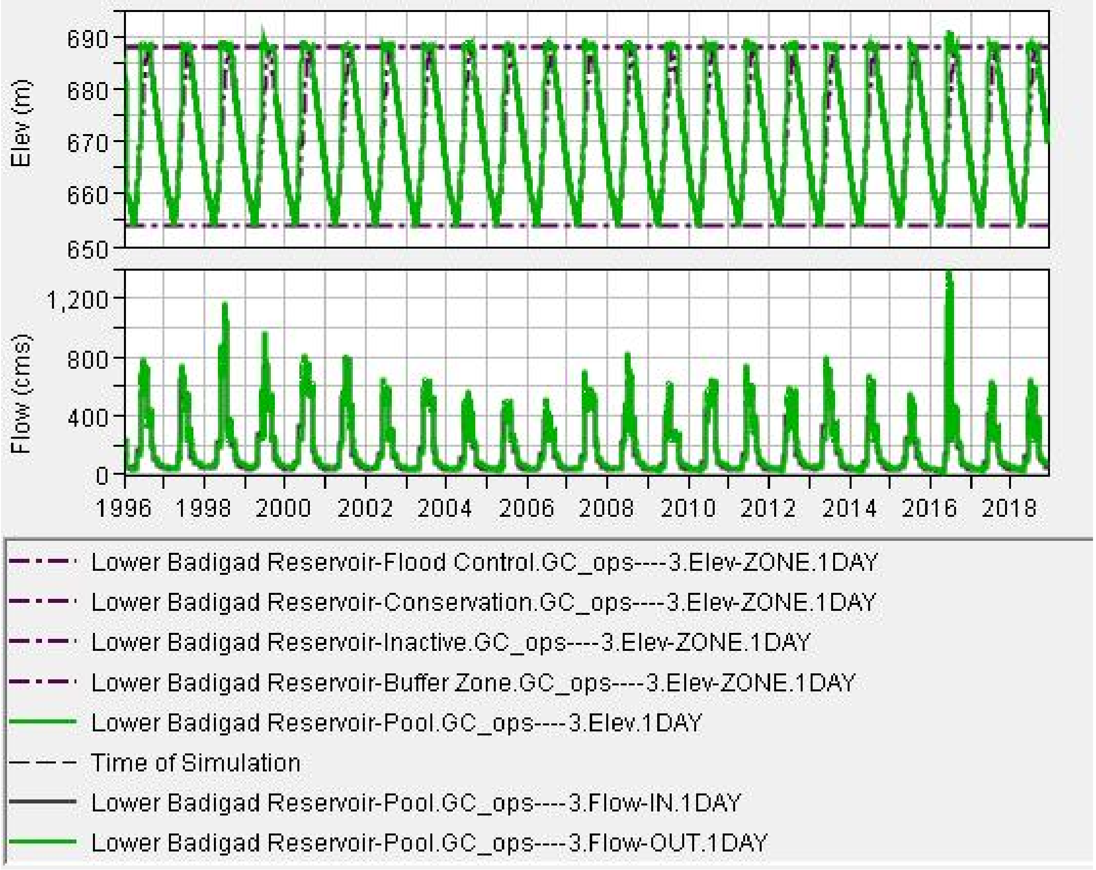


Figure 5.12: Inflow-Outflow Curve of Lower Badigad Project

The reservoir operating policy of Trail 4 generated the annual average total energy of 1842.23 GWh and dry energy of 600.37 GWh as shown in Figure 5.13 and Figure 5.14 respectively.

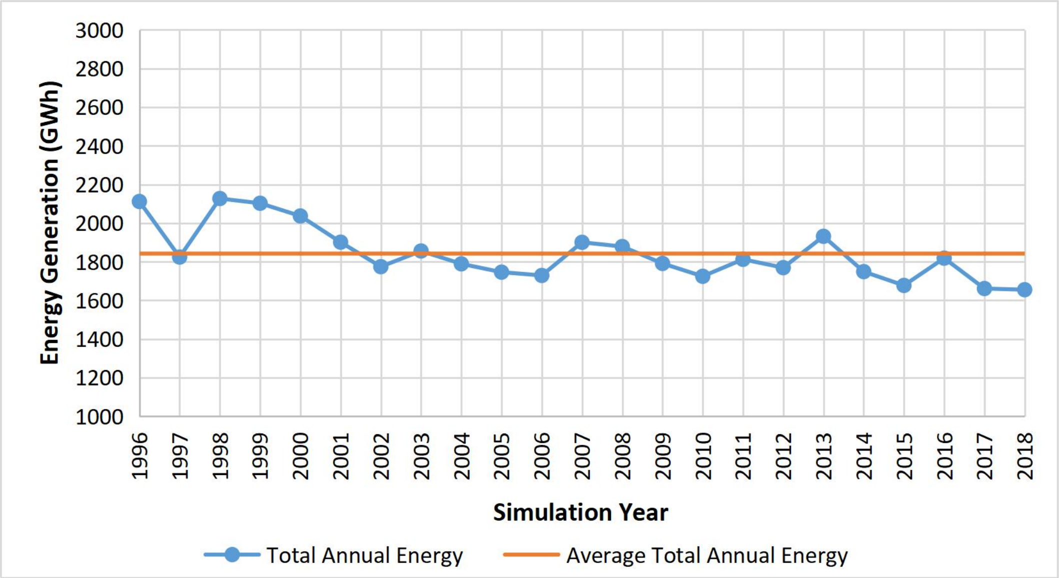


Figure 5.13: Energy generation trend over simulation years in Lower Badigad storage project

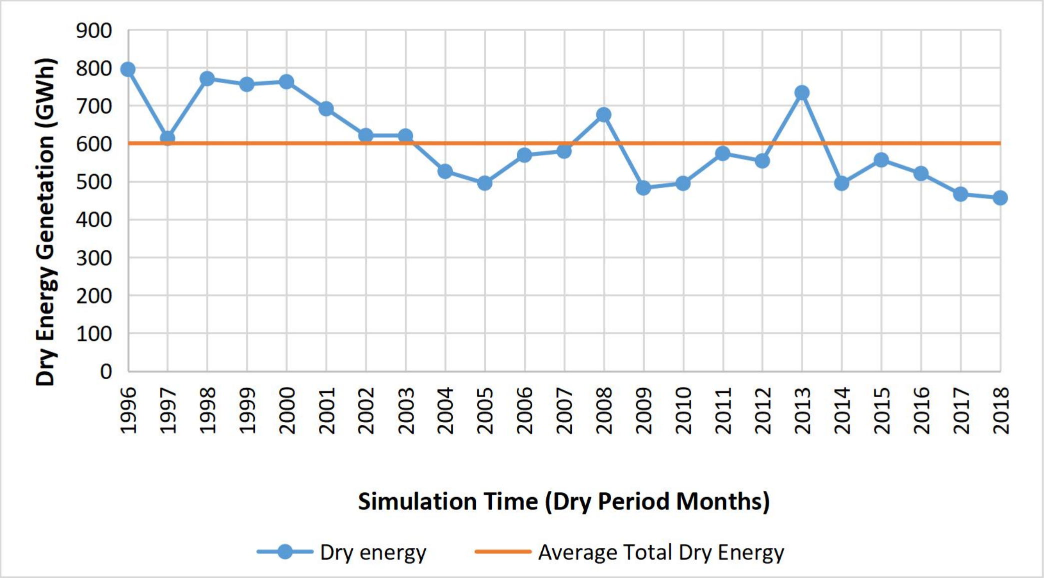


Figure 5.14: Dry Period Energy Generation of Lower Badigad

Trial 4 has a capacity of generating 80 MW of firm power during the dry period with 96% of dry firm power reliability. The reservoir has low vulnerability of 8.3% and low resiliency of 3.7%. The dry period firm power graph of the Lower Badigad reservoir as per trial 4 operating rule policy is shown in Figure 5.15.

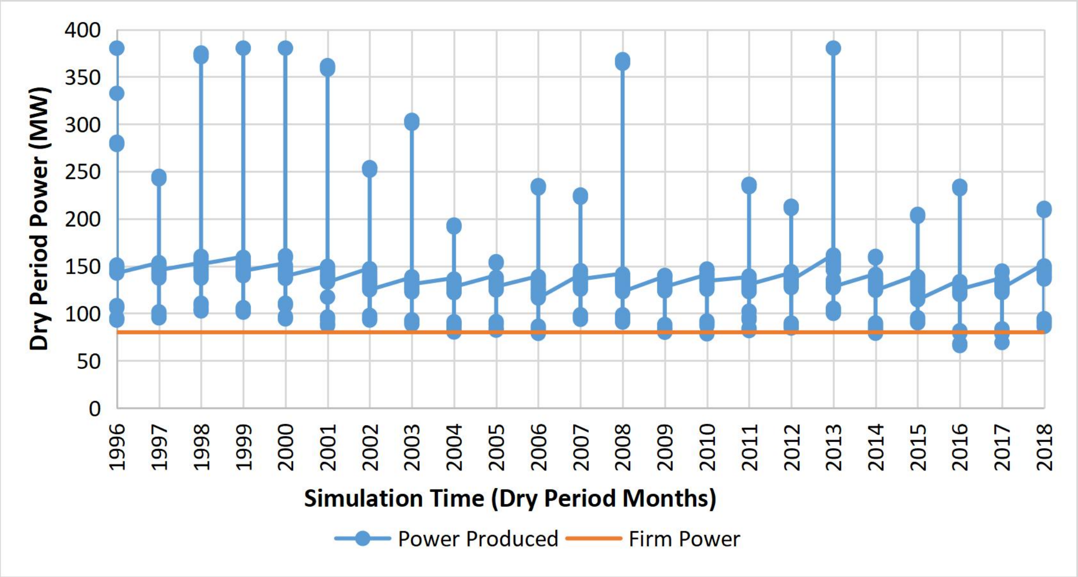


Figure 5.15: Dry Period Power of Lower Badigad Reservoir

In both scenarios, Trial 4 obtains the optimum result in terms of energy and performance indicators. As trial 4 OP generates the maximum annual and dry energy with the best performance indicators, trial 4 OP is selected as a reservoir operation rule for the Lower Badigad reservoir in both scenarios.

iv. Kaligandaki Diversion Multipurpose Project

A constant of 82 m^3/s diversion flows all around the year is assured for Kaligandaki Diversion Multipurpose Project in both scenarios. KTDMP has the capacity to produce a total annual energy of 1128.6 GWh and 128.8 MW of firm power in both scenarios.

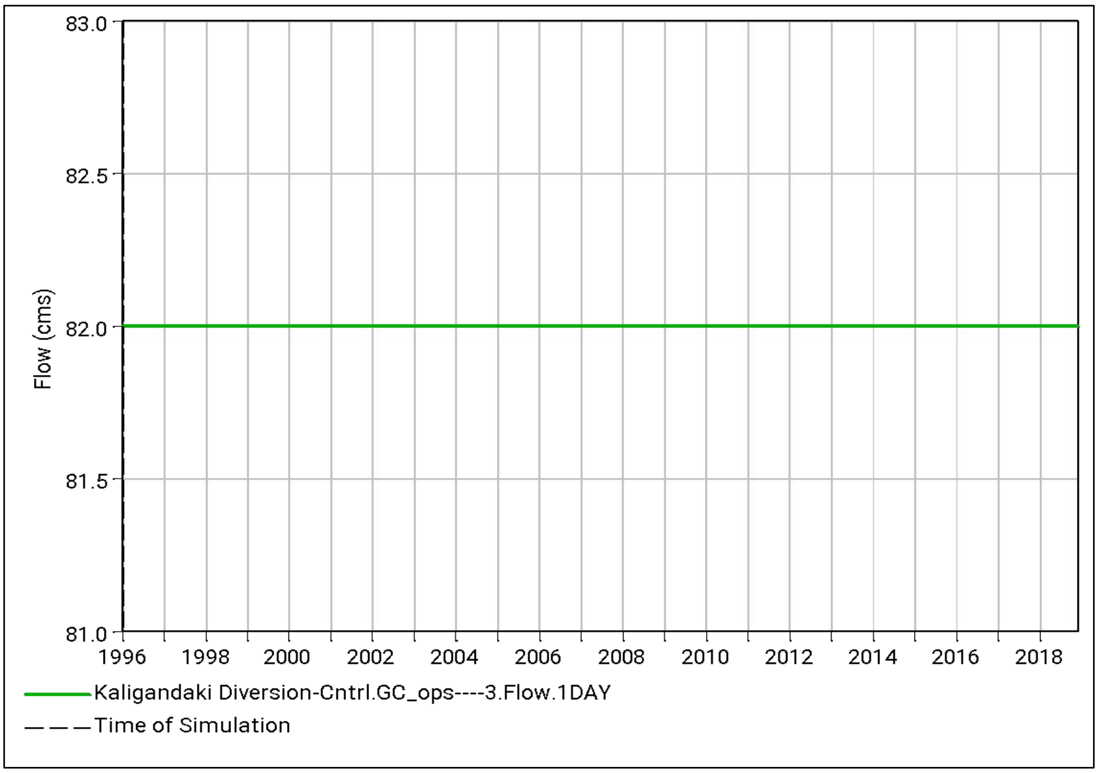


Figure 5.16: Curve showing constant diversion from Kaligandaki Diversion

5.3 Comparison of Individual Projects in Different Scenarios

i. Kaligandaki Project

There will be no significant changes in the energy production and performance indicators of Kaligandaki in changing scenarios. Table 5.1 provides the result of Kaligandaki reservoir operating in the operating policy of Trial 4, which is the best operating policy of all four trials.

Table 5.1: Comparison of Kaligandaki Reservoir in both Scenarios

	Project		**Kaligandaki**
Scenario 1 & 2	Firm Power (MW)		220.0
	Energy (GWh)	Total	4825.586
		Dry	1731.067
	PI for Dry Period Firm Power (%)	Reliability	92.96
		Vulnerability	3.78
		Resiliency	2.98

ii. Adhikhola Project

Similarly, while changing scenarios no significant changes in the energy production and performance indicators are found in the Adhikhola reservoir. Table 5.2 shows the result of Adhikhola reservoir while operating under the operating policy of trial 4, which gives the best output among all four trials.

Table 5.2: Comparison of Adhikhola Reservoir in both Scenarios

	Project		**Adhikhola**
Scenario 1 & 2	Firm Power (MW)		38.0
	Energy (GWh)	Total	955.61
		Dry	426.74
	PI for Dry Period Firm Power (%)	Reliability	93.4
		Vulnerability	32.1
		Resiliency	9.5

iii. Lower Badigad Project

Table 5.3 shows the result Lower Badigad reservoir operating under the operating policy of trial 4, which gives the best output among all four trials. No significant changes have been observed in the Lower Badigad reservoir in terms of energy generation and performance indicators while changing scenarios.

Table 5.3: Comparison of Lower Badigad reservoir in both Scenarios

	Project		**Lower Badigad**
Scenario 1 & 2	Firm Power (MW)		80.0
	Energy (GWh)	Total	1842.228
		Dry	600.3678
	PI for Dry Period Firm Power (%)	Reliability	96.0
		Vulnerability	8.3
		Resiliency	3.6

iv. Kaligandaki Tinau Diversion Multipurpose Project

In both scenarios, 82 m^3/s of water is constantly diverted for this project. The energy production capacity of KTDMP is 1128.6 GWh/year, which can be seen in Table 5.4.

Table 5.4: Comparison of Kaligandaki Diversion Energy in both Scenarios

	Project		**KTDMP**
Scenario 1 & 2	Firm Power (MW)		128.8
	Energy (GWh)	Total	1128.6
		Dry	564.3
	PI for Dry Period Firm Power (%)	Reliability	100.0
		Vulnerability	-
		Resiliency	-

5.4 Comparison of System Energy in each scenario

The maximum energy generation and performance indicators obtained from the best operating rule policy of Scenario 1 is shown in Table 5.5. When the system is operated in Scenario 1, the system will produce a dry period firm power of 466.8 MW and generate an average total annual energy of 8752.0 GWh/year in which 3322.4 GWh/year of energy comes from the dry period.

Table 5.5: 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	-	

Similarly, when the system operates in Scenario 2, the optimum energy generation and the performance indicators criteria in all the three cases are shown in Table 5.6. Case 2 of scenario 2 has the capacity to 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 5.6: Comparison of System Energy in Scenario 2

Cases of scenario 2	**Project**	**Firm Power (MW)**	**Average Total Annual Energy (GWh)**	**Dry Energy (GWh)**	**Wet Energy (GWh)**	**Dry Percent**	**PI for Dry Period Firm Power (%)**		
							Reliability	**Vulnerability**	**Resiliency**
Case 1	Kaligandaki Storage HEP	220	4825.6	1731.1	3094.5	0.4	96.0	3.8	3.0
	Adhikhola Storage HEP	38	955.6	426.7	528.9	0.4	93.4	32.2	9.5
	KTDMP	128.8	1128.6	564.3	564.3	0.5	100		
	Total	386.8	6909.8	2722.1	4187.7				
Case 2	Kaligandaki Storage HEP	220	4825.6	1731.1	3094.5	0.4	96	3.8	3.0
	Lower Badigad Storage HEP	80	1842.2	600.4	1241.9	0.3	96.0	8.3	3.6
	KTDMP	128.8	1128.6	564.3	564.3	0.5	100		
	Total	428.8	7796.4	2895.7	4900.7				
Case 3	Adhikhola Storage HEP	38	955.6	426.7	528.9	0.4	93.4	32.2	9.5
	Lower Badigad Storage HEP	80	1842.2	600.4	1241.9	0.3	96.0	8.3	3.6
	KTDMP	128.8	1128.6	564.3	564.3	0.5	100		
	Total	246.8	3926.4	1591.4	2335.1				

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1 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) from the system. This study aimed to examine planned reservoirs and diversion projects as part of an integrated system, moving away from the practice of isolating and simulating individual projects within the same basin. This helps in making rational decisions regarding the selection of optimum development at the basin-wide scale.

The system of three planned reservoirs and an inter-basin transfer project of Kaligandaki basin has the ability to produce a dry firm power of 466.8 MW. This system is capable of producing the average total annual energy of 8752 GWh/year of which 3322.4 GWh/year energy comes during the dry period. 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. Thus, this study has succeeded in generating the maximum annual energy of the planned reservoirs fulfilling the design discharge of 82 m^3/s as the constant diversion requirement of KTDMP.

The second objective of the study was to recommend the best operation rule for each planned reservoir which not only assures the maximum energy production but also, critically analyzes the reservoir performance to power reliability. Thus, the results of numerous simulations and the critical analysis of the results lead us to the conclusion that all three reservoirs i.e. Kaligandaki, Adhikhola, and Lower Badigad should be operated for Trial 4 reservoir operation rule.

Thus, an integrated study of the planned projects of a basin helps us to overview the wide range of scope of maximizing the total energy of the reservoir or improving the performance of the reservoir while meeting the other requirements. The findings of this study will be helpful for the different stakeholders and decision-makers to engage actively in decision-making processes concerning projects within the Kaligandaki basin.

6. 2 Recommendations

This study aimed to model and simulate the proposed dams along the Kaligandaki River, evaluating the benefits in terms of energy generation for various projects, all while ensuring the fulfillment of irrigation water requirements. Notably, even a minor adjustment in the rule curve can lead to a significant impact on both total energy production and performance indicators. So, the reservoir operating policies as mentioned in the study should be selected.

The best-operating policies in simulation studies should be assessed using different performance indicators. Generally, only the reliability criteria is taken to check reservoir performance during the project commencement. As reliability lacks to assess the intensity and nature of failure, two new performance indicators i.e. resiliency and vulnerability have to be checked during reservoir simulation as performed in this study.

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. Climate change will challenge water and energy management by causing more water variability and extreme weather events, such as severe floods, drought, etc. It will change the distribution, intensity, and frequency of precipitation events, and consequently change river flows and water resources reliability in global and regional scales. Energy systems are becoming more and more vulnerable to the impact of climate change on the hydrological phenomenon. So, it is recommended to consider climate change impacts to minimize uncertainty and risk. This approach enhances the adaptability and long-term success of proposed projects within evolving climatic patterns.

REFERENCES

Ahmad, A. *et al.* (2014) 'Reservoir optimization in water resources: A review', *Water Resources Management*, 28(11), pp. 3391–3405. DOI: 10.1007/s11269-014-0700-5.

Ahmadianfar, I., & Zamani, R. (2020). Assessment of the hedging policy on reservoir operation for future drought conditions under climate change. *Climatic Change*, *159*(2), 253-268.

Ahn, J. M., Lyu, S., & Kim, J. C. (2012). Study of operation rules for flood control to Seomjin River Dam using HEC-ResSim. Journal of The Korean Society of Civil Engineers, 32(2B), 93-101.

AL-AQEELI, Y. H. (2016). Optimization of Operations of Reservoir Systems for Hydropower Generation in Tigris River Basin, Iraq.

Anand, J., Ashvani Kumar Gosain, & Rakesh Khosa. (2018). Optimisation of Multipurpose Reservoir Operation by Coupling Soil and Water Assessment Tool (SWAT) and Genetic Algorithm for Optimal Operating Policy (Case Study: Ganga River Basin). 20.

Asadieh, B., & Abbas Afshar. (2019). Optimization of Water-Supply and Hydropower Reservoir Operation Using the Charged System Search Algorith. 16.

Authority, N. E. (2021). Updated Feasibility Study Report of Adhikhola Storage Hydroelectric Project.

Azad, A. S. (2020). Optimization of the hydropower energy generation using Meta-Heuristic approaches.

Babazadeh, H., Sedghi, H., Kaveh, F., & Jahromi, H. M. (2007). Performance evaluation of Jiroft storage dam operation using HEC-RESSIM 2.0. In Eleventh International Water Technology Conference (pp. 449-459).

Bista, M. (2021). Trade-Off Evaluation among Planned Reservoir Projects and Inter-Basin Transfer Projects: A Case Study of Sunkoshi River in Koshi Basin, Nepal.

Bonner. (1980). Application of the HEC-5 hydropower routines.

Bosona, &Gebresenbet. (2010). Modeling hydropower plant system to improve its reservoir operation.

Branche, E. (2017). The multipurpose water uses of hydropower reservoir:The share concept. 10.

Cai, X., Feng Ye, & Fatemeh Gholinia. (2020). Application of artificial neural network and Soil and Water Assessment Tools in evaluating power generation of small hydropower stations.

Chen, J., & Wu, Y. (2012). Advancing representation of hydrologic processes in the Soil and Water Assessment Tool (SWAT) through integration of the TOPographic MODEL (TOPMODEL) features. Journal of Hydrology.

Chou, F. N.-F., & Chia-Wen Wu. (2020). Optimizing the Management Strategies of a Multi-Purpose Multi-Reservoir System in Vietnam. Department of Hydraulic and Oceanic Engineering, 8.

Department of Hydrology & Meteorology (2018), Hydro-met data, Kathmandu, Nepal.

DOED (2021). Feasibility and Environmental Impact Assessment Study of Kaligandaki Storage Hydropower Project Gulmi, Parbat and Baglung District

DEVELOPMENT, D. O. (2022). FEASIBILITY STUDY AND ENVIRONMENT IMPACT ASSESSMENT STUDY OF LOWER BADIGAD HYDROPOWER PROJECT.

DWRI (2011). PREFEASIBILITY STUDY OF KALIGANDAKI-TINAU DIVERSION PROJECT

DWRI. (2019). Irrigation Master Plan.

DWRI. (2077). Retrieved from https://dwri.gov.np/report/pipeline-project/detail/kaligandaki-tinau-diversion-multipurpose-project-2077-11-23.

Emerson, B. D., Vecchi, A. V., & Dahl, A. L. (2005). Evaluation of Drainage-Area Ratio Method Used to Estimate Streamflow for the Red River of the North Basin, North Dakota and Minnesota.

Farmer, W. H. (2012). Estimating monthly time series of streamflows at ungauged locations in the united states.

Fayaed, S. S. (2013, March). Reservoir-system simulation and optimization techniques. 22.

Gibbs, C. J., Norrie, D. J., & Cook, H. J. (1989). Simulations of Multireservoir System Operation. In Waterpower'89 (pp. 153-162). ASCE.

Golmohammadi, G. et al. (2014) ‘Evaluating three hydrological distributed watershed models: MIKE-SHE, APEX, SWAT’, Hydrology, 1(1), pp. 20–39. DOI: 10.3390/hydrology1010020.

Goor, Q. (2010). Optimal Operation of Multiple Reservoirs in Hydropower-Irrigation Systems : a stochastic dual dynamic programming approach. 149.

HEC. (2021). Hec-ResSim, Reservoir system simulation software version 3.3.

HerathGunatilake, Priyantha Wijayatunga, & David Roland-Holst. (2020). HYDROPOWER DEVELOPMENT AND ECONOMIC GROWTH IN NEPAL. ADB SOUTH ASIA , 24.

ICIMOD. (2017, March). The Gandaki Basin Maintaining Livelihoods in the Face of Landslides, Floods, and Drought.

Jahandideh-Tehrani, M., Bozorg Haddad, O., & Marino, M. A. (2014). Power generation simulation of a hydropower reservoir system using system dynamics: case study of Karoon reservoir system. Journal of Energy Engineering, 140(4), 04014003.

JICA (2014). Nationwide Master Plan Study on Storage-type Hydroelectric Power Development in Nepal.

Joan D. Klipsch, Marilyn B. Hurst, George C. Modini, Daniel L. Black, S. M. O. (2021) ‘HEC-ResSim_33_UsersManual.pdf’, US Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center (HEC), p. 670.

Joan D. Klipsch, T. A. (2010). RESERVOIR OPERATIONS MODELING WITH HEC-RESSIM.

KaligandakiTinau Diversion Multipurpose Project- DWRI. (n.d.).

Kangrang, A. (2018). Development of Future Rule Curves for Multipurpose Reservoir Operation Using Conditional Genetic and Tabu Search Algorithms. 11.

Koç, C. (2018). A study on operation problems of hydropower plants integrated with irrigation schemes opearted in Turkey. 8.

Lauri, H., Moel, H. D., Ward, P. J., Räsänen, T. A., Keskinen, M., & Kummu, M. (2012). Future changes in Mekong River hydrology: impact of climate change and reservoir operation on discharge. Hydrology and Earth System Sciences, 16(12), 4603-4619.

Legates, D. R., Gregory J, & McCabe Jr. (1999). Evaluating the use of “goodness-of-fit” Measures in hydrologic and hydroclimatic model validation.

Li, J., May Myat Moe Saw, Siyu Chen, & Hongjie Yu. (2020). Short-Term Optimal Operation of Baluchaung II Hydropower Plant in Myanmar. 14.

Limited, H.-C. E. (2019). Bathymetric Survey of Kaligandaki River at Dam Site of Kaligandaki-Tinau Diversion Multipurpose Project.

Limited, U. P. (2019). Draft Feasibility Study Report of Uttarganga Storage Hydroelectric Project.

Loucks, D. P., &Beek, E. v. (2017). Water resource systems planning and management: An introduction to methods, models, and applications.

Loucs, D. P., &Beek, E. V. (2005). Water Resources Systems Planning and Management.

Meng, Y., Junguo Liu, Zifeng Wang, GanquanWao, Kai Wang, & Hong Yang. (2020). Undermined co-benefits of hydropower and irrigation under climate change., (p. 11).

Ministry of Irrigation, D. o. (2011). PREFEASIBILITY STUDY OF KALIGANDAKI TINAU DIVERSION PROJECT.Jawlakhel, Lalitpur.

Nash, J., & Sutcliffe, J. S. (1970). River flow forecasting through conceptual models part I — A discussion of principles. Journal of Hydrology.

NEA. (2021). Updated Feasibility Study Report of Adhikhola Hydroelectric Project.

Ngo, L. A., Masih, I., Jiang, Y., & Douven, W. (2018). Impact of reservoir operation and climate change on the hydrological regime of the Sesan and Srepok Rivers in the Lower Mekong Basin. Climatic change, 149(1), 107-119.

Olani, W. T. (2006). Operational Analysis of the CascaddedWadecha-Belbela Reservoir System.

Piman, T. (2016, June). Effect of Proposed Large Dams on Water Flows and Hydropower Production in the Sekong, Sesan and Srepok Rivers of the Mekong Basin.

Rani, D. and Moreira, M. M. (2010) ‘Simulation-optimization modeling: A survey and potential application in reservoir systems operation', Water Resources Management, 24(6), pp. 1107–1138. doi: 10.1007/s11269-009-9488-0.

Ren, X. (2021). Predicting optimal hydropower generation with help optimal management of water resources by Developed Wildebeest Herd Optimization (DWHO).

Rosero, N. (2013). Minimization of water losses for optimal hydroelectric power generation., (p. 7).

Sahukhal, R., &Bajracharya, T. R. (2019). Modeling water resources under competing demands for sustainable development: A case study of Kaligandaki Gorge Hydropower Project in Nepal. 8.

SAKA, F., & BABACAN, H. T. (2019). Discharge Estimation by Drainage Area Ratio Method at Some Specific Discharges for 2251 Stream Gauging Station in East Black Sea Basin, Turkey.

Sanstha, J. V. (2021, October). Strengthening Inter-Provincial/Municipal Cooperation in Gandaki Basin A Case Study of Kaligandaki-Tinau Diversion Project.

Santhi et al. (2012). SWAT: Model Use, Calibration and Validation.

Sieber, J. (2006). WEAP water evaluation and planning system.

Singh, J., Knapp, V. H., Arnold, J. G., &Demissie, M. (2005). HYDROLOGICAL MODELING OF THE IROQUOIS RIVER WATERSHED USING HSPF AND SWAT. Journal of the American Water Resources Association.

Singh, V. K., & Singal, S. K. (2017). Operation of hydro power plants-a review. Renewable and Sustainable Energy Reviews, 69, 610-619.

SIVAPALAN, M., TAKEUCHI, K., FRANKS, W. S., V. K. GUPTA, H. KARAMBIRI , V. LAKSHMI , & X. LIANG. (2010). IAHS Decade on Predictions in Ungauged Basins (PUB), 2003–2012: Shaping an exciting future for the hydrological sciences. Hydrological Sciences Journal.

SREENIVASAN, K. R., & S VEDULA. (1995). Reservoir operation for hydropower optimization: A chance-constrained approach. 8.

Suhardiman, D. (2015). Integrated water resources management in Nepal; key stakeholders' perceptions and lessons learned. International Journal of Water Resources Development, 17.

Suhardiman, D., Clement, F., & Bharati, L. (2015, March 13). Integrated water resources management in Nepal: key stakeholders' perceptions and lessons learned. International Journal of Water Resources Development.

Thapa, D. A. (2019). KALI-GANDAKI DAMS AND PROVINCIAL DISPUTE NEPAL'S FEDERALISM. doi:584/074-75

Theobald, T. S. (2014). Modeling of Cascade Dams and Reservoirs Operation for Hydropower Energy Generation. 9.

Tilmant, A., Q. Goor, & D. Pinte. (2009). Agricultural-to-hydropower water transfers: sharing water and benefits in hydropower-irrigation systems., (p. 11).

Tsuyoshi Hashimoto, J. R. (1982). Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation.

WECS. (2021). Preparation of River Basin Plans and Hydropower Development Master Plans and Strategic Environmental and Social Assessment.

Wu, Y., & Ji Chen. (2012). Estimating irrigation water demand using an improved method and optimizing. 12.

Wurbs, R. (1993). Reservoir System Simulation and Optimization Models.

Wurbs, R. (1998). Dissemination of generalized water resources models in the United States.

Yeh, W. W.-G. (1985). Reservoir Management and Operations Models: A State-of-the-Art Review.

Yoshioka, H. (2020). Mathematical modeling and computation of a dam–reservoir system balancing environmental management and hydropower generation.

Yun, X., Tang, Q., Wang, J., Liu, X., Zhang, Y., Lu, H., ... & Chen, D. (2020). Impacts of climate change and reservoir operation on streamflow and flood characteristics in the Lancang-Mekong River Basin. Journal of Hydrology, 590, 125472.

APPENDIX – A

Reservoir Physical Data

Table: Height-Area-Volume Data of Kaligandaki Reservoir

S.N.	Elevation (m)	Area (sq.km)	Volume (MCM)	S.N.	Elevation (m)	Area (sq.km)	Volume (MCM)
1	570	0	0	22	675	5.24	215.86
2	575	0.02	0.06	23	680	5.72	243.47
3	580	0.1	0.48	24	685	6.21	273.44
4	585	0.24	1.57	25	690	6.72	305.9
5	590	0.41	3.43	26	695	7.26	341.02
6	595	0.58	6.07	27	700	7.8	378.82
7	600	0.74	9.5	28	705	8.36	419.36
8	605	0.95	13.9	29	710	8.94	462.77
9	610	1.19	19.47	30	715	9.58	509.3
10	615	1.4	26.09	31	720	10.31	559.27
11	620	1.64	33.87	32	725	11.11	613.1
12	625	1.87	42.78	33	730	11.98	671.15
13	630	2.16	53.07	34	735	12.81	733.27
14	635	2.41	64.59	35	740	13.67	799.7
15	640	2.68	77.42	36	745	14.64	870.75
16	645	3.02	91.9	37	750	15.68	946.85
17	650	3.36	108.05	38	755	16.72	1028.1
18	655	3.71	125.9	39	760	17.91	1115.01
19	660	4.1	145.63	40	765	19.17	1208.09
20	665	4.47	167.18	41	770	20.33	1307.21
21	670	4.83	190.52	42	775	20.46	1409.48

Table: Height-Area-Volume Data of Lower Badigad Reservoir

S.N.	Elevation (m)	Area (sq.km)	Volume (MCM)	S.N	Elevation (m)	Area (sq.km)	Volume (MCM)
1	535	0.00	0.00	134	668	9.48	378.88
2	536	0.00	0.00	135	669	9.61	388.43
3	537	0.00	0.01	136	670	9.75	398.11
4	538	0.00	0.01	137	671	10.04	408.08
5	539	0.01	0.02	138	672	10.19	418.19
6	540	0.01	0.02	139	673	10.33	428.45
7	541	0.02	0.04	140	674	10.47	438.85
8	542	0.02	0.06	141	675	10.61	449.39
9	543	0.02	0.07	142	676	10.84	460.16
10	544	0.02	0.10	143	677	10.97	471.06
11	545	0.02	0.12	144	678	11.11	482.11
12	546	0.04	0.15	145	679	11.25	493.29
13	547	0.04	0.19	146	680	11.39	504.61
14	548	0.04	0.23	147	681	11.64	516.18
15	549	0.04	0.27	148	682	11.78	527.89
16	550	0.05	0.32	149	683	11.93	539.75
17	551	0.06	0.37	150	684	12.07	551.75
18	552	0.06	0.44	151	685	12.21	563.89
19	553	0.07	0.50	152	686	12.50	576.31
20	554	0.07	0.58	153	687	12.65	588.89
21	555	0.08	0.65	154	688	12.81	601.62
22	556	0.09	0.74	155	689	12.96	614.50
23	557	0.09	0.83	156	690	13.12	627.54
24	558	0.10	0.93	157	691	13.35	640.81
25	559	0.10	1.02	158	692	13.49	654.23
26	560	0.10	1.13	159	693	13.64	667.79
27	561	0.12	1.24	160	694	13.78	681.50
28	562	0.12	1.36	161	695	13.93	695.36
29	563	0.12	1.48	162	696	14.23	709.51
30	564	0.13	1.61	163	697	14.39	723.82
31	565	0.13	1.74	164	698	14.54	738.29
32	566	0.15	1.89	165	699	14.70	752.91

33	567	0.15	2.04	166	700	14.87	767.70
34	568	0.16	2.19	167	701	15.13	782.75
35	569	0.16	2.36	168	702	15.29	797.96
36	570	0.17	2.52	169	703	15.44	813.33
37	571	0.28	2.79	170	704	15.60	828.85
38	572	0.29	3.08	171	705	15.76	844.53
39	573	0.31	3.38	172	706	16.01	860.47
40	574	0.32	3.69	173	707	16.17	876.56
41	575	0.34	4.02	174	708	16.32	892.80
42	576	0.46	4.48	175	709	16.47	909.20
43	577	0.48	4.95	176	710	16.63	925.75
44	578	0.50	5.43	177	711	16.95	942.62
45	579	0.51	5.94	178	712	17.11	959.65
46	580	0.53	6.46	179	713	17.28	976.85
47	581	0.69	7.14	180	714	17.44	994.21
48	582	0.72	7.84	181	715	17.60	1011.73
49	583	0.74	8.57	182	716	17.87	1029.52
50	584	0.78	9.33	183	717	18.03	1047.47
51	585	0.81	10.12	184	718	18.19	1065.58
52	586	0.91	11.02	185	719	18.35	1083.85
53	587	0.94	11.94	186	720	18.52	1102.28
54	588	0.98	12.90	187	721	18.82	1121.03
55	589	1.01	13.90	188	722	18.98	1139.93
56	590	1.04	14.92	189	723	19.14	1158.98
57	591	1.17	16.08	190	724	19.30	1178.20
58	592	1.21	17.27	191	725	19.45	1197.57
59	593	1.24	18.50	192	726	19.63	1217.12
60	594	1.28	19.76	193	727	19.79	1236.84
61	595	1.32	21.06	194	728	19.96	1256.71
62	596	1.44	22.48	195	729	20.13	1276.76
63	597	1.49	23.94	196	730	20.30	1296.97
64	598	1.53	25.45	197	731	20.61	1317.50
65	599	1.57	27.00	198	732	20.78	1338.20
66	600	1.61	28.59	199	733	20.95	1359.06
67	601	1.80	30.37	200	734	21.11	1380.09

68	602	1.85	32.20	201	735	21.28	1401.28
69	603	1.89	34.06	202	736	21.49	1422.69
70	604	1.93	35.97	203	737	21.65	1444.26
71	605	1.97	37.93	204	738	21.81	1465.99
72	606	2.16	40.06	205	739	21.97	1487.88
73	607	2.21	42.24	206	740	22.14	1509.94
74	608	2.27	44.48	207	741	22.36	1532.21
75	609	2.32	46.78	208	742	22.52	1554.65
76	610	2.38	49.13	209	743	22.69	1577.25
77	611	2.59	51.70	210	744	22.86	1600.03
78	612	2.65	54.32	211	745	23.02	1622.97
79	613	2.71	57.00	212	746	23.25	1646.14
80	614	2.76	59.73	213	747	23.42	1669.47
81	615	2.82	62.52	214	748	23.59	1692.98
82	616	3.02	65.51	215	749	23.76	1716.65
83	617	3.09	68.57	216	750	23.93	1740.50
84	618	3.16	71.69	217	751	24.15	1764.56
85	619	3.22	74.88	218	752	24.32	1788.79
86	620	3.29	78.13	219	753	24.50	1813.21
87	621	3.42	81.51	220	754	24.68	1837.79
88	622	3.49	84.96	221	755	24.85	1862.56
89	623	3.57	88.50	222	756	25.08	1887.55
90	624	3.65	92.11	223	757	25.27	1912.73
91	625	3.73	95.80	224	758	25.45	1938.09
92	626	3.89	99.65	225	759	25.63	1963.63
93	627	3.98	103.58	226	760	25.82	1989.36
94	628	4.06	107.60	227	761	26.05	2015.32
95	629	4.16	111.71	228	762	26.24	2041.46
96	630	4.25	115.91	229	763	26.43	2067.79
97	631	4.55	120.41	230	764	26.61	2094.31
98	632	4.66	125.02	231	765	26.80	2121.02
99	633	4.78	129.74	232	766	27.04	2147.96
100	634	4.90	134.58	233	767	27.23	2175.10
101	635	5.03	139.55	234	768	27.43	2202.43
102	636	5.37	144.87	235	769	27.62	2229.95

103	637	5.47	150.29	236	770	27.82	2257.67
104	638	5.57	155.81	237	771	28.06	2285.63
105	639	5.67	161.43	238	772	28.26	2313.79
106	640	5.77	167.15	239	773	28.45	2342.14
107	641	6.03	173.12	240	774	28.65	2370.69
108	642	6.13	179.20	241	775	28.85	2399.45
109	643	6.23	185.37	242	776	29.11	2428.45
110	644	6.33	191.65	243	777	29.31	2457.66
111	645	6.42	198.03	244	778	29.51	2487.07
112	646	6.62	204.60	245	779	29.72	2516.68
113	647	6.72	211.27	246	780	29.92	2546.50
114	648	6.81	218.03	247	781	30.18	2576.58
115	649	6.91	224.89	248	782	30.38	2606.85
116	650	7.00	231.85	249	783	30.59	2637.34
117	651	7.19	238.99	250	784	30.80	2668.03
118	652	7.28	246.23	251	785	31.01	2698.94
119	653	7.37	253.55	252	786	31.27	2730.10
120	654	7.46	260.96	253	787	31.49	2761.48
121	655	7.55	268.47	254	788	31.70	2793.08
122	656	7.72	276.13	255	789	31.92	2824.89
123	657	7.82	283.90	256	790	32.14	2856.92
124	658	7.93	291.78	257	791	32.42	2889.23
125	659	8.05	299.76	258	792	32.64	2921.75
126	660	8.16	307.87	259	793	32.86	2954.50
127	661	8.45	316.26	260	794	33.08	2987.47
128	662	8.58	324.78	261	795	33.31	3020.67
129	663	8.70	333.41	262	796	33.59	3054.14
130	664	8.82	342.17	263	797	33.81	3087.84
131	665	8.94	351.05	264	798	34.04	3121.76
132	666	9.21	360.19	265	799	34.26	3155.91
133	667	9.34	369.47	266	800	34.49	3190.29

Table: Height-Area-Volume Data of Adhikhola Reservoir

S.N.	Elevation （m）	Area (sq.km）	Volume (MCM)
1	560	0.04	0.00
2	580	0.48	5.18
3	600	1.16	21.61
4	620	1.92	52.37
5	623	2.07	59.68
6	640	2.96	101.10
7	660	4.22	172.84
8	680	5.55	270.58
9	700	7.51	401.10
10	710	8.38	464.58

APPENDIX – B

Hydrological data from DHM

Station number: 404.7
Location: Mangla Ghat Latitude: 28 21 10
River: Myagdi Khola Longitude: 83 32 16

AVERAGE MONTHLY AND YEARLY DISCHARGE (in m3/s)
==

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Yearly
1996	20.9	20.9	15.5	23.0	20.9	33.3	216.0	282.0	121.0	55.9	24.3	15.5	70.8
1997	20.4	17.8	16.2	18.1	17.8	35.2	114.0	89.0	66.2	32.7	20.6	17.6	38.8
1998	21.1	17.8	17.9	21.5	37.6	93.5	174.0	267.0	153.0	70.1	37.9	28.2	78.3
1999	15.5	11.2	12.2	24.3	36.5	117.4	198.3	222.0	133.0	100.6	42.6	26.4	78.3
2000	20.9	17.7	10.3	18.4	32.2	110.0	218.0	251.0	174.0	54.0	28.4	17.1	79.3
2001	13.0	11.5	9.4	11.9	20.9	71.9	229.0	268.0	130.0	40.0	22.5	14.1	70.2
2002	13.1	10.2	11.4	17.2	28.1	53.4	235.0	202.0	97.6	41.9	29.9	21.0	63.4
2003	15.5	14.2	14.8	20.5	20.4	75.7	219.0	244.8	198.3	66.8	31.8	20.5	78.5
2004	17.7	12.0	14.0	16.5	21.3	42.4	156.0	179.0	160.0	76.8	29.3	21.3	62.2
2005	15.7	13.3	13.9	14.7	18.0	37.9	140.0	142.0	96.0	49.9	29.4	19.0	49.2
2006	14.4	13.6	12.7	14.0	30.7	58.3	117.0	113.0	92.4	44.6	24.9	17.6	46.1
2007	14.5	13.1	15.9	21.4	26.4	72.8	177.0	197.0	128.0	82.9	38.6	22.9	67.6
2008	18.9	15.2	15.2	18.2	22.0	335.0	438.0	485.0	135.4	56.5	30.4	22.6	132.7
2009	15.8	14.5	17.4	20.3	29.4	66.5	240.0	299.0	153.0	144.0	47.5	22.9	89.2

2010	14.6	11.1	13.1	19.5	31.1	85.4	211.0	225.0	366.0	128.0	61.3	25.4	99.3
2011	20.3	17.4	15.4	15.4	24.4	60.0	172.0	192.0	132.0	109.0	47.2	26.7	69.2
2012	19.4	13.0	9.8	16.9	28.7	61.0	140.0	174.0	145.0	58.6	33.7	26.9	60.5
2013	21.6	16.6	19.1	25.1	38.9	164.0	221.0	187.0	103.0	62.6	37.5	21.0	76.4
2014	14.9	13.7	16.3	20.0	28.6	55.3	194.0	222.0	169.0	78.8	44.7	31.4	74.0
2015	15.4	9.9	12.0	20.8	30.3	70.3	194.0	261.0	134.0	50.2	18.3	14.8	69.3
2016	11.8	9.1	8.9	16.0	34.3	153.0	372.0	320.0	312.0	85.5	38.9	24.0	115.5
2017	15.4	12.3	11.4	21.2	37.8	87.8	158.0	393.0	287.0	68.5	27.6	19.4	95.0
2018	13.8	11.2	9.6	16.6	23.9	50.8	191.0	271.0	181.0	49.0	22.4	15.7	71.3

Station number: 406.5

Location: Nayapul near Jhapre Bagar Latitude: 28 15 15

River: Modi Khola Longitude: 83 43 27

AVERAGE MONTHLY AND YEARLY DISCHARGE (in m3/s)

==

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Yearly
1996	11.2	10.1	7.8	10.8	16.8	60.1	167.0	189.0	103.0	52.9	21.2	14.6	55.4
1997	10.1	9.2	9.4	18.3	19.3	43.2	192.0	156.0	89.6	28.1	14.7	16.2	50.5
1998	10.5	6.8	6.2	12.0	28.7	70.0	164.0	274.0	95.8	48.8	23.7	15.3	63.0
1999	10.7	8.2	7.9	12.0	24.5	73.4	128.0	179.0	179.0	52.2	25.3	15.5	59.6
2000	11.7	9.8	7.6	12.8	23.3	86.1	176.0	180.0	133.0	37.1	21.7	15.4	59.5
2001	12.2	11.3	10.7	11.8	19.6	67.1	145.0	166.0	108.0	40.3	21.4	16.6	52.4
2002	14.0	12.0	12.0	14.9	23.2	43.5	136.0	168.0	64.4	32.2	17.7	13.2	45.9
2003	10.5	10.0	9.2	11.0	12.7	51.3	131.0	150.0	108.0	43.9	24.0	14.7	48.0
2004	10.5	9.9	11.2	13.7	15.5	33.9	133.0	119.5	102.0	48.2	18.3	15.6	44.3
2005	11.4	11.3	11.3	12.2	15.1	30.4	144.0	128.0	95.1	35.3	21.6	15.7	44.3
2006	14.1	10.9	10.3	11.1	21.4	49.3	115.0	111.0	81.0	29.5	16.2	12.4	40.2
2007	12.8	11.8	10.1	13.8	18.7	50.9	148.0	141.0	159.0	35.7	21.4	14.9	53.2
2008	12.2	10.3	9.4	11.6	15.8	81.9	114.0	207.0	62.9	25.1	12.6	12.6	48.0
2009	10.0	9.5	9.3	10.3	13.2	21.5	96.7	158.0	85.8	50.2	13.9	10.8	40.7
2010	8.9	8.1	8.7	10.4	11.2	21.1	117.0	191.0	167.0	48.8	20.2	14.2	52.3

2011	9.6	9.3	6.9	6.8	11.0	53.2	231.0	264.0	125.0	47.3	16.6	14.3	66.2
2012	9.3	8.0	7.7	10.3	15.6	57.9	170.0	179.0	132.0	39.9	18.9	14.2	55.3
2013	9.3	8.3	9.6	12.0	65.3	93.6	186.0	159.0	79.5	37.1	24.2	16.1	58.3
2014	10.4	7.7	7.8	8.0	13.4	29.8	232.0	385.0	150.0	47.3	26.9	15.1	77.8
2015	12.0	8.1	9.2	14.0	21.3	50.0	133.0	204.0	96.0	42.8	25.9	17.1	52.8
2016	8.8	8.6	7.7	6.6	8.9	39.8	233.4	110.0	112.0	55.3	22.8	15.7	52.5
2017	10.5	8.9	7.7	8.7	9.2	23.6	125.8	164.9	84.7	38.0	19.6	14.2	43.0
2018	10.7	11.3	9.5	10.6	12.2	35.6	119.1	163.6	92.4	33.3	24.1	14.9	44.8

Station number: 415.1
Location: Borlangpul Latitude: 27 58 27
River: Andhi Khola Longitude: 83 34 26

AVERAGE MONTHLY AND YEARLY DISCHARGE (in m3/s)
==

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Yearly
1996	2.8	2.8	2.5	2.2	3.4	12.9	60.9	77.3	36.0	14.2	6.7	3.7	18.8
1997	2.7	2.3	2.0	2.3	3.1	10.8	68.7	50.0	23.2	8.3	4.6	4.6	15.2
1998	2.8	2.3	2.3	2.9	5.9	18.6	80.8	124.0	26.7	16.2	7.1	4.1	24.5
1999	3.1	2.5	2.2	2.6	4.9	24.7	47.9	80.8	49.0	20.3	6.9	3.8	20.7
2000	2.8	2.3	2.0	2.9	5.9	43.5	66.7	65.1	34.2	8.9	4.6	2.7	20.1
2001	2.3	2.1	1.8	1.5	5.4	31.2	47.1	78.8	30.7	6.1	2.5	1.6	17.6

2002	1.5	1.2	0.8	1.2	5.6	22.8	88.2	51.3	14.8	7.0	3.0	1.8	16.6
2003	1.6	1.5	1.1	1.9	3.4	25.2	65.5	28.3	34.7	8.2	4.1	3.0	14.9
2004	2.8	2.4	2.3	2.6	3.2	13.8	44.7	31.9	38.2	14.3	4.5	2.9	13.6
2005	2.4	2.0	1.8	1.9	3.0	5.7	30.1	36.1	19.7	15.4	6.4	3.4	10.7
2006	2.6	2.1	2.1	2.1	11.3	20.5	38.2	39.3	42.3	9.4	4.8	3.5	14.8
2007	2.6	3.8	2.9	2.8	4.0	20.6	55.5	31.3	61.2	12.0	3.9	2.4	16.9
2008	2.0	1.7	1.6	1.8	2.7	20.9	22.3	37.9	38.2	9.9	4.4	2.9	12.2
2009	2.4	2.0	1.7	1.5	3.0	11.5	24.4	57.5	20.4	20.5	1.9	0.8	12.3
2010	2.0	2.0	1.7	1.6	2.8	10.6	57.2	51.7	36.9	9.1	4.1	2.5	15.2
2011	2.1	1.7	1.3	1.1	4.5	15.3	55.2	45.9	36.3	11.4	5.1	3.0	15.2
2012	2.1	2.0	1.6	2.1	2.2	11.4	58.3	34.6	33.5	7.5	3.4	2.2	13.4
2013	1.8	1.9	1.5	1.9	3.1	23.6	66.2	41.4	20.0	10.1	4.6	3.0	14.9
2014	2.1	1.7	1.5	1.0	1.2	12.9	41.4	108.0	26.1	10.5	3.3	1.9	17.6
2015	1.7	1.3	1.3	1.3	1.9	7.7	41.4	50.8	42.6	10.0	5.5	3.0	14.0
2016	2.0	1.7	1.3	0.9	3.3	27.7	92.3	11.3	38.8	17.0	8.2	4.1	17.4
2017	2.9	1.9	1.8	2.0	3.4	11.9	43.3	48.6	33.0	16.8	5.7	3.6	14.6
2018	2.6	2.0	1.7	2.0	3.0	23.4	60.2	58.0	36.0	10.8	3.9	2.2	17.1

Station number: 419.1

Location: Ansing Latitude: 27 53 5

River: Kali Gandaki Longitude: 83 47 42

AVERAGE MONTHLY AND YEARLY DISCHARGE (in m3/s)

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Yearly
1996	112.0	112.0	101.0	93.0	130.0	386.0	1360.0	1650.0	889.0	417.0	227.0	140.0	468.0
1997	109.0	95.0	86.1	96.4	123.0	334.0	1500.0	1160.0	622.0	270.0	169.0	169.0	395.0
1998	113.0	94.9	95.3	115.0	204.0	519.0	1710.0	2420.0	696.0	464.0	238.0	152.0	568.0
1999	121.0	103.0	93.5	106.0	177.0	655.0	1120.0	1710.0	1140.0	559.0	232.0	142.0	513.0
2000	112.0	94.4	85.4	115.0	204.0	779.0	1430.0	1690.0	1340.0	375.0	206.0	132.0	546.0
2001	105.0	91.0	82.6	84.9	145.0	500.0	1230.0	1830.0	913.0	312.0	179.0	115.0	466.0
2002	97.0	87.8	82.2	96.1	167.0	347.0	1260.0	1240.0	618.0	270.0	138.0	105.0	376.0
2003	86.8	75.6	76.1	90.6	109.0	418.0	1240.0	1390.0	1120.0	368.0	172.0	110.0	438.0
2004	94.3	74.6	74.6	75.5	107.0	261.0	880.0	929.0	756.0	424.0	158.0	114.0	329.0
2005	90.8	78.3	76.2	78.2	95.9	206.0	1010.0	989.0	573.0	371.0	185.0	119.0	323.0
2006	91.1	77.2	69.2	73.5	155.0	320.0	862.0	767.0	629.0	283.0	143.0	97.3	297.0
2007	75.8	79.5	83.3	98.0	118.0	306.0	1140.0	1230.0	1160.0	459.0	210.0	123.0	423.0
2008	101.0	80.6	80.8	97.0	118.0	509.0	921.0	1540.0	758.0	310.0	164.0	121.0	399.0
2009	84.3	77.0	68.8	75.1	104.0	186.0	895.0	1310.0	607.0	595.0	190.0	121.0	360.0
2010	90.8	79.3	75.7	84.6	89.9	195.0	1020.0	1220.0	1390.0	349.0	172.0	119.0	408.0

2011	98.6	75.9	82.8	77.6	124.0	322.0	1210.0	1310.0	798.0	349.0	186.0	120.0	396.0
2012	94.0	81.7	72.3	85.5	106.0	289.0	928.0	1140.0	959.0	314.0	182.0	119.0	364.0
2013	99.4	106.0	93.2	103.0	159.0	769.0	1640.0	1190.0	687.0	343.0	145.0	98.7	453.0
2014	91.0	80.1	74.3	73.7	97.2	214.0	916.0	1380.0	665.0	367.0	196.0	117.0	356.0
2015	86.1	78.8	78.2	92.9	146.0	277.0	600.0	1020.0	528.0	269.0	141.0	83.1	283.0
2016	73.5	72.0	64.8	55.5	74.6	319.0	1780.0	857.0	872.0	439.0	186.0	129.0	410.0
2017	87.5	74.8	64.7	72.8	76.9	192.0	976.0	1270.0	665.0	305.0	160.0	117.0	339.0
2018	89.0	93.6	79.1	88.2	101.0	286.0	926.0	1260.0	723.0	268.0	196.0	123.0	352.0

APPENDIX – C

Trial Rule Curve Elevation

Table: Trial Rule Curve Elevation of Kaligandaki Reservoir in both Scenarios

Date	Trial 1	Trial 2	Trial 3	Trial 4
1-Jan	735	745	747	746
1-Feb	730	735	732	735
1-Mar	725	725	726	728
1-Apr	721	721	723	726
1-May	730	726	720	724
1-Jun	735	730	727	721
1-Jul	740	740	745	735
1-Aug	750	749	749	748
1-Sep	749	750	750	750
1-Oct	745	750	750	750
1-Nov	742	750	750	750
1-Dec	740	750	750	749

Table: Trial Rule Curve Elevation of Adhikhola Reservoir in both Scenarios

Date	Trial 1	Trial 2	Trial 3	Trial 4
Jan	670	695	695	698
Feb	660	680	680	680
Mar	645	665	665	665
Apr	633	633	633	633
May	623	623	628	628
Jun	630	630	624	624
Jul	640	650	650	650
Aug	650	690	680	680
Sep	700	700	695	699
Oct	695	700	700	700
Nov	690	700	700	700
Dec	680	700	700	700

Table: Trial Rule Curve Elevation of Lower Badigad Reservoir in both Scenarios

Date	Trial 1	Trial 2	Trial 3	Trial 4
1-Jan	665	670	675	680
1-Feb	660	660	665	670
1-Mar	658	655	657	665
1-Apr	654	654	655	660
1-May	660	655	654	657
1-Jun	670	670	665	655
1-Jul	680	683	680	670
1-Aug	688	685	686	686
1-Sep	685	688	688	688
1-Oct	680	688	688	688
1-Nov	675	688	688	688
1-Dec	670	688	688	687

APPENDIX – D

Trial Simulation Output

Table: Simulation Output of all Reservoirs in both Scenarios

Storage Project	Operation Rule Curve Trial	Firm Power (MW)	Average Annual Energy Generation (GWh)				PI for Dry Period Firm Power (%)		
			Total	Dry	Wet	Dry Percent	Reliability	Vulnerability	Resiliency
Kaligandaki	1	220	4735.9	1606.4	3129.5	0.3	89.3	6.1	2.7
	2	220	4801.8	1714.8	3086.9	0.4	98.5	1.9	3.2
	3	220	4818.6	1731.6	3086.9	0.4	95.5	5.8	3.2
	4	220	4825.6	1731.1	3094.5	0.4	96.0	3.8	3.0
Adhikhola	1	38	950.4	319.5	630.9	0.3	98.8	113.0	39.1
	2	38	953.5	422.6	530.9	0.4	97.1	40.2	12.6
	3	38	950.6	426.6	524.0	0.4	93.4	18.2	5.5
	4	38	955.6	426.7	528.9	0.4	93.4	32.2	9.5
Lower Badigad	1	80	1759.5	448.7	1310.8	0.3	62.6	21.8	1.9
	2	80	1786.5	550.7	1235.8	0.3	66.8	17.6	1.5
	3	80	1806.8	571.4	1235.4	0.3	78.3	13.5	2.2
	4	80	1842.2	600.4	1241.9	0.3	96.0	8.3	3.6