# Hydropower Optimization of Cascading Run-of-River Projects on Kunhar River

By

**Zarak Khan Mahsud**

**(MS WRE&M 2020, 00000327567)**

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This is to certify that the

Thesis entitled.

# Hydropower Optimization of Cascading Run-of-River Projects on Kunhar River

Submitted by

**Zarak Khan Mahsud**

(MS WRE&M 2020, 00000327567)

Has been accepted in partial fulfilment
Of the requirements
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**Dr. Shakil Ahmad**
**Associate Professor**
**NUST Institute of Civil Engineering (NICE)**
**School of Civil & Environmental Engineering (SCEE)**
**National University of Sciences & Technology, Islamabad**

# THESIS ACCEPTANCE CERTIFICATE

It is certified that final copy of MS thesis written by Mr. Zarak Khan Mahsud, Registration No. 00000327567, of MS Water Resources Engineering and Management (WRE&M) batch 2020 (NICE), has completed his thesis work and submitted the final copy which was evaluated & found to be complete in all aspects as per the policy of NUST Statutes/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfilment for award of MS degree.

Signature:

Name of Supervisor: Dr. Shakil Ahmed

Date: 26/07/2023

Signature (HOD): H. F. Gabriel

HoD Water Resources Engineering and Management
UST Institute of Civil Engineering
School of Civil & Environmental Engineering
ational University of Sciences and Technology

Date: 26/07/2023

Signature (Dean/Principal):

PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

Date: 29 AUG 2023

# DEDICATION

Dedicated to my believed Parents, Family and Teachers for their unwavering support throughout my academic journey.

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# ABSTRACT

Pakistan has a huge potential for the natural resources and the exploitation of surface water for the generation of hydropower energy is the cheapest option for the country. The province of KP is a reserve for untapped 30,000 MW and Kunhar river is a major stakeholder in energy potential. Kunhar River is currently selected for five hydropower projects for generating enough electricity for the people of KP and Kashmir. Of the five projects, the study focused on the effect of Suki Kinari dam on the downstream Patrind Weir under optimized release conditions, the latter being in operational. The first phase was rearranging of Patrind Weir to match the observed outcome of the plant as the existing operation of the project contradicted the design. An efficiency curve was deduced with R^2 =0.8,0.79,0.8 &0.79 for the available information from 2018-2021. Separate calibration and validation tools were employed to convince the applicability of the global efficiency of the turbines. The second phase involved the cascading effect of Suki Kinari on Patrind's power output which constituted the core of the study. Operational guide curves for Suki Kinari's impact were considered for 2018-2021 and witnessed a low impact on the power production from turbines at D/s plant. Two scenarios were tested under the guise of optimal annual energy from both projects working in cascade. Optimal guide curves were produced for Suki-Kinari under the limited data, but they produced satisfactory response. The low turnout of the scheme can be directed to actual flow not according to design flow duration curve. Furthermore, the shallow impact of Suki Kinari on Patrind might possibly be due to vast distance between the two reservoirs separated by large catchment area that is subjected to strong climatic event of precipitation at Balakot and Talhatta. Thus, analyzation of cascading effect of Suki Kinari requires the involvement of Balakot dam which lies in between the reservoirs in this study and longer duration of hydrological dataset for the catchment in necessary.

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# List of Abbreviations

**ResSIM:** Reservoir Simulation

**HEC:** Hydrologic Engineering Center

**ROR:** Run-Of-River

**PPIB:** Power and Private Infrastructure Board

# CHAPTER 1

# 1- INTRODUCTION

## 1.1 Background

Water resources were the cornerstone the source of the beginnings of civilizations, and their abundance was a measure of growth and success. exists as an aquifer beneath the A major role played in the survival of civilization was the use of surface water, especially streams and rivers to drain watersheds. Rivers are used to meet multiple human and marine needs, including irrigation supply, industrial consumption, sanitation, waste collection, transportation, treatment and disposal, fisheries supply, domestic use, and environmental protection. To take advantage of this versatile and diverse river expectation, dams are built to meet them. One of the most compelling benefits of reservoir formation is the ability to harness the potential and kinetic energy of water to generate electricity. Hydropower is by far the most widespread form of renewable energy (OECD/IEA, 2010). Harnessing Hydropower to Maximize Hydropower Potential (Khan & Zaidi. 2015)

Energy production is not an easy task, as multiple interests must be considered, such as Dams can be employed for fulfilling irrigational needs, industrial needs, domestic needs etc., and managing all of them together proves to be a complex challenge for Water Managers and operators. Coupled with Climatic Uncertainty, it becomes necessary for proper and careful operation of reservoirs. The complexity of pool control and release depends based on functionality. The Reservoir projects can be divided into single or multipurpose and management becomes difficult with ever increase in priorities. A single purpose can be solely attributed for irrigational transmission or hydropower production and the latter is the core interest of this study, specifically termed as Run-Of-River Hydropower Projects (ROR-HPPs). ROR projects has the advantage of being less costly, small in structure thus reducing quantity of material, and can work without a reservoir thereby reducing environmental impact caused by floods (Pedro Ney Stroski, 2019). The operation of RORs became sophisticated when a river hosts a cascade of them with sustainable reservoirs. A cascade system of reservoirs means dams that exist in a series from upstream to downstream on one river network and the flow from U/S reservoir has a profound effect on D/S reservoirs storage and release. The planned structures in Kunhar River basin are an example of cascade dams and a unique feature in Pakistan.

As mentioned, complex situation arises when a reservoir has to feed various downstream interests and prioritizing needs special techniques to handle them. In replacement of conventional methods, mathematical programming setups such as simulation and optimization models have been heavily used for optimum results and decisions. Simulation models have been used for decades and innovation in technology is bringing improvement in precision and accuracy of results. It is based on a trial-and-error approach where input parameters are used to obtain certain results. This method is time consuming but is computer friendly and provides near-optimum solutions. Based on such approach USACE has a powerful tool for reservoir simulation known as HEC-ResSim which has built-in physical and operational constraints in simplified, user-friendly interface that acts as an alternate mathematical expression for interrelation of variables within the reservoir system. Optimization models are gaining wide interests among researchers due to their optimal and quick solutions which outweighs simulation models but due to their complexity in usage and expressing constraints, valuable expertise is required. But, as HEC-ResSim have showed in many studies as being a competitive tool in optimizing flows, the study employs to test its performance.

## 1.2 Problem Statement

Only 6,600 MW of Pakistan's 60,000 MW hydro potential has been utilised, with KP province housing roughly half of it. The Khyber Pakhtunkhwa is capable of producing close to 30,000 MW of power (PEDO, 2016). The governments have recently started to understand the importance of such potential. The existing reservoirs and dams in Pakistan have been operated for power production using traditional methods, such as zoning and SLOP, which doesn’t account for environmental and economics of water flow. This technique causes rigidness and operation has no flexibility to change, thus leading to losses and drawbacks. And the current operating reservoirs are wasting a lot of water with high sediment deposition and poor power generation. Previous HPPs have not been designed and operated to their full extent because dam’s operation followed rule curves that has been a product of an engineer’s knowledge and experience which is open to errors and mistakes and full potential of reservoirs are missed out and remain untapped. Reservoir operation is a complex process for operators and engineers as it involves many constraints, purposes and stakeholders and requires modern models. Previously, operation of dams has been optimized but only on an individual level which excluded the use of technological advance methods and models. It has been a cause of concern and with changing climate situation a mathematical program is necessary for daily management of reservoirs in Pakistan. The present case study utilizes 2 hydropower projects, existing in series of a cascade system, on the Kunhar River of which 1 is operational. Using a simulation model to prepare for optimal dam functioning of the 2 HPPs is the objective for this study. The projects have been initiated by the provincial government to remove dependency from fossil fuels and IPPS to a greener form of energy, and Kunhar River Basin with its steep gradient provides an optimal area for hydropower generation. Therefore, the employment of a simulation model, such as HEC-ResSim, can be helpful to present the real time situation of the cascade dams beginning at Suki Kinari and ending at Patrind. The real challenge posed by the operation of the cascade is the un-existence of dam structure and daily operational rule curves. Thus, the model will be employed to find the optimal guide curves for future operation. The simulation model uses the storage equation and displays the entire stream network in a user-friendly graphical user interface. Using the model, the cascade system can be optimized, and suitable guide curves can be developed for maximum energy production at minimum cost during peak hours. It will be the required result of the research.

## 1.3 Research Objectives

Preparing regulations for maximum hydropower generation when all three dams are operated in tandem in a cascade is the research study's overall priority. As a result, the impact of Suki-Kinari on Patrind will be examined, with power generation serving as the primary research goal. This study aims to accomplish the following:

a) To successfully replicate real on-ground hydrological and hydraulic features of the Kunhar River Basin,
b) To use HEC-ResSim for alternate scenarios and effect,
c) To evaluate the cascading effect of U/S project on the D/S projects in relation to power,
d) To prepare guide curves for under construction dams,
e) To optimize the release of water from reservoirs,
f) To obtain optimal operational rule curves for hydropower generation,
g) To optimal usage of reservoir capacity in tandem for optimal power production during seasonal variation,
h) To successfully calibrate and validate HEC-ResSim model,
i) To Prepare model for future use,

## 1.4 Scope of the Study

This study will collect data from ArcGIS and feasibility reports as a basis for creating a hydrological model with USACE's proprietary numerical simulation model. HEC-ResSim evaluates different control curves to arrive at a near-optimal solution for the optimal trajectory for hydropower. Reservoir discharge and storage are operated simultaneously as a series of U/S dams impact the dams below. Observed and simulated reports are analysed and final rules are developed to mimic the project at the start of the project. The Patrind Weir HPP is positioned as closely as possible to ground-based observations and reality through simulations in HEC-ResSim. It will be used as a guide to prepare the dam for Pakistan.

## 1.5 Significance of Study

The study is considered important for water management and power generation in a country like Pakistan. The state is deeply scrutinized by the inadequate operation of consumer consumption reservoirs, resulting in low storage, low discharge and accumulation of sediments. Current research is focused on providing a control curve for the generation of successive His three reservoirs and proper operation to maximize reservoir capacity. Suki Kinari and Patrind series. This reduces water loss downstream and minimizes costs.

## 1.6 Organization of Thesis

The organization of chapters are as following:

**Chapter 2**: Study Area Description

This chapter covers the Kunhar river basin, mainly from Suki-Kinari Station to Patrind Weir. Provides details of HPPs en-route from U/S to D/S along with their numbers and reservoir details.

**Chapter 3**: Literature Review

The research that HEC-ResSim has used for the past 20 years is summarised in this chapter, along with the numerous reservoir modification methods employed by dam operators. The management of reservoirs using traditional and contemporary methods is also covered in this chapter.

**Chapter 4**: Research Methodology

The strategies employed in the study to reach the desired conclusions are discussed in this chapter. The approach picked is what determines the outcomes and reviews. It focuses on outlining the HEC ResSim model, including the data needed, how it is collected, and how it is produced.

**Chapter 5**: Results

Results of the simulations' reliability, resilience, and vulnerability indices are discussed in this chapter with examples.

**Chapter 6**: Model Evaluation and Calibration

The statistical methods and tools for calibrating and validating the best fit model will be briefly described in this chapter.

**Chapter 7**: Discussion and recommendations

Conclusions and suggestions derived from the simulation of the cascading Kunhar catchment dams.

# CHAPTER 2

# 2- LITERATURE REVIEW

## 2.1- RESERVOIR

Water resource systems are made up of many natural and man-made elements such as atmospheres, watersheds (watersheds), rivers, wetlands, floodplains, aquifers, lakes, estuaries, seas and oceans. Reservoirs are the most important of them. A reservoir is created by building a dam or weir over a stream. The main function of reservoirs is to store water during the rainy season and release it as needed during future dry seasons, helping to regulate the supply of water for runoff. It manages the spatial and temporal availability of water for various purposes such as hydropower, irrigation, navigation, and recreation.

Half of the world's major river systems are affected by reservoirs and dams through which people manage water resources for power generation, water supply, navigation, disaster prevention, flood control and mitigation, and drought mitigation and use (Dynesius and Nilsso, 1994; WCD, 2000; ICOLD, 2011; Lehner et al., 2011; Shang et al., 2018).

As one of the clean energy sources, hydropower is the most important renewable energy source worldwide and can be developed on a large scale (Tayebiyan et.al., 2019). We can reduce the use of fossil fuels to generate electricity and reduce her CO2 emissions in the world. Hydropower contributed 16.5% to global electricity generation in 2012, while other renewables contributed only 5.2% (Spaenhoff, 2014 & Jiang et al. 2018).

Compared to other energy sources, hydropower is clean, non-polluting, fast in output, and able to adapt quickly to load fluctuations in the power system (Sharma et al., 2002 & Jiang et. al., 2018). Moreover, water is the only significant input for hydropower (Paish, 2005 & Jiang et.al., 2018), an intermittent technology, unlike wind and solar, which use resources only now. Unlike, water is available and usable all year round. Hydropower is therefore an excellent source of energy that helps maintain stable production, sustainable growth, and quality of life (Sánchez et al.).

## 2.2- RESERVOIR OPERATION

### 2.2.1 Operation

Operation of the stored water or flood water is of utmost importance for stakeholders downstream of a reservoir. The functioning of the reservoir complexity depends on the objective and purpose of the structure. Various uses for the stored water create conflict of need and purpose, leading to complexity in reservoir operation with less effort for coordination required for compatible interests (Jain, 2003). The various purposes surround recreational, navigational, irrigational, hydroelectric power, Municipal and industrial water supply, Flood control needs. For multipurpose dam, conflict emerges among the various needs in time, space and discharge of the reservoir.

Our study specifies on the single purpose of the cascade reservoirs on the Kunhar River, that is, hydroelectric power generation.

### 2.2.2 Operation Techniques/Policies/Rules

According to the condition of the reservoir, the degree of demand, and any knowledge of the probable inflow into the reservoir, a reservoir operation policy determines the amount of water to be released from the storage at any moment. Making decisions about reservoir releases that will maximise the benefits for that purpose is the operation challenge for reservoirs with a single use. The primary aim of reservoir operation is to determine how much water should be released now and how much should be conserved for future usage based on information that is now available and/or anticipated. (Celeste & Bilibe, 2009).

A reservoir is operated according to a set of rules or guidelines for storing and releasing water depending upon the purposes it is required to serve. Based on the temporal and spatial demand variability, the release policy of the reservoir is affected. For a multipurpose dam, care is taken to understand the correlation of each purpose and the release in accordance with the demands of stakeholders. Our study solely focusses on cascade of Run-Of-River dams that are single-purpose oriented towards electricity generation.

### 2.2.3 Slope

The simplest of the reservoir operation policies is the Standard Linear Operating Policy (SLOP) or Standard Operating Policy (Men et al., 2019, You & Cai, 2006, Neelakantan & Sasireka, 2013, Jain, 2003). It stresses, in a single period, on the release of water to meet target demands downstream without careful reservoir capacity preservation (Neelakantan & Sasireka, 2013, Jain, 2003). This policy releases water even if water inflow is low, or capacity is not enough to meet the target. Thus, creating water shortage, wastage, stiffness in operation. Day to day operation of reservoir comes with financial repercussions as no economic values are attached to water beyond target output (Jain, 2003) and leads to potential shortage crisis in later periods (You & Cai, 2006).

### 2.2.4 Zoning

This is a good technique in which a reservoir is conceptually divided into several storage zones based on calculated downstream requirements. These zones are known explicitly as runoff, flood control, conservation, buffer, and dead storage zones. The distribution of reservoirs within the zone depends on the engineer's knowledge and dam operating instructions, so the horizontal distribution may vary. In practical operation, it is expected that the contents of the pool will be kept in the designated zone to achieve the maximum expected profit (Jain, 2003).

This method is very flexible and gives the operator the freedom to manipulate the storage level in each zone depending on system inflow and hydrological conditions. If there is water in the floodplain zone or flood control zone, it is obligatory and implemented to drain all water within the two zones to prevent damage, and the downstream one has the largest amount and area of conservation zones. may be in Used for different needs. Although this policy is suitable for flood control, other purposes of reservoirs are difficult and contradictory.

### 2.2.5 Rule Curves

Rule curves are rule lines that manages the extent of storage capacity or empty spaces in the reservoir pool with respect to temporal variability of water availability or inflow. It does not direct the amount of water to be released and depends upon the inflows to the reservoir (Jain, 2003). Strict following of rule curves can be rigid as different routes have to be adopted to fulfil downstream target demands, such as when the storage levels are below release sufficient.

### 2.2.6 Simulation

In addition to the standard techniques mentioned above, researchers can ascertain a reservoir system's function and the interactions that occur within it by defining an objective function that is subject to a variety of social, political, financial, and other restraints. We have created a decision-support technique that takes the components into account. It is referred to as a system engineering approach that resolves the previously mentioned stiffness and time issues. Simulation and optimization are the two most common.

Simulation models are used to describe the behaviour of a system and predict changes resulting from a particular course of action (Ralph A. Wurbs, 1992). Such models are sometimes called causality models (Simonovic, 2009). The system's response is determined and described by the input parameters, but they lack the exact decision-making capacity to raise the system's performance. As a result, simulation is a system for solving problems, and simulation models are crucial to the management of water resource systems. (Simonovic, 2009).

The essence of simulation is an iterative process of modelling and experimentation (Simonovic, 2009), which does not lead to the exact results achieved by the optimization model. Simulation models use inflows (hydrology), operations (decision rules), and mass balance basin balances (connectivity) to describe the hydrological behaviour of a reservoir system.

Reservoir operators generally prefer simulation models to optimization models. This is due to the need for complex mathematical programming and computation of simulation models, especially where stochasticity exists in reservoir operation (Celeste & Bilibe, 2009). Optimization models can provide accurate solutions for complex water resource system scenarios, but their real-world application is sceptical because the models ignore uncertainty (Seifollahi-Aghmiuni et al. al., 2016). Simulation models are therefore useful to complement optimization models for more practical solutions. Perform reservoir system simulation studies to evaluate alternative operating policies and the impact of adding new reservoirs to the system.

Simulations are typically based on maintaining specific water use requirements and operational policies during assumed repetitions of historical hydrology (Wurbs & Yerramreddy, 2007).

Simulation models, unlike mathematical programming models, do not provide optimal solutions (Molnar, 2005), and focus on understanding the behaviour of water resources systems when they are operated at specific times with variable inputs. The ability to employ simulation models as analytical tools to foretell the effects of process modifications is a significant benefit of these models. It will happen a long time from now. The fact that simulation results are challenging to comprehend, and that simulation modelling and analysis are frequently time- and money-consuming are two significant drawbacks of simulation models.

As noted in Wurbs (1993), there are many generalized simulation models for river/reservoir operation, and the Texas Water Journal (2012) cites four state-of-the-art models: HEC - ResSim, RiverWare, MODSIM, and WRAP (Texas Water Journal, 2012). The main simulation model used in this study is HEC-ResSim, a continuation of HEC-5. All four alternative modelling frameworks are intended to replicate reservoir management goals such as flood control, environmental flows, water supply, and flood prevention.

The three models were developed primarily for conservation purposes, but HEC-ResSim is coded for flood control and management, an improvement over its predecessor HEC-5 for this purpose. HEC-ResSim computes in short time steps, providing great flexibility for flood control and reservoir operational simulations. In addition to the fundamental water accounting calculations, the modelling system offers a wide range of optional dependability features. WRAP has particularly extensive capabilities for reliability and frequency analysis (TEXAS WATER JOURNAL, 2012) and frequency analysis, economic assessment, water quality, and surface-groundwater interactions. Neither model can simulate groundwater, but there are no restrictions on the interaction of surface and groundwater, and WRAP and MODSIM have this special ability to access and compute information from MODFLOW.

### 2.2.7 Optimization

Over the past decade, researchers and water managers have implemented optimization methods in reservoir planning, design, and management to replace or complement simulation (Reznecik and Cheng, 1991).

This term refers to the maximization/minimization of project or system goals under various boundary conditions. Optimization eliminates the iterative process of simulating design changes to reach the right conclusions. Instead, optimization models automatically change design parameters using mathematical formulas that act as constraints, describe the system, and generate design changes based on these parameters (Mays and Tung, 1992). An optimization procedure depends on three aspects: objective function, constraints, and decision variables. In doing so, it employs traditional reservoir operation methods that rely heavily on the operator's experience and intuition to provide optimal decisions for operating the reservoir. The essence of simulation is a trial-and-error process of modelling and experimentation. Simulation does not directly provide an answer to a given problem but represents a time-consuming process of achieving near-optimal results (Simonovic, 2009).

Optimization procedures have mathematical formulas that describe the system and its response to system inputs for various design parameters. These formulas are the constraints of the optimization model. However, simulation models are less mathematically and graphically complex than optimization models. As the focus of this study is based on reservoir utilization for power generation under different scenarios and rules using simulation models, this study is based on HEC-RESSIM, approved simulation models and HEC-RESSIM. 5 updated version and used for best results. It is the result of an iterative function for maximizing the hydroelectric power generation of the Cascade Reservoir on the Kunhar River.

## 2.3 HEC-RESSIM MODEL

### 2.3.1 Background

For controlling flood discharge, water consumption, and the production of hydroelectric power, the US Army Corps of Engineers creates reservoir simulation tools and models like HEC-3, HEC-5, and HEC-ResSim. The reservoir operations simulation calculator, graphical window, data management features, and results display of the HEC-ResSim model replace the HEC-5 model (Klipsch and Hurst 2007).

Complex scenarios such as multi-objective systems with multiple reservoirs are simulated using built-in algorithms, requiring the application of formal mathematical programming (optimization) such as linear programming or dynamic programming. there is no. The

model can simulate a single event or events over a period. HEC-ResSim has been used to simulate reservoir manipulation for a variety of purposes, including B. Water supply for planning studies, flood management, hydropower, low-flow augmentation, extensive analysis of reservoir regulation plans, and real-time decision support for reservoir operators (TEXAS WATER JOURNAL, 2012). A shared data storage system (DSS) with another HEC model is a crucial component of HEC-ResSim. In an effort to mimic the decision-making process that real reservoir operators must employ to determine clearances, this tool stands out among reservoir simulation models (Klipsch and Hurst, 2007).

### 2.3.2 Working

Three distinct modules make up the HEC-ResSim model, each of which is crucial for creating and computing results for changing input parameters. The first one, the Watershed Design module, enables the setup of stream alignment, the drawing of the locations of reservoirs, levees, diversions, and off-storage regions, and the use of computation points and junctions as rating curve inputs into the streams. The user can create the network map details and describe the reservoir's operational and physical components, including additional routing reaches and alternate analysis scenarios, in the reservoir module. The simulation module establishes the simulation's parameters and analyses the outcomes. HEC-ResSim can be used to model practically any single- or multi-purpose reservoir system because to its generalised nature, flexible methodology for describing reservoir operations, and potent new features (Klipsch and Hurst, 2007).

Control points typically come before computations in an upstream-to-downstream order. A user may choose a computation time step that lasts anything between 15 minutes and a day. Muskingum, Muskingum-Cunge, modified Puls, and more approaches are available for streamflow routing. Streamflow hydrographs can be generated using the HEC-HMS or provided as input to HEC-ResSim from any source. Modeling is possible for multi-reservoir systems with several outlet structures in each reservoir. Release decisions are made in accordance with a set of regulations that outline the objectives and limitations controlling releases while the storage level is within each of the designated storage zones, which are determined by elevation. (TEXAS WATER JOURNAL, 2012).

### 2.3.3 Review

The recently updated version of HEC-ResSim, which offers the increased features that help to address complicated difficulties in reservoir operation, is briefly described in **Klipsch and Evans' (2005)** brief overview. A network made up of junctions, routing reaches, diversions, and reservoirs is how HEC-ResSim depicts a system of reservoirs. The most intricate part of the reservoir network is the reservoir and the pools. The dam is where the reservoir network in HEC-ResSim becomes truly intricate. The scientists predicted that the existing model would have quick computations and better simulations in the future.

**Mulungu et al., (2007)** used HEC-ResSim as a vital tool to understand the poor hydropower performance of NyM reservoir in Tanzania by comparing it with results of Water Balance Model (NWBM), (Mulungu, 1997). Two scenarios of irrigation abstraction and non-abstraction were considered to see the hydropower generation where the abstraction caused a reduction of inflow to the reservoir and subsequent lower production. Without including information on water losses due to evaporation, seepage, and unaccounted-for water in the water balance, the reservoir simulation model HEC-ResSim gave findings that were comparable to the water balance. As a result, HEC-ResSim produced results that were less precise than those of the water balance model, but it was also more realistic and accurate due to the inclusion of numerous new constraints.

**Piman et al., (2013)** conducted a crucial study on the effects of potential dams and reservoirs within the 3S Basin of Mekong River by incorporating SWAT and HEC-ResSim models. SWAT was used for hydrological assessment and providing inflow data for the simulation model, HEC-ResSim. The simulation, based on 20 years historical data for the 3S Basin, performed satisfactorily and gave good prospects for future power generation by releasing and storing water in different seasons. The authors showed hope of improved results if climate change effects on inflow streams and hourly inflow records are available.

**Uysal et al., (2013)** evaluates the flexibility of HEC-ResSim model performance by comparing simulated guide curves using the original operation and model's user defined curves. An acceptable conclusion was drawn that the simulation model was capable for real time operation. The model can be utilised as a decision support tool for operators because there is no water scarcity, the risk of flooding is reduced by late storage, and spillways flows do not exceed channel capacity.

By integrating LINGO, an optimization model, and HEC-ResSim, a simulation model, **Ziaei et al. (2014)** demonstrated the value of using optimization-simulation approaches and carried out an important study to lay out monthly operating rules for the Zayandeh Rud Reservoir system. This study covered two main objectives: to derive an optimal operation policy for distributing the amount of allocated water and to simulate reservoir conditions using optimised data. The test was run to compare the favourable outcomes of dam releases based on both the non-optimized and optimised conditions of the dam. According to the findings, Zayandeh Rud Dam operation might be optimised to improve reservoir storage and decrease the ratio of full to empty reservoirs. The most encouraging feature of the model revealed that, compared to standard settings, the reliability index under optimised conditions was quite high and that, under ideal operating conditions, a higher percentage of water supply would be guaranteed.

**MERSHA et al., (2014)** conducted a survey on cascade dams based in the Eastern Nile Basin and HEC-ResSim was used a simulation tool for simulating the water system in the basin. Eight scenarios were tested using the established HEC-ResSim Model, and the results were evaluated based on the basin's capability for generating power and the availability of water at important locations. Although no such rule curves or operation rules were implemented, the paper did claim that the model had been successfully configured to allow flexible combination of management actions in the basin to simulate varied effects for the downstream countries. As a result, the paper's illustration of the model results was unclear.

**Khaing (2015)** presents a study to understand the climate change effect on the future of hydropower generation in the Mytinge River Basin by applying HEC-ResSim, the reservoir simulation model. Climate model coupled with HEC-HMS generated the inflows into the reservoir and HEC-ResSim was used to examine how hydropower generation can vary for future climate scenarios. The simulation produced acceptable results for calibration a validation and showed a trustworthy model for analysing future impacts of climate change.

**Wondimagegnehu and Tadele (Dec-2015)** complimented the use of HEC-ResSim with HEC-HMS for the future climatic impact on the Beko-Abo, Mandaya and Border reservoirs storage capacity, release, and power generation efficiency. The performance of the hydrological model was assessed under the NSE ratio alone which gives rise to some scepticism over the proper validation and calibration. Even the RCM climate scenarios are not clearly mentioned, or detailed, just temporal values are given. The authors fail to provide graphical evidence to HEC-ResSim simulation for all the three reservoirs in terms of power and flow release except for origin of the cascade reservoir system, i.e., Beko-Abo. Hopeful results were presented without proof and no calibration or verification tests conducted for the validity of the simulation model.

To arrive at a definite conclusion in favour of either model in the short-term operation of flood management of the Yuvack Dam Reservoir, **Uysal et al. (2016)** compared simulation and optimization models. The simulation model HEC-RESSIM and the optimization method RTC-Tools package of Deltares were used. The following were the short-term operating success criteria for both models:

- to achieve the initial daily level once more at the conclusion of the event.

- to avoid flood risk for downstream channel with the scenario flood hydrograph (to turn back daily operation strategy),

The study's findings indicated benefits for both approaches. The advantage of the optimization model was that it immediately offered the best options for the pre-release and maximum spillway discharge, whereas the HEC-ResSim simulation model only provided the maximum discharge based on the operator's trial-and-error approach. But as it delivers spillway discharge in terms of individual gates, ResSim integrates user-friendly modules, regulations, and complete information of the reservoir management. In terms of flood control and reservoir replenishment after the storm, both models met their intended goals. Using either model will depend on the operator's knowledge and expertise because the RTC optimization model requires a higher skill set than the simulation model, which uses the fundamental mass balance equation for simple release guidance principles.

**Jebbo and Awchi (May-2016)** studied the performance and accuracy of HEC-ResSim in simulating the Mosul Dam reservoir by comparing the control rule curves and annual hydroelectric generation with the original observed status. The model efficiently showed its resemblance to observed data especially in the annual average energy generation. But the comparison with optimization models was not a correct standard as the energy generation simulated using HEC-ResSim falls behind the other studies, though the real system replication was impressive.

For the Nowane Catchment in Botswana, **Alemaw et al., (Oct-2016)** used a hybrid modelling technique with HEC-ResSim as the simulation model and a reservoir reliability analysis (RRA) model. Reliability, resilience, and vulnerability are all included in this study's use of the RRA model. Using a Microsoft Excel application, the HEC-ResSim model's output was analysed using the RRA model. Based on numerous scenarios, both models worked well, and the results did show that the dams' prospects could be dire. However, the scientists did point out a significant drawback of HEC-ResSim, namely that it is unable to run simulations on a monthly time scale. As a result, the computer model's ability to evaluate and analyse historical data for the operation of water supply reservoirs is limited.

For the evaluation of three projects in the Panama Canal for discharges in spillways, hydroelectric generation, navigation, industrial usage, and consumptive use, **Gobetti (2017)** used HEC-ResSim throughout the planning phase. The HEC-ResSim model preserved the reservoir level as close to the guide curves as possible since the operation of each reservoir was governed by the storage and release zone in which the reservoir level was positioned, leading to guide curves. The R2, NSCE, and RMSE coefficients were satisfactory, and there were small variations between simulation and observed values. There was also evidence of an exceptional reliability percentage. Therefore, HEC-ResSim can be a simple to use tool for planning and operating multi-reservoir systems with proper check on state variables and key parameters.

**Jebbo and Awchi (Apr-2019)** utilized HEC-ResSim to maximize the output of the undergoing construction of Jazeera Irrigation projects connected with Mosul Dam. Six different scenarios were analysed each with different priorities, one alternative preferring hydropower generation and the other irrigation water supply. Using statistical performance perimeters, the model performed well and projected values for the different scenarios. The conclusion was disappointing for the authors as with operation of the three irrigation projects, the model showed that reduced energy and water supply were to be suspected.

**Theara et al., (May-2019)** published a paper to assess the behaviour and effect of the post-construction of a multipurpose dam in the Stung Sen River, Cambodia. Fulfilling prerequisite data requirement from SWAT and other sources, the HEC-ResSim tool was employed to simulate regulated flow from the dam. The study integrates a hydrological model and reservoir simulation model to analyse different release regimes and scenarios, namely Full-Level, Low level and Seasonal Flow alternatives. Based on water availability on the downstream side for communities and fisheries, HEC-ResSim tool showed that the Seasonal variation rules helped to increase flow downstream by highest percentage in the wet and dry periods and flood impact was manageable.

**Sorachampa et al., (Nov-2019)** integrated HEC-ResSim model with modern optimization algorithm, known as PSO for the maximum production of hydroelectricity in the cascade reservoir system. Particle swarm optimization algorithms provided optimal reservoir operation for the 3 reservoirs under study for 3 specific cases of dry, wet and normal years. The simulation of the operation was successfully calibrated and validated and the optimized operation showed a reduced spillway discharge and higher power generation in the 3 cases compared to traditional operation procedure. Thus, this study approves of a combined optimization and simulation approach with HEC-ResSim as the simulation model and any modern algorithm for optimization.

To prepare an operation model for the Kakki Reservoir combined with remote sensing data and to illustrate the alternative operational methods to lessen the impact of the 2018 floods, **Ryan et al. (July-2020)** adopts a novel methodology by integrating HEC-Hms and HEC-ResSim. The model was successful in pointing out that reserving greater storage, reducing peak outflow, and early reservoir water release could have helped to mitigate the damage caused by the 2018 floods. The innovative method demonstrated that, when in situ data for reservoir properties, such as storage-area-elevation curves, are lacking, remote sensing data can be a useful substitute for them. Such a methodology allows a plan to be tested in different nations and is appropriate for any reservoir.

**Ampitiyawatta (Sept-2020)** provides clarified report on the difference between the output of a conventional operation model and HEC-ResSim simulation model over the hydropower generation and flood discharge control. The target of the study was Qingjiang cascade reservoir system and analyses were to be done for wet, dry and normal years of inflow, outflow and storage of the reservoirs in series. HEC-ResSim, in comparison produces better and higher values of power output and less spill release during wet and normal years and there was no significant difference in the dry and non-flooding season. But the author still did not mention optimal release, storage or power generation and no recommendation has been given. Thus, it stresses the point that the author’s result can be improved further with more detailed parameters and iteration.

**Ampitiyawatta (Oct-2020)** reattempts the study of **Gao (2009)** by adding HEC-ResSim as the third alternative to compare with combined reservoir operation model, and conventional model. The study was performed on the Qingjiang cascade reservoir system. Though, the optimization model using PSO in combined model produced exemplary results in spill release reduction and saved a lot of flood water compared to HEC-ResSim. But the annual power generation values, for the two operation models, were far better than conventional model with insignificant difference between each other. Thus, with proper time intervals and accurate computer inputs, HEC-ResSim might provide near-optimum results.

The Seyhan Reservoir is at the end of a cascade of reservoirs upstream, and **Ozkaya and Zerberg (Mar-2021)** offered a conclusive and detailed explanation of applying the HEC-ResSim model for the optimal functioning of the reservoir. The USACE tool was used on 33 years of hydrological data for the reservoirs mentioned above as well. The use of alternate scenarios, such as using an open channel or a pressurised channel, for the provision of irrigational water from a reservoir is provided for the first time in this study. A notable difference in the amount preservation was noted while employing the latter form of transmission. With this study, it was made clear that the transmission line modernization via tandem reservoir operation regulations can help to alleviate the water supply issues for current reservoir systems.

**Abdulateef et al., (Aug-2021)** used HEC-ResSim tool to simulate discharge from Mosul and Dokan reservoirs to Samarra Barrage downstream during dry season. The model successfully simulated a flow from the barrage close to the reported values and the storage pool elevation remained in the active conservation zone. The authors used the interesting new algorithmic operation rule of IF-BLOCK function and provided strict constraints for release, whereby the storage capacity in the two upstream reservoirs was properly modelled and positive release yields with verification ratios of R^2 = 0.94 and NS = 0.87 were obtained.

**Skoulikaris (Dec-2021)** used a complex methodology for his research, which included the linking of free hydropower simulation models (such as the HEC-ResSim model) with large-scale hydrologic models (such as the E-HYPE model) and big-data simulations (such as the Euro-CORDEX climate data). Using HEC-ResSim, the ROR-SHPPs hydropower simulation demonstrated strong correlation between the predicted and actual results. The model was successful in demonstrating the immediate and long-term effects of hydrological changes on the HPPs' ability to generate hydropower.

## 2.4 STUDY AREA LITERATURE

The foundation for potential sites for reliable and successful hydropower generating was laid by **Khan and Zaidi (2015**). The goal of this study was to create a method for evaluating the Kunhar River's run-of-river hydropower potential using geospatial data and methods. For geoprocessing and watershed delineation in Arc-GIS, satellite data from ASTER was used to make suggestions for feasible places. The capacity of power generation at various altitudes at 500 metre intervals along the river stream was calculated using data from gauge stations. The map schematic that was attached to the paper indicated a variety of locations where hydropower potential could be exploited, but it lacked a table with the coordinates and names of the locations that would have vividly described the picture. The spots for major energy production shown in the paper reciprocates to this paper's hydropower locations i.e., Suki-Kinari, Balakot and Patrind.

**Khan et al., 2019**, attempted to use a different method for analysing the impact of climate change on the rainfall events in Kunhar river basin. Rather than GCM models or hydrological tools, the authors used analytical model of non-parameter elasticity technique for finding the sensitivity at 3 gauges namely, Naran, Garhi Habibullah and Talhatta. The rainfall elasticity values increased from Naran to Garhi Habibullah increasing from 0.3 -0.8. The areas having high rainfall elasticity values are relatively more sensitive and at higher risk of floods.

**Somroo et al., (2021)** used high-resolution GCM model as an input for the HBV model to predict and analyse the Kunhar River basin response to varying future climate changes. The model showed satisfactory calibration and validation performance and correlation was good. Regarding future outcome for the year 2059-2079, the model showed increased temperature, precipitation, and evapotranspiration in basin and predicted increased rainfall to increase in streamflow compared to snow accumulation. It predicted the hydrological phenomenon and the intensity for the future important for hydrologists, and planners.

Using data from 1971 to 2010, **Saifullah et al. (2021)** examined the impact of anthropogenic activities on the yearly flow of the Kunhar river basin. The researchers concluded that natural mean runoff decreased between 1997 and 2010 compared to 1971 to 1996 using the SWAT analysis technique. The regional water resources of the basin have been impacted by climate change, urbanisation, and recreational activities, which have all contributed to variations in streamflow. This analysis serves as a baseline for upcoming infrastructure and hydropower developments on the basin that are impacted by human interests and climate change.

# CHAPTER 3

# 3- METHODOLOGY

## 3.1 **DESCRIPTION OF THE STUDY AREA**:

The Kunhar River is located in the Khyber Pakhtunkhwa province, bordering Azad Kashmir. The basin covers an area of 2632 km2 and is located between the longitudes of 73°17′E and 74°08′E and the latitudes of 34°11′N and 35°10′N. (Moiz et al.,2018). Draining the southern Himalayas from the Lulusar Lake in the Kaghan Valley, with snowmelt as the main source of flow (Mahmood et al., 2016). In the short term, the river basin's elevation varies quickly from 636 to 5216 metres above sea level, making it a safe and viable location for Pakistan's hydropower development (PPIB, 2011).

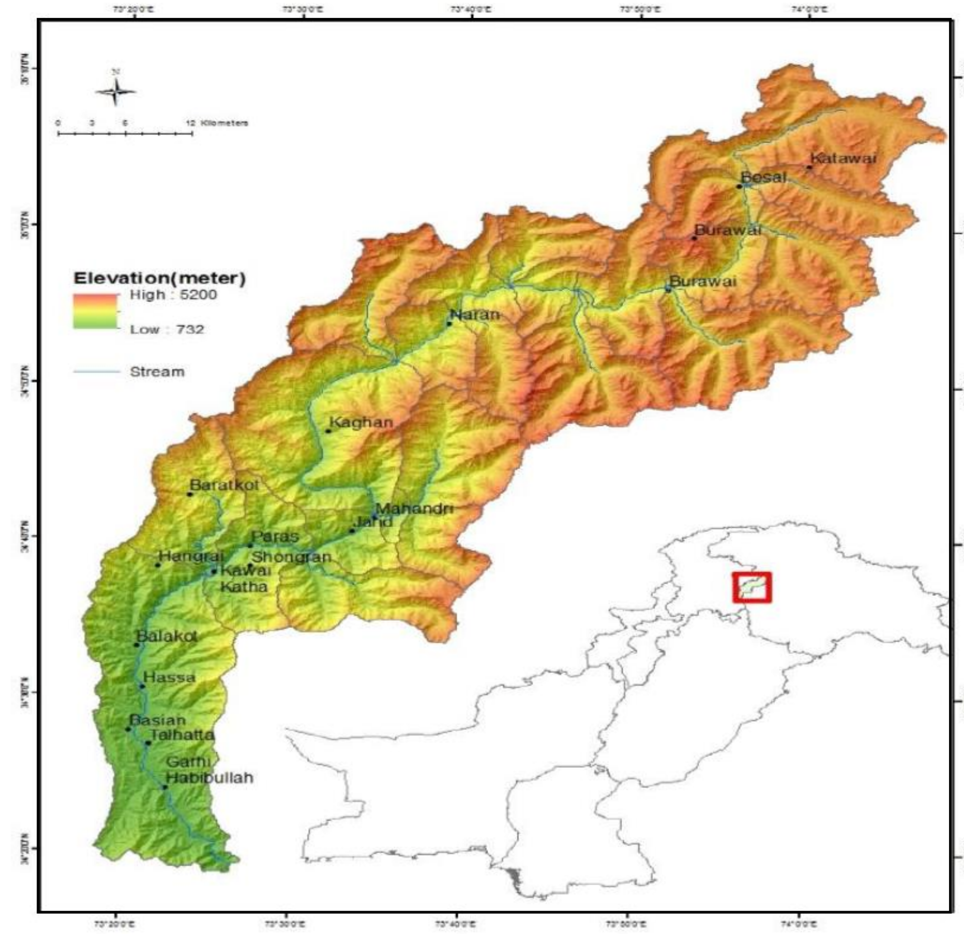


Figure 1: DEM profile of Kunhar River Basin, Assessment of ROR Hydropower Potential of Kunhar River using Geospatial Techniques, 2015

### 3.1.1 Location:

The study doesn’t cover the entire basin for the purpose of analysis of Hydropower Projects, though the flow and precipitation effect is considered from Naran discharge Gauge Station from Latitude 34° 54' E & Longitude 73° 39' N till the end of the basin at Patrind Weir with Latitude 73°25’E & Longitude 34°20′N approximately 12.3 km downstream Garhi Habibullah (Figure 2).

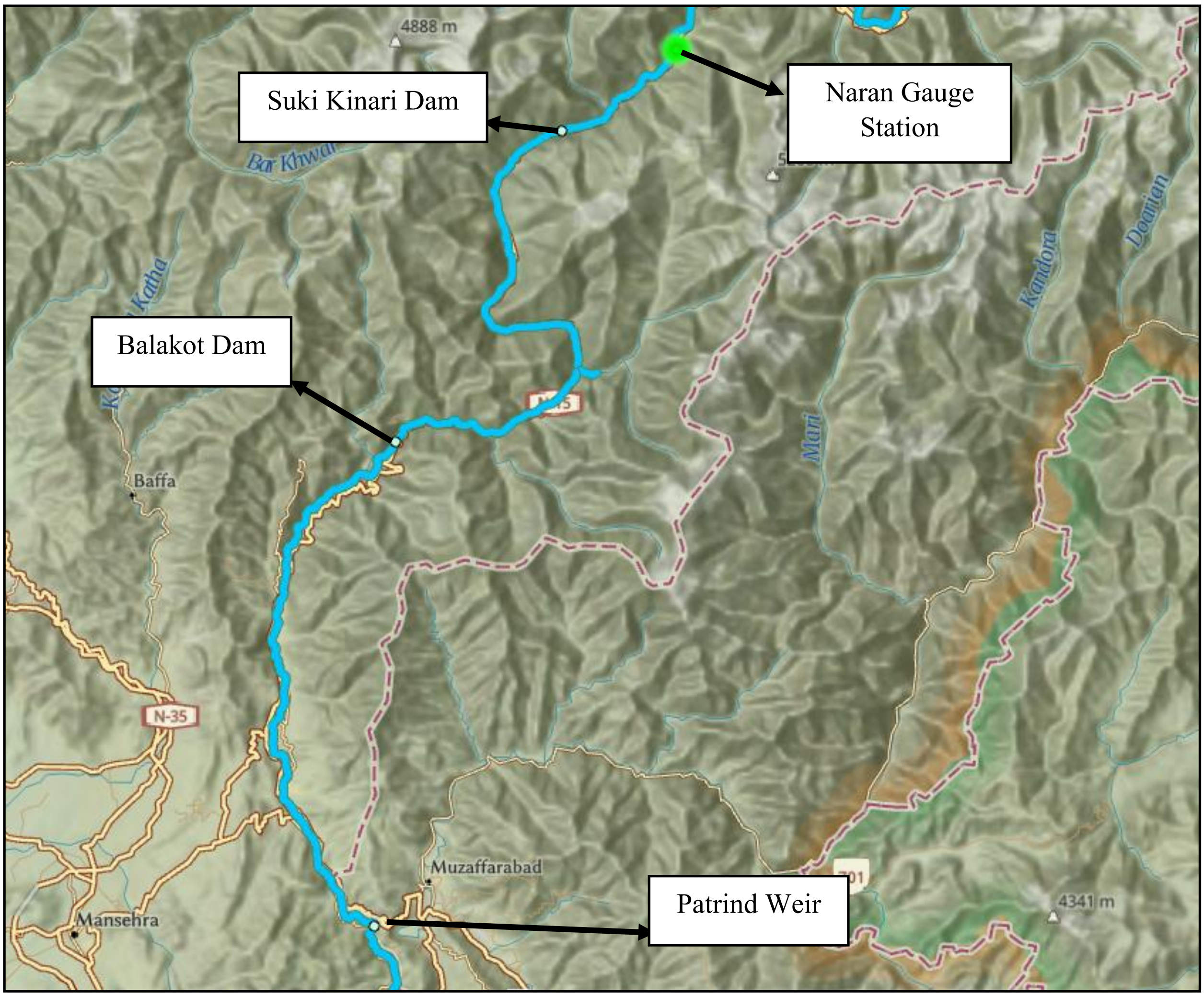


Figure 2: ArcMap for the River section under consideration

### 3.1.2 Topography

One of the primary tributaries of the Indus, the Jhelum River, includes the Kunhar River as one of its major right bank tributaries. With a total area of around 2660 km2, the Kunhar River drainage basin (Kaghan Valley) is situated along an extended valley that is situated between latitudes N 34o10' and 35o10' and longitudes E 73o15' and 74o10'. The Kunhar River is approximately 145 km long, with an average slope of 2%. It primarily runs from the northeast to the southwest, passing through Balakot before continuing to Garhi Habibullah, where it merges with the Jhelum River.

The valley is bordered on the north by Diamer District and Baltistan, the east by Neelum Valley of Azad Kashmir, the south and southwest by Abbottabad District, and the west by Manshera District and Kohistan District. Balakot, Kaghan, and Naran are the three largest settlements in the valley of the Kunhar River.

The Kunhar valley's geography is primarily mountainous, as seen in (Figure 3), with steep valley sides. An altitudinal difference of almost 4400 m from its origin, the neighbouring Lake Lulu Sar, reflects the fundamental geomorphic feature. In actuality, the glacial lakes—especially the 0.8 km2 Lulu Sar Lake and the 0.5 km2 Saif-ul-Muluk Lake—play a significant role in the upper watershed of the valley.

### 3.1.3 Land Cover and Soil

There is a wide variety of vegetation in the Kunhar River valley, including subtropical coniferous woods, alpine meadows, agricultural land, and snow. The land cover of the Kunhar River basin is depicted in Figure 3(a), which was created by the Joint Research Centre (JRC) of the European Commission. Forest, agricultural, and snow are the most prevalent types of land cover in the Kunhar River basin, as illustrated in Figure 3(a) and Table 1. The digital soil map of the world created by the FAO geo-network is used in Figure 3(b) to depict the soil properties of the Kunhar River basin. Leptosol is the most common soil type in the Kunhar River basin, especially in the upper half of the basin, as shown by Figure 3(b) and Table 2.

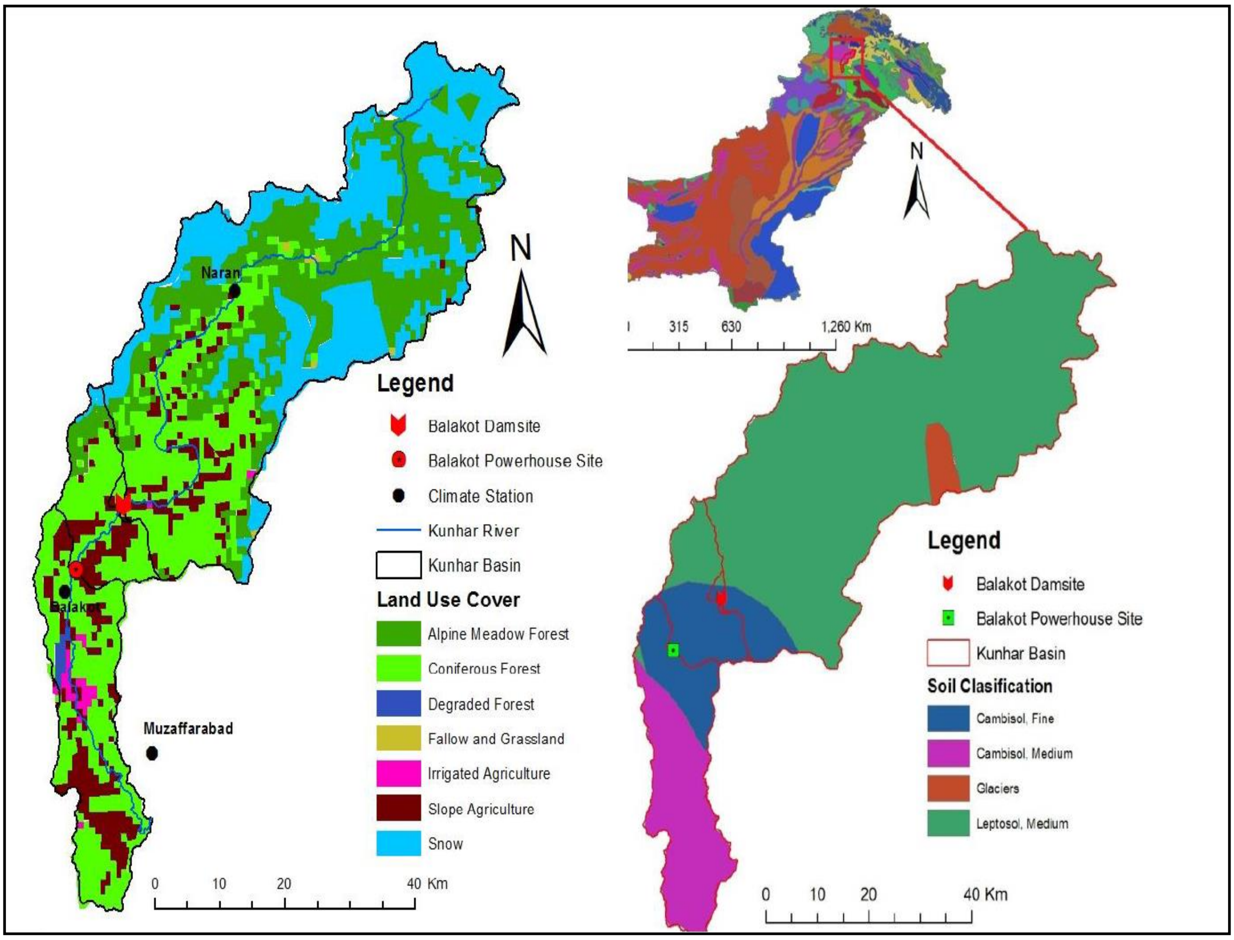


Figure 3: Land use (a) and soil characteristics (b) in Kunhar River catchment

Table 1: Soil classification and soil fraction of Kunhar River Catchment (source: FAO)

| **Soil Type** | **Area** | | **Topsoil Fraction** | | |
|---|---|---|---|---|---|
| | (%) | $Km^2$ | Sand (%) | Silt (%) | Clay (%) |
| Cambisol, Fine | 13 | 337 | 22 | 30 | 48 |
| Cambisol, Medium | 13 | 336 | 22 | 30 | 48 |
| Leptosol, Medium | 73 | 1908 | 43 | 34 | 23 |
| Glacier | 2 | 48 | 0 | 0 | 0 |
| **Total** | ***100*** | ***2629*** | | | |

Table 2: Land use type of Kunhar River catchment (source: JRC)

| **Land Use Type** | **Area** | |
|---|---|---|
| | $Km^2$ | (%) |
| Alpine Meadow Forest | 754 | 28.7 |
| Coniferous Forest | 852 | 32.4 |
| Degraded Forest | 10 | 0.4 |
| Fallow and Grassland | 7 | 0.3 |
| Irrigated Agriculture | 3 | 0.1 |
| Slope Agriculture | 301 | 11.4 |
| Snow | 702 | 26.7 |

### 3.1.4 Dam Projects:

The general physical features of the dams under consideration are given below:

Table 3: Balakot, Patrind and Suki Kinari HPPs

| | **Patrind Weir** | **Suki Kinari Dam** |
|---|---|---|
| **River** | | |
| River | Kunhar River | Kunhar River |
| Catchment Area | 2429 km2 | 1306 |
| Mean Annual Discharge | 104 m3/s | 460 m3/s |
| **Reservoir** | | |
| Normal Operation Level | 765.0 m a.s.l. | 2275 m |

| | | |
|---|---|---|
| Storage capacity | (At 765 m a.s.l.) 6.42 MCM | (At 2275 m.a.s.l) 2.7 MCM |
| **Operating Levels** | | |
| Max. Operating level | 765 m.a.s.l | 2275 m |
| Min. operation level | 760 m.a.s.l | 2265 m |
| Gross head | 114.5 m | 912.5 m |
| Max. Net head | 113.7 m | 824.2 m |
| **Power & Energy** | | |
| Power generation Capacity | 150 MW | 887 MW |
| Annual Energy | 690 GWh | 2 958.1 GWh |
| Plant Factor | 52.53% | 40.2% |
| **Dam Structure** | | |
| Type | Roller Compacted Concrete | Concrete gravity |
| Crest Height | 26 m | |
| Crest Elevation | 760 m.a.s.l | 2277 m |
| Crest Width | 99 m | 317 m |
| Flip bucket lip Elevation | 743 m.a.s.l | 2238 m |
| Design flood | 2670 m3/s | 1500 m3/s |
| Crest Gates No. | 7 | 4 |
| Crest Gates size | 12 x 7 m high each | 3.5 m x 4.5 m high each |
| Bottom outlets No. | 3 | 6 |
| Bottom outlets size | 3 m dia each | 5 m x 4.5 m high each |

|  | **Patrind Weir** | **Suki Kinari Dam** |
|---|---|---|
| **Intake Structure** |  |  |
| Intake type | Forebay intake | Horizontal intake |
| Design discharge | 153 m3/s | 114.6 m3/s |
| Trash rack nos. | 4 | 2 |
| Trash rack size | 10 m x 7 m | 5.5 m x 5.5 m |
| Gates nos. | 3 | 2 |
| Gates size | 5.3m x 5.3m | 7 m height |
| Intake crest El. | 754 m.a.s.l | 2262 m |
| Intake floor El. | 747 m.a.s.l | 2255 |
| **TurbineMechanical Equipment** |  |  |
| Turbine type | Vertical Francis | Pelton |
| Turbine nos. | 3 | 4 |
| Runner Diameter | 2.320 m | 3.17 m |

Apart from the physical features which provides numerical figures for the general structure of the 2 infrastructures, there are further certain information which are necessary to be noted on the dam sites respectively.

### 3.1.5 Suki Kinari Dam:

The Suki Kinari Hydropower Project lies below Naran stream gauge station and above Balakot Dam site at Longitude:34°43′23.24″N & Latitude: 073°32′33.58″E. Pelton Wheel has been installed to utilize all or part of the gross head of approximately 913 m available for hydroelectric power generation on the Kunhar River in the eastern part of the North West Frontier Province of Pakistan.

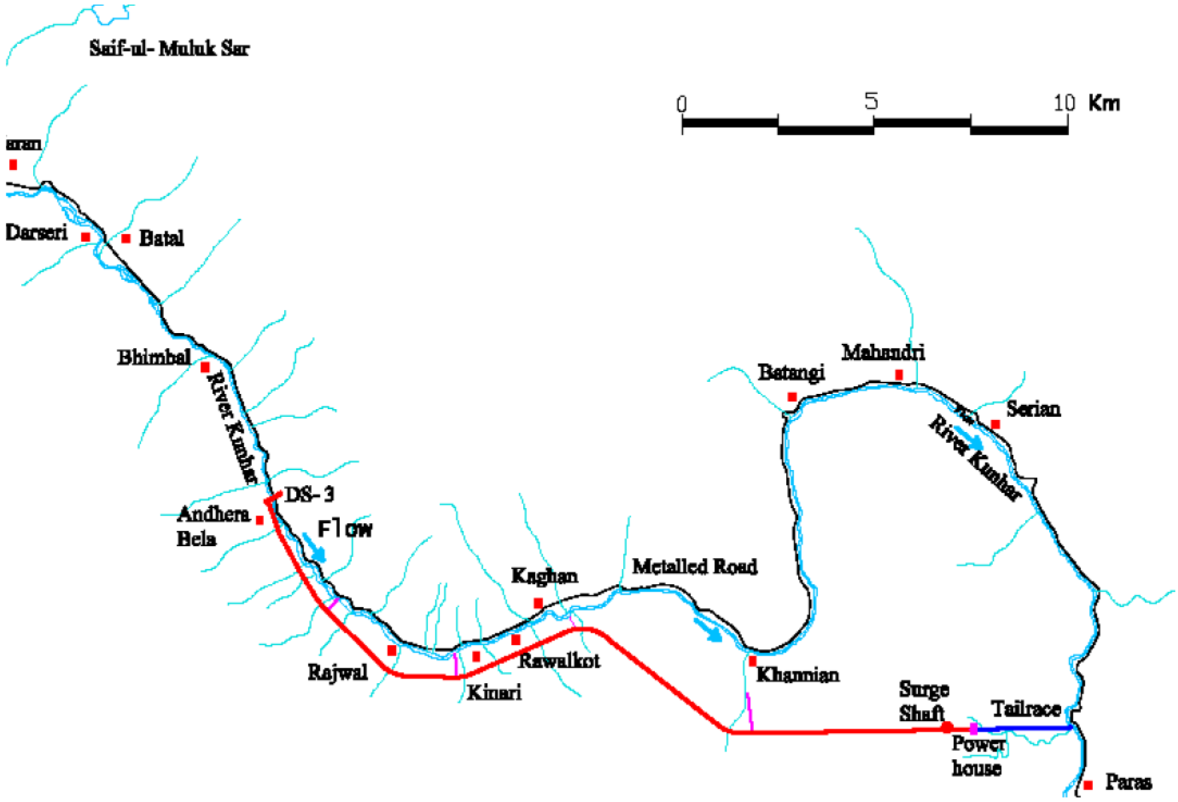


Figure 4: Location Map of Suki Kinari Dam/Powerhouse

PPIB had identified the Suki Kinari project as one of the more promising hydropower prospects not only in the Kunhar River but in the Jhelum basin. SK Hydro (Pvt) has gained the right to develop the site and had commissioned Mott MacDonald to prepare the feasibility study to demonstrate the technical and financial viability of the project from which the study has acquired the hydraulic and hydrological information.

### 3.1.6 Patrind Weir:

The Weir structure on Kunhar River, just upstream of Patrind village, is situated at Latitude 34°20′38.32″N & Longitude 73°25′43.73″E in order to divert flows from Kunhar River to Jhelum River through a system of intake, sand trap, power shaft and power tunnel. A surface type powerhouse is located on river Jhelum opposite lower Chattar area of Muzaffarabad. Installed capacity of the power plant is proposed to be 150 MW.

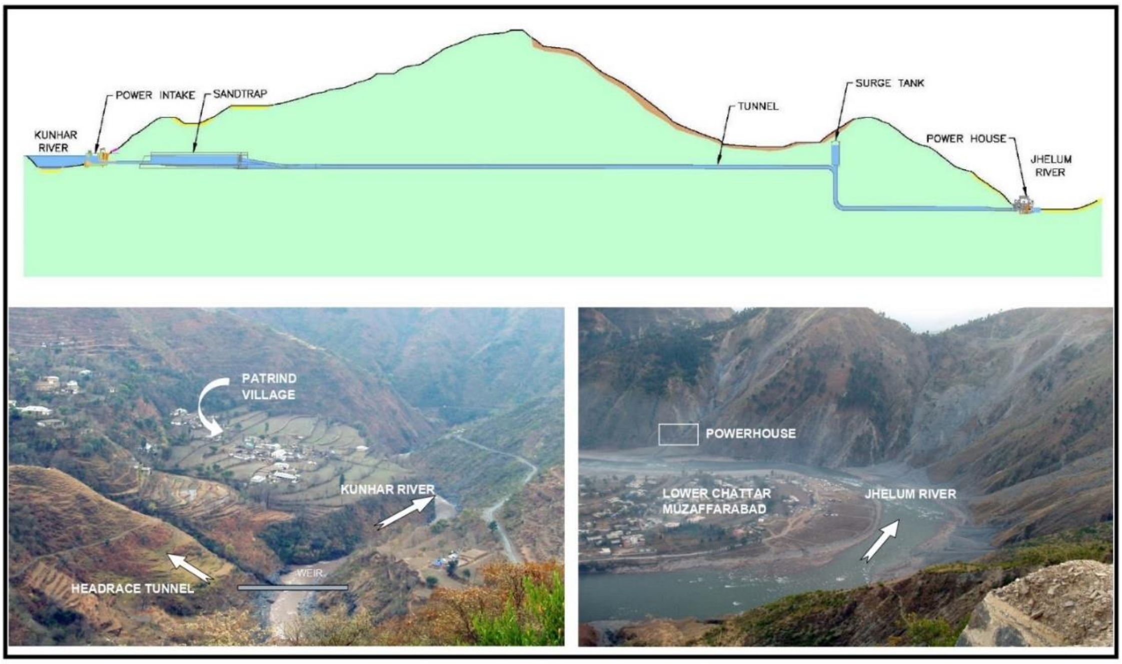


Figure 5: (a) Diagram of dam and power house in lateral view (b) Kunhar River at Patrind (c) Jhelum River at Lower Chatter, Muzaffarabad

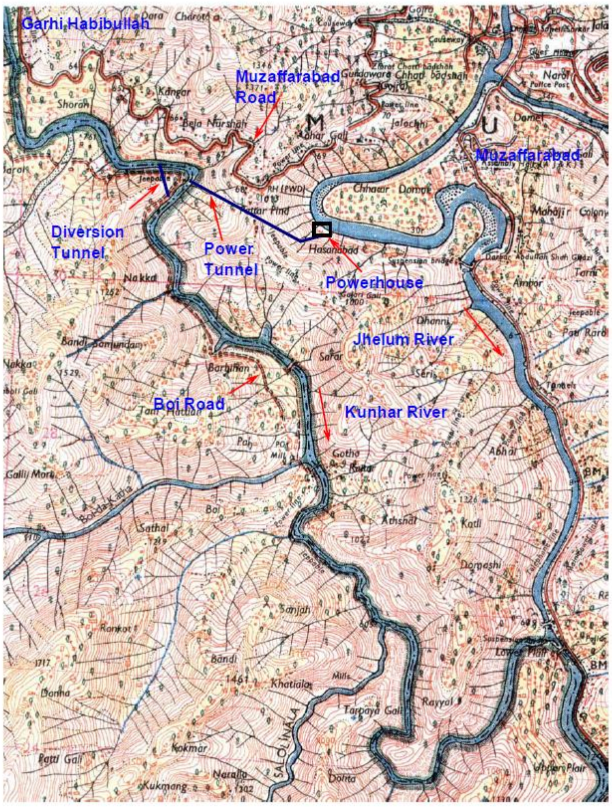
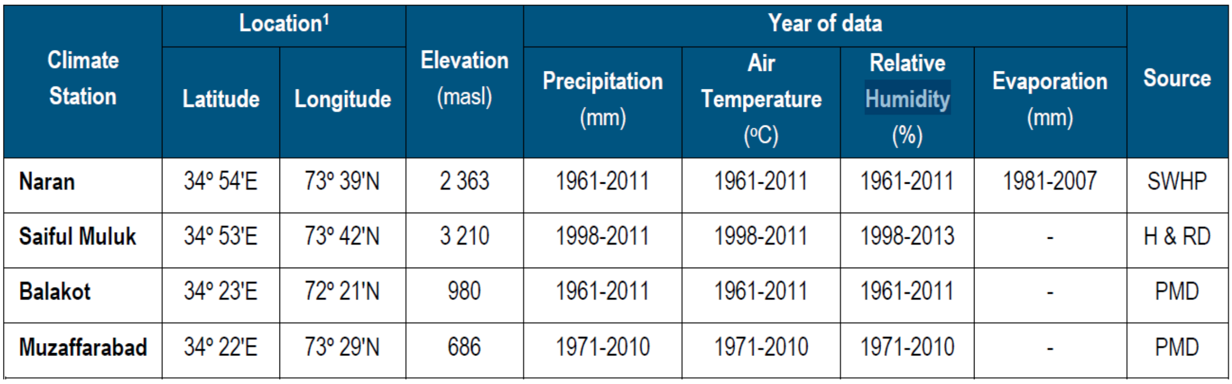


Figure 6: Project map of Patrind, Volume 1, Patrind Feasibility Report

### 3.1.7 Climate Study

This section will detail the climatological features over the climate stations. The following Table shows the data availability upon which the PPIB have accumulated their feasibility Report:

Table 4: Annex-II, Volume 2, Flood Hydrology, Coordinate System WGS84, Balakot Feasibility Study



| Climate Station | Location[1] | | Elevation (masl) | Year of data | | | | Source |
|---|---|---|---|---|---|---|---|---|
| | Latitude | Longitude | | Precipitation (mm) | Air Temperature (ºC) | Relative Humidity (%) | Evaporation (mm) | |
| **Naran** | 34º 54'E | 73º 39'N | 2 363 | 1961-2011 | 1961-2011 | 1961-2011 | 1981-2007 | SWHP |
| **Saiful Muluk** | 34º 53'E | 73º 42'N | 3 210 | 1998-2011 | 1998-2011 | 1998-2013 | - | H & RD |
| **Balakot** | 34º 23'E | 72º 21'N | 980 | 1961-2011 | 1961-2011 | 1961-2011 | - | PMD |
| **Muzaffarabad** | 34º 22'E | 73º 29'N | 686 | 1971-2010 | 1971-2010 | 1971-2010 | - | PMD |

### 3.1.8 Rainfall

The geography of the location and the season have a significant impact on the distribution of precipitation throughout the year. Westerly disturbances, sometimes referred to locally as extra tropical zones of low pressure, are the primary cause of precipitation in the project region. The monsoon precipitation on the upstream portion of the project area likewise diminishes over the summer months, as does the frequency and intensity of the Western Disturbances. Downstream of the basin, the intensity of monsoon summer precipitation increases.

There are 2 major climate stations in our study area: namely Naran, and Balakot whereas the former is the beginning of our catchment area and latter being excluded. The monthly average precipitations are shown in (Figure: 7) below, observed at the Naran and Balakot climate stations, in the vicinity of the project area. According to statistical data of the Naran climate Station upstream of the project, the annual average precipitation is 1575 mm, with uneven distribution during the year. The maximum precipitation (242 mm) is in March, and the minimum precipitation (57 mm) is in August. According to statistical data of the Balakot climate station, downstream of the project, the annual average precipitation is 1500 mm, with uneven distribution during the year. The maximum precipitation (355 mm) is in July, and the minimum precipitation (37 mm) is in November (Main Report, Balakot Feasibility Report, 2015).

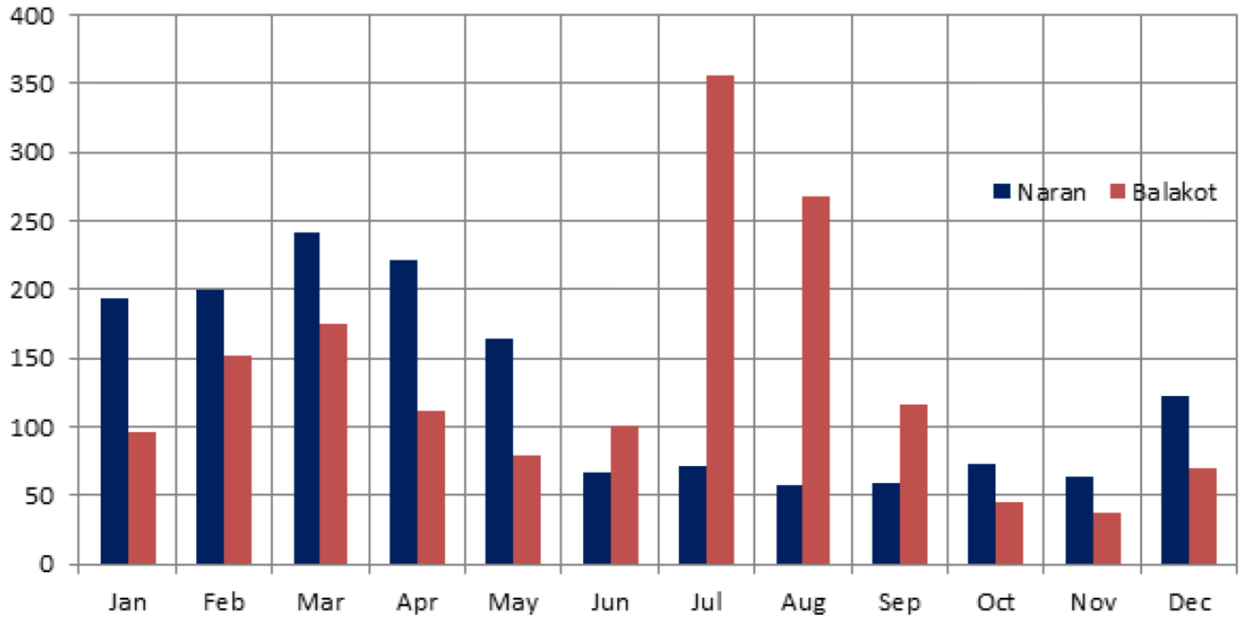


Figure 7: Monthly average rainfall observed at the climate stations in the vicinity of the project areas.

### 3.1.9 Temperature:

The temperature regime follows the temperature pattern in the northern hemisphere. The temperature during the winter months from December to February falls below freezing point at most upper part of the catchment. On the other hand, during the summer months from June to August the temperature rises to over 20 ºC at most upper part of the catchment and over 30 ºC in the lower part of the catchment. Moreover, the temperature daily variation is higher in the upper part of the Kunhar River basin (Main Report, Balakot Feasibility Report, 2015). The (Figures 4 & 5) shows the details:

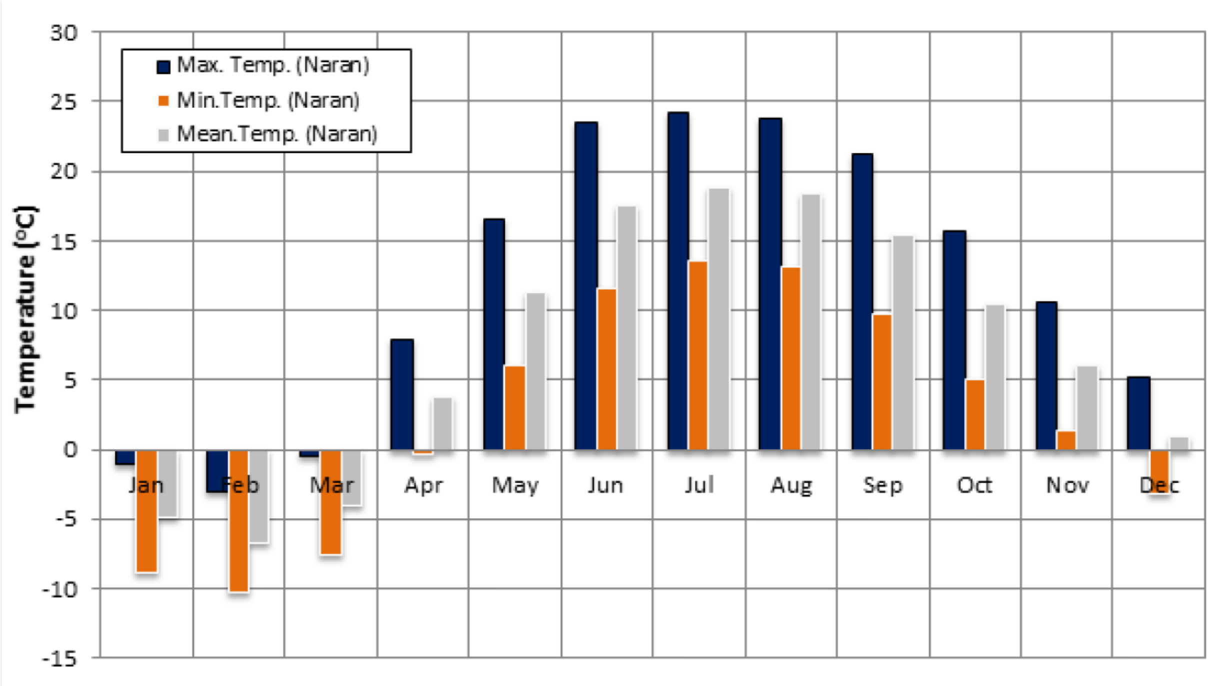


Figure 8: Monthly average maximum and minimum temperature observed at Naran Station

### 3.1.10 Evaporation:

The Kunhar River basin's evaporation analysis uses evaporation data from the climatological stations at Naran and Balakot. SWHP, WAPDA, and Pakistan Meteorological Department installed and maintained the Naran station, whereas Pakistan Meteorological Department installed and maintained the Balakot station (PMD). Data on mean monthly pan evaporation are available for the years 1981 to 2007 at the Naran gauging station and for the years 1970 to 1979 at the Balakot gauging station.

(Figure 9) displays the average monthly evaporation for Naran and Balakot. At Naran station, evaporation is greatest in the month of July with a value of 156 mm and lowest in the month of November with a value of 29 mm. Whereas in Balakot station, evaporation reaches its peak in June with a value of 294 mm and its lowest point in December with a value of 49 mm.

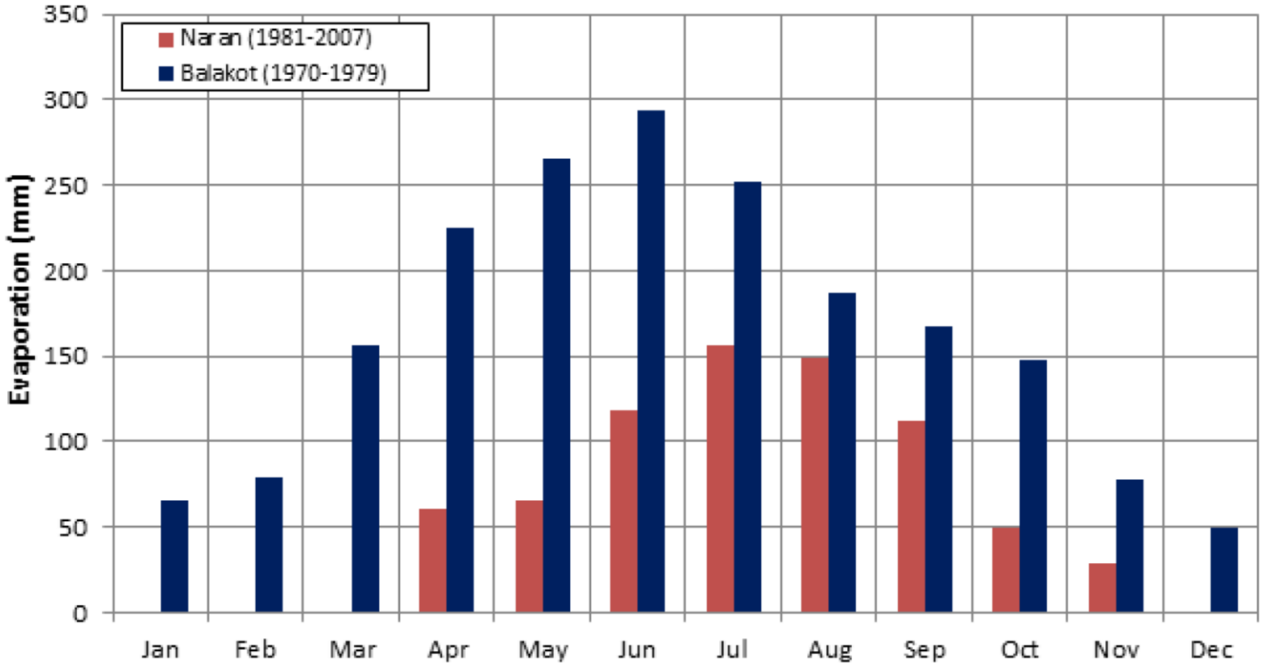


Figure 9: Monthly average evaporation observed at Naran and Balakot stations.

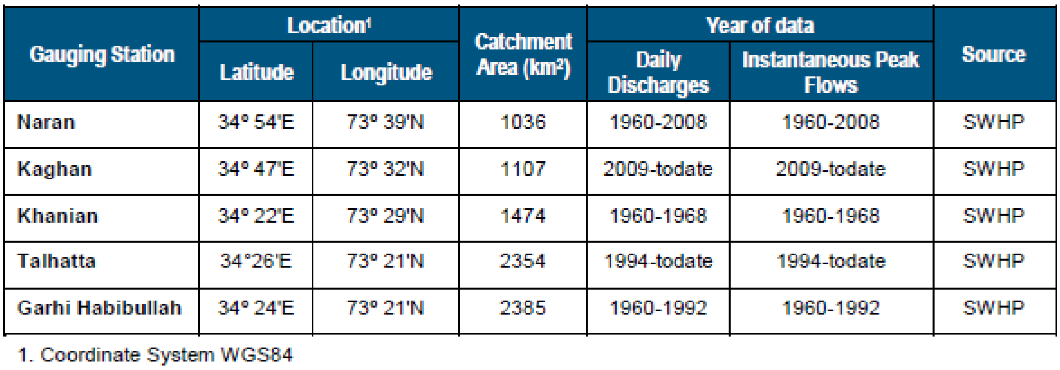
### 3.1.11 Surface Water Hydrology:

The study involves 5 major stream gauge stations for flow measurement and observation, i.e., Naran, Kaghan, Garhi Habibullah, Talhatta where GH gauge have stopped operation since 1994.

SWHP, WAPDA provide daily flow information for the Naran stream gauging station from 1960 to 2008. The gauging station was moved to Kaghan after 2008, and starting in 2009, the Kaghan stream gauging station is where the daily flows are recorded.

Stream gauging sites on the Kunhar River are at Naran, which is 13 km upstream of Dam site 3 (Suki-Kinari HPP), and Khannian which is about 16 km downstream and Garhi Habibullah/Talhatta, which is 80 km downstream.

Table 5: Gauging Stations and Available Hydrological Data in Kunhar River



| Gauging Station | Location[1] |  | Catchment Area (km²) | Year of data |  | Source |
|---|---|---|---|---|---|---|
|  | Latitude | Longitude |  | Daily Discharges | Instantaneous Peak Flows |  |
| **Naran** | 34° 54'E | 73° 39'N | 1036 | 1960-2008 | 1960-2008 | SWHP |
| **Kaghan** | 34° 47'E | 73° 32'N | 1107 | 2009-todate | 2009-todate | SWHP |
| **Khanian** | 34° 22'E | 73° 29'N | 1474 | 1960-1968 | 1960-1968 | SWHP |
| **Talhatta** | 34°26'E | 73° 21'N | 2354 | 1994-todate | 1994-todate | SWHP |
| **Garhi Habibullah** | 34° 24'E | 73° 21'N | 2385 | 1960-1992 | 1960-1992 | SWHP |

1. Coordinate System WGS84

At the location of the dam, there is no stream gauging station. Data on stream flow, sediment, and water quality are available from 1960 to the present at Naran and Garhi Habibullah. Due to the station's closure in 1969, only the years 1960 to 1968 of data for Khannian are now available (Main Report, Suki Kinari Feasibility Study).

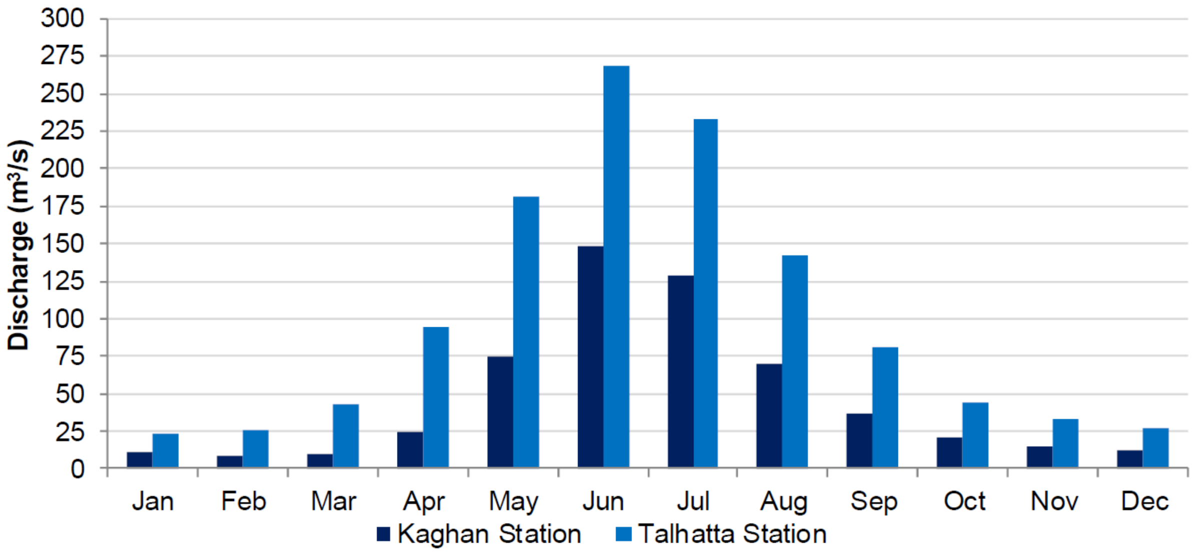


Figure 10: Mean Monthly Precipitation at Kaghan and Talhatta (1962 - 2015), Balakot Feasibility Report

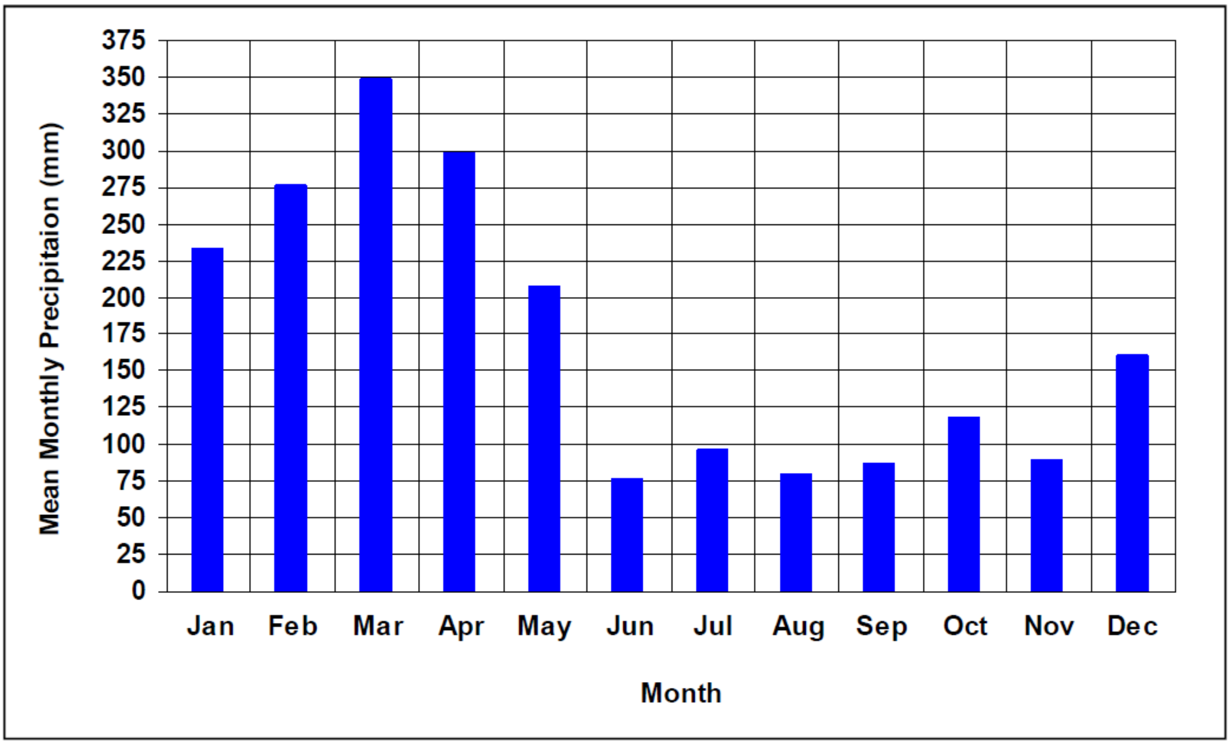


Figure 11: Mean Monthly Precipitation at Naran (1962 - 2009), Volume-4-1, Naran Feasibility Report

In summary, for all the main discharge gauges the flow pattern in graphical interface from Naran to Garhi Habibullah is also extracted from the feasibility report for Suki Kinari which explains the and provides the average monthly flows that covers the 2 HPPs.

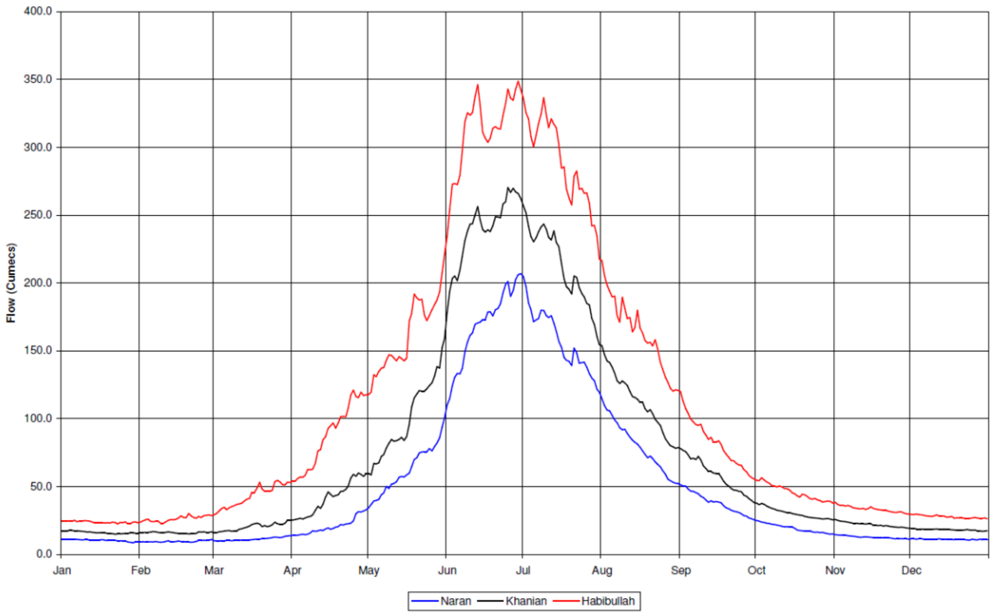
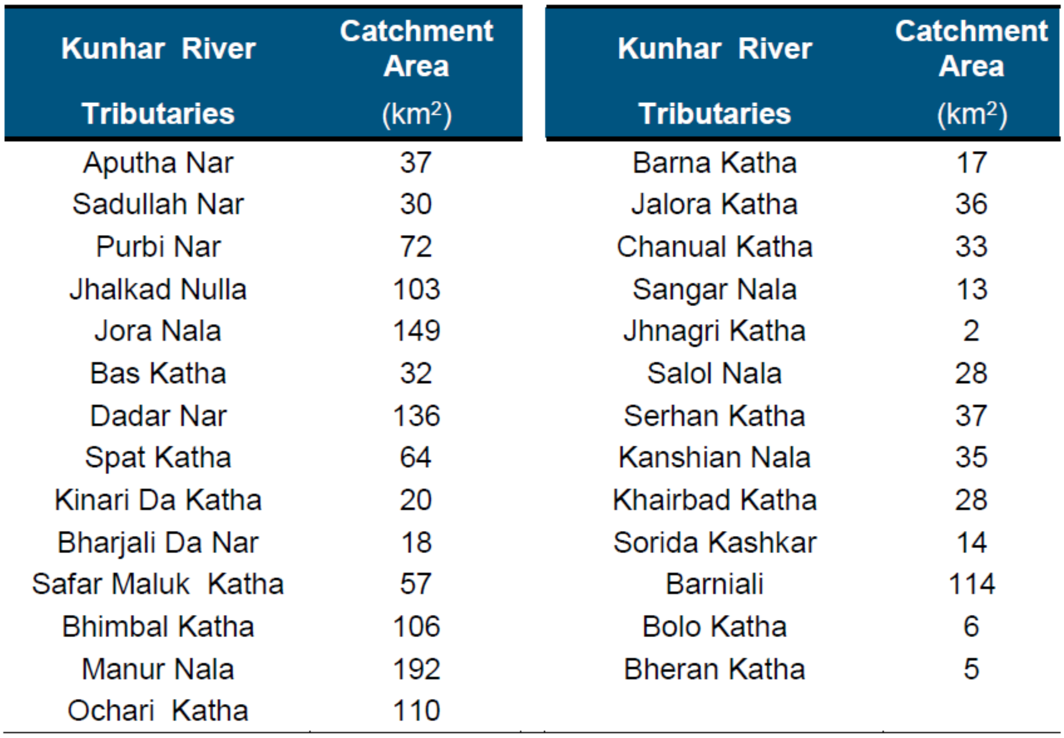


Figure 12: Kunhar River – Average Flow Patterns

All the above discharge data has been due to the snow melt and precipitation covering the main river and its tributaries as given in the (Figure: 13). These major tributaries have not been physically considered in the model as shown in the next chapter, but the main drainage lane is under study with stream gauge stations labelled for flow to begin and flow comparison has been used.



| Kunhar River Tributaries | Catchment Area ($km^2$) | Kunhar River Tributaries | Catchment Area ($km^2$) |
|---|---|---|---|
| Aputha Nar | 37 | Barna Katha | 17 |
| Sadullah Nar | 30 | Jalora Katha | 36 |
| Purbi Nar | 72 | Chanual Katha | 33 |
| Jhalkad Nulla | 103 | Sangar Nala | 13 |
| Jora Nala | 149 | Jhnagri Katha | 2 |
| Bas Katha | 32 | Salol Nala | 28 |
| Dadar Nar | 136 | Serhan Katha | 37 |
| Spat Katha | 64 | Kanshian Nala | 35 |
| Kinari Da Katha | 20 | Khairbad Katha | 28 |
| Bharjali Da Nar | 18 | Sorida Kashkar | 14 |
| Safar Maluk Katha | 57 | Barniali | 114 |
| Bhimbal Katha | 106 | Bolo Katha | 6 |
| Manur Nala | 192 | Bheran Katha | 5 |
| Ochari Katha | 110 | | |

Figure 13: Major Tributaries of Kunhar River

## 3.2 METHODOLOGY

### 3.2.1 General Framework of the Study

The study followed a 4-step procedure in the preparation and execution of HEC-ResSim model to simulate best suitable guide curves for the dams in cascade. The research initially begins with reading and analysing of the feasibility reports for Suki Kinari, Balakot and Patrind hydropower projects. The specifications of the reservoir such the storage, surface area, evaporation, seepage and leakage in the dam and etc. The most important data for model analysis is the inflow time series available to the dam site. There is unavailability of real time release from the reservoirs except the Patrind Weir which has for the past 4 years; the inflow & release operation exists between 2018-2022 that is not suitable for proper validation and calibration. The Flow Chart below depicts the phase wise follow up of the study:

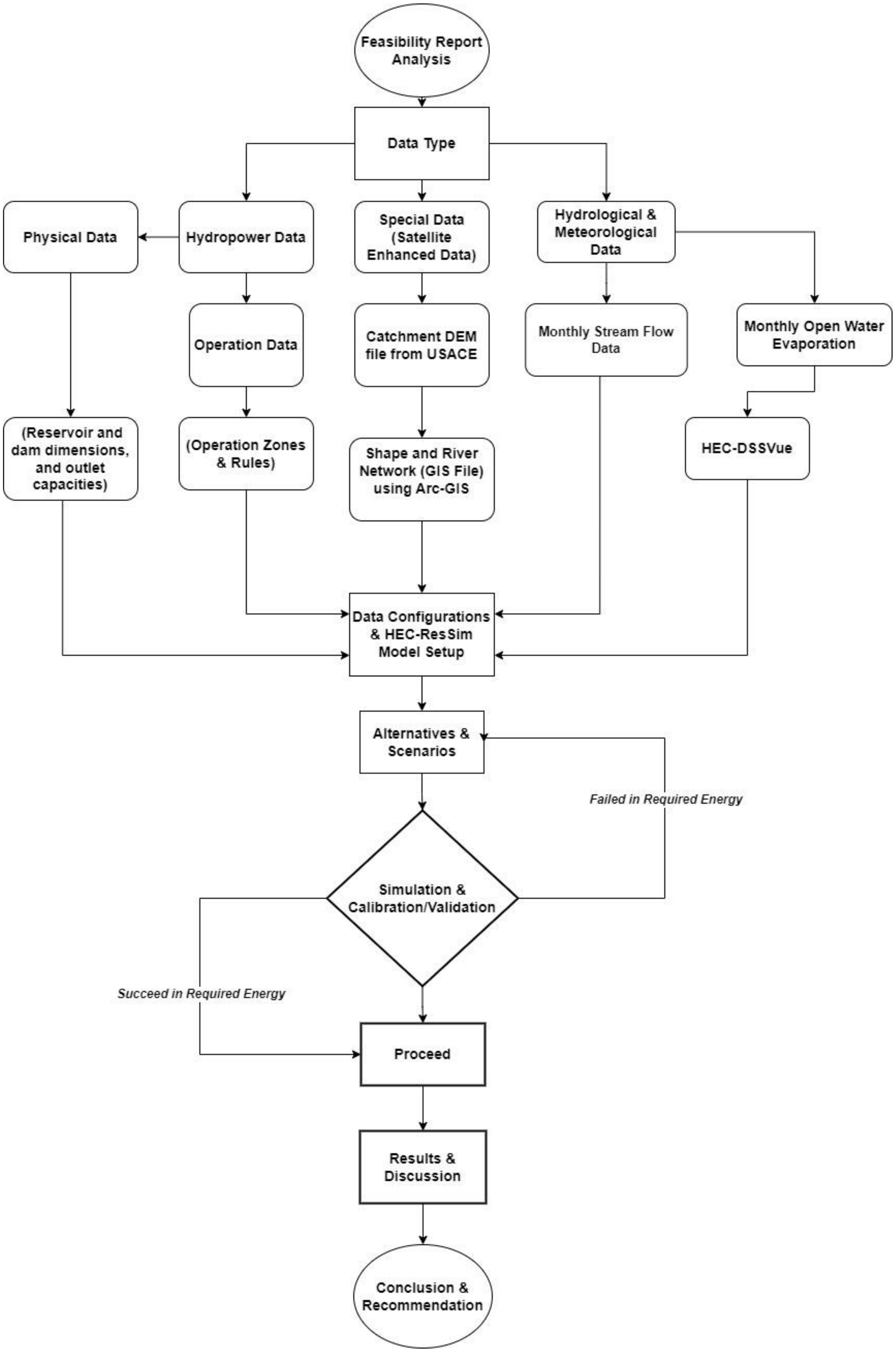


Figure 14: Framework Flowchart of Model Simulation

### 3.2.2 Data Collection

The Feasibility reports provided the benchmark for the necessary data of the reservoirs and is detailed in figures and tables. The initial research will be conducted on 1960-1985.

### 3.2.3 Inflow Time Series

The mean monthly annual flows for Suki Kinari and Patrind Weir are provided in Figures below and have been used for input parameter for the model and as a comparison with the actual hydrological flow that reached the two project sites.

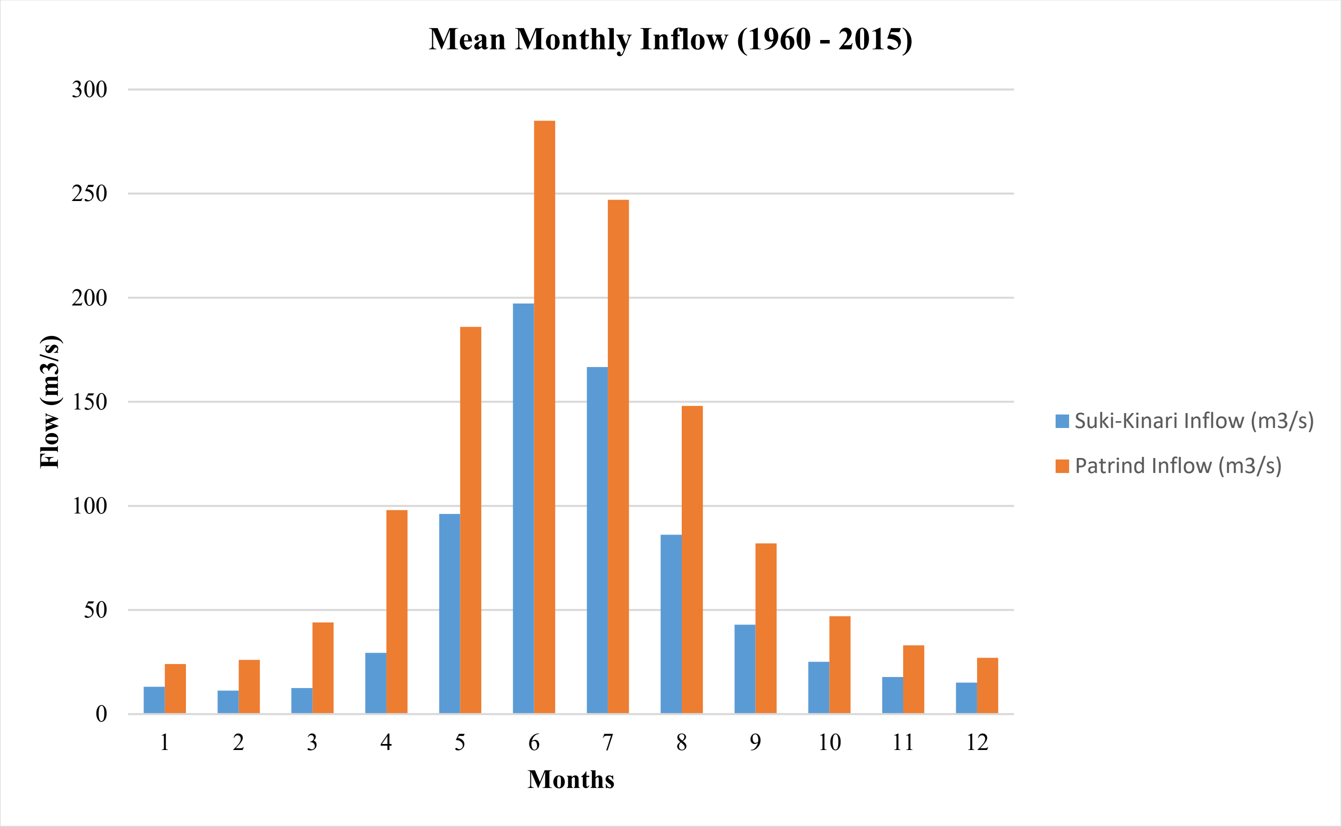


Figure 15: Average Monthly Inflow to Suki-Kinari & Patrind Reservoirs

### 3.2.4 Flow Duration:

This is an important aspect that defined the power plant structure for the dam structures and thus the following graphs in (Figures:16 & 17) provides the flow duration for both sites extracted from their respective feasibility studies.

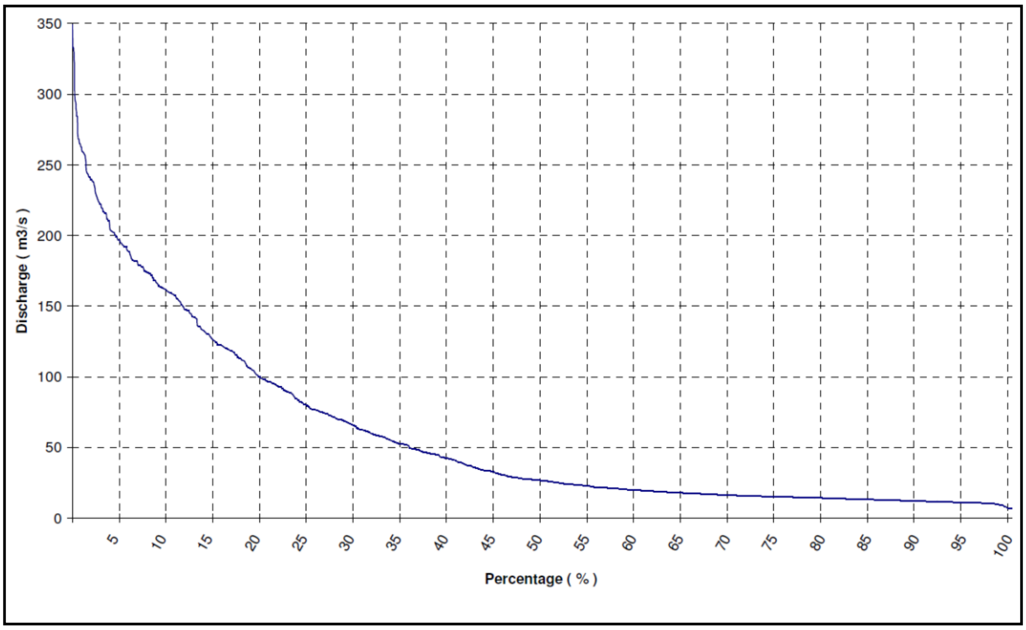


Figure 16: Flow Duration Curve at Suki Kinari Dam

To evaluate the flow availability at the proposed Patrind Weir site, the flow duration curve was computed and is presented in (Figure: 17)

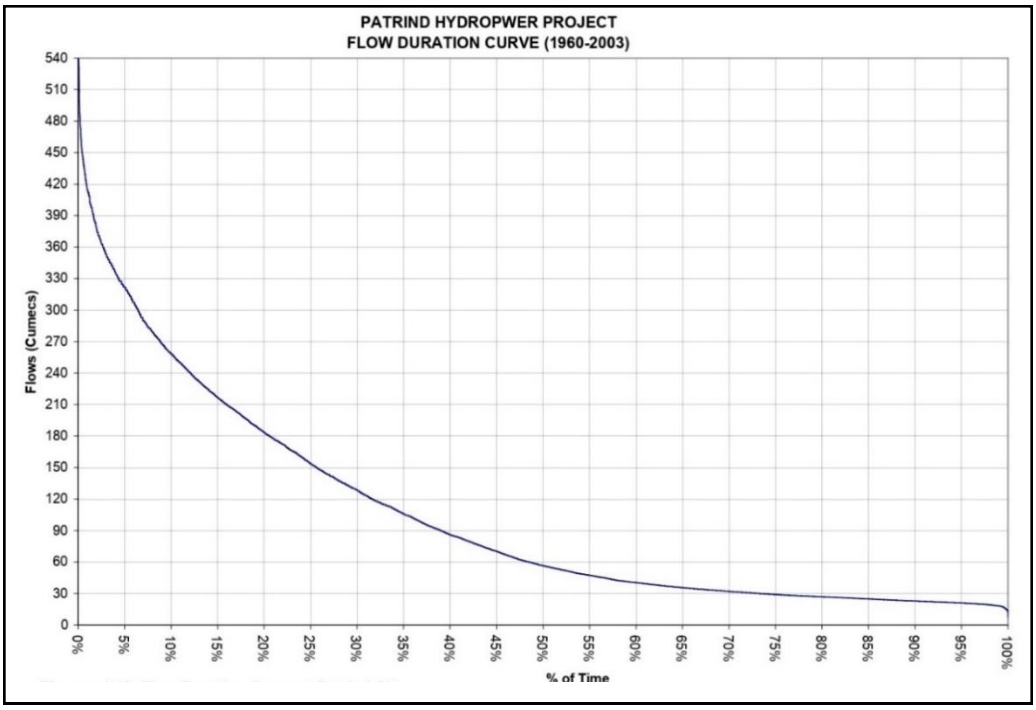


Figure 17: Flow Duration Curve at Patrind Weir Site (1960-2003).

### 3.2.5 Reservoir Evaporation Data

Table 6: Evaporation at Suki Kinari, Patrind Reservoirs

| Month | Evaporation at Suki Kinari (mm) | Evaporation at Patrind (mm) |
|---|---|---|
| Jan | 39 | 46.07 |
| Feb | 37 | 57.4 |
| Mar | 50 | 85.64 |
| Apr | 75 | 125.74 |
| May | 108 | 168.1 |
| Jun | 178 | 198.27 |
| Jul | 241 | 187.83 |
| Aug | 200 | 181.21 |
| Sep | 162 | 170.13 |
| Oct | 59 | 129.99 |
| Nov | 47 | 91.39 |
| Dec | 40 | 55.1 |

### 3.2.6 Reservoir Stage - Area – Volume Relation:

The maximum reservoir level is 2 275 m, and the minimum reservoir level is 2 265 m. From (Figure:18) after flushing the volume available between these two levels is (4.35-1.7) x 106 i.e., 2.65 x 106 m3. However, prior to flushing the live storage will be further reduced due to the sediment that will be deposited at the upstream end of the reservoir and to guarantee that 2000000 m3 is available for peaking generation it is estimated that the full 10 m operating range will need to be used.

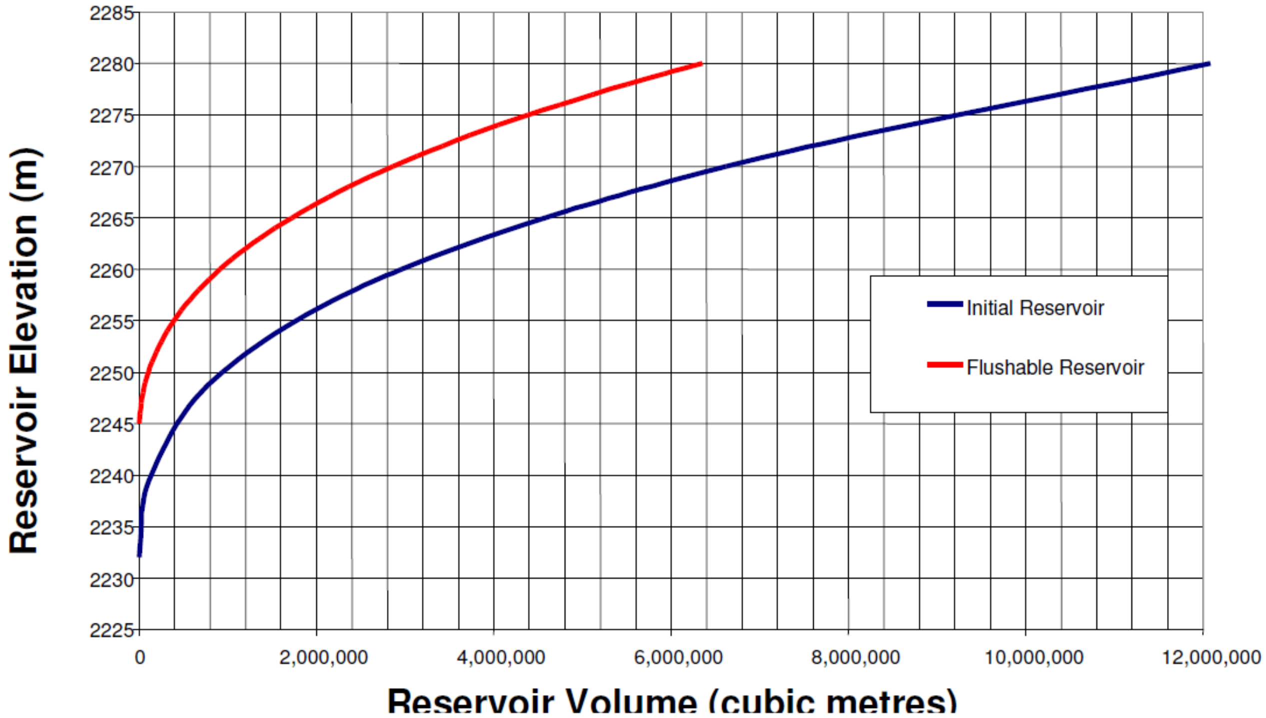


Figure 18: Suki Kinari Stage Storage Characteristics

Area capacities of reservoir behind Patrind weir at various elevations have been calculated from contour plan of reservoir at 5 m contour interval. (Figure: 19) below shows area capacity relation of the reservoir.

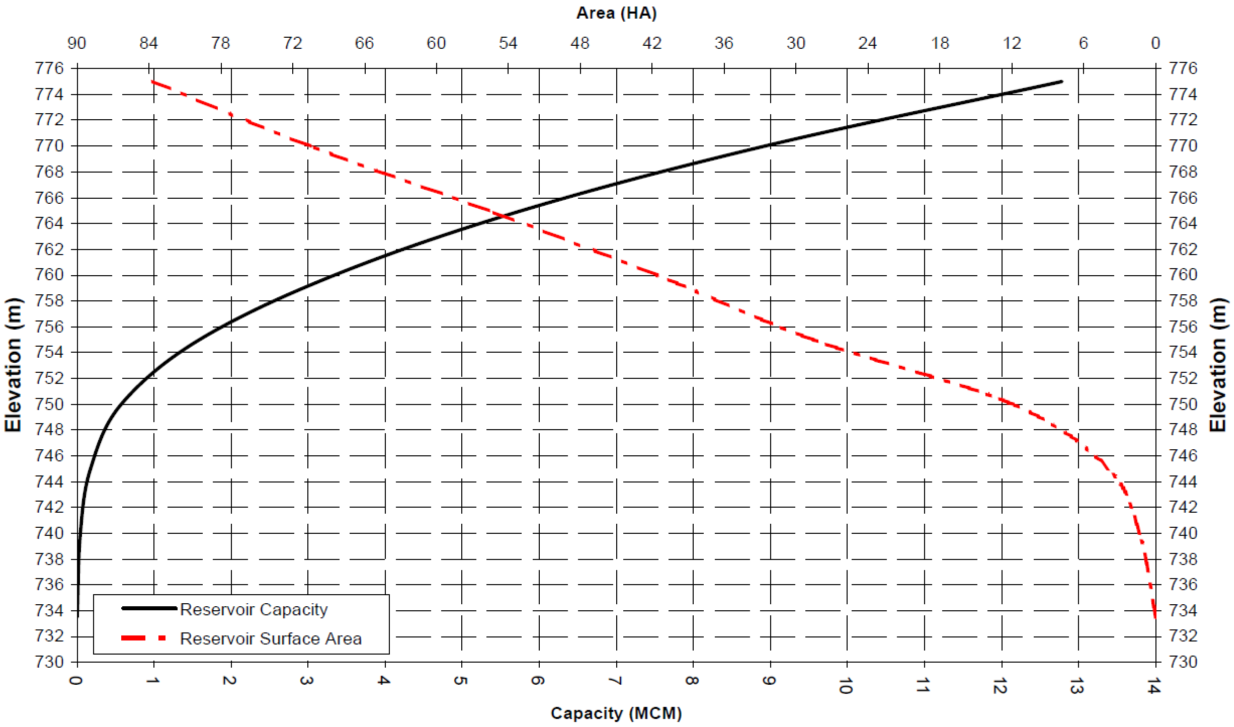


Figure 19: Patrind Area-Elevation-Storage Characteristics

### 3.2.7 Seepage/Leakage

The Dams are yet to be constructed to see leakage and has not observed for the Patrind since its commencement in 2017. The feasibility reports share slight seepage that can be considered insignificant for major impact of release or storage. Leakage of water from the weir at Patrind has not happened yet and no significance given for either project in their particular main reports given by PPIB.

### 3.2.8 Upper/Lower Spillway:

The proposed Suki-Kinari layout uses a gated low level main spillway which doubles as the flushing outlet and a high-level spillway for regulation of the reservoir level except during the major floods as the low-level gates are not suitable for constant use for regulating the reservoir level during normal flow periods due to limitations regarding cavitation, hydrodynamic forces, abrasion, and vibration.

The proposed high-level spillway, which would pass up to the average annual flood of 380 m3/s when routed through the reservoir is also gated. The main spillway/flushing outlets are sized to pass the spillway design flood of 1 500 m3/s without flood surcharge on the reservoir. The gates would be lifted during flushing to allow free discharge.

The below Free Discharge equation has been used to determine the head required to pass the design flow:

Equation 1: Gate Design Flow Equation

$$Q = bC_dY_G(2gy_1)^{0.5}$$

**Where:**

$$C_d = Cc/(1+(C_cY_G/Y_1))^{0.5}$$

$$C_c = 1\text{-}0.75(\varphi) + 0.36(\varphi)^2]$$

**b= width (m)**

**$C_d$= discharge co-efficient**

$C_c$= contraction co-efficient

$y_1$ = upstream water level

$Y_G$ = gate opening (m)

φ = gate angle (degrees)

g = gravitational constant (m/s/s)

To maintain the area close to the power intake relatively clear of sediments that may accumulate upstream of the dam structure, a low-level flushing spillway was considered close to the left abutment of the dam structure and to the power intake. Additionally, the low-level spillway is designed to support in high flood discharges, ensuring the safely passage of flood peaks and avoid dam overtopping. The low-level gated spillway is located as low as possible to maximise the flushing capacity of suspended sediments during major floods and minimise the size of the gates, whilst still ensuring the passage of the spillway design flood during the combined operation with the upper gated spillway. The below table provides the main gate release for Patrind Weir. It shows the capacity to release in relation to the level of head at the head pond.

Table 7: Patrind Weir Regulation Flow Control

| Reservoir Level (m) | Release (cms) | Max Release (cms) |
|---|---|---|
| 760 | 0 | 0 |
| 760.5 | 42.86 | 300.02 |
| 761 | 84.43 | 591.01 |
| 761.5 | 125 | 875 |
| 762 | 162.43 | 1137.01 |
| 763 | 232.86 | 1630.02 |
| 763.5 | 268.57 | 1879.99 |
| 764 | 299.29 | 2095.03 |
| 764.5 | 328.57 | 2299.99 |
| 765 | 355.71 | 2489.97 |

### 3.2.9 Hec-ResSim Setup

Operational modelling or simulation analysis of the Tekeze Reservoir will be done in this study using the Corps of Engineers software HEC ResSim. The Hydrological Engineering Centre of the Corps of Engineers created the reservoir simulation programme HEC-ResSim, which is accessible online (USACE, HEC-ResSim, 2007, http://www.hec.usace.army.mil/software/hec-ressim /hecressim-hecressim.htm).

Software with a graphical user interface called HEC-ResSim (GUI). The examination of run-of-river, peaking, pumped storage, and grid power operations is one of its hydropower simulation capabilities. The reservoir release is chosen to achieve the desired level of power generation to imitate hydropower operation. The goal for power generation may alter every month, every day, even every hour. In addition, penstock capacities, losses, and leakage factors are considered by hydropower components. Users of this model can provide alternatives and run simulations at the same time to compare the outcomes.

The schematic components of HEC-ResSim allow for the interactive visual depiction of simulation data, reservoir networks, and watersheds in a georeferenced context. HEC-ResSim can also be utilised as background layers to better portray physical systems and is compatible with Arc-GIS shapefiles. Reservoirs, canal networks, catchment lines, detours, etc.

### 3.2.10 Watershed Model

The model's first module establishes the framework for the model that is the subject of the inquiry. This module's goal is to offer a standard framework for defining and building watersheds. A watershed is connected to a geographical area that may include numerous models and layers of data (DEMs, area coverages in ArcGIS). All streams and initiatives may be included in a watershed. B. Information on reservoirs, dams, measurement sites, impact areas, time series sites, and specific areas' hydrological and hydraulic conditions. This collection of information creates a tipping point.

Watersheds were extracted from Arc-Gis using a hydrological analysis tool. Arc-Map output is suitable for use with HEC-ResSim. The diagram below shows the basin phase starting at Narang Station and ending at Patrind Weir.

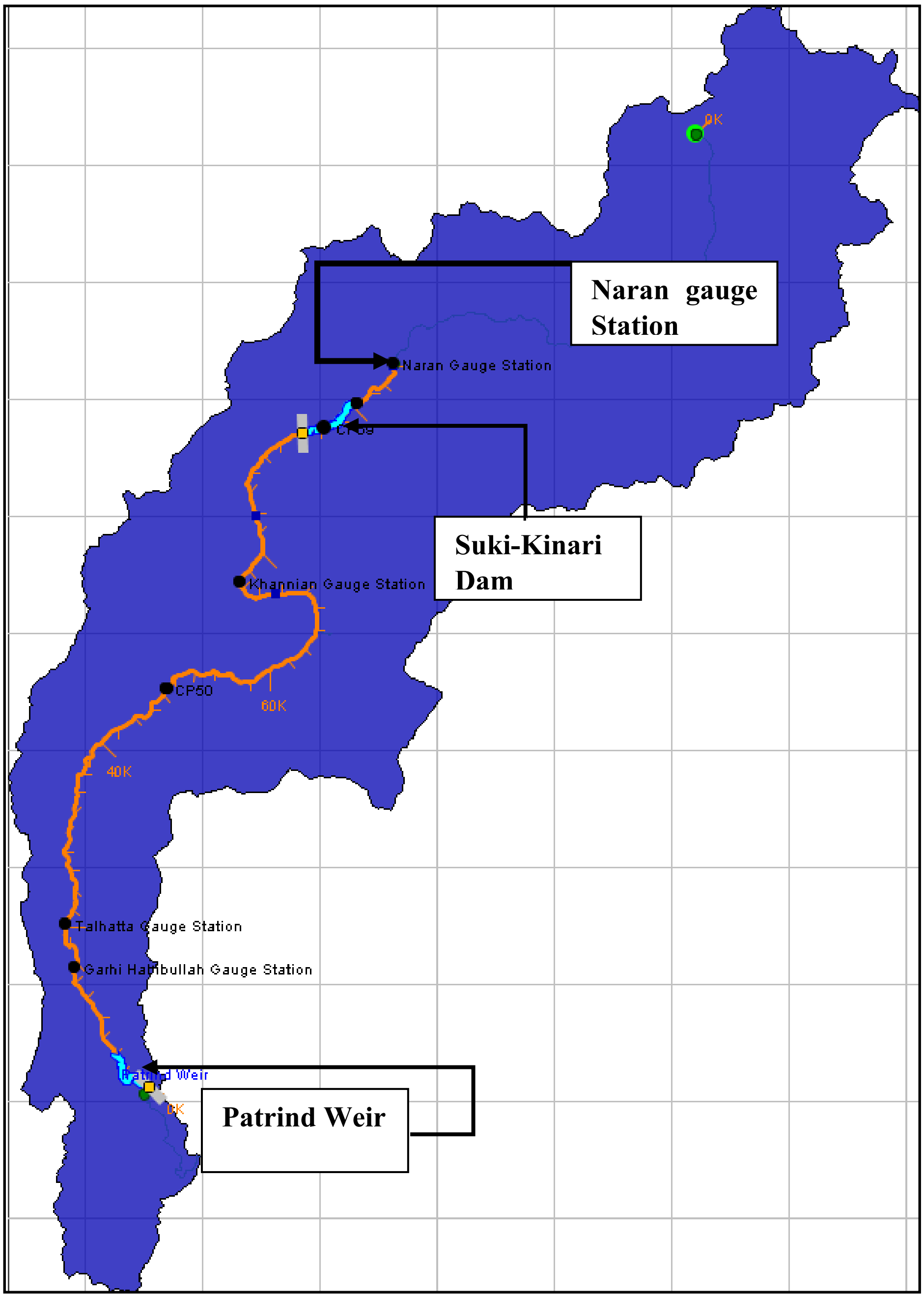


Figure 20: Watershed Module

### 3.2.11 Reservoir Networks

The Reservoir Network module's goal is to keep the creation of the reservoir model and the analysis of the outcomes separate. This module makes it easier to create network diagrams, describe the operational and physical components of reservoir models, and provide management options for analysis. Additional engineering categories for reservoirs include basins, dams, and one or more outflows. Individual pool heights, generation levels, and a set of release rules are used to determine the criteria for reservoir release decisions. Both river networks and branches or branches have reservoirs connected to them. Define the physical and operational data for each network element after the interconnection network strategy is finished. Management options are created to compare outcomes using various model methods. Physical traits, operational configurations, influx, and/or beginning circumstances. A reservoir network created for three hydroelectric projects with predetermined specifications is shown in (Fig. 32).

The main purpose of this module is to detail alternatives that can be used to prepare a study area for simulation. An operational set placed on each reservoir has been neatly added, with numerically outlined elevation, discharge to turbine, and gate review values. It serves as the last parameter the model needs to move to the last module.

### 3.2.12 Simulation

The simulation engine's goal is to keep the model construction and output analysis independent. The simulation is set up using the simulation engine after the reservoir modelling is finished and the options are determined. The simulation module carries out calculations and interprets the outcomes. We must specify the simulation time window, the calculation interval, and the alternatives to be considered during the experiment. The simulation start, block, and finish times are in this instance the provided time windows. The simulation is then represented by a directory structure that ResSim generates inside the watershed root folder. A copy of the watershed that only contains the files required for the chosen alternative is contained within this simulation tree. Additionally, the simulation generates a DSS file (simulation.dss) containing all the DSS records corresponding to the input and output data for the chosen alternative. The ability to alter and save pieces for future simulation is also available.

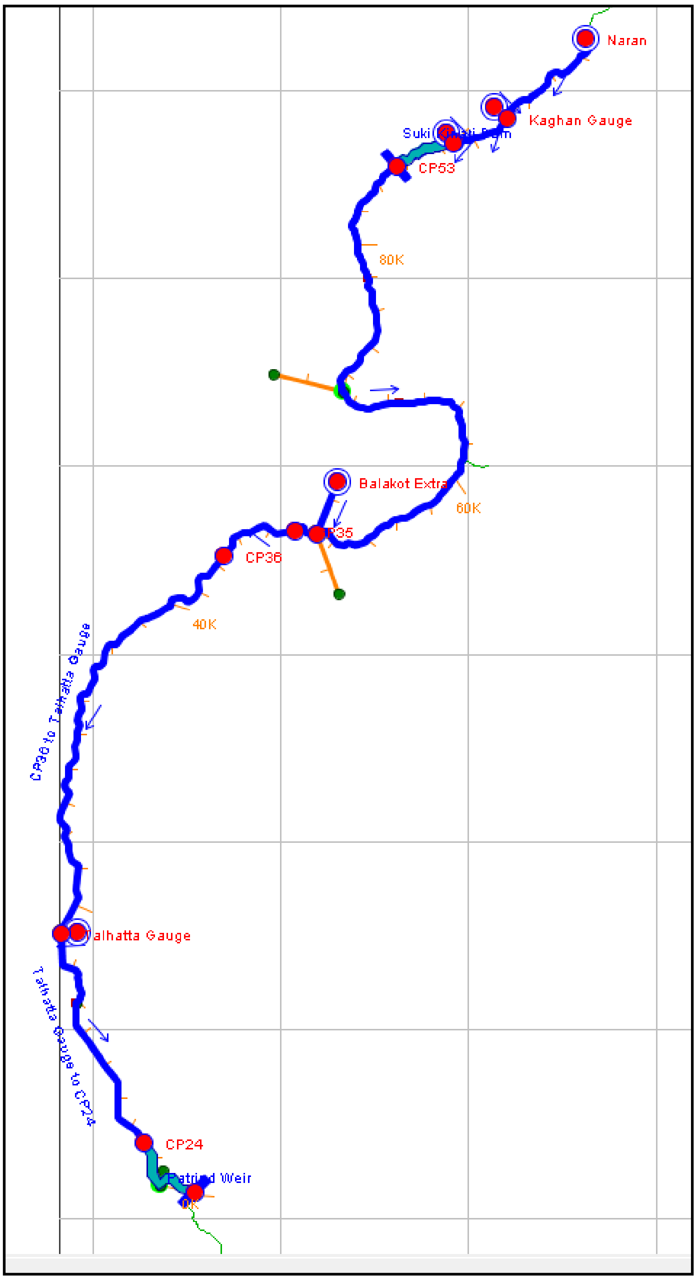


Figure 21: Reservoir Network for Lower Kunhar River Basin

### 3.2.13 Scenarios:

Two main scenarios are under study. The first trial was set to mimic Patrind Weir for its efficiency curve. As the efficiency curve was not available, thus, 4 years of actual operation will be used to develop the actual efficiency for the powerplant.

The second scenario will be involved in the simulation of Suki Kinari impact on Patrind. This will be to study the future impact of U/S reservoir on the downstream and also the power output. Calibration and Validation will be used for fine-tuning of the model for scenario 1 and 2 separately.

# CHAPTER 4

# 4- MODEL EVALUATION AND APPLICATION

## 4.1 Model Efficiency

Four parameters—R2 (second-order correlation coefficient) and NS—are used to assess the effectiveness and calibration and validation performance of the HEC-ResSim model for estimating and reproducing past and future reservoir behaviour (Nash-Sutcliffe efficiency parameter). controlled by statistical criteria. values from simulation and observation.

## 4.2 Co-efficienct of Determination ($R^2$)

Equation is used to get the coefficient of determination (2). Between observed and simulated water levels, the coefficient of determination values spans from 0 to 1, with 0 being the worst and 1 being the best. This component shows the difference between the observed and simulated water levels, expressed as a percentage. A value of 1 indicates that all of the observed variation is duplicated by the model predictions, whereas a value of 0 indicates that the observed variance is not replicated by the simulated model values.
Mathematically, coefficient of determination ($R^2$) is presented as:

Equation 2: Co-efficient of Determination (R^2) Formula

$$r = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{\sqrt{[n\Sigma x^2 - (\Sigma x)^2][n\Sigma y^2 - (\Sigma y)^2]}}$$

n = Total number of observations
Σx = Total of the First Variable Value
Σy = Total of the Second Variable Value
Σxy = Sum of the Product of first & Second Value
Σx2 = Sum of the Squares of the First Value
Σy2 = Sum of the Squares of the Second Value
Thus, the coefficient of determination = (correlation coefficient)2 = r2

### 4.3 Root Mean Square Error

The difference between values predicted by a model and values observed at a station is frequently measured using the root mean square error (RMSE), also known as root mean square deviation (RMSD). Using RMSE, these individual differences—also known as residuals—are pooled into a single indicator of predictive potential.

The RMSE of the model predictions with respect to the estimated variable X model is defined as the square root of the mean squared error.:

Equation 3: RMSE Formula

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y})^2}{n}}$$

where *y(i)* is observed values and *y^* is modelled values at time/place *i*.

### 4.4 Nash-Sutcliffe Co-Efficient (N-S)

Using the mean of the actual values across the comparison period, NS calculates how well the simulated results predict or fit the observed data. NS is a better performance test than R2, and it is consistently smaller. An efficiency of 1 is the ideal number since it indicates that the modelled values are an exact match to the actual data. The NS spans from negative infinity to 1. While values less than 0 are unsatisfactory and suggest that the observed data mean is a better predictor of the observed values than the model predictions, values between 0 and 1 show that the model is a better predictor of the observed values than the observed data average (Nash and Sutcliffe, 1970).

The NS is calculated as follows:

Equation 4: NS Coefficient Formula

$$NSE = 1 - \frac{\sum_{t=1}^{T}\left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T}\left(Q_o^t - \overline{Q}_o\right)^2}$$

Here, Qo is observed flow, Qm is modelled flow and $Qo^{-}$ is mean of Observed flow.

## 4.5 Model Calibration

The main objective of calibration was to determine if HEC-ResSim can accurately predict water levels in relation to actual water levels at the dam. To evaluate the quality of the model calibration, four methods were used. both subjective and objective appraisal, in other words. Subjective evaluations are based on graphical visual comparisons of actual hydrographs and simulations. Calculating quantifiable statistical parameters like R2, RMSE, NRMSE, and NS is the foundation of an objective methodology.

There are various methods for lowering uncertainty in model parameter estimation. Picking beginning values from a given range was a frequent strategy. After that, make continuous adjustments to the parameter values until the model's simulated water levels nearly match the observed water levels. Although this modification process was human, it can be carried out utilising automated and digital techniques. The manual technique was a little difficult and time-consuming, but it produced exaggerated efficiency parameters and outcomes since hand calibration required a deeper comprehension of Patrind and Suki-operation Kinari's than automatic calibration did. The likelihood of having it is thought to be minimal. The D/S Patrind facility's daily observed and computed energy values were the calibration goal, and the calibration period ran from January 1, 2018, to December 31, 2019. The model was individually tweaked for each dam using the observed water level simulated at the bottom of the dam because only observed values are provided here. A comparison of power levels and turbine flows representing simulated and actual water levels from HEC-ResSim will be shown in the graphics in the following chapter.

## 4.6 Model Validation

Model validation demonstrates that the calibrated parameters function effectively when applied to independent data, whereas model calibration reveals optimal, or at least reasonable, values. To determine the model's effectiveness for making future forecasts of dam water levels in the basin, it should be tested on independent data without changing the parameter values established during calibration. From January 1, 2020, to December 31, 2021, was the evaluation period. In the following chapter, it is also addressed and illustrated how power outputs for simulated and actual water levels during the HEC-ResSim review period compare.

# CHAPTER 5

## 5- RESULTS and DISCUSSIONS

In the beginning of Patrind HPP reports' review, an important miscalculation resulted in exaggeration of the annual generation capacity of Patrind hydropower. Hydropower potential is a function of flow and head (the difference in height between the water levels upstream and downstream of the turbine). The basic equation for the potential power output is:

Equation 5: Energy Equation for Potential Head

$$P = Q.\ H_n.\ \eta_t.\ \eta_g.\ g.\ \rho$$

where, $P$ = Power in Watt

$Q$ = turbine flow, m3/s

$H_n$= net head, m

$\eta_t$ = turbine efficiency

$\eta_g$ = generator efficiency

$g$ = gravitational acceleration, $m/s^2$

$\rho$ = density of water, $kg/m^3$

Using this equation, the feasibility study showed a value of 690 GWh but recalculation as a careful attempt showed the final value of 670 GWh. This is just a correction deduced from re-evaluation of the power values given for 10 Daily Average flows as shown in the (Table:8).

This difference is not an achievement for the research but was the by-product of a thorough study of the feasibility study. There was unavailability of efficiency curve which acted as a barrier in preparing of HEC-ResSim model and thus using four years of flow release and power generated from Patrind on ground helped to shape the efficiency curve as near as possible to the correct one.

The results were supported by various graphs (method:1) and statistical equations (method:2) to confirm the authenticity of the efficiency values and power values.

Table 8: Original vs Corrected Annual Energy Table

| | 10 Daily Average | **Energy (GWH) (This was given in the Feasibility Report)** | **Energy (This is the corrected form of the Feasibility Report Value after multiplying 24 with Power Output)** | **New Energy (Corrected but with changed Head Loss)** |
|---|---|---|---|---|
| | | N | N | N' |
| January | (1-10) | 5.262 | 5.262 | 5.264 |
| | (11-20) | 5.025 | 5.025 | 5.028 |
| | (21-31) | 5.560 | 5.054 | 5.052 |
| February | (1-10) | 5.251 | 5.251 | 5.253 |
| | (11-20) | 5.671 | 5.671 | 5.673 |
| | (21-28) | 4.880 | 6.100 | 6.101 |
| March | (1-10) | 7.226 | 7.226 | 7.225 |
| | (11-20) | 9.245 | 9.245 | 9.239 |
| | 21-31) | 13.845 | 12.587 | 12.583 |
| April | (1-10) | 15.524 | 15.524 | 15.523 |
| | (11-20) | 21.780 | 21.780 | 21.780 |
| | (21-30) | 28.984 | 28.984 | 28.978 |
| May | (1-10) | 35.604 | 35.604 | 35.600 |
| | (11-20) | 35.898 | 35.898 | 35.883 |
| | (21-31) | 39.462 | 35.874 | 35.860 |
| June | (1-10) | 35.891 | 35.891 | 35.909 |
| | (11-20) | 35.932 | 35.933 | 35.918 |
| | (21-30) | 36.004 | 36.004 | 35.989 |
| July | (1-10) | 36.008 | 36.008 | 35.993 |
| | (11-20) | 36.077 | 36.077 | 36.095 |
| | (21-31) | 39.681 | 36.073 | 36.059 |
| August | (1-10) | 36.150 | 36.150 | 36.168 |

| | | | | |
|---|---|---|---|---|
| | (11-20) | 34.124 | 34.124 | 34.152 |
| | (21-31) | 30.094 | 27.358 | 27.364 |
| September | (1-10) | 23.798 | 23.798 | 23.796 |
| | (11-20) | 18.359 | 18.360 | 18.362 |
| | (21-30) | 14.790 | 14.790 | 14.784 |
| October | (1-10) | 12.620 | 12.620 | 12.620 |
| | (11-20) | 10.454 | 10.454 | 10.452 |
| | (21-31) | 10.183 | 9.257 | 9.259 |
| November | (1-10) | 7.968 | 7.968 | 7.966 |
| | (11-20) | 7.469 | 7.469 | 7.469 |
| | (21-30) | 6.818 | 6.818 | 6.818 |
| December | (1-10) | 6.281 | 6.282 | 6.283 |
| | (11-20) | 5.977 | 5.977 | 5.979 |
| | (21-31) | 6.324 | 5.749 | 5.750 |
| | | ***690.219*** | ***678.243*** | ***678.227*** |

The study as mentioned above worked on two scenarios which are explained as follows:

## 5.1 Patrind Weir Setup

The Patrind Weir is under work since November 2017 and the actual operation report available is not helpful due to the small range of time which is 4 years from 2018-2021. The actual report indicated an interesting aspect that contradicts the information provided in the feasibility report. In the report the turbine was supposed to generating power of 150 MW at the design discharge of 153 m3/s. According to newly reports, there has been an update of design discharge and the new value of 155.86 m3/s. But, with the change of design flow, the design capacity has not changed from 150 MW.

Discussion with the Patrind Operating Engineer does not contradict the feasibility report. This leads to two questions which was dealt to clarify the reasons behind the low generation of electricity.

## 5.2 Availability of Design Flow

This was judged by the formation of a flow duration curve for the available inflow time series during 2018-2021. The resulting curve is given in the graph provided below. The 25% exceedance of flow per year was the actual design but this was not the case.

The graph shows that at 25% of time, the flow doesn't show the value of 155.86 m3/s. Instead, during Summer the flow available is 110 m3/s and this shows a matter of concern and can be seen from the (Figure:22). This can't be a reason for low energy. The low design flow can be assigned to the droughts that was faced by Kunhar till 2020 and in the year 2021, the flow duration curve did show a value of 155.86 m3/s at 25% of time. Thus, it either shows no problem in hydrological study or there is a need for more data for final evaluation.

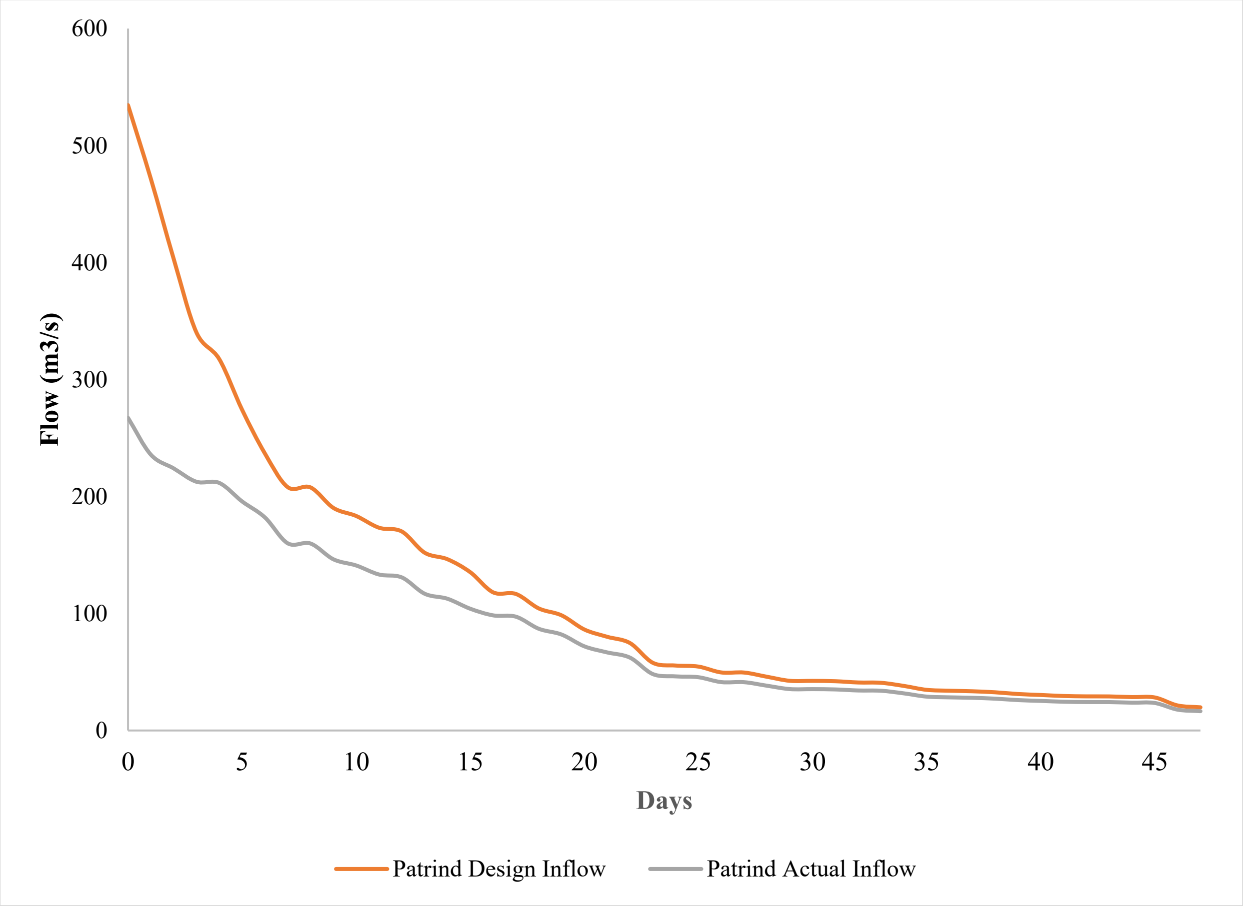


*Figure 22: Flow Duration Curve for Patrind turbine (2018-2021)*

## 5.3 Design Inefficiency of Turbines

In this trial, I compared the simulated and real power generation as shown in (Figure:23) and the conclusion showed that at the efficiency curve given in (Figure:27) best suits the total generation at the end of the year. The efficiency relation was tested on year 2018-2021 and this gave the result in equal to observed. (Table:9) provides the extracted relationship extracted from dense simulation in HEC-ResSim.

Table 9: Release vs Efficiency Relation used in HEC-ResSim

| Release (cms) | Efficiency (%) |
|---|---|
| 18 | 75 |
| 22 | 83.3 |
| 33 | 84.5 |
| 40 | 85.5 |
| 55 | 86.4 |
| 65 | 87 |
| 74 | 88 |
| 81 | 88.7 |
| 110 | 90 |
| 130 | 90.5 |
| 145 | 91 |
| 151 | 90 |
| 155.56 | 89.6 |
| 158 | 87.7 |
| 162 | 86 |

The second probability and a competent reason for the poor performance could directed to the poor manufacturing of the turbines. The simulated efficiency curve for the power plant turbines shows that performance quality of the turbines might be the greater reason for the low outcome from the plant. The quality of the plant is reciprocated in the design efficiency of the turbine and this efficiency plays a major role in the power equation:

For the years 2019–2021, calibration and validation were used to make close to accurate predictions of reality. To evaluate the accuracy of the model calibration, two methods were used. both subjective and objective appraisal, in other words. Subjective evaluations are based on graphical visual comparisons of actual hydrographs and simulations. Calculating R2, RMSE, and NS, three quantitative statistical measures, is the foundation of an objective method.

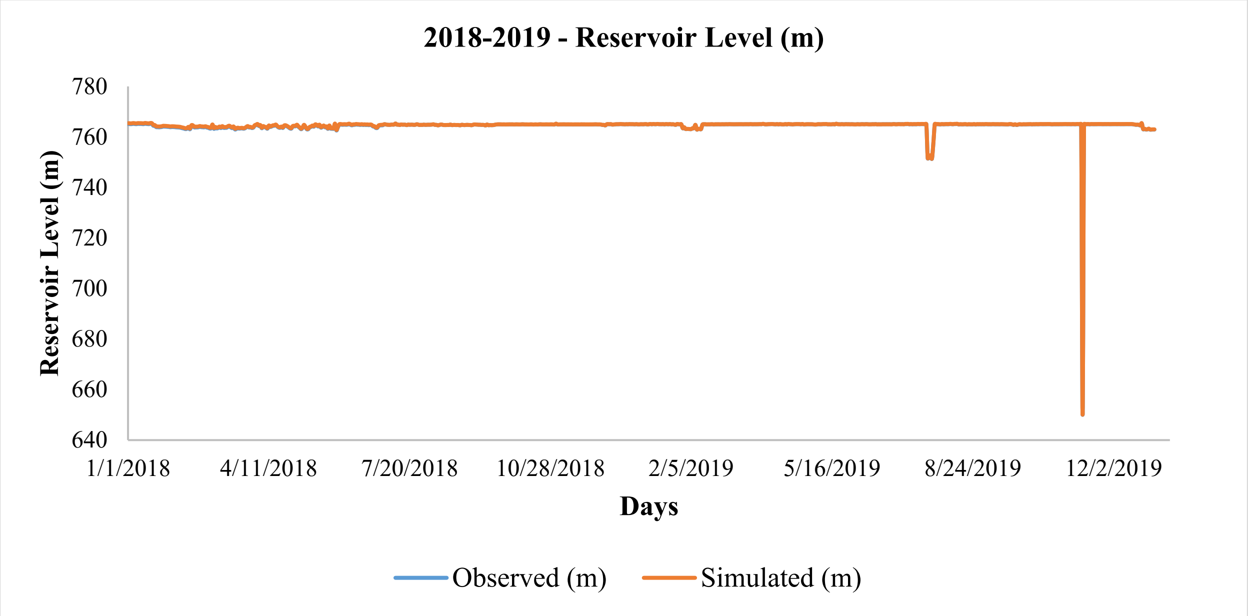


Figure 23: Reservoir Levels at Patrind Weir - (2018-2019)

To clarify the graphical comparison between the observed and the HEC-ResSim simulation has been provided tabular data in (Table: 10) and the result is favourable for a good model setup.

Table 10: Comparison of Power (MW)

| Date | Power (GWh) | Observed (GWh) |
|---|---|---|
| **2018** | 472.23 | 471.81 |
| **2019** | 553.65 | 553.82 |

The Power output comparison is graphically presented below and compliments the tabular values:

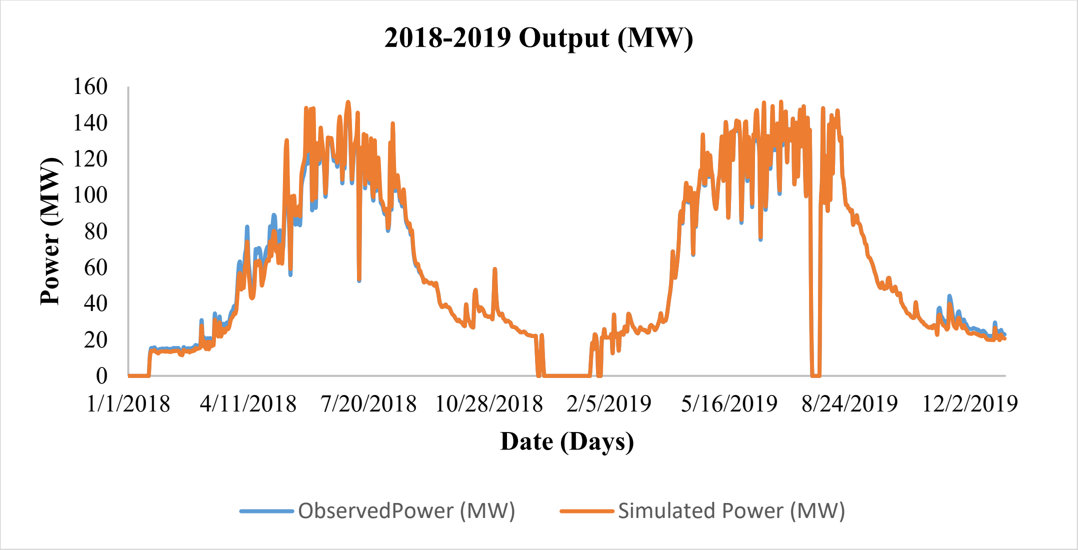


Figure 24: Reservoir elevation and power comparisons for the years 2018-2019

Calibration was performed for the simulation on both reservoir level and power produced at Patrind Weir. The four performance ratios generated successful values as shown in (Table: 11).

Table 11: Calibration Numerical Results

| Reservoir Level (m) | | | | |
|---|---|---|---|---|
| **Year** | **R^2** | **RMSE** | **NRMSE** | **NS** |
| **2018-2019** | 0.901 | 115 | 0.1 | 0.88 |
| **Power (MW)** | | | | |
| **2018-2019** | 0.879 | 105.03 | 0.11 | 0.91 |

The years 2020-2021 were selected for the validation of the model. The graphical and numerical representations proved to be satisfying as seen in the table for the final two years.

The graphical overlapping can be in the subsequent figures for both reservoir elevation in the Head Pond and power generated at the turbines. The results once again compliment the parameters and arrangement of the Patrind Plant setup in HEC-ResSim.

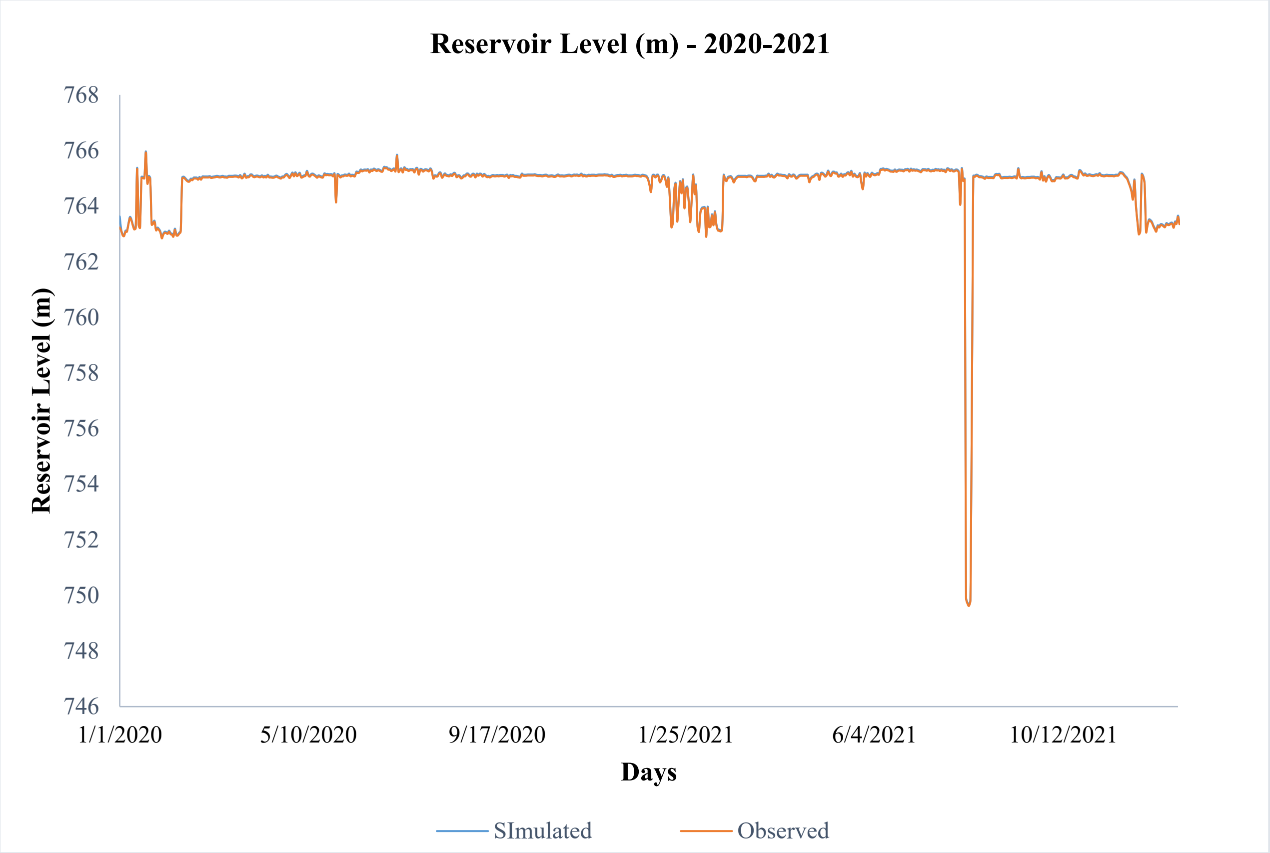


Figure 25: Observed & Simulated Elevation values.

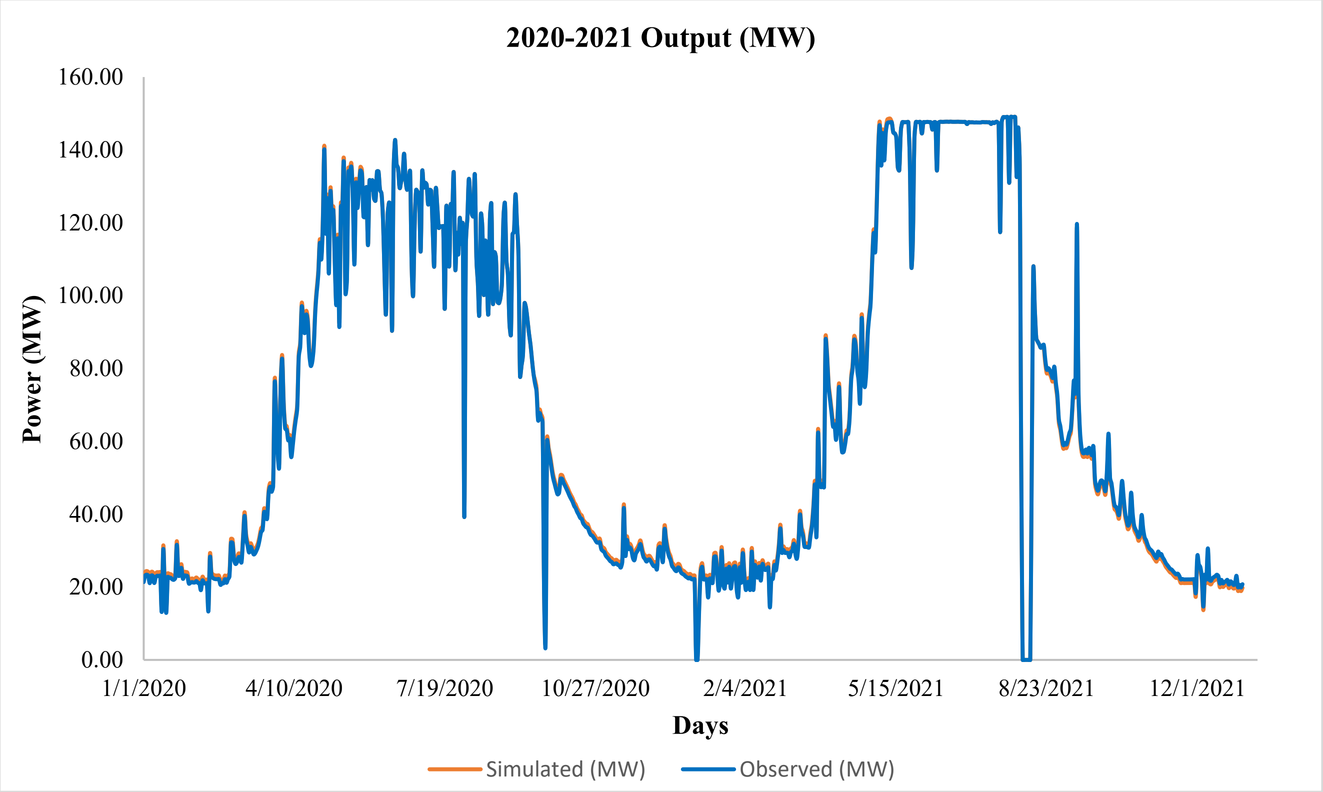


Figure 26: Power Generation for years 2020-2021

The Tabular data evaluates the outcomes presented in Table (12 & 13).

Table 12: Numerical Validation for year 2020-2021

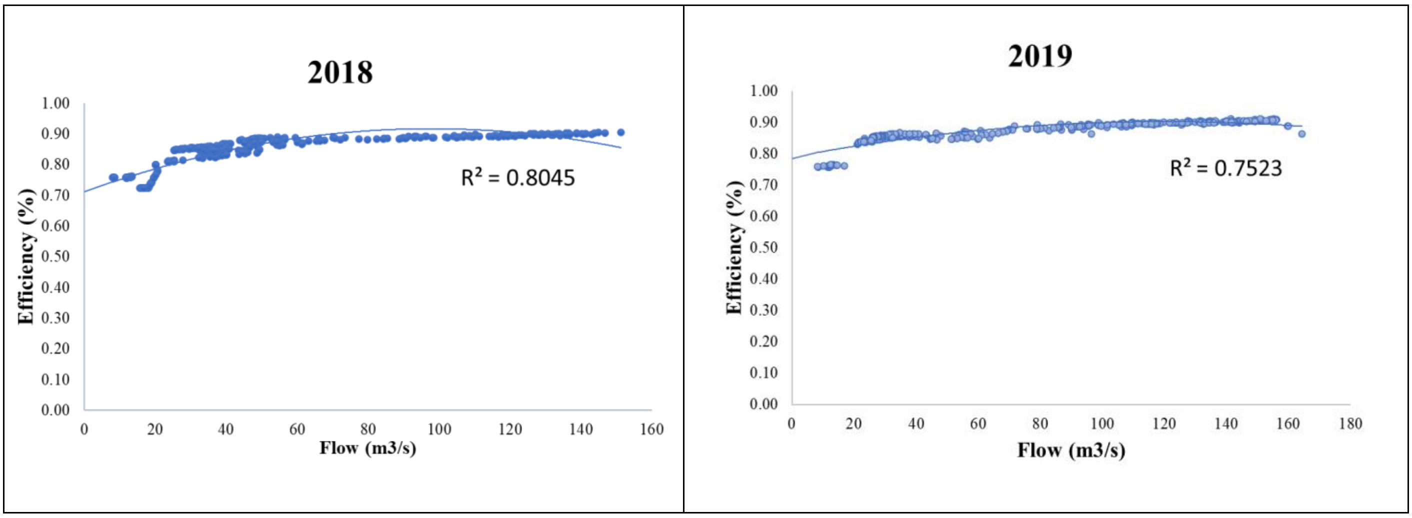
| Reservoir Level (m) | | | | |
|---|---|---|---|---|
| **Year** | **R^2** | **RMSE** | **NRMSE** | **NS** |
| 2020-2021 | 0.93 | 8.11 | 0.03 | 0.9 |
| **Power** | | | | |
| 2020-2021 | 0.921 | 68.61 | 0.07 | 1 |

To further support the above ratios the power table validates the results properly:

Table 13: Power Comparison for years 2020-2021

| Date | Power (GWh) | Observed (GWh) |
|---|---|---|
| 2020 | 598.8 | 598.3 |
| 2021 | 600.7 | 600.52 |

With these values, the approximate turbine power efficiency curves were extracted from the model for the Patrind. The graphical curves represent the global efficiency (η%) used in the power equation, more appropriately, the combined efficiency of Turbines and generators. Combined efficiency is used due to the in-built feature HEC-ResSim which incorporates the effect of all involved machinery in power generation.



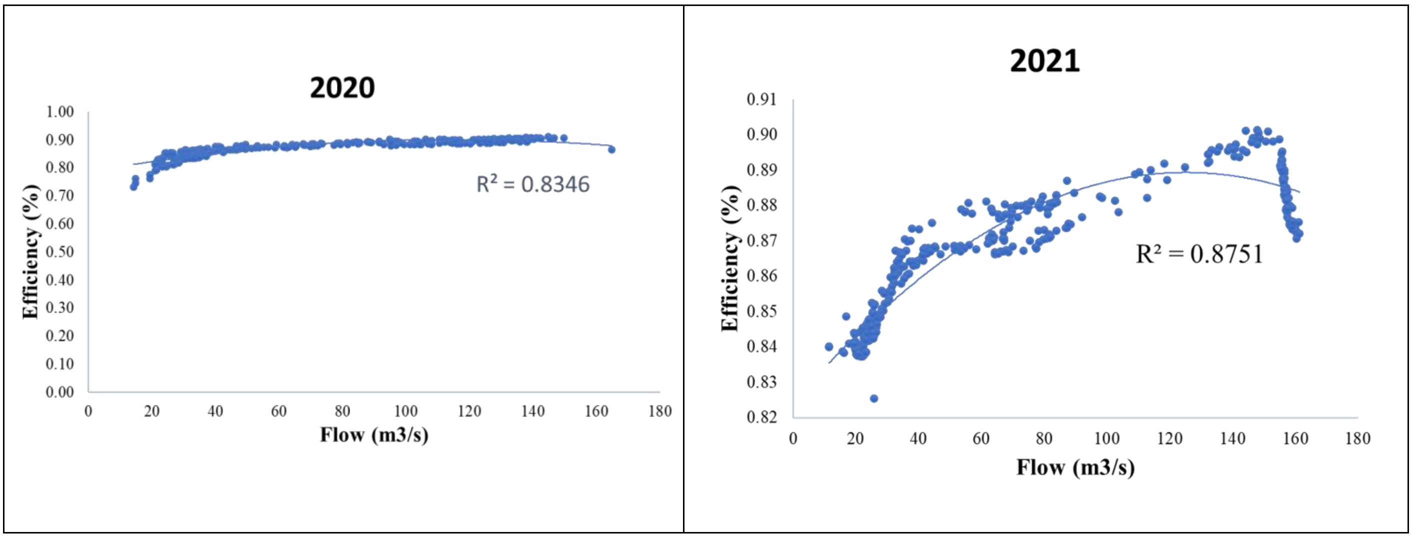


Figure 27: Efficiency Curve 2021

The R^2 suggests that the efficiency curve is approximately concludes to the relationship of Flow(cms) to Efficiency (%) in the above-mentioned table. Thus, Patrind Dam reduced power production as mentioned in feasibility report can be due to mechanical inefficiency of turbines which answers the low power output from the powerplant at design discharge.

Finally, the curve indicates that the efficiency of the Plant is less than what is given in the feasibility report for Patrind HPP which mentions a value of varying between 88% - 91.63%. As HEC-ResSim shows variance between 75% - 90%, this shows with the generator being constant for 98% which usually universal, the peak efficiency of the turbine is around 91.8% which is below 93.5%. Not only the peak but entire range is low compared to the design. This efficiency curve is the benchmark for the next step of Suki Kinari effect.

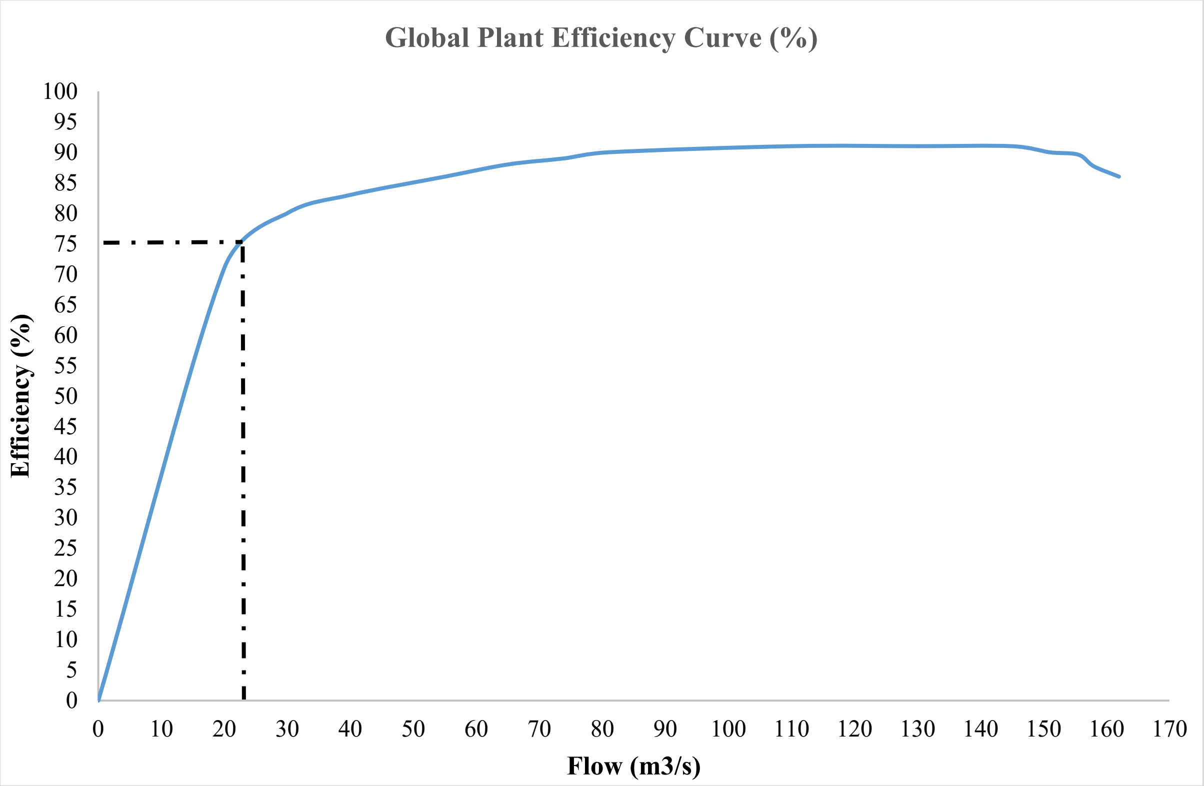


*Figure 28: Efficiency Curve*

### 5.4 Suki-Kinari Dam's Effect

The real focus of the study was to see effect on the generation of Suki Kinari on Patrind when both are operated simultaneously under optimal rules and the following graphs shows the results under two main scenarios:

#### 5.4.1 Scenario (1): Max Power Production

In the first scenario, the reservoir level of both the schemes have been left fluctuating between upper and lower limit of the conservation zone depending on the inflow and design outflow. In this case max power is released at both power houses. HEC-ResSim used a special in-built rule of cascading and with special release functions accordingly given in original design, the network arrangement was simulated. The results have been given in the shape of graphs and table. It is important to keep in mind that Suki Kinari's outflow and impact on Patrind will be under consideration for calibration and simulation.

(Figure: 29 & 30) shows the outcome at the end of simulation of Suki Kinari – Patrind operation in tandem. The graphical picture provides a satisfactory response as the total energy generation in the drought months of 2018-2019, Suki Kinari produced favourable and reasonable values. Graphs for Reservoir levels and power fluctuations have been displayed for understanding the changes in water and power profiles when optimal power is considered for both power plant projects. Suki-Kinari showed massive variation within the limits of the conservation zone, i.e., between the upper and lower limits of normal operating levels: 2265-2275m. Patrind's head pond showed changes like the actual operation of the plant. Similar situation is for the power values and have been provided in the tables.

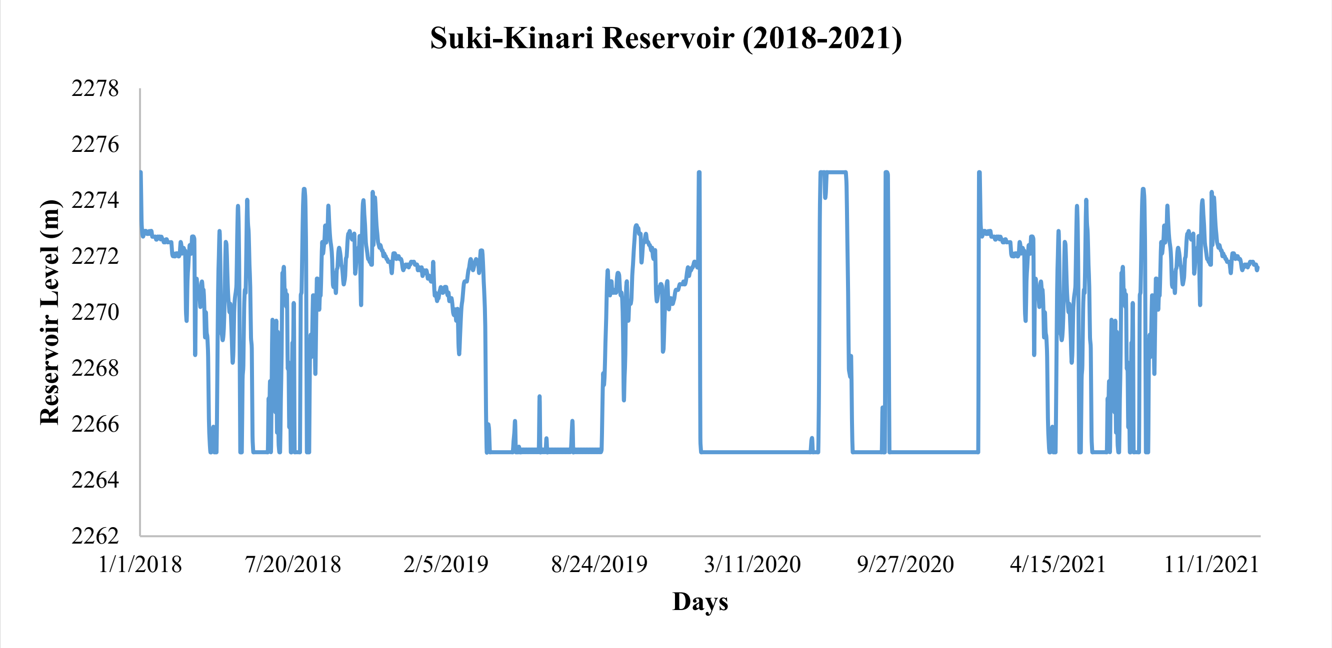


*Figure 29: Suki Kinari Reservoir Level (m) - 2018-2019*

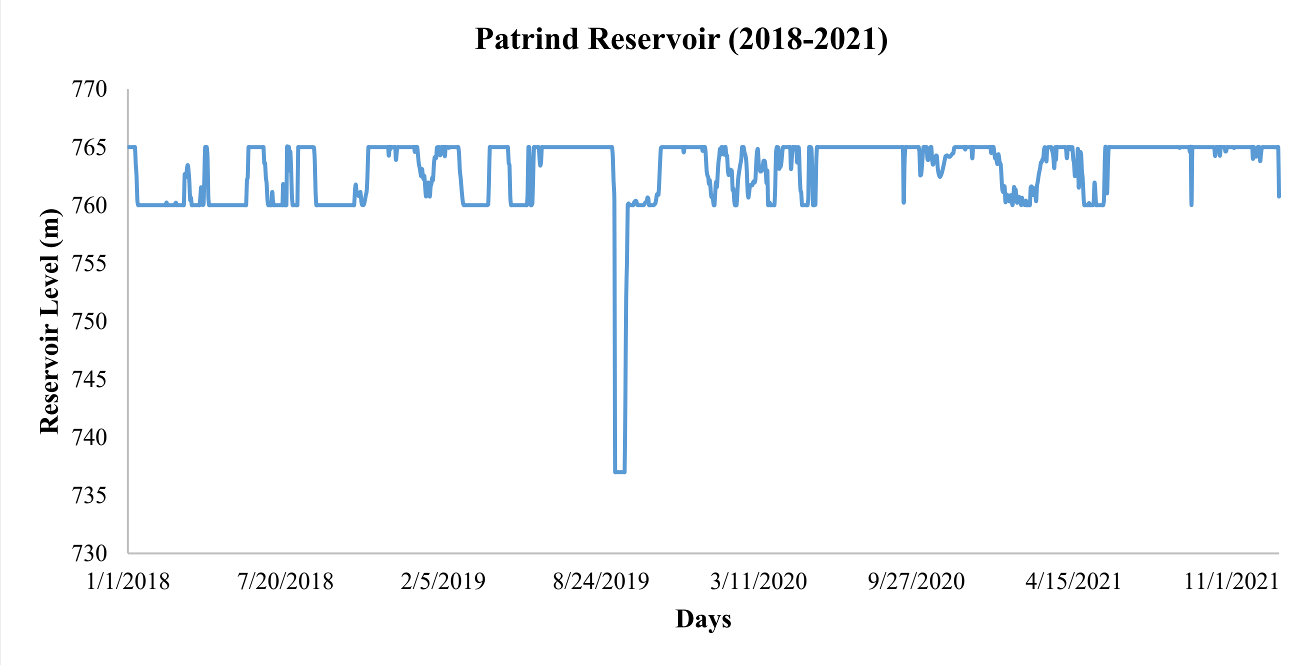


*Figure 30: Patrind Head Pond Level (m) - 2018-2019*

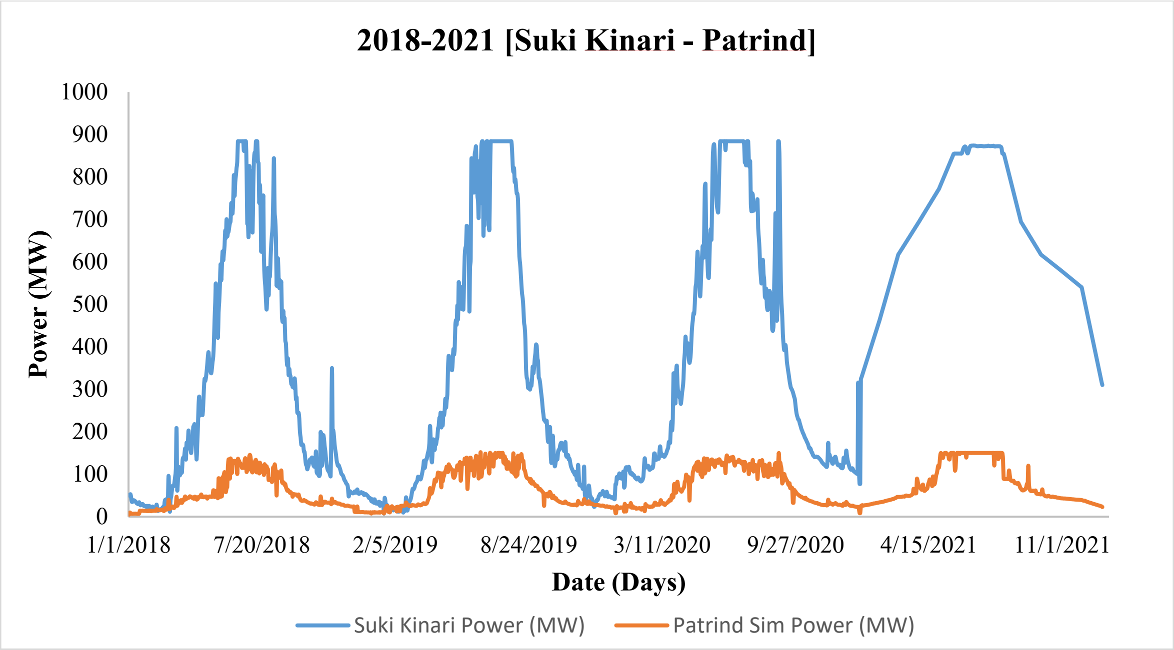


Figure 31: Suki-Kinari & Patrind Reservoir Output (MW) - 2018-2021

Table 14: Suki-Kinari Power Plant Production (2018-2021)

| Date | Power (GWh) | Design (GWh) |
|---|---|---|
| **2018** | 2556 | 3129 |
| **2019** | 2686 | 3129 |
| **2020** | 2820 | 3129 |
| **2021** | 3002.95 | 3129 |

Table 15: Patrind power plant production (2018-2021)

| Date | Power (GWh) | Observed (GWh) |
|---|---|---|
| **2018** | 477 | 471 |
| **2019** | 581 | 553.5 |
| **2020** | 602.5 | 598.8 |
| **2021** | 611.2 | 600.52 |

The tables provide the yearly energy outcomes from the controlled manipulation of the dams under cascading system and below is the graphical representation. After hefty iteration process, the optimal guide curve for scenario (1) has been provided in (Figures: 32 & 33)

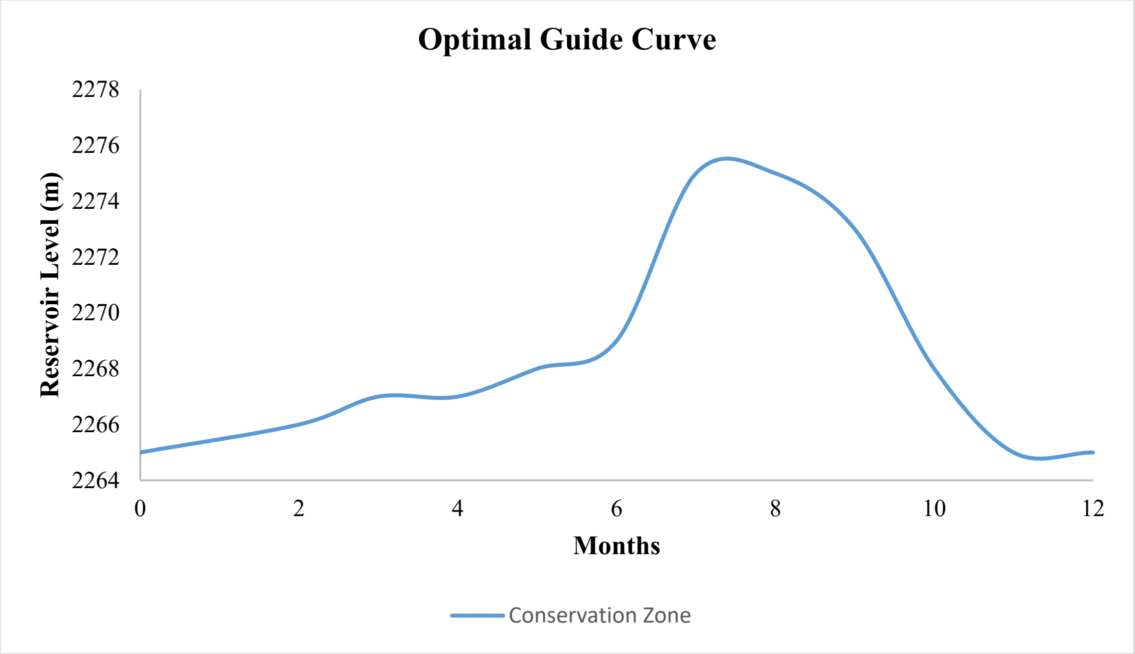


Figure 32: Suki-Kinari Guide Curve in Scenario (1)

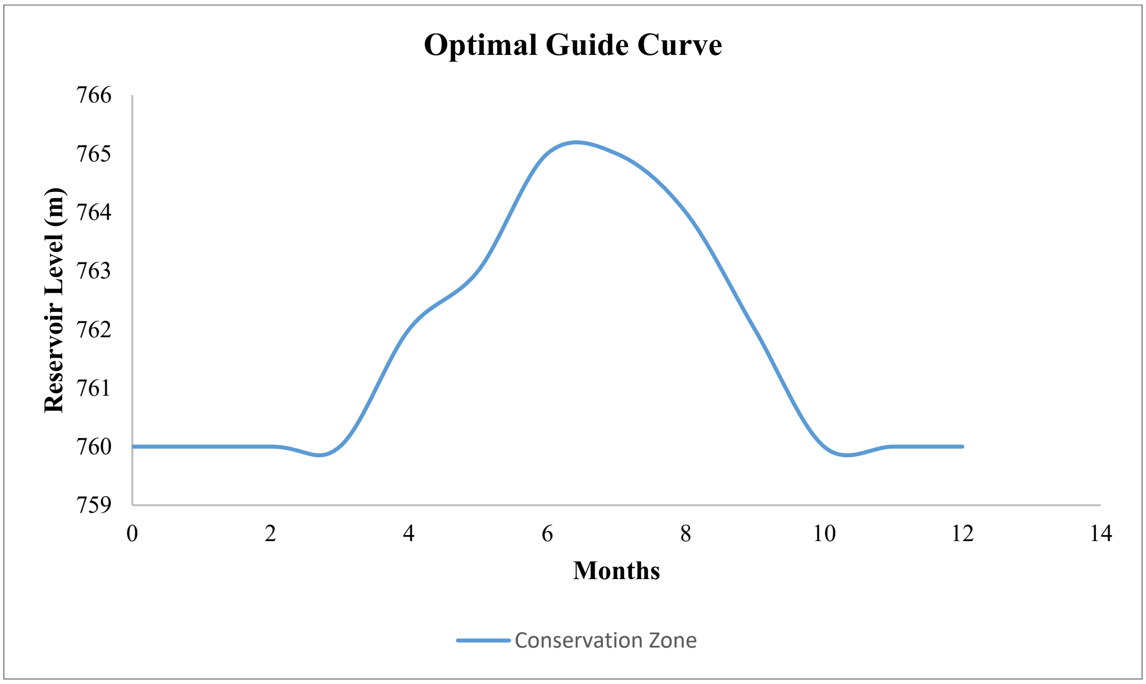


Figure 33: Patrind Guide Curve in Scenario (1)

### 5.4.2 Scenario (2): Optimal Cascading with Max Reservoir Levels

This time the cascading effect of Suki Kinari on Patrind with reservoir levels at both HPPs targeted to reach normal operating level. In this case, control rules have been used to optimize power output while the reservoir level is kept mostly at normal operating level (NOL = 2275m/765m), especially during the summer season of the year. The hourly effect was not considered due to unavailability of daily hourly inflows and release. There was a drop in Suki-Kinari's total output of energy, but it had little impact on Patrind in comparison to the first scenario. Suki-Kinari still proved to be successfully up to design power in the last two years especially 2021.

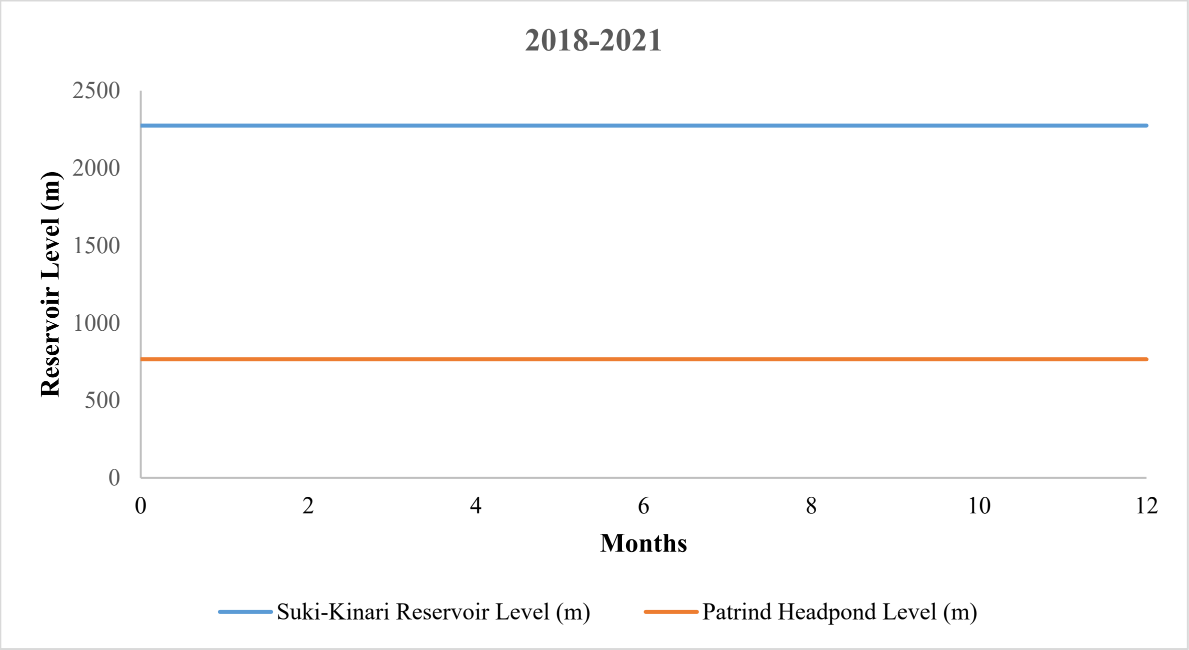


Figure 34: Reservoir levels at respective NOL for Suki-Kinari & Patrind

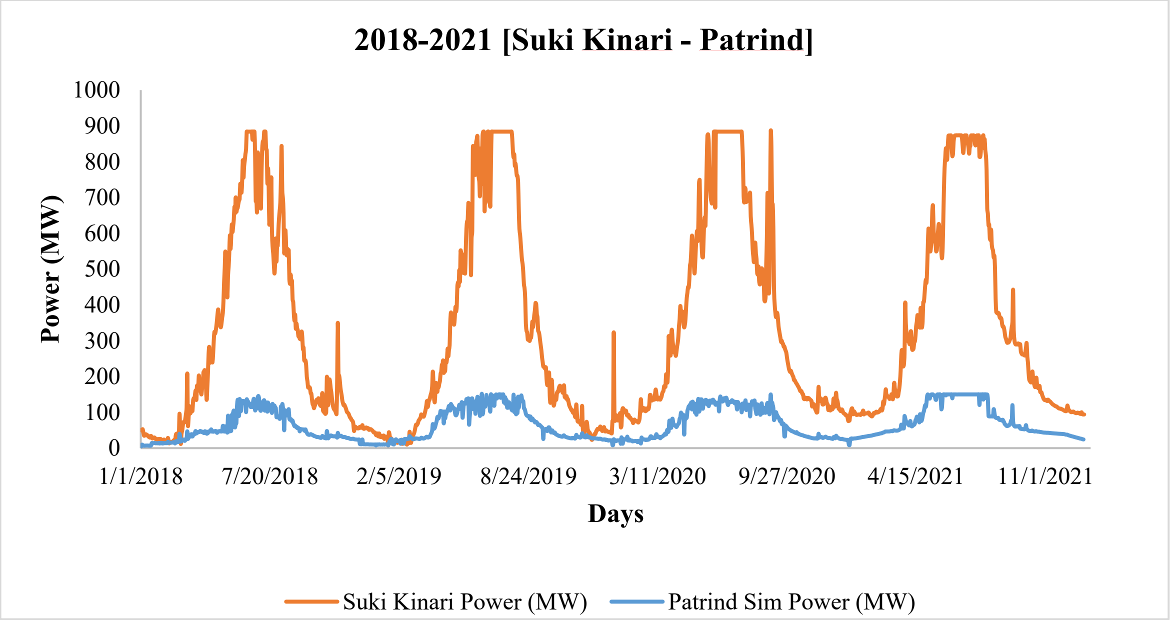


Figure 35: Suki-Kinari and Patrind sim power (MW)

It shows that when controlled release is performed and the reservoir level kept at NOL at both reservoir sites, energy production annually increases. But Suki-Kinari has little impact on Patrind Turbine as seen in both alternatives. The second scenario suits the reality as water is available for power production throughout the day compared the former where certain days forces the reservoir to stop generating and refilling of conservation zone becomes the priority. The optimized decisions showed annual increase in energy production due to increase hydrological inflow to the sites. But Suki-Kinari had little impact on Patrind Turbine as seen in both alternatives. The final optimized guide curve for Suki-Kinari and Patrind are given in (Figure: 36 and 37).

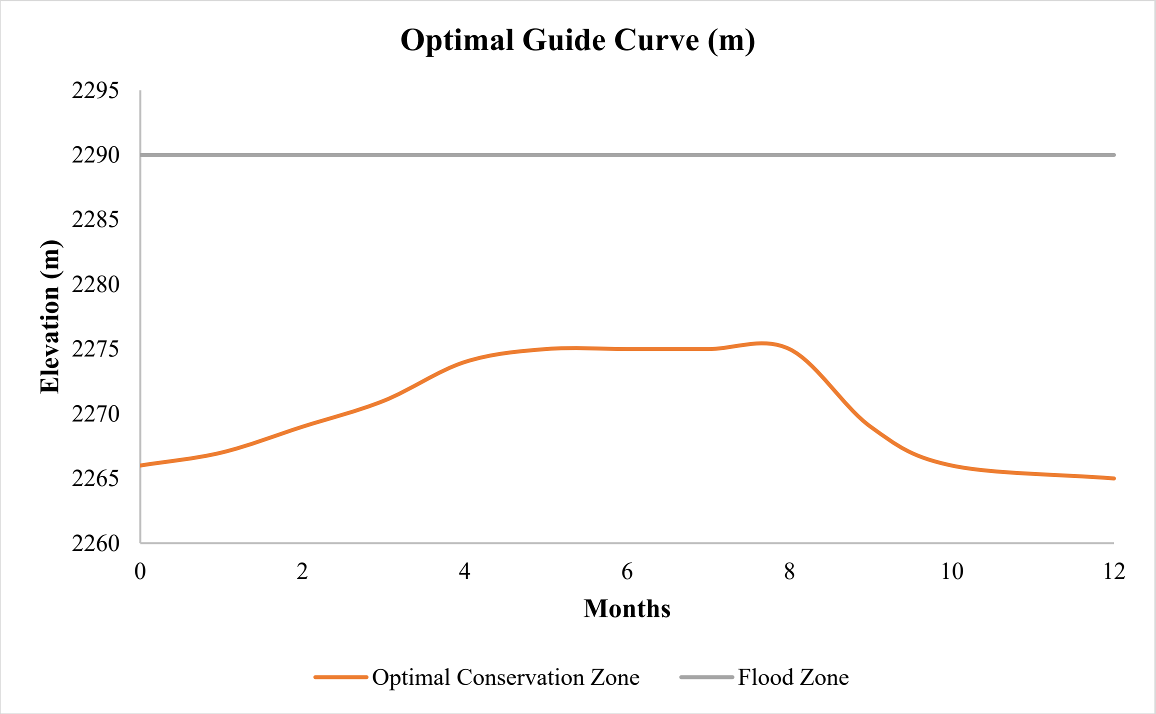


Figure 36: The Optimal guide curve for Suki-Kinari in Scenario (2)

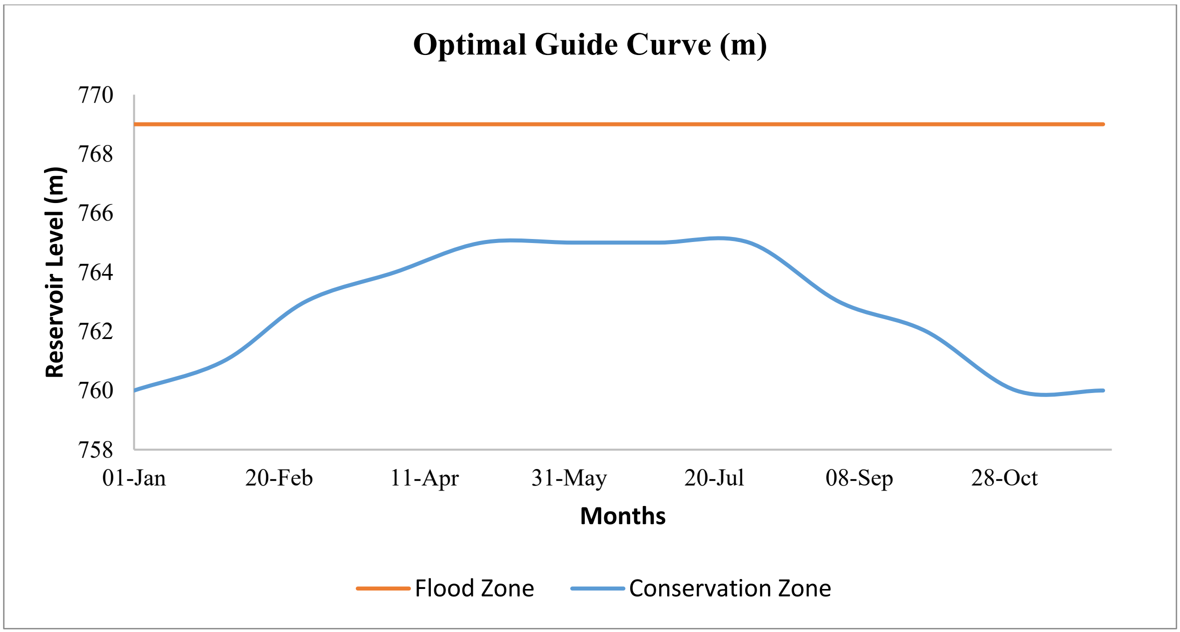


Figure 37: The Optimal guide curve for Patrind in Scenario (2)

The procedure of iteration in HEC-ResSim evaluated the two scenarios and led to the conclusion of the optimal release rules for the projects acting in cascade is shown in (Figure: 36).

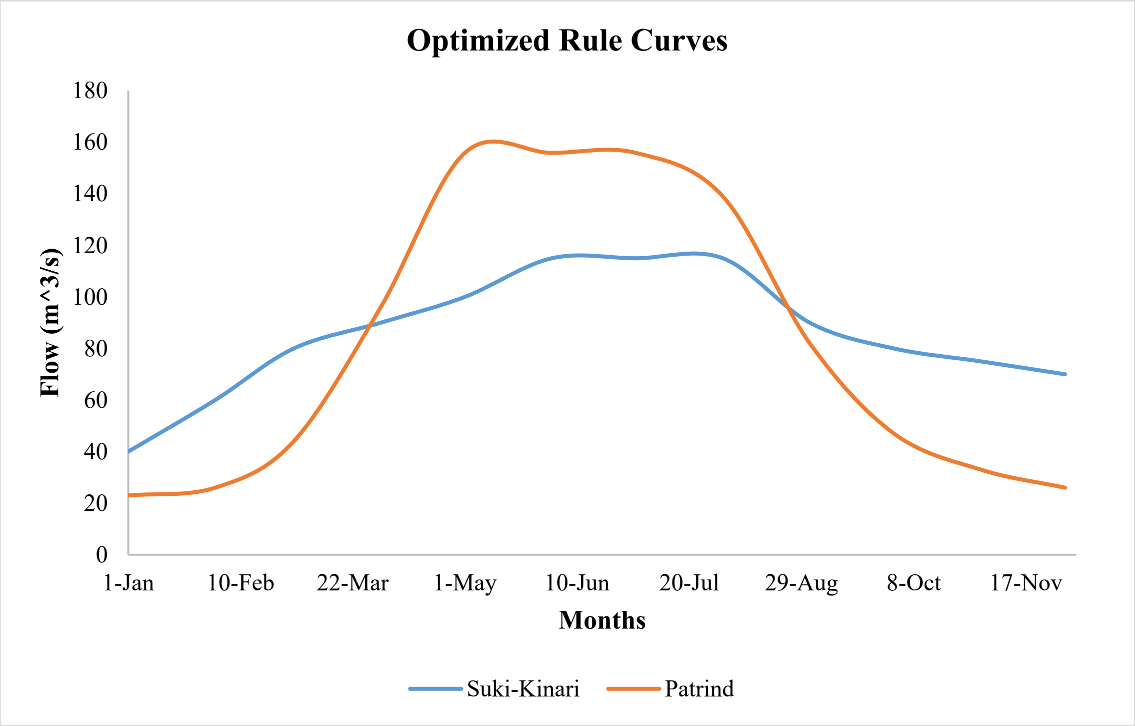


Figure 36: Optimal Guide Curve at the end of the two scenarios

The release rules extracted in (Figure: 36) for HPPs under study corresponds optimal release of the reservoirs to the turbines for maximum power generation with keeping the inflow to the reservoir under consideration. The guide curves will be used in the future by the operator for maximum conservation and maximum power generation.

The release rules are directed to the controlled release of the reservoirs to the turbines for maximum generation possible keeping the inflow to the reservoir under consideration.

## 5.5 Discussion

It is important to be noted that the inflow to the reservoirs during the years under study were below the average hydrological stream inflow as per design mentioned in the feasibility report. This coupled with reservoir requirement for keeping water elevation at normal operating levels restricted the power plants from operating at designed set. This reality existed primarily between 2018-2021, with severely drought season during the first two years of the study. But the study did show that with different release options, more power could have been produced than observed in the four years. Therefore, the total inflow was not according to design flow duration curve and far less leading to low generation for Patrind and Suki Kinari.

The low results after simulating showed that efficiency of turbines have been manufactured poorly against what the technical report given in feasibility study for Patrind Weir. This was a huge achievement in the course of the study notably verified by the efficiency curves for years 2018-2021 supported by R^2 = 0.801,0.79,0.79 & 0.83. Observation and HEC-ResSim simulation concluded that with keeping all other parameters identical, the efficiency of the turbines was the major weak link that reacted in low turn-out of energy from the turbine.

The calibration and validation performed did provide effectively suitable and acceptable statistical values for R^2, RMSE & NS. There are certain assumptions that were made which helped the model reach the conclusions. The initial prerequisites came to be necessary due to lack of some data available in the feasibility report. The limitations existed in the hydrological data at Kaghan and Talhatta stations for the years 2020-2021 which were assigned for calibration and validation of the model. Due to certain restrictions, WAPDA provided streamflow data till 2019. Therefore, catchment ratio method was adopted using data available on Patrind Weir in the Operation Report provided by site engineer for D/S HPP and different stations' information were calculated. This though envelopes some error. The flow and power efficiency curves for the turbines were unavailable in the feasibility report which led to the foremost task of deducing a curve for Patrind Weir. Using trial and error on HEC-ResSim enabled with sufficient correlation between flow and percentage power. As for Suki Kinari, no observable data was available for calibration or validation of turbines to extract the efficiency curve, thus a generally available curve from a research paper (Kimambo & Nielson, 2012) was selected to produce results. This overshadowed the mechanical differences in turbines that are always associated in manufacturing by a certain mechanic or manufacturer. Furthermore, the efficiencies applied in producing energy was the combined effect of turbine and generator as HEC-ResSim employs both the equipment's' impact. Though this restriction didn't affect the energy values, just individual performances of turbines/generators could not be precisely finalised.

As seen from the graphical plots for Suki Kinari and Patrind, there has been seen little impact on overall generation of Suki-Kinari on Patrind power output. The outcome against general thinking must be due to huge spatial difference between Suki Kinari and Patrind as both are separated by more than 1600 $km^2$ of catchment area and furthermore the areas of Balakot and Talhatta receive a lot of precipitation, and this contributed a lot of flow to Patrind. The more power at Patrind was produced because the model simulated during the dry seasons contrary to the scheme adopted during actual operation of Patrind. There also a huge contribution of tributaries to the Kunhar River down Suki Kinari. But the main reason of little impact is due to different release options that were employed in the study which kept high power production. It shows that in the drought years of 2018-2019, it was possible to release more energy contrary to observed based on release options in day, which was showed in research.

# CHAPTER 6

# 6- CONCLUSION and RECOMMENDATION

## 6.1 Conclusion

The research reached positive end with identifying design error in the Patrind Weir structure and satisfactory cascade simulation was performed. Under HEC-ResSim, due to low operational range, the optimal reservoir operation still produced satisfactory response and two scenarios of extreme nature were studied.

## 6.2 Recommendations

It is recommended for future reflection is to engage different departments related to the dams and obtain complete data to remove many of the limitations due to technical and organizational issues, causing some shortcomings. This was a major reason for working on two scenarios where one touched full power and the other based on observed.

The use of Python and advance methods, including the scripting for different plug-ins for the model will be very advantageous for researchers. An example can be the separation of hydraulic losses and efficiency curves for turbines, generators and transmission will be beneficial in understanding the relative work of each component and that could have helped in concluding for Patrind Weir's inefficient generation.

The important fine-tuning of our results can be done if a stochastic model is used based on the 2 scenarios discussed in the study. This can be an important step to see the effect of using an entirely different mathematical program and compare with HEC-ResSim which is deterministic in algorithms. A weak number of studies have been done for HEC-ResSim comparison with others. This can be a novel approach and advance algorithms can be used in tandem for appropriating or enhancing the results produced by HEC-ResSim. Though, friendly usage interface comes with HEC-ResSim but stochastic models can be implored in the future for the Kunhar River Basin

To clearly understand power changes, Balakot dam which lies in between Suki Kinari and Patrind can be introduced, and a proper cascading effect can be visualized and simulated. Balakot HPP is the next project to be laid down after Suki Kinari and it has been designed to act as downstream cascade for Suki Kinari. The Tailwater of Suki Kinari is the reservoir level for Balakot and the Balakot's tailrace will be source for Patrind Weir. Thus, future consideration can be done in consideration of Balakot. Furthermore, proper research must be done to solve other limitations in the study which might over or under-estimate some values. Thus, effort must be oriented to solving the issues.

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