MODELLING OF NALGAD DAM AND RESERVOIR OPERATION FOR HYDROPOWER GENERATION IN NEPAL USING HEC-RESSIM

A DISSERTATION

Submitted in partial fulfilment of the

Requirements for the award of the degree

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WATER RESOURCES DEVELOPMENT

By

HARI BAHADUR OLI

DEPARTMENT OF WATER RESOURCES DEVELOPMENT AND MANAGEMENT

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

ROORKEE-247667 (INDIA)

MAY 2019

CANDIDATE'S DECLARATION

I hereby declare that the dissertation, entitled **"Modelling of Nalgad Dam and Reservoir Operation for Hydropower Generation in Nepal using HEC-ResSim"** is an authentic and genuine record of my own work conducted in my own capacity. It is presented on behalf of partial fulfilment of the requirement for the award of the degree of "**Master of Technology"** with specialization in "**Water Resources Development (Civil)"**, submitted to the department of **Water Resources Development and Management, Indian Institute of Technology Roorkee, India**, under the supervision of **Dr. S. K. Mishra**, Professor, Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, India and under the guidance of **Mr. J. P. Patra**, Scientist-C, National Institute of Hydrology, Roorkee, India.

I have not submitted the matter embodied in this report for the award of any other degree or diploma.

Date: 20th May, 2019 **Hari Bahadur Oli**

Place: IITR, Roorkee **Enrolment No: 17548006**

CERTIFICATION

This is to certify that the above statement made by the candidate is correct to the best of our knowledge and belief.

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Mr. J. P. Patra
Scientist–C
NIH, Roorkee, UK-247667, India
Date: May, 2019

Dr. S. K. Mishra
Professor Department of WRD&M
IIT Roorkee, UK-247667, India
Date: May, 2019

ABSTRACT

Theoretical power generation potential of Nepal was estimated as 83,500 MW in 1966, out of which 42,000 MW is technically and economically feasible to be produced. However, so far the country has managed to generate only 914.6 MW, which is about 2% of economically feasible power generation potential, and 2% of the total energy consumption in the country. Despite harbouring a huge hydropower potential, Nepal has not been able to meet its own domestic demand for electricity. Recently, Nepal is focusing highly on development of hydropower to fulfil its ever increasing demand of energy and economic development of the country. This Study aims at to build a simulation model of the proposed Nalgad dam reservoir operation for hydropower generation in Nepal using HEC-ResSim. The historical daily discharge data for the period 1966 to 2016 have been used for analysis with consideration to seasonal (dry and wet season) and hourly energy demand. Six months from December to May are categorized as dry period and remaining six months June to November are categorized as wet period. Five operation scenarios with various turbine units and generation patterns are analysed. Four turbine units in operation for ten-hour in dry season and one-hour in wet season, maintaining reservoir level between 1498 masl and 1580 masl found to be optimum. The dry season energy generation is 735.04GWh/year with 90.19% reliability and total annual energy generation is 1247.72 GWh/year. In addition to simulation, the monthly reservoir operation policy is also developed solving the formulated optimization problem using LINGO model for 90% dependable year. It is observed that the energy generation, reservoir storage and reservoir elevation, spill etc. obtained from both the methods are almost similar. However, the simulation model is considered to be more effective tool for analyzing reservoir operation simulation as it reflects real system behavior. Sensitivity of change in inflow, environmental release and full supply level (FSL) on of energy generation are analysed. It is observed that the effect of change in inflow on dry season energy generation is very less in comparision to wet season energy generation. The reduction in dry season energy is about 6% for a 20% decrease in inflow. The average annual dry season energy generation decreases in the range of 22-29 GWh/year with total annual opportunity cost of Nrs. 338-396 Million per year by increasing environmental release by 1 m^3/s. The energy generation and gross return from energy linearly increases from FSL in the range of 1550 to 1580 masl and after this level there is negligible increment in energy generation. Hence the selected FSL at breakeven point i.e. 1580 masl is justified. The empirical area reduction method was used to develop Elevation-Area-Capacity curve after 25, 50, 75 and 100 years from reservoir operation date due to sedimentation. It is estimated that total storage volume is reduced by 14.23 MCM, 28.36 MCM, 42.46 MCM and 56.58 MCM after 25, 50, 75 and 100 years respectively. There is very less or negligible decrease in annual average total and dry season energy generation due to sedimentation even after 100 years as only about 2% loss in live storage capacity is observed. Each 1 Mm^3 loss of live storage will reduce dry season energy by about 0.57 - 0.9 GWh/year after 25 years to 100 years. Moreover, due to sedimentation zero deficit years decreases from 22 years in present conditions to 14 years due to sedimentation after 100 years. Moreover, the 5-10% energy deficit years are almost doubled after sedimentation of 50 years. The future drinking water demand from the reservoir to downstream municipality such as Nalgad, Athbiskot, Bheri and Chaurjhari is estimated to be about 2.5 m^3/s. To meet this demand and maintaining reliability of energy generation, the hydro power generation hour need to be reduced to nine-hour in dry season. In such situation there will be reduction of about 73.138 GWh/year in dry season energy.

Keywords: Nalgad Dam Reservoir, HEC-ResSim, Reservoir Simulation, Hydropower-Schedule-Rule, optimum energy, Reliability, LINGO, Environmental release.

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HARI BAHADUR OLI

(17548006)

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LIST OF ABBREVIATIONS

CWC	Centre Water Commission
DEM	Digital Elevation Model
DSS	Data Storage System
D/S	Downstream
E	Easting
FSL	Full supply Level
GIS	Geographical Information System
GoN	Government of Nepal
GRC	Guide Rule Curve
GWh	Gigawatt Hour
Ha	Hectare
HEC	Hydrologic Engineering Centre
HEC-ResSim	Hydrologic Engineering Centre- Reservoir System Simulation
IFSSP	Identification and Feasibility Study of Storage Projects
IIT	Indian Institute of Technology
IWMI	International Water Management Institute (Sri Lanka)
Km	kilometre
LP	Linear Programming
Lps	Litre per second
m	Meter
m^3	Cubic Meter
masl	Meter Above Sea Level
MCM	Million Cubic Meter
Mm3	Million Cubic Meter
MOL	Minimum Operating Level
MOEWRI	Ministry of Energy, Water Resources and Irrigation
M.Tech	Masters of Technology
m^3/s	Cubic Meter Per Second
MWh	Megawatt Hour
N	Northing
NEA	Nepal Electricity Authority

NHCL	Nalgad Hydropower Company Limited
NIH	National Institute of Hydrology
PMF	Probable Maximum Flood
Q	Discharge
SD	Standard Deviation
U/S	Upstream
USACE	United States Army Corps of Engineers
WECS	Water and Energy Commission Secretariat
WRDM	Water Resources Development and Management

CHAPTER 1: INTRODUCTION

1.1 General

Water is one of the limited natural resource, under increasing stress with increase in per capita demand and population all over the world (IWMI 2000). The water demand for various purposes viz. agricultural, industrial, power generation, domestic use, waste collection treatment etc. are rising with the economic growth of world. Random and cyclic seasonal fluctuation of flow is observed in most of the rivers fed by monsoon. Hence, storage of water in reservoir plays a key role in regulating stream flow fluctuation. Optimal reservoir operation policy is essential for development of trustworthy water supplies, hydropower generation etc. (Wurbs and James 2001).

Computer simulation models are generally used as analysis tools when the water demands, equitable allocation and distribution is complex (Asit 1976). To come up with the optimal strategies for distribution and allocation of water resources, several run of simulation models with various scenarios can be used (Wurbs and James 2001). Sustainable and equitable water supply from the reservoir can be achieved using river system simulation models. These models also help in management strategies of reservoir operation policies. Basin- scale analysis are often carried out using one of two type of models; first one is to simulate behaviour of water resource as per the predefined operation set prevailing water allocation and infrastructure operations. Next is to optimize and select water allocation and set-up based on an objective function and associated constraints. The system performance assessment can best be done through simulation model, whereas, optimization model become more useful when the system improvement is the main goal. Reservoir simulation model can be defined as the mathematical simulation model of river system with reservoir. The simulation model includes the mass balance of reservoir inflow outflow and storage fluctuation. Simulation model provides an economic evaluation of damage due to flood, benefit from irrigation, power generation, water supply and/or other such activities. Simulation model also provide a realistic and detailed representation of reservoir operation.

Per capita energy consumption is one of the main indicators of the economic development of a nation. Economic activities expand with the availability of adequate energy at a reasonable and affordable price. Surplus energy encourages individuals to initiate and expand income generating activities boosting the economic development of a country. Therefore, the role of energy in the overall development of a nation need not be over emphasized. Nepal's energy sources consist of a combination of both traditional and commercial energy. Over two-third of the total population meet their energy demand, through traditional sources. Consumption of commercial energy in the form of electricity, coal and petroleum products is ever increasing. Nepal is importing all petroleum products and coal for energy need by spending scarce foreign currencies. Further, there is tremendous pressure on forest sector in rural areas as regards energy consumption practice. Therefore, Nepal needs to develop hydropower to fulfil its ever increasing demand of energy and for the economic development of the country.

Nepal has been endowed with tremendous hydropower potential due to numerous rivers and favourable terrain. Nepal has a theoretical potential to generate 83,000 MW of hydropower, out of which about 43,000 MW could be generated economically as per today’s available infrastructure/s. Country is entering a phase of economic development based on the harvestmen of its immense water resources potential. At present, the Integrated Nepal Power System (INPS) has only one seasonal storage project - Kulekhani -I. After the completion of this project in 1982, the peak power demand of the country was met for almost a decade. However, the country has been facing an acute shortage of both base and peak load since the last few years. The actual grid connected generating capacity as reported for 2016-17 was approximately 968 MW (NEA Annual Report 2016-17). The approximate total of 968 MW is comprised mainly of hydropower generation, except for 53.4 MW of thermal and a negligible amount of solar. Much of the capacity is run-of-river and is therefore not always available for meeting peak power demands, although Kaligandaki, Marsyangdi and Middle Marsyangdi power plants (combined capacity of 283 MW) were run for peaking operation during the 2016-17 dry season (Annual Report 2016-17, page 12). There are some 60 hydropower plants in operation: 38 in the public sector, 22 in the private sector and some 23 small hydropower plants in isolated operation. Only about 40 % of the total population has access to electricity. The quality of supply is relatively poor. The dry season generation as well as wet season capacity is inadequate. System losses are fairly high at 25 % and outages are quite frequent. Out of 25%, approximately 16% is the technical loss and the rest is system loss. To cope with system demand, there is urgent need of combined RoR and Storage Project for the system.

1.2 Project Background

The "Identification and Feasibility Study of Storage Projects" (IFSSP) was carried out during 1999-2001 to recognize the potential storage hydroelectric projects in the nation so that the projects could be executed to fulfil the peaking power demand in the INPS. Nalgad Storage Hydropower Project was considered as one of the attractive project among the screened and ranked storage projects during (IFSSP-2001). This coarse screening and ranking phase of the study has been identified a total of 93 potential storage projects, out of which 40 schemes are in the eastern basin, 26 schemes in the central basin and 27 in the western basin. Finally, selection of five projects out of 93 schemes has been made based on the threshold criteria on project economics, access road length, storage volume, and geological and environmental consideration. Nalgad Storage Hydropower Project has been one of the selected projects recommended for the further study but due to the unfavourable situation of the country, the project could not be studied further. However, up to the pre-feasibility level study was carried out during that period.

1.3 Study Objectives

This study aims to develop simulation model of Nalgad dams and reservoirs operation in the Nalgad river basin to develop reservoir operation policy for hydropower Generation using HEC-ResSim (Hydrologic Engineering Centre-Reservoir System Simulation) model. The specific objectives of the study are:

1. To develop Nalgad dam and reservoir simulation model using the HEC-ResSim.
2. To develop reservoir operation rule by evaluating the best way to utilize the reservoir storage for power generation.
3. To select and evaluate optimal dam and reservoir operation rule for maximum dry season energy generation based on evaluating the feasibility of various reservoir operating alternatives.

4. To analyse the sensitivity of energy generation due to change in inflow, environmental release, full supply level and volume loss by reservoir sedimentation.

1.4 Structure of Thesis

This M.Tech dissertation has been structured to have six chapters including the introductory section. General overviews of each chapter are discussed as follows:

- Chapter 1 comprises the introduction part, project background and objectives of the study.
- Chapter 2 is the literature review and discusses about methods how to manage water resources at a river basin scale and general river/reservoir simulation and operation techniques. The chapter reviews the available simulation models and describes the HEC-ResSim model, its characteristics and applications. Besides, the general condition and previous studies conducted in the basin are broadly discussed in this chapter.
- Chapter 3 gives a description of the study area, including the main characteristics of the Nalgad river basin including the location, rainfall characteristics. The chapter focuses on hydrological, meteorological, physical, operational, features of the power plants data collection.
- Chapter 4 includes the data analysis and methodology used to achieve the objectives of the thesis. This chapter also deals with how HEC-ResSim model was developed for Nalgad Reservoir and the number of alternatives used for the analysis to get the optimal power and/or energy from the system.
- The results are discussed in Chapter 5 and summary and conclusion are given on Chapter 6.
- Finally list of references are provided.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter reviews the literature of previous reservoir simulation studies to understand and explore the latest methodologies adopted in previous studies for different basins, which facilitates choice of programming and appropriate models to carry out the simulation study of the reservoir operation simulation.

Over the last forty years, a number of analytical techniques have been developed for the study of water resource systems, comprising simulation and optimization algorithms, (Labadie 1997, Loucks et al. 1981, Simonovic 1992, Wurbs 1993). Simulation is the replicating flow of water through a river/ reservoir system while optimization technique seeks an optimal operational policy to attain a particular objective. Yeh (1985) examines examples of the state of the art of both types of models. Labadie (1997), studies enormous multi-reservoir systems, summaries that the difference between simulation and optimization modelling, optimization is frequently overshadowed, as optimization models almost always incorporate simulation models to validate and check the planned operational policies.

Combined use of simulation and optimization model is an effective and efficient approach to define reservoir operation rule (Ngo et al. 2007). The key benefit of the simulation model is that they replicate the behaviour of real system over period under varying conditions. To simulate the history of the event, especially during periods of flood and drought, reservoir simulation arse generally used (Hanbali 2004). Babazadeh et al. (2007) examined the performance of the reservoir operation policy using simulation model HEC-ResSim for several scenarios under current conditions and in different periods considering sedimentation.

Shortage of water during the dry seasons / drought and surplus during the wet seasons often leads to conflicts in meeting water demands of various competing sectors. The dam operators have to take difficult choice in such conditions. The academic community and researcher have highlighted use of optimization techniques in the water resources projects in such scenarios. Particularly different programming methods have been applied to improve the efficiency of the operation of the dam. Some of these techniques are: linear, nonlinear, dynamic, stochastic and stochastic approach (genetic algorithms, mixed complex evolution, complex logic and artificial neural networks) Tuncok et al. (1999).

Application of optimization techniques for reservoir operation problems has been a major focus of water resource management for some time (Wurbs 1993, Labadie 2004). Bower et al. (1962) suggested couple of rules to define releases over a specified time such as standard operation policy (SOP) & hedging rule. The SOP appeals for same release as per requirement in each time step, if possible. If available water is unable to meet the demand, then the all available water releases and reservoir becomes empty; reservoir can fill up to FRL and spill the excess water when sufficient water is available. Various optimization models such as linear, nonlinear, and dynamic programming was used to develop the hedging rules with respect to maximize return from project or to other system variables such as system reliability to meet the demand (Hashimoto et al. 1982, Shih and ReVelle 1995, Neelakantan and Pundarikanthan 1999, Shiau and Lee 2005). For optimization problems linear-based models are still popular and effective technique (Rani and Moreira 2009). Latif and James (1991) developed a LP-based conjunctive model and applied it in the Indus basin in Pakistan to maximize benefit from irrigation. Peralta et al. (1995) developed a LP-based simulation optimization model to achieve sustainable groundwater extractions over a period of fifty years, under a conjunctive water use scenario. Shih and ReVelle (1995) probed a distinct hedging rule for water supply operation during droughts and impending droughts through a mixed integer LP model. Devi et al. (2005) developed LP model for optimal water allocation in large river basin system, which is applied to Subernarekha River in India. Loucks and Beek (2005) compared different techniques of water resource system optimization based on LP in the LINGO model. Sudha et al. (2007) conduct a study on the effects of optimization on the efficiency of water use in agriculture and pointed out what is needed for reservoir operation optimization.

The inefficient reservoir operation policies, impact of individual decisions, analysis of costs-benefits of unrealistic technologies etc. are examined in a comprehensive framework (Chen 2003, Labadie 2004). Many reservoirs are still operated by a constant-rule curve and these curves are generally presented in graphical or tabular form (Yeh 1985), which work as guidelines for the reservoir level, hydrological conditions and spillway releases based on seasonal variation. On the other hand, operators use their own judgment to decide the target elevations and the selected target would be subjective (Akter and Simonovic 2004). Many researchers (Guariso et al. 1986, Oliveira and Loucks 1997, Chen 2003, Labadie 2004) have underlined the inefficient operational problem due to subjective operational practices and the better technologies are suggested.

Classic operating policies doesn't allow the analysis of system within an integrated framework. Simulation models should be evaluated in the context of integrated watershed management for the development of operational policies and optimization methods should be used to determine these policies (Tuncok et al.1999). In recent decades, several systems analysis techniques including simulation and optimization algorithms was developed and applied to study river/reservoir basin systems (Yeh 1985, Wurbs 1993, Labadie 2004).

Despite new development and increasing use of optimization techniques, simulation models remain a prominent tool in practice for reservoir planning and management studies. In addition, optimizations of integrated reservoir systems are still difficult for operators and real implementations are still limited or not compatible. On the other hand, development and application of decision support tools for the development and management of water resources are gaining popularity. Optimization models often calculate releases that optimize an objective function without directly addressing the finer details of the operating rules. Several policies may be assumed to apply simulation models. The chain of runs are usually performed to relate system performance for alternate reservoir arrangements, storage allocations, operation policy, demand and / or inflow series (Wurbs 1993). The most effective technique is to use a simulation modelling that allows the decision maker to question the operation of existing reservoir system curves for different scenarios (Ngo et al., 2007, Yeh 1985). Ahmad and Simonovic (2000) developed a tool to evaluate alternative operating rules by modifying reservoir storage allocation, reservoir levels at the beginning of the flood season and reservoir outflows for the Shellmouth basin on the Assiniboine River in Canada. In another study, HEC (2002) developed a strategy to implement anticipated early release (pre-release strategy prior to the flood event) that allows operators to efficiently use short-term forecasts to provide protection against floods for the Folsom Reservoir in the American River.

2.2 Reservoir Simulation Models

Simulation is a modelling technique used to track the flow behaviour of the river /reservoir under predefined set of settings, which represent all the features of the system largely from a mathematical or algebraic description (Yeh 1985). Simulation models are being widely used for the analysis of water resources systems. This is particularly true for systems with multi reservoir and for those that have non-quantifiable benefits. While there are literally thousands of simulation models used in practice by water resources management agencies to support the planning of the reservoir system and / or operational decisions. To provide a useful test structure, specific sets of possibilities are used to simulate the operation of reservoir in parallel or in tandem. Some of the widely used simulation models for joint operations for reservoir in series or in parallel at all levels are: HEC-3, SIMYLD-II, Oswego system, Acri mu1ti tank model, HEC-5, SUPER, HEC-ResSim, RiverWare, MODSIM, HEC PRM and WRAP. These models include the simulation model of the reservoir system of the Southwest Division of the USACE (SUPER), Hydrological Engineering of USACE (HEC) (ResSim), Rivers and Reservoirs operations (RiverWare), Generalized River Basin Network Flow Model (MODSIM)) modelling systems, the Water Rights Analysis Package (WRAP) Prescriptive Reservoir Model (PRM) and the Hydrological Engineering Centre (HEC) are representative of the modelling capabilities of river systems / fluvial in general and are particularly relevant for practical applications through water resources planning and management agencies in Texas and elsewhere (Wurbs 2005a). A detailed review of the literature on the simulation of reservoir system operations is provided. Out of these models, recent models are of particular interest. Some of the most common applicable reservoir simulation models are described briefly.

HEC-3

The HEC-3 was developed by the United States Corps of Engineers. This model is used to simulate the behaviour of water resources systems planned to satisfy various water demands at time. HEC-3 is flexible enough to consider any arbitrary configuration of reservoir and river basin system. The algorithm examines through system in u/s to d/s direction, determining in turn each system requirement and the amount of this requirement that each reservoir must fulfil. Since the separable project responses are not identified until the whole system is explored, it is generally required to perform three successive searches throughout the system at each time step to obtain the required reservoir balance. Then, the model goes to the next time step (the monthly time step are typical) and the procedure repeats. After performing all time intervals, which may take into account several years of hydrology, the simulated responses are suitably summarized.

SIMYLD-II

The SIMYLD-II model is developed in the research part of the Texas Water Study. This can simulate multiple reservoirs. However, in each time interval, an optimization sub-model is used, which uses the out-of-order algorithm to specify the optimal operational policy. The objective of the secondary model is to minimize the costs of the system (mainly the costs of pumping) in each time step. The operational policies are characterised by varying the limit restrictions of each arc that represent either reservoir release or storage volumes.

Oswego Modelling System

Department of Environmental Conservation of the State of New York (Tedrow 1970) developed this model as the multi reservoir model for the Oswego system. This model is worrisome because it has prolonged some of the fundamental concepts of multi-reservoir zoning essential in the HEC-3 model of the United States Corps. In this model there are four zones such as flood control, conservation, buffer and inactive zones while there are six zones in HEC-3.

Acres Multi Reservoir Modelling System

The Acri reservoir model is initially developed to explore alternative policies for the management of the Trent River basin in Ontario, Canada, Sigvaldason et al. (1975). The algorithm for this model was revision and addition of the basic concepts explained in the above three models. It included the combined representation of the rule curve zoning that was inherent in the HEC-3 and Oswego models. However, this representation has been extended to include an additional "spill zone" and to place the rule curve located anywhere in the conservation zone (and not necessarily only in the top of this zone). This model was planned for any assumed configuration of reservoirs and interconnection rivers, was used as an aid to define the operational policies of the reservoir for 8 distinct watersheds. It has been modified slightly and is now used as a daily operational tool for the definition of watershed releases in the Trent River system in Ontario, Sigvaldason et al. (1975).

Water Evaluation and Planning (WEAP)

The WEAP model is developed by Stockholm Environment Institute Boston Centre at the Tellus Institute, Boston, Massachusetts. This model was developed to evaluate the planning and management problems related to development of water resources. This model can be used for both municipal and agricultural systems, and can address a wide range of problems, including: sectoral demand analysis, water conservation, water rights and allocation priority, reservoir operation simulation and cost benefit analysis of the project (http: // weap21.org / index.asp).

Acres Reservoir Simulation program (ARSP)

Acres International Corporation was developed ARSP to evaluate alternative operational strategies for a multi-purpose reservoir having water supply, hydropower and flood control purpose with 48 reservoirs in the Trent River basin in Ontario, Canada. The model based on ARSP network flow programming simulates multi reservoir systems with multipurpose. Operation rules are assigned by giving priority to various water demands. Simulation time step available in ARSP are monthly, weekly, daily or hourly. The software assigns maximum and minimum limits and cost functions to the network flow paths for the formulation of the network flow schedule according to the input provided by the user.

MIKE BASIN/HYDRO

It runs inside and is an extension of ArcView, which is a software product of the geographic information system (GIS) available at the ESRI (Environmental Systems Research Institute). MIKE BASIN assimilates the GIS functionality with watershed system modelling. There is also facility of combined use of Microsoft Excel with MIKE BASIN. Simulation of multipurpose multi reservoir systems can be performed through MIKE BASIN HYDRO based on the formulation of network of nodes and branches. In this model monthly time step is common. The time series of the basin inflow to each branch of the reservoir system are usually provided as input. However, the model can also be linked to the rainfall-runoff functions of the basin provided by the MIKE11.

HEC-5

This is similar to HEC-3 model, developed by the Hydrogeological Engineering Corps of the US Army at Davis, California (Eichert 1979). HEC-5 model is effective tool for simulation of multi reservoir system in a river basin, and can be used to study the planned operational policies for flood control and conservation purposes. The HEC-5 flood control operation is based on the water release from the flood control zone of each reservoir as soon as possible with in the certain predefined maximum flows which may cause flood damage at several D/S locations. When choosing which discharge rates should be made from which reservoir, the decision is based on a pre-established equilibrium rule, similar to that used to balance storage volumes in multiple reservoirs. The effects of the flow routing are considered, since together with the discharge rate determine the spatial and temporal distributions of the flows D/S of several reservoirs. The simulation time step of this model varies from month to hour. Primarily this model is for hydrological simulation but it can also be used to assess the economic loss from the flood hazard and benefit from power generation and such other activity. By simulating alternative operational rules, it is possible to improve the rule curves and study the size and location of the potential reservoir. HEC-5 provides a means to accurately simulate and refine the results of any optimization model developed and used for the preliminary definition of multiple reservoir operation policies. The model is well documented and maintained for use by anyone. During 1979, more than 500 executions of HEC-5 per month were recorded in the HEC-5 program executed by HEC and more than 70 decks were distributed from sources.

SWD SUPER Modelling System

Southwest Division (SWD) of the US Army Corps of Engineers (USACE) developed SUPER model and applied by the SWD office in Dallas and the SWD offices of Forth Worth, Tulsa and Little Rock District. SUPER is a computer program system developed to simulate the daily time step rule of a multi-purpose reservoir system and its hydrological and economic impacts (Hula 1981). A simulation replicates a specific operation policy, economic parameters and long sequences of daily flows and reservoir evaporation rate. To compare alternative variations in the adjustment plans multiple simulations are performed. The hydrological results can be expressed as monthly and annual frequency ratios for maximum and minimum reservoir storage and stream flow storage, flow duration curve and diversion rates and lack of in stream flow. Economic results may include damage due to flood, recreational benefits, energy value, dredging costs and navigation costs (Wurbs 2005).

HEC-ResSim

The ResSim modelling system was developed by the USAC Hydrologic Engineering Centre in 2007 as the successor of the HEC-5 model. The object-oriented ResSim consists of a graphical user interface (GUI), a calculation program to simulate reservoir operation, data storage and management capabilities, and graphic and reporting functions. In HEC- ResSim there are three sets of modules such as watershed, reservoir network and simulation module to provide access to specific types of data within a river basin. Each module has specific purposes and a related set of functions reachable through menus, toolbars and schematic elements. The computational time step is 15 minutes to a day. Stream flow routing methods are the routing of the coefficients, Muskingum, Muskingum-Cunge, modified plus routing and a routing method of the SSARR (Synthesis and Reservoir Regulation) model of the flow of USACE. The simulation progresses from u/s to d/s. single or multiple reservoirs are modelled, with each reservoir with multipurpose pools and multiple outlet structures. The operations are controlled by specific objectives and restricted releases. The river / reservoir study system was modelled with HEC-ResSim and the expanded WRAP-SIM simulation model to compare and test the modelling capabilities.

HEC-PRM

The Prescriptive Reservoir Model (PRM) of the Hydrological Engineering Center (HEC) was originally developed along with studies on Missouri and Columbia river basins basin systems in the (USACE HEC, February 1991, October 1991, 1992, 1993). However, the generalized model can be employed to any reservoir system. HEC-PRM is a network flow programming model designed for prescriptive-oriented applications. Computational algorithms of improved network flow have been developed in collaboration with the model. HEC-PRM is used in conjunction with HEC-DSS that provides input data preparation and output analysis capabilities. The studies to date have used a monthly time interval with a historical record period or a critical sub-period, hydrology.

RIVERWARE Modelling System

The RiverWare Modelling System (Zagona et al., 2001), object-oriented, was developed by Centre for the Advanced Decision Support for Water and the Environmental of the University of Colorado, sponsored by the U.S Bureau of Reclamation and Tennessee Valley. The computation time step is from one hour to one year.

RIBASIM

RIBASIM is a set of generic models to track the flow behaviour of watersheds under various hydrological conditions. The model package is a complete and flexible tool that connects hydrological water input to various locations with specific water users in the basin. RIBASIM can be linked with the WFlow runoff flow model, the SEAWAT groundwater flow model and the detailed model of the water quality process DELWAQ. An online link is being made with the groundwater flow model iMOD / Modflow (2018) is in progress. In addition, RIBASIM is used in an operational environment of water allocation and demand using the Delft-FEWS software.

eWater Source

eWater Source, the National Hydrological Modelling Platform of Australia (NHMP), was developed to simulate all features of water resources systems to support integrated planning, operations and governance from urban watersheds to sub-regional basins. Watersheds, taking into account the influences of people and ecology. The source is adapted to different climate, terrestrial, water policy and governance contexts for Australian and international climate conditions. Source offers a steady framework for the development of hydrological and water quality models to make transparent management decisions for urban areas, watersheds and rivers. This design is based on the flexibility that makes it easily customizable and easy to update as new scientific data becomes available. New capabilities can be incorporated through complements developed to meet particular needs while maintaining the overall coherent decision and policy framework. Free version of model is suitable for studies on IWRM and the development of customized decision support systems.

MODSIM Modelling System

MODSIM was developed at the Colorado State University (Labadie et al. 2000). The computational time step is a month, a week or a day. The object-oriented simulation model is based on the programming of network flow and the priorities specified by the user. The objective function is to add all the network links of the flow in each link, multiplied by a priority or cost coefficient. The user assigns relative priorities to meet diversion, performance, hydropower and storage objectives, as well as lower and upper flow and storage limits. The program is divided into two functions; a graphical user interface allows the model user to create the topology of the fluvial system / reservoir and the fluvial system / reservoir as a network of nodes connected by links. The nodes represent river gages, diversion dams and tributary confluences, sites where the return flows enter the river, deviations due to consumption, required flows, reservoirs, facilities and hydroelectric structures. The links represent artificial, general, natural, storage and acquisition flows.

2.3 Reservoir Simulation Using HEC-ResSim

Deogratias M. M Mulungu et al. (2007) applied HEC-ResSim model in the Nyumba Ya Mungu reservoir system for effective water allocation for storage conservation and production of hydroelectric energy. Several models were used in the study: the GFFS model (Galway river flow forecasting system) was used to complete the missing data and the HEC-ResSim model and the Nyungba and Mungu water balance model (NWBM) used for reservoir system simulation and water balance respectively. The actual inflows to the NyM basin were determined using the HEC-ResSim. The NWBM model used to check the total water loss in the system (Mulungu 1997). The average value of effective water that reaches the NyM is found to be comparable with measured value. The release obtained from HEC-ResSim simulation was used to determine the energy generation from the NyM hydroelectric plant. Considerong water extractions, the first simulated alternative favoured the conservation of storage in the reservoir. The power obtained with this alternative was 7% higher than the production of Tanzania Electric Supply Company Limited (TANESCO) (41.6 GWh / year). The second simulated alternative was to maximize energy production at the NyM hydroelectric plant. This alternative produced 13% more than the production of TANESCO. Despite the high energy achievable as a maximization option, the trend in water levels of the reservoir has been seen to drop dramatically. The study also examined the magnitude of the impact caused by abstract water. If the irrigation extractions were limited by the two reaches, the production of energy would increase by 11.5 GWh. This increase is approximately 24% higher than the power produced when extraction is allowed in the stretches of the Ruvu and Kikuletwa rivers.

Mina Ziaei et al. (2012) Combined optimization (LINGO) and simulation (HEC-ResSim) models was developed the operating rules for the Zayandeh Rud reservoir in Iran. The system behaviour was simulated for 47 years based on the optimized flow obtained through single objective function. From study result it has been observed that the increases in reservoir storage by 88.9% and regulated water reliability index for all subsequent application increased by more than 10% due to optimization of the reservoir operation policy.

P. G. Lara et al. (2014) simulated the reservoir operation of Tucurui dam, in Brazil using Hec-ResSim. Simulation was carried out for period of 2001 to 2006. A simple case study using HEC-ResSim was performed, to revise the operational policy of the Tucuru dam. Observed and simulated data including reservoir level and release was compared to measure the efficiency of the HEC-ResSim model in the representation of the operating policy of the Tucuru dam. The obtained efficiency (NSE) of the daily outflow hydrograph throughout simulation period is 0.98, while the efficiency of RR throughout the simulation period is 1.20%. For operation pool levels of time series groupings, NSE is 0.99 and RR is 0.01%. Finally, it was concluded that the HEC-ResSim model is a remarkable technique to reduce the uncertainties of the outflow forecasts and support the improvement of the Tucuru Dam flood warning program. By inserting the hydrological database of the Tucuru dam in combination with HEC-ResSim, it is possible to reproduce the reservoir operational policy and check various operating scenarios, even in real time. The HEC-ResSim model offers functionality to improve the accuracy of flood alarms, reduce the cost of dam safety and increase hydroelectric energy generation. HEC-ResSim is also an effective tool for risk management and water control.

Azeb Mersha et al. (2014) developed a Hec-ResSim model of the water system of the East Nile Basin analysed nine different scenarios by evaluating water availability of the basin at the key location and capacity of power generation at basin level with a hydrological variation pattern. These practices were intended to meet several objectives, such as responding to direct and subsequent demands, providing a reliable source of power generation, achieving target elevations, making target releases and meeting environmental requirement. The calibration of the model was considered successful, although the lack of historical data on exhaustion was a major problem. Losses and lags in reaches and evaporation rates have been adjusted to allow the model to match historical data. The model has been configured to allow the user to call essentially any combination management action in the basin. The cascade options were simulated to assess the impact on downstream countries and the existing infrastructure that provided a better understanding of the water resources potential of the basin and can be used as a starting point for priority investment related to water in basin. The model can support the decision-making process by giving quantitative results taking into account the actions of management. More importantly, the model has been developed to allow easy modifications to the model, such as adding a new infrastructure, changing operational rules, addressing climate change or improving climate change or improving input data.

Baraa E. A. Jebbo and Taymoor A. Awchi (2016) developed a simulation model for the Mosul dam and reservoir using the HEC-ResSim 3.0 package to study the operational behavior of the reservoir and capacity of the program to represent and simulate the real system. The study was based on monthly data for the period 1988-2006. The results of the research were compared with the results of previous studies that considered for the same reservoir. The results showed that the program is very convenient to simulate the real system by testing and comparing the results of the model with the historical data recorded. The results showed that the curve of the control rules of the operation of the real reservoir does not correspond to the developed operation rule of the project (Original Rule Curve); due to the fact that the Mosul reservoir has a problem with its foundation containing large amounts of gypsum, therefore, a decrease in water storage is required to prevent its collapse. The comparison of these studies with previous studies has shown that the current results of the simulation model are the closest to the actual observed operational data, this because HEC-ResSim 3.0 is a specialized software to simulate water resources systems and considering many variables were not taken into account in previous studies.

Sangam Shrestha et al. (2014) performed a study on impact of climate change on the flow of rivers and the generation of hydroelectric power in the Kulekhani Hydroelectric Project in Nepal. Their studies aimed to predict the flow variation in Kulekhani river basin in climate change scenario and analyse its effect on the energy generation from the Kulekhani Hydroelectric Project. To achieve the objectives, they used the hydrological model HEC-HMS to simulate flows in the rivers and HEC-ResSim was used to simulate a reservoir for analysing future evolution of electricity generation for different operating time setting. Finally, they concluded that the change in river flow in the various (Two) scenarios didn't show any defined trend. The future runoff in the basin decreases during wet months such as June and August, and for most months during the dry season, the flows increase in two scenarios (that had been foreseen). The HEC-ResSim model was used to simulate the generation of hydroelectric energy in different hours of operation in future climate scenarios. Assuming 7 h / d of hydropower operating time during the reference period 1982 to 2009, the average energy generation may decrease by at least 30% in several future scenarios. However, the maximum energy generation was obtained when the reservoir operated for 10 h / d during the dry season and 4 h / d during the wet season, which reduces the energy generation by only 8 to 13% compared to the baseline period. The operation policy of Kulekhani hydroelectric power was developed in 1982 when the country did not face a blackout problem and there was not much difference between electricity demand and supply. Therefore, operating the reservoir follow the same rule curve become difficult to match the water release in all month in future. Therefore, it is essential to review the operation policy of Kulekhani hydropower to maintain or increase the generation of electricity in the climate change scenarios of the Kulekhani basin.

2.4 Rule Curves

An operational policy is basic requirement for simulation study. In general, rule curves represent the operational policies of a reservoir. A rule curve can be defined as graphic representation of reservoir elevation with respect to time throughout the year. Here, the implicit assumption is that the reservoir able to meet its purposes if the reservoir levels or empty spaces, as specified by the rules curve, are kept in the reservoir at the specified period. The released from the reservoir will depend on inflows to reservoir. Rule curves are generally developed through operational studies that use historical inflow or forecasted flows where long-term historical data is not available. Often, it is not possible to strictly adhere to the rule curve in relation to reservoir levels due to specific conditions such as low inflows, minimum requirements for demands etc. The rules curves are discussed and analysed by many researchers (Maass et al. 1962, Stedigner 1984, Lund and Ferreria 1996, and Ahmed 1996).

Conditional rules are generally defined in some cases for multiple reservoir systems. These policies delineate reservoir releases not only on the basis of existing storage volumes and time of year, but also on the basis of inflow to reservoirs for a predefined time period in future. These rules can be defined as functions, in tabular form or in graphical form. While there are approximate methods for determining these conditional rules, Beard, L.R (1976), research continues to seek better methods to define conditional operational policies for multiple reservoir systems.

With the general components of the operational rules and their reforms as described above, various computer programs are developed for new release decision (Sigvalda son et al. 1975, W.W-G.et al. 1975). The input data for these programs generally includes flow predictions, the recent status of the system, the operation rules of the system, and the appropriate objective functions for the operation of the reservoir. The result of the program includes the calculated releases at each reservoir site or control structure that will best meet the predefined operational objectives. When reviewed approximations of future inflow, storage volumes, and probably environmental or ecological economic constraints are found, the program is re-run to get new value of the suitable releases of the reservoir and their effects. This process can be repeated at regular intervals (every day or every week or even every hour during flood events).

2.5 Reservoir Sediment Distribution

The sediment particles in the river come in the form of sand, silt, gravel and even large boulders. The water that flows in the river scours its bed and banks, loosens these sediment particles from the surface and transports them downstream. If a dam is built in the river, the velocity of the flowing water is reduced due to an obstruction, which helps the sediment particles to settle in the reservoir. This phenomenon is called "Reservoir Sedimentation". Due to this reservoir storage capacity is gradually reduced. This problem can be addressed in the planning stage by predicting sedimentation in the future. In addition, it is possible to plan the proper management of the reservoir operations to minimize the sedimentation. Reservoir sedimentation studies are essential to control sedimentation in the years after the closure of the dam. By knowing the quality of the distribution and prediction of sediments, one can choose the reservoir operation policies and the decision making on the sediment problems with greater confidence (Shinde et al. 2016).

The sedimentation is not uniform. With research conducted in India on 14 different reservoirs, sediments often settle to the upper part of the reservoir, where the water depth is 20 to 30% of the maximum depth of the reservoir Houshmandzaeh et al. (2001). Due to the non-uniform and complex settlement of the particles, different methods have been developed to predict the distribution of sediments in different zone of the reservoir. These methods are based on the presentation of mathematical models, the suggestion of experimental and semi-experimental methods or the creation of laboratory models, which are used only when it is necessary to obtain high precision. These models are expensive and it takes time and they are limited. In addition, mathematical models presented require several parameters, which are difficult to measure in most reservoirs or have not been measured accurately, but if they exist, they are extremely accurate. Numerous experimental methods have been presented to calculate the characteristics of sediment distribution in reservoirs of dams, viz. Khosla procedure, Soil Conservation Service (SCS), Musgrave method, CBIP research method, Fournier method, Douglas method, Joglekar method, trigonometric method, volume reduction method, manual design curve method, Van't Hul method, Empirical area reduction method and Area increment method etc. Empirical area reduction method and Area increment method suggested by Borland and Miller in 1958 are the most common (Amini et al. 2010). The reason for the advantages of these two methods over others is that they need input data. On the basis of extensive field data of reservoir in USA, Borland and Miller classified the reservoir in to four standard types as presented in table 2.2.

Table 2. 1: Reservoir classification based on slope parameter 'm'

Classification Number	Reservoir Type	Parameter m
I	Lake	>3.5
II	Flood plain, Foot-hill region	2.5-3.5
III	Hilly region	1.5-2.5
IV	Gorge	1.0-1.5

2.6 Research Gap

The development of hydroelectric power in Nepal is one of the most beneficial uses of water resources and can play an important role in the overall growth of the nation. Nepal is endowed with approximately 6,000 rivers that drain about 222 billion m^3 of water annually into the sea (Sharma and Awal 2013). The perennial nature of rivers and the steep topography provide a great potential to tap this resource for hydropower generation. It is no surprise that Nepal relies heavily on hydroelectric projects, especially run-of-the-river (R-o-R) facilities. The theoretical power generation potential was estimated to be 83,500 MW in 1966, out of which 42,000 MW is technically and economically feasible to be produced (Jha 2010). However, so far the country has managed to generate only 914.6 MW, which is about 2 % of economically feasible power generation potential, and 2 % of the total energy consumption in the country. In spite of harbouring a huge hydropower potential, Nepal has unable to meet its own domestic electricity demand with its resources. As a result, the country is currently going through an unadorned energy crisis. Consequently, each year, power cuts are increasing at an disquieting rate. The power outage was around 12 h/day in 2009–10 and 2010–11, and steeply rose to 14 h/day in 2011–12 (Sharma and Awal 2013). The power generation during the monsoon period reaches to its full installed capacity but declines to 16.66 % of the installed capacity during the dry months (Paudyal and Shrestha 2010). The discrepancy in power production arises due to the RoR type of the hydropower, where power production is guided by river discharge, which is generally high during the monsoon and low during the rest of the months. In order to alleviate the magnitude of power outage and to promote the hydropower sector, the Government of Nepal first developed a policy plan in 2008 in order to generate 10,000 MW in 10 years (2010–2020) and 25,000 MW in 20 years (2010–2030) (Pradhan 2009).

For better planning and management of project, detail reservoir simulation study is essential to analyse power generation for different operation settings and various scenarios. Over the time various models viz. HEC-ResSim (Jebbo et al. 2016; Lin et al. 2016; Lara et al. 2014; Shrestha et al. 2014; Tsegazeab Dejene 2014; Mersha et al. (2014; Gökçen UYSAL 2012; Ziaei et al. 2012 ; Babazadeh et al. 2007 ; Deogratias M.M. Mulung 2007), HEC-5, MIKE HYDRO Basin , RIBASIM, WEAP, ARSP, MODSIM, eWater Source, RiverWare etc. have been developed and applied for reservoir simulation studies in various countries over the world. HEC-ResSim developed by the U.S. Army Corps of Engineers for reservoir operation for flood control, water supply, hydropower generation, and releases for environmental flows etc. is a very good freely available tool.

Optimal use of available water resources is an essential part of the process of determining the parameters of a storage energy system. An oversized facility will not be able to fully utilize its capacity due to lack of sufficient water during the dry season and will generate abundant spill energy during the wet season, while a power station will cause a loss of precious water while an undersized installed capacity. Both scenarios will have a negative impact on the economic parameters of the power project. Hence, the importance of reservoir simulation is quite obvious. Therefore, it is considered prudent to perform a reservoir simulation study for the proposed Nalgad reservoir Project. It was planned to carry out a detailed study of the possibility of energy generation in relation to the available water resources. Operation policy for Nalgad reservoir operation for power generation is not developed till that’s why this study aims to develop the reservoir operation simulation model of proposed Nalgad reservoir using HEC-ResSim model for Hydropower generation for daily inflow data for the period 1966 to 2016 to develop operation rule for maximum dry season energy generation. Further this study also analyses the effect of change in basin hydrology, variation in minimum environmental release and effect of reservoir sedimentation on energy generation. This study may serve as the base study for the development of reservoir operation policy for Nalgad hydropower project and other similar projects in Nepal.

CHAPTER 3: STUDY AREA AND DATA

3.1 Location and Physical Features

Nepal lies on the lap of the highest mountain ranges of the Himalaya. It extends between the Tibetan plateau of the People's Republic of China in the North and Republic of India in the South and it is roughly rectangular in shape. Nepal embraces in itself a unique variety of geographical settings ranging from the southern lowland to the high mountain in the North. There are basically three richly varied regions - the Terai Region, the Middle Region and the Himalayan Region.

Nalgad hydropower Project is located in Jajarkot District in Krnali province of Nepal between Longitude $82^0$17'15"E - $82^0$17'55"E and Latitude $28^0$47'28.8"N - $28^0$54'15"N. Nalgad is a tributary of the Bheri River in the Karnali Basin. The dam site of the project is situated about 9.25 km U/S from the confluence of the Nalgad and the Bheri-River and the powerhouse is situated on the left bank of Nalgad River about 700 m U/S from the confluence of the Nalgad and the Bheri-River. The powerhouse is proposed to be underground and is founded on the solid rock base. Study area map and overall layout of Nalgad Hydropower Project is shown in figure 3.1 & 3.2.

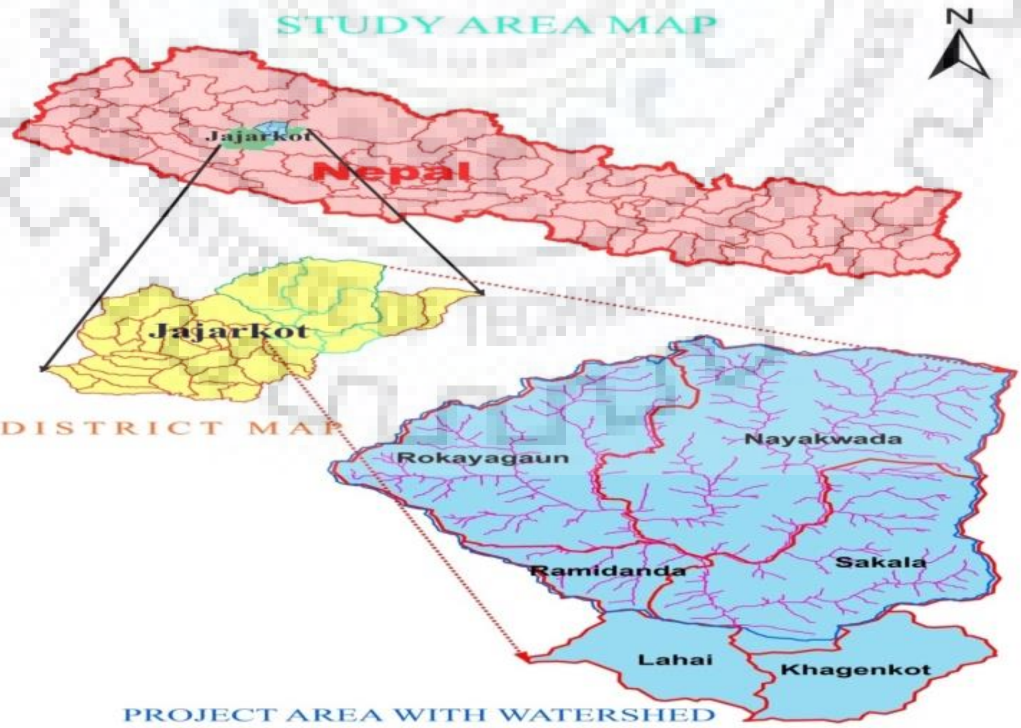


Figure 3. 1: Study area map of Nalgad hydropower project

Figure 3. 2: Over all layout of Nalgad hydropower project

3.1.1 Climate

Extending from 800 m to 5,500 m, the project area experiences wide variation in climatic conditions from sub-tropical to alpine climates. Areas above 4,500 m lie in the freezing zone during most of the year. Precipitation in the form of rain is expected in areas below 2,500 m, whereas snowfall is expected above 5,000 m throughout the year. Seasonal snow is observed in areas between 5,000 mand 2,500 m. The lower valleys are hot in summer but most of the mountainous areas with settlements have a relatively comfortable climate. Under the strong influence of monsoons, the watershed is wet with greenery in most of the areas during the summer monsoon season. Winter is generally dry with chilly weather conditions. Average elevations of the Nalgad basin at the Bheri River confluence and at the intake site are 2,890 and 3,110 m which indicate an annual average temperature of 8^{o}C and 9^{o}C respectively (based on the annual average temperature of 12.7^{o}C at Jumla). Average precipitation ranges from 1244 mm to 1793 mm

3.1.2 Access

Chinchu Jajarkot road serve as main access for the Nalgad Storage Hydroelectric Project. Powerhouse of project connected with Dolpa Rajmarg (Puspa Lal Marg). This road starts from Salli Bazar and ends at the Dunai. A bridge over Nalsgad River at Kalimati will be required to connect the project site at powerhouse. Apart from this approximately 25 km of project road is required between Powerhouse and headwork to provide access to the major structures of the project during the construction of this project. Excess road of about 11 km river route along Nalgad river to connect powerhouse and dam is in under construction and another alternate excess road of about 35 km hill route gone through Khantakura is also under construction. An alternative main access, a seasonal motorable road, from the Rukum airport to the powerhouse site is also available at the site. Numerous routes are available to access project site of Nalgad Storage Hydroelectric Project.

3.1.3 Social Aspects

The project area has an area of 2230 sq. km. The population of the district is 134,868, out of which 68,508 are male and 66,360 are female and the population density is 60 persons per sq. km. The literacy rate is 39.36 percent and the average household size is 5.59. The project area encompasses 6 VDCs of Jajarkot, viz. Lanha, Sakala, Khagenikhet, Ramidanda, Rokayagaun and Nawakunda.

Agriculture is the main activity of the people residing in the proposed project area. The predominant religion in the project area is Hinduism. Majority of the population in this area are Brahmins, Chhetris and Kiratis. In Jajarkot District about 95% of people are Hindu. Other people of the area comprise Kirati, Islam, Jain and Christian.
Health and sanitation condition of the people around the area is not good. There are one hospital, eight health posts and twenty-six sub-health posts in the district. There is no electricity around the project area till date.

3.1.4 Nalgad Hydropower Project

The Nalgad hydroelectric project is planned to have total installed capacity of 417 MW is located in Jajarkot district of Karnali provenance of Nepal between Longitude $82^0$17’15”E - $82^0$17’55”E and Latitude $28^0$47’28.8”N - $28^0$54’15”N. This project was conceived as one of the attractive project among the 93 potential screened and ranked storage projects during (IFSSP-2001). Salient features of proposed project recorded in updated feasibility study report 2018 are given in table 3.1.

Table 3. 1: The salient features of the Nalgad hydropower project

Name of the Project	Nalgad Storage Project
District	Jajarkot
River Name	Nalgadad River
Geology	
Dam Site	Dolomite with frequent intercalation of black Shale
Headrace Tunnel	Limestone, Dolomite and Shale
Power station	Sandstone
Hydrology	
Catchment Area (up to Dam site)	569 km^2
Average Precipitation	1718 mm
Average Monthly Flow	27.3 m^3/s
Flood Discharge	(1 in 20 years wet season) 653 m^3/s
Flood Discharge	(1 in 10,000 years wet season) 1975 m^3/s
Probable Maximum Flood (PMF)	4759 m^3/s
Sediment Yield	1490 $t/km^2/year$
Reservoir	
Full Supply Level (FSL)	1580 masl
Minimum Operating Level (MOL)	1498 masl
Total Storage Volume	474 Million m^3
Live Storage Volume	350 Million m^3
Dam	
Type of Dam	Curved Gravity Roller Compacted Concrete
Height above Foundation	210 m
Crest Elevation	1588 masl
Crest Wall Height	1000 mm
Length of Crest	545 m
Width of Crest	10 m
Environmental In-stream flow	release 0.584 m^3/s
Spillway	
Type	Ogee shaped, non - gated overflow weir
Design flood	1,000 yr peak inflow 1408 m^3/s 10,000 yr peak inflow 1975 m^3/s
PMF peak inflow	4759 m^3/s
Overflow Crest Elevation	EL. 1580 masl
Overflow Crest Width	60 m
Main Intake	
Type	Bellmouth
Invert Level	1478.5 masl
Intake Tunnel	1 no
Intake gates	2 nos. 4.5 m x 3 m

Power	
Maximum Gross Head	708 m
Design Net Head	635.5 m
Maximum Net Head	694.0 m
Minimum Net head	613.0 m
Design Discharge	78.4 m^3/s
Overall Efficiency	87.80%
Tail water Level (turbine Pit)	867.6 masl

3.2 Data Collection and Processing

The required data for the study were collected from review of previous reports as well as data from institutions such as Ministry of Energy, Water Resources & Irrigation, Nepal, Water and Energy Commission Secretariat (WECS), Nepal, Nalgad Hydropower Company Limited (NHCL), Nepal, Nepal Electricity Authority (NEA), Nepal. The details of the collected data are described below.

3.2.1 Hydrological Data

Various hydrological data such as reservoir inflow, evaporation seepage and sedimentation etc. collected are described as below.

Inflow

The Nalgad River flow has is not been measured on a regular basis in the past. Some measurements were undertaken as part of the 2012 Nalgad Feasibility Study and as part of the Updated Feasibility study 2018. These do not provide a basis for a long-term estimate. An estimate of daily time-step daily discharge was derived for Nalgad by transposing recorded Chameliya flow for the period 1965 to 2016. But inflow data of year 1965 is not included in analysis as it is considered as warm out period for reservoir filling. The derived daily inflow hydrograph of Nalgad river is shown in figure 3.3.

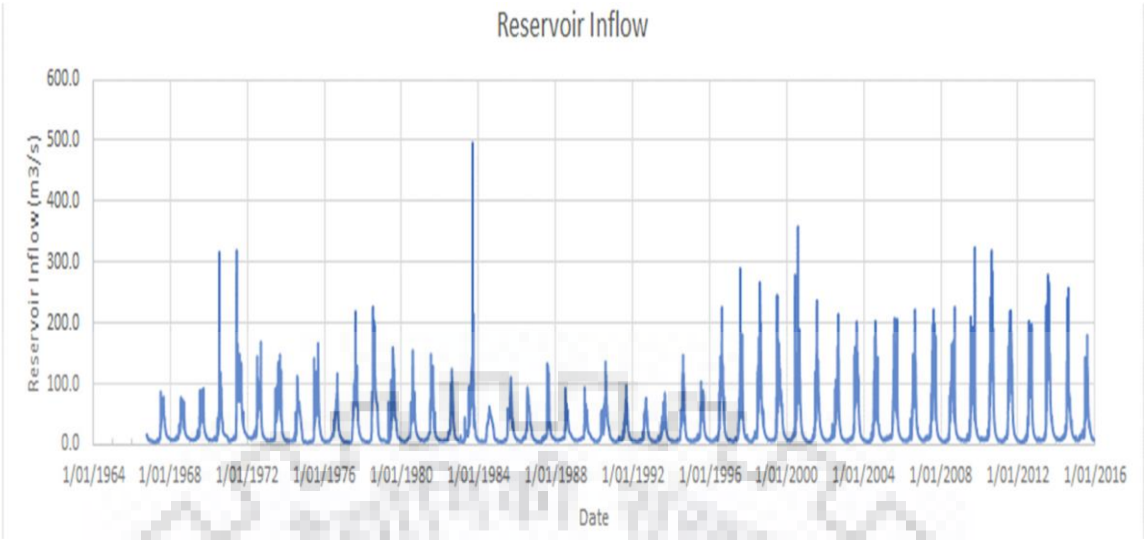


Figure 3. 3: Inflow hydrograph of Nalgad River at dam Site

(Source: Updated Feasibility Study Report of Nalgad Hydropower Project)

Estimated mean monthly hydrograph of the Nalgad river at dam site is shown in figure 3.4.

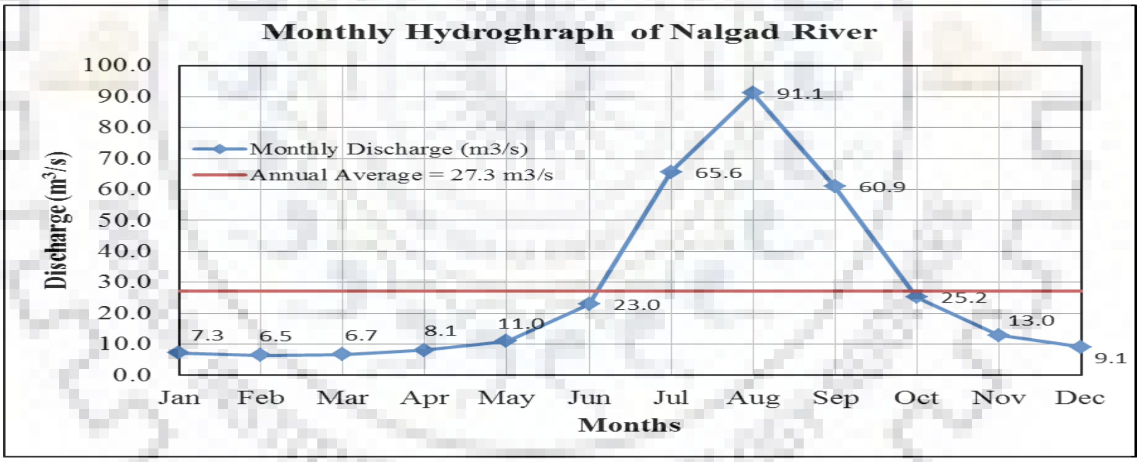


Figure 3. 4: Estimated mean monthly flow at the Nalgad dam site

Evaporation and Seepage

The evaporation losses from reservoir depend upon several factors such as: water surface area, water depth, humidity wind velocity, temperature, atmospheric pressure and quality of water.Net reservoir evaporation is needed in the reservoir water balance operational simulation study. Monthly estimates of net reservoir evaporation were derived and applied; the daily share of each month's net reservoir evaporation is applied in each day's calculations. A set of typical and average 12 monthly values were derived and applied in all years. Climatic conditions could affect actual evaporation, but as the effect of reservoir evaporation on energy generation is small, further refinement in evaporation estimates to reflect climatic condition variations is not considered here. The mean monthly evaporation data used for this study was collected from Updated Feasibility Study Report of Nalgad Hydropower Project (2018) and presented table 3.2.

Table 3. 2: Monthly evaporation data of Nalgad reservoir

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly Total Evaporation in (mm)	31.0	44.8	89.9	111.0	114.7	36.0	105.4	102.3	12.0	58.9	63.0	46.5

(Source : Updated Feasibility Study Report of Nalgad Hydropower Project (2018))

For most of the reservoir, the banks are permable but the permability is very less so seepage loss is of no more importance as its effect on energy generation is very small. But constant seepage of 100 lps is reported in updated feasibility study report (2018) which is used in reservoir simulation study.

Sediment Data:

Sediment yield and reservoir half-life (the time required to lose half of the original 474 Mm^3 reservoir capacity to sedimentation) were both computed based on the measured suspended sediment data and the other assumptions. All data related to sediment are collected from pervious study report of project are presented in table 3.3.

Table 3. 3: Estimates of sediment yield and reservoir half-life from gage data sets

Parameter	Sampling Location				
	Kalimati D-74	Kalimati Bucket Sampler	Kalimati Bed Sampler	Kailital Bucket Sampler	All combined Data
Suspended load by rating eqn. Mt/yr	**0.576**	0.111	0.261	0.113	0.265
Adjustment factor for long term total load	**1.5**	1.5	1.5	1.5	1.5
Annual total load, Mt/yr	**0.851**	0.167	0.391	0.169	0.398
Specific yield, $t/km^2/yr$	**1490**	292	684	296	696
Specific Weight, t/m^3	**1.5**	1.5	1.5	1.5	1.5
Annual volume loss, Mm^3/yr	**0.567**	0.111	0.261	0.113	0.265
100-yrs storage loss, Mm^3	**56.7**	11.1	26.1	11.3	26.5
Reservoir half-life years	**421**	2142	916	2117	900

(Source : Updated Feasibility Study Report of Nalgad Hydropower Project (2018))

The Kalimati D-74 sampling location data used to calculate storage loss which is input data for development of the revised Area - Elevation -Capicity curve after 25 years, 50years, 75 years and 100 years which will used to analyse the effect of sedimet on energy generation.

3.2.2 Physical Data

Dam and reservoir physical data required for reservoir operation simulation study are described as below;

Elevation-Area-Capacity Relationship

The main reservoir physical data which are input for the pool include the reservoir surface area mainly used to compute the reservoir evaporation loss and the storage are used to estimate the stage at any time based on storage equation. The reservoir stage-area-storage data for Nalgad reservoir was collected from pervious study report and shown in Table 3.4 and elevation–area–capacity curve is shown in figure 3.5.

Table 3. 4: Elevation-Area-Storage data of Nalgad reservoir

Elevation (m)	Storage (m3)	Area (ha)	Elevation (m)	Storage (m3)	Area (ha)
1380	0	0	1495	116000000	248
1385	1	0	1500	129000000	265
1390	2	0	1505	143000000	282
1395	3	1	1510	158000000	300
1400	4	5	1515	174000000	317
1405	1000000	10	1520	191000000	335
1410	2000000	18	1525	208000000	355
1415	3000000	29	1530	227000000	375
1420	5000000	42	1535	247000000	395
1425	8000000	59	1540	268000000	415
1430	12000000	72	1545	289000000	436
1435	16000000	81	1550	312000000	457
1440	20000000	92	1555	336000000	478
1445	26000000	104	1560	361000000	501
1450	32000000	118	1565	388000000	527
1455	38000000	132	1570	415000000	552
1460	45000000	144	1575	444000000	578
1465	53000000	155	1580	474000000	603
1470	62000000	170	1585	506000000	632
1475	71000000	187	1590	539000000	661

1480	81000000	201	1595	573000000	690
1485	92000000	215	1600	609000000	718
1490	103000000	231			

(Source : Updated Feasibility Study Report of Nalgad Hydropower Project (2018))

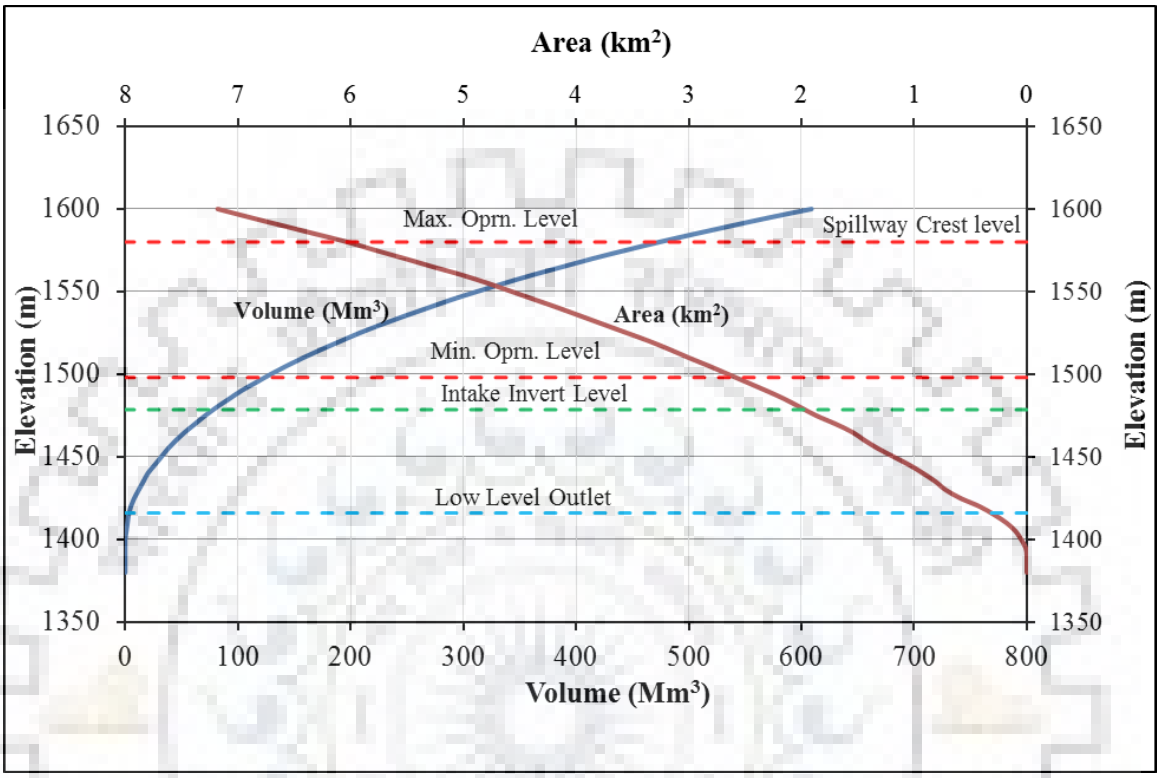


Figure 3. 5: Elevation–Area–Capacity curve of Nalgad reservoir

Dam

The main purpose of the dam is to create the necessary head and storage necessary to provide the discharge through the power plant with the varying head and discharge with the season. The crest level of the dam is at 1589 masl and has a crest length of 545 m. The dam is a Curved Gravity Roller Compacted Concrete type with the 210 m in height. The top width of the dam is kept 10 m wide for the transportation purpose.

Spillway:

Ogee shaped, non-gated overflow weir spillway has been designed to pass the flood that safely passes the probable maximum flood (PMF) 4759 m^3/s. The design of spillway is based on the PMF. Designed overflow crest elevation 1580 masl and overflow crest width 60 m. Rating curve of ogee shaped, non-gated overflow weir spillway defined in dam physical data tab inside HEC-ResSim shown in figure 4.15.

Intake:

Rating curve of inlet of power intake tunnel is required for reservoir operation simulation which was collected from the updated feasibility study report (2018) of Nalgad hydropower. Detail of intake feature is shown in table 3.5 and intake rating defined in dam physical data tab inside HEC-ResSim shown in figure 4.14.

Table 3. 5: Features of intake

Type	Bellmouth
Invert Level	1478.5 masl
Intake Tunnel	1 no
Intake gates	2 nos. 4.5 m x 3 m
Stop logs	2 nos. 4.5 m x 3 m

(Source : Updated Feasibility Study Report of Nalgad Hydropower Project (2018))

The Power Plant Parameters

The power plant parameters define the constraint and requirements for the energy production. The installed capacity of the Nalgad Reservoir plant is 417 MW with the design discharge of 78.4 m^3/s as per the updated feasibility study report of Nalgad hydropower project. The tail water elevation is set at 867.6 masl. In this study station use is taken as zero and overload factor as 1.0 for simulation. Overall efficiency of the power plant is taken as 87.8%. Four turbine units with 104.25 MW capacity each.

Low Level Outlets

During reservoir filling, an environmental release will need to be maintained. Once the reservoir level reaches approximately at elevation 1470 m, that function can be assumed by the low level outlets or later by the flushing pipes-perhaps with a small bypass around the downstream cone valve as the normal flows will be considerably less than the capacity of the cone valves. However, in order to maintain the required flow while the reservoir fills, a 600 mm steel pipe will be placed within the dam body at elevation 1416 m. The pipe will discharge at the downstream face of the spillway flip bucket, controlled by a small fixed cone valve, but after the reservoir level has reached the low-level outlets, the environmental flow release outlet will be grouted closed. In-stream releases are anticipated as 600 lit/s; at the time of preparing updated feasibility study, the environmental sciences team had not established a minimum flow requirement. The proposed dam site is just upstream of the Nalgad River's confluence with the Bheri River, so there is a very short segment of Nalgad River that would be affected by the dam and the power plant supply tunnel by-pass. The Bheri River flow is substantially greater than the Nalgad River flow; effects downstream of the confluence are mitigated by the substantial flow of the Bheri.

3.2.3 Reservoir Operational Data

Reservoir rule curve could be defined as the operational rule for a regulating the water stored in the reservoir in order to full fill the system demand. The operation rule for the reservoir varies from project to project. Further it should be revised from year to year depending upon the new plant addition and new demand pattern in the system. In case of INPS, no such rules have been formulated yet. Hence, in order to formulate a storage project, an analysis was done to formulate an appropriate reservoir rule curve which fits into INPS. There appears to be sufficient capacity and energy entering service in future years to meet the June to December situation at the time Nalgad would enter service. There is, however, a significant energy supply deficit in the December to May period, and there is a deficit in generating capacity reserve. Nalgad optimization should focus on meeting the dry season supply need. There appears to be little reason to provide wet-season energy or capacity (Updated feasibility study report, 2018).

Reservoir operational set includes, the various zone or pool level assignment along with the operation rules prevailing the operations in each zone. Nalgad reservoir has three major water management zones or pools such as flood control zone, inactive zone and the conservation zone. The inactive zone is often referred to as dead storage since water stored in this zone is not released to meet any purpose but this zone for accumulation of some portion sediment in reservoir. Top of flood control zone is same as the elevation of dam crest. The top of conservation zone is assigned to the maximum operating level of reservoir, level above which the water is automatically spilled through the uncontrolled spillway and top of inactive zone is equal to minimum drawdown level or minimum operating level of reservoir. Water management zones of Nalgad reservoir are shown in table 3.6.

Table 3. 6: Detail of the water management zones of Nalgad reservoir

Zones	Elevation (m)	Remarks
Flood control zone	1589	Top of maximum reservoir level
Conservation zone	1580	Top of maximum operating level
Inactive zone	1498	Top of dead storage zone
Low Level Outlet	1416	For Environmental Release
Controlled Outlet	1478.5	Invert level of power intake
Uncontrolled Outlet	1580	Crest level of uncontrolled spillway
River bed level	1380	Existing river bed level

In HEC-ResSim various rules such as D/S control function rule, Tandem operation rule, induced surcharge rule, Flow rate of change limit rule, Elevation rate of change limit rule, Hydropower rules, Releases function rule, Pumped schedule rule, Scripted rules and IF_BLOCKS can assigned within all zones except inactive zone which is known as operation set which is one of the most important input parameter for simulation study.

CHAPTER 4: METHODOLOGY

4.1 General

The HEC-ResSim model calculates reservoir storage, evaporation, power generation and stream flows for system-specific operation rules and input series of stream inflow and evaporation rates. Various types of data required for simulation of the proposed Nalgad reservoir viz. Spatial configuration of the river basin system, river basin hydrological data, evaporation and seepage, physical characteristics of reservoir (Area-Elevation-Capacity curve), spillway and other outlets, hydroelectric power plant etc. are collected from previous studies as well as from institutions such as the Ministry of Energy, Water Resources and Irrigation of Nepal, Water and Energy Commission Secretariat (WECS), Nalgad Hydropower Company Limited (NHCL), Nepal and Nepal Electricity Authority (NEA), Nepal. After collection of necessary data and quality check, they are used for creating HEC-ResSim model set up. The general framework of the methodology is presented in Figure 4.1. The ArcGIS software is used for delineation of river network and watershed boundary etc. The shape files are imported in to HEC-ResSim model for setting up the reservoir definition with various outlets. In watershed module watershed configuration was made for reservoir network then reservoir network was created in reservoir network module and all the collected data required for simulation study was input to HEC-ResSim through reservoir editor window. Inflow data was input in to HEC-ResSim in DSS file format through DSSVue menu. After defining all required data various alternatives are made for different operation scenarios and generation pattern and inflow series etc. simulation was performed for each defined alternative. Result obtained through simulation was imported in to Microsoft Excel and analysed to develop optimal operation policy for maximum dry season energy generation. Operation policy is selected as optimal operation policy when maximum dry season energy generation with reliability above 90% is obtained through simulation study. Further simulation was performed to analyse the sensitivity of energy generation due to change in inflow, environmental release, full supply level and storage loss due to reservoir sedimentation.

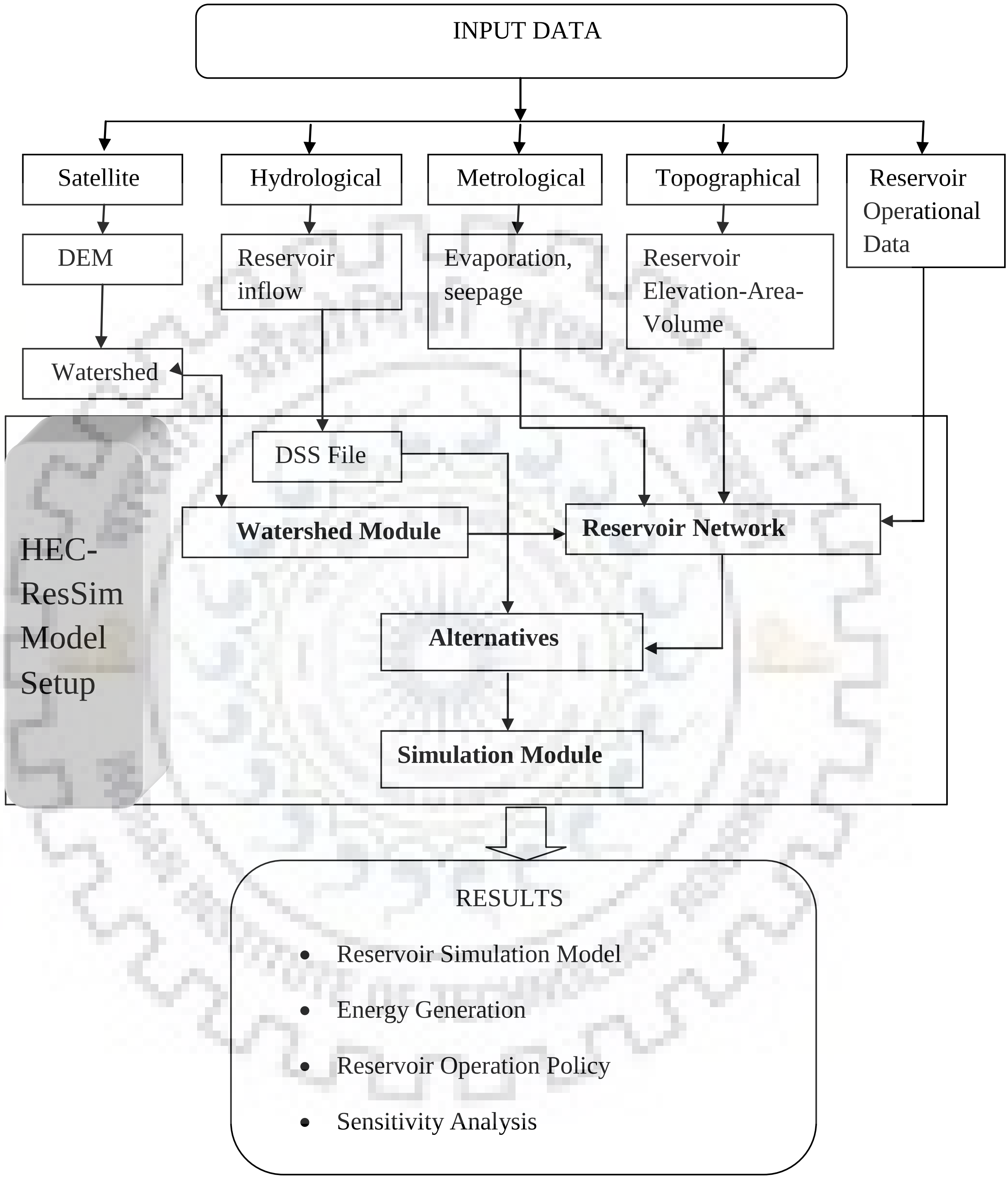


Figure 4. 1: General methodology for reservoir simulation

4.2 Analysis of Inlflow

Annual volume of water yield was calculated from the daily inflow discharge data and analysed to find wet and dry water years, as well as critical water years. All the years having annual yield less than the mean minus standard deviation are considered as dry years and years having annual yield more than mean plus standard deviation are considered as wet years. Years having annual yield nearly equal to mean annual yield are considered as average/normal water years. Graphical representation of annual yield to Nalgad reservoir at intake site is shown in figure 4.2.

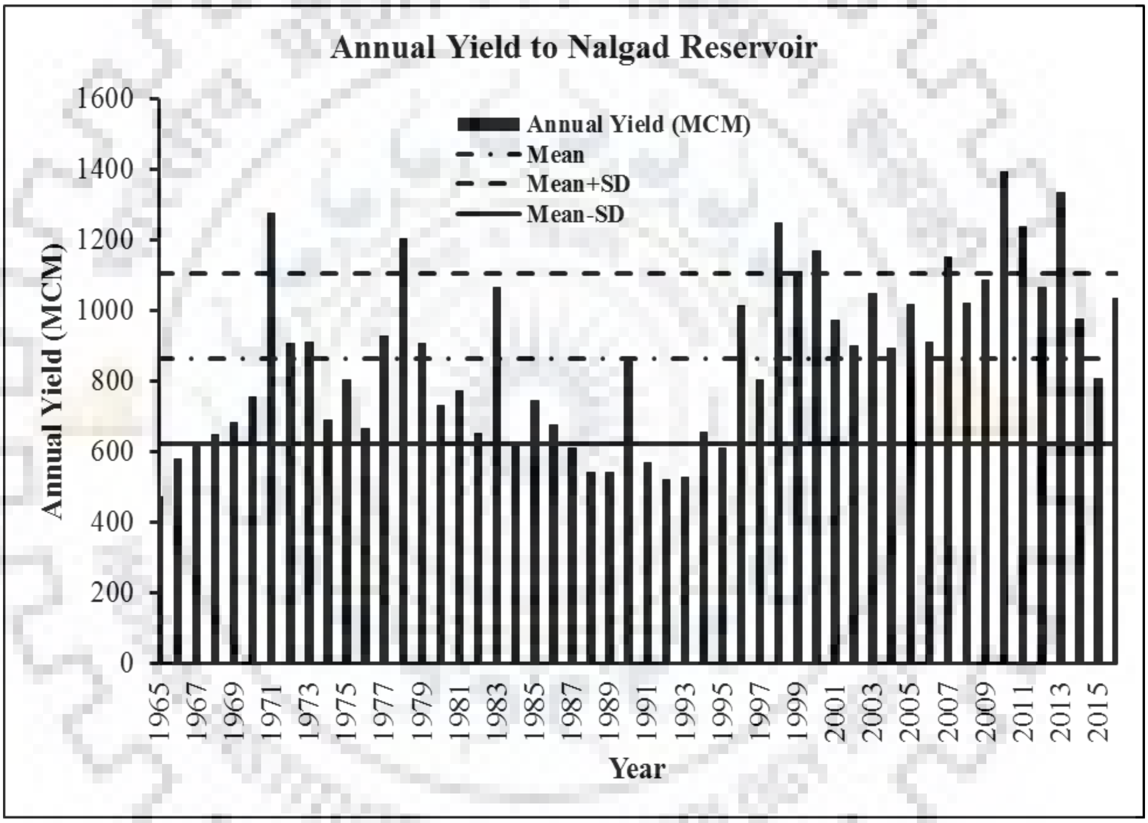


Figure 4. 2: Annual yield volume to Nalgad reservoir at dam site

Flow duration curve from annual flow series (Yield of all months), lean season flow (Yield of Jan, Feb, Mar, Dec), monsoon season flow (Yield of Jun, Jul, Aug, Sep) and other period flow (Yield of Apr, May, Oct, Nov) are developed to find the different dependable year. These are used to develop guide rule curve and to check the feasibility of the developed operation policy. The developed flow duration curves are shown in figure 4.3 & 4.4.

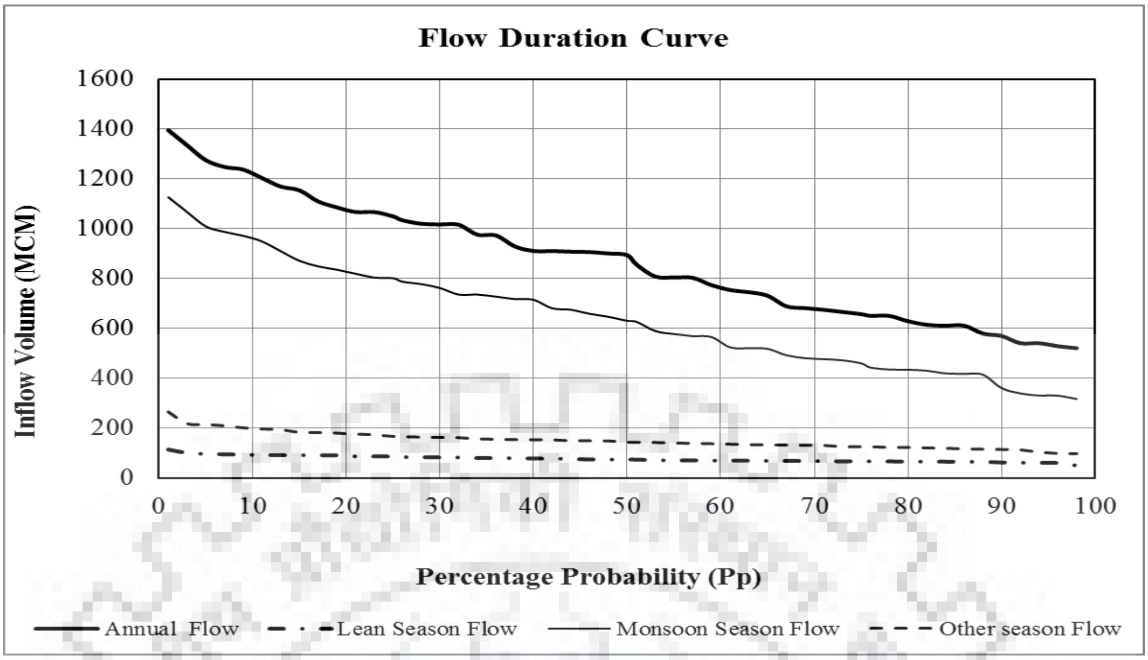


Figure 4. 3: Flow duration curve of annual, lean, monsoon and normal season flow volume (yield).

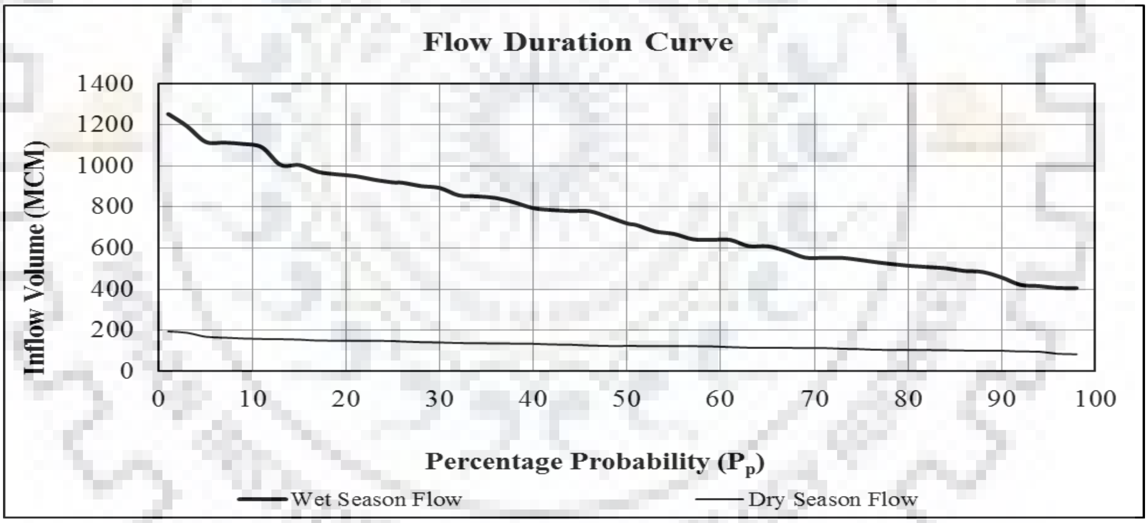


Figure 4. 4: Flow duration curve of dry season and wet season inflow volume (yield)

Before considering results of simulations performed for various FSL options, it is useful to examine the reservoir in light of the quantum of water available for wet season refill. For this purpose, historical wet season / dry season annual yield is tabulated and ranked according to the wet season amount. For this ranking, the wet season is considered as June 01 to November 30. The result is illustrated graphically in Figure 4.5.

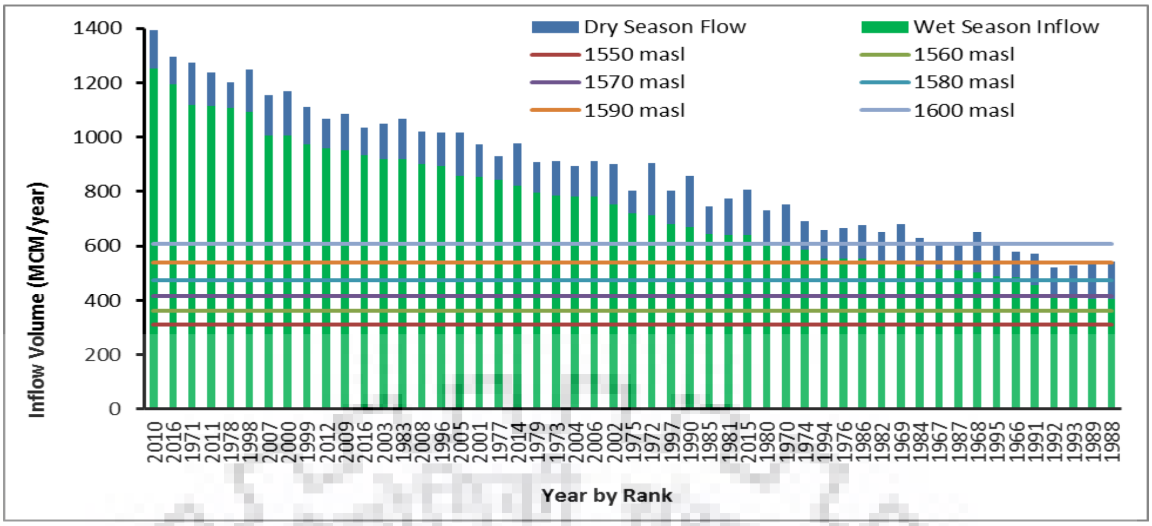


Figure 4. 5: Annual yield with wet and dry season yield indicated, ranked by wet season yield

Figure 4.5 shows that annual reservoir refill can be achieved in nearly all historical years with a FSL of El 1550, 1560, 1570 m; a reservoir with FSL set at El 1580 can achieve refill in about 90% of the historical years; a reservoir with FSL set at 1590 m can achieve refill in about 80% of the historical years and a reservoir with FSL set at 1600 m can achieve refill in about 65% of the historical years. Based on this analysis, the simulation will be done for FSL of 1550 m, 1560 m, 1570 m, 1580 m, 1590 m and 1600 m to suggest best FSL based on the dry season and total annual energy generation per year and reservoir refill time on historical flow data.

4.3 Simulation of Reservoir Operation

Reservoirs storage play major role to regulate highly variable water flows to meet the almost constant demand, such as water supply for municipal as well as industrial use, irrigation, and power generation and navigation purpose. In general, water drawn/release from a reservoir is almost constant and regular as compared to flow and constancy of the inflow to reservoir which may be represented by inflow and outflow hydrograph as represented in figure 4.6. Generally, reservoir modelling has been used to help scale storage capacities of reservoir, establish operational policies, evaluate operating policy, manage water allocations, develop management plans and for real-time operation.

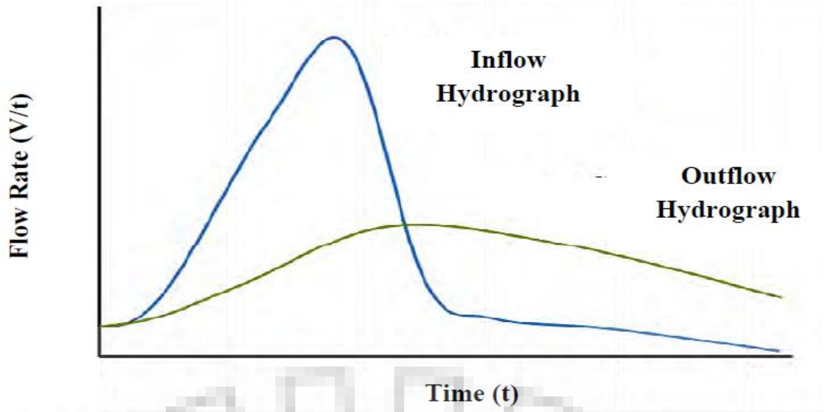


Figure 4. 6: Inflow and out flow hydrograph

The reservoir is represented by the water balance equation or continuity equation or the conservation of the volume with respect to time. It is a function that co-operates dynamically with the current state of the reservoir. Mathematically water balance equation for reservoir can expressed as below;

$$S_{t+1} = S_t + I_t - R_t - E_t - O_t$$

Where,

S_t = storage at the beginning of a time period *t*,

I_t = reservoir inflow during the time period *t*,

R_t = release required for the specified demand for the time period *t*,

E_t = evaporation during the period *t* and

O_t = spill from the reservoir during the period *t*.

4.3.1 Simulation of Reservoir Operation for Hydropower Generation

The amount of power generated through hydraulic turbine is function of turbine discharge and available net head to turbine and overall efficiency of system (Donald, 1954)

$$P = \gamma \times \eta \times Q \times H \quad \text{in KW}$$

Where,

P = Power output in KW

γ = specific weight of water in KN/m^3 = 9.81 KN/m^3

η = Overall efficiency of system

Q = Discharge through the turbine (m^3/s)

H = Designed net head in the turbine (m)

If R_t and H_t is the total volume of the flow through turbine in Mm^3 and designed net head during time period t power generated P in KWh will be

$P = 9.81 \times 10^6 \times \eta \times R_t \times H_t/3600 = 2725 \times \eta \times R_t \times H_t$

Hence hydroelectric power produced in MW for one month (about 30 days)

$P = 2725 \times R_t \times H_t / (1000\times30\times24) = 0.003785 \times R_t \times H_t$ in Mw

So that the total monthly release R_t required to generate power value equal to P Mw is given by

$R_t = P/ (0.003785 \times H_t)$ in Mm^3

4.4 Description of HEC-ResSim

The reservoir simulation model HEC-ResSim is developed by the Hydrological Engineering Centre of the USACE to support water resources engineer to predict the behaviour of reservoir/river basin systems in management studies. Water, as well as to help reservoir operators to plan daily and emergency operations in real time. To provide a useful test framework, specific opportunities were used for the optimal generation of energy and the calculation of the release from reservoir simulation models. HEC-ResSim differs from other reservoir simulation models in that it tries to replicate the decision-making process followed by reservoir operators to define releases. The program characterizes the physical behaviour of the reservoir systems in conjunction of hydraulic calculations for flows through control structures and hydrological routing to represent the lag and attenuation of the flows through the stream segments. It represents the operating objectives and operational constraints through an original logical system based on rules specially established to denote the process of decision making for the reservoir operation.

HEC-ResSim is the successor of HEC-5 as the crops's reservoir simulation model. The development of HEC-ResSim follows the path established by HEC with the introduction of HEC-RAS and HEC-HMS as successors of the river hydraulic model HEC-2 and the hydrological model HEC-1. Although it performs functions similar to those of HEC-5, HEC-ResSim, such as HEC-RAS and HEC-HMS, is an original program, which does not share any code with its predecessor.

HEC developed HEC-ResSim in the mid-1990s by surveying water regulatory and Management personnel to determine what was thought in the field in a modern reservoir modelling program. The results of the survey were compiled into a requirements document that details the physical and operational elements necessary for an effective reservoir simulation program. This requirements document formed the basis for the design and development of HEC-ResSim. The two main requirements were: it must be physically realistic and capable of representing a complex set of operational goal and constraints.

4.5 HEC-ResSim Modules

In HEC-ResSim model there are three sets of different utilities to provide access to specific types of data in a basin, which are called as module. These modules are the configuration of watersheds, reservoir network and simulation. Each module has a specific function and a related set of functions go through menu bar, toolbars and schematic elements. Figure 4.7 illustrates the basic modelling features available in each module.

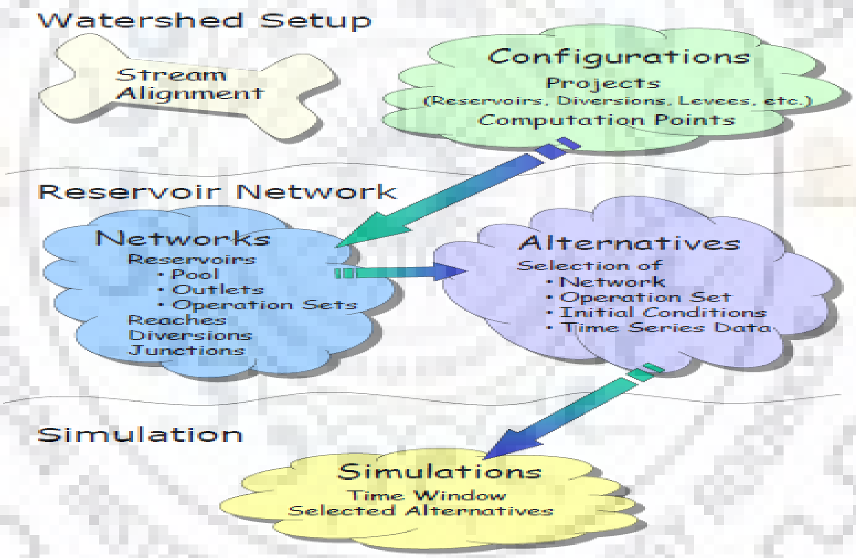


Figure 4. 7: Concepts of HEC-ResSim module (HEC-ResSim user manual)

4.5.1 Watershed Module

This module provides a common framework for creating and defining watersheds. A watershed is related with the terrestrial area for which models to be setup. A watershed includes all the streams & projects, such as reservoirs, levees, gage stations, impact area, time series locations, and hydro-metrological and hydraulic data of watershed. Once configured, all these features form watershed module (Wakena, 2006). The watershed module was created by importing basins delineated from the Nalgad River generated from GIS.

4.5.2 Reservoir Network Module

The main purpose of the Reservoir Network module is to separate the developed reservoir network model from the output. The river scheme is created in the reservoir network module and the all dam and reservoir physical data and operational rules are assigned in reservoir network from reservoir editor window and the alternatives for the assigned data sets are create in reservoir network module through alternative menu. The fundamental of the reservoir network is created through the configurations created in the watershed module, as a template. To complete the connectivity of the network schematic, routing reaches and other possibly network elements are also added. All the physical and operational data are assigned for each element of the network after the development of scheme. Alternatives are also created to stipulate the reservoir network; the sets of operations and time series path which is created in DDSVue file (Wakena, 2006). The reservoir network includes four main tools, such as junctions, routing reaches, diversions and reservoirs. Each element is defined with adequate information to be physically realistic without demanding extreme details that retard the calculation time.

4.5.3 Simulation Module

The main function of simulation module is to isolate the output from the model setup. The simulation module is used to perform the simulation after development of reservoir model and alternatives have been defined. The calculations are performed and the results are displayed in the Simulation module. When creating the simulation model, it was necessary to specify a simulation time window, a computational time step and the alternative to be analysed. The time window given for the present case was the beginning, the look back and the end time of the simulation. Then, ResSim creates a directory structure in the watershed RSS folder that represents the "simulation". In simulation tree, there is a copy of the watershed, which contains such files only which are need for alternatives. A output DSS file is also created in the simulation module which will obviously comprises all the DSS records that denote the input and output of the selected alternative. In addition, the features can be edited and saved for subsequent simulations (Wakena, 2006). Figure 4.8 represent the relationship of reservoir network and simulation model to manage simulation data.

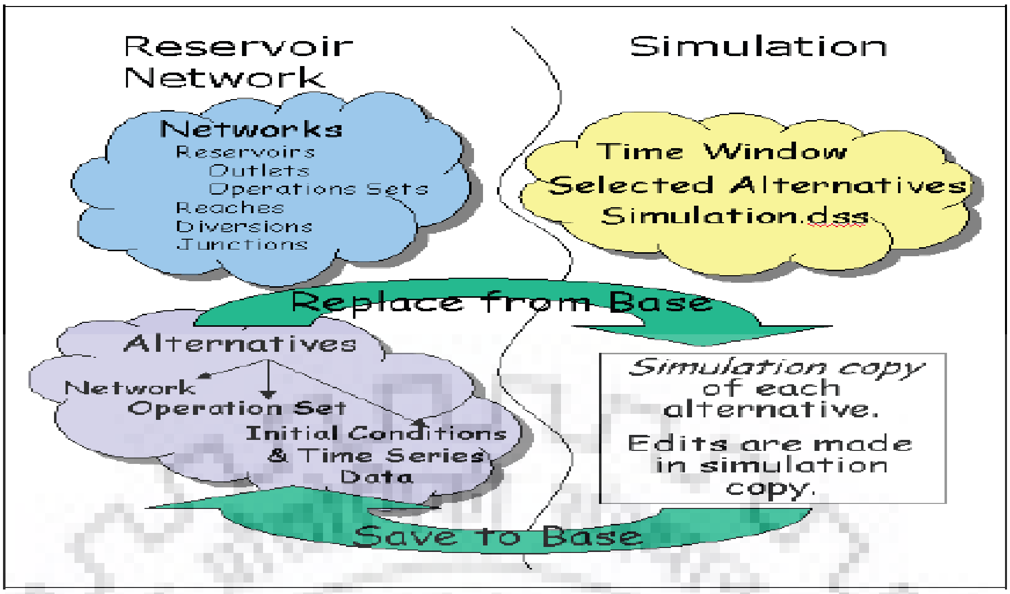


Figure 4. 8: Relationship of reservoir network and simulation modules to manage the simulation data

4.6 Theoretical Development of Reservoir Network

The main concepts of theoretical reservoir network development consist two distinct but interrelated parts. The physical part that includes different parts of the dam and the reservoir, such as Elevation-Area-Capacity (mandatory) and evaporation and seepage losses (optional) comes in reservoir physical part. Controlled and uncontrolled outlet groups, spillway and such other outlets, power plants, tail water levels, information on the structure of the dam are comes under dam physical parts. The correct definition of each one is very important to obtain satisfactory result. Next theoretical development is assignment of operation set which is the artery and the main body of the reservoir operation simulation model. The designation of this part is multifaceted and requires a lot of information; the computations are made using hydraulic and hydrological equations and formulas. With a conditional representation as if, then, or, and rules can be developed, modelling is conditioned for a better simulation. Basic theoretical component associated with theoretical development of reservoir network module are discussed as succeeding title below.

4.6.1 Physical Part

The most important part of the HEC model is to define the physical parameters. Even small changes significantly affect the behaviour of the system and the impacts deteriorate or meliorate the results of the simulation. The data to be taken into account for the physical part are the details of the reservoir and dam. In this project, it is controlled outlets power plants and out let for water supply and uncontrolled outlets un gated spillway and low level outlet for continuous environmental releases are dam physical parameters and EAC relationship, evaporation and seepage losses are physical parameters of reservoir pool. The power plants for the regulating part necessarily considered. Mathematical models track the water flow in large and multifaceted system. The following elements are considered: water inflow to system, flow in open courses, flow through outlet structures in the dams and flow through power plant for the generation of electricity. Different flows that get along with reservoirs are: Inflow to reservoir, Transformations of inflow in the storage, In-stream flow (Environmental releases), Evaporation, Leakage/seepage through dam, Flow through power plant for hydropower generation and Spilling over the spillway structures on dams.

4.6.2 Network Operating Rules

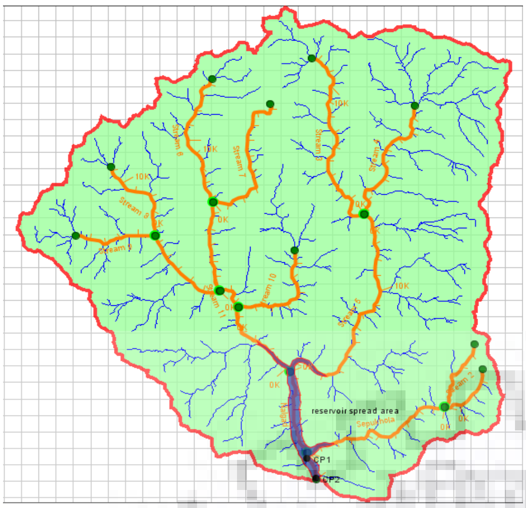
The operation rules are one of the most important elements of reservoir simulation models. The operation rule describes the logic used to decide whether to store or release water. The planning and operation of the dam requires decisions on the quantity and timing of the releases. The main anxiety in the operating process partly depends on the objectives of the project. That is, the rules that define the quantity of water stored in the reservoir. As a result, the generation of hydroelectric power is only one aspect of the operating rules developed in accordance with this decision.

Here, three zones were taken into account, such as the flood control zone for temporary storage to absorb high flow to alleviating D/S flood damages. This space should be emptied as soon as possible to accommodate next flood. Conservation zone used to conserve water to meet various water demand but only hydropower demand here in this project and the inactive zone in which storage for absorbed some of sediment entering into the reservoir no releases was made from this zone. Among these three zones, the conservation zone includes different rules to achieve the expected result. The inactive zone is a special zone in HEC-ResSim, because if it is deleted, it cannot be added later with its original function and this zone does not include as an additional rules.

The time series of inflow data in HEC-DSS from 1966 to 2016 was considered and the inflow into the reservoir was introduced into the junction inflow to reservoir. The operating rules briefly described are the following: elevation rate and changes in the water level according to the inflow discharge and daily and monthly hydropower requirements (MWh), hydropower system schedule, annual production, impact factor of the reservoir capacity in the conservation zone. The reason to define the rule is to keep the water level in the desired guide curve (DG) i.e. the target reservoir level. When the reservoir level is below top of DG 1580, conservation zone have been used with the associated rules and when the elevation and water level exceed DG 1580, the water is automatically discharged through an uncontrolled spillway. Here the operation rule used for the Nalgad reservoir is the hydropower schedule rule with the generation pattern total daily energy requirements (MWh) and the total monthly energy requirements (MWh) with seasonal as well as hourly variations in generation pattern. For better result release function rule having second priority for dry season month and third and least priority for wet season month in association with hydropower schedule rule is also assigned.

4.7 Development of Reservoir Model in HEC-ResSim

The initiation of the basin model development includes importing the ArcGIS stream alignment data, shape file of the reservoir point. The common approach of the reservoir simulation model setup may include more than one reservoir creating the reservoir network. Here, in this study, only one reservoir network has been created. The river reach created in ArcGis was imported in to watershed setup model in HEC-ResSim for the Nalgad Reservoir Project. The Watershed setup model and reservoir network models developed in HEC-ResSim shown in figure 4.9 & 4.10.



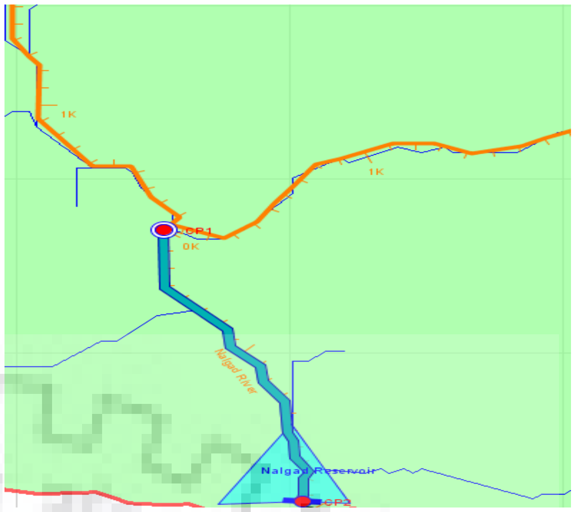


Figure 4. 9: Watershed setup **Figure 4. 10: Reservoir network**

4.7.1 Data Input for HEC-ResSim Model Setup

The data input for the model setup can be basically divided into Physical part, operation rule and the creation of the HEC-DSS time series data for running the simulation for specified time control. The data given as input for each reservoir network module is as follows:

Hydrological data input

HEC-DSS system is intended to competently store and repossess scientific data which are in sequential. HEC-DSS not only permits the plotting, tabulation and editing of data, but also the manipulation of stored data using a gathering of mathematical functions. In this study 52 years daily inflow data was input in the HEC-DSS system. When transforming time series data in to HEC-DSS format it is essential that the time series should be incessant, after converting the time series data to this file format, it can be used in the simulation by setting the pathname to DSS-path for this inflow points to the reservoirs in the alternative editor. The HEC-DSS file of daily discharge data for the period 1965 to 2016 was prepared and provided as input to HEC-ResSim. The graphical representation of HEC-DSS input daily inflow time series data is shown in figure 4.11.

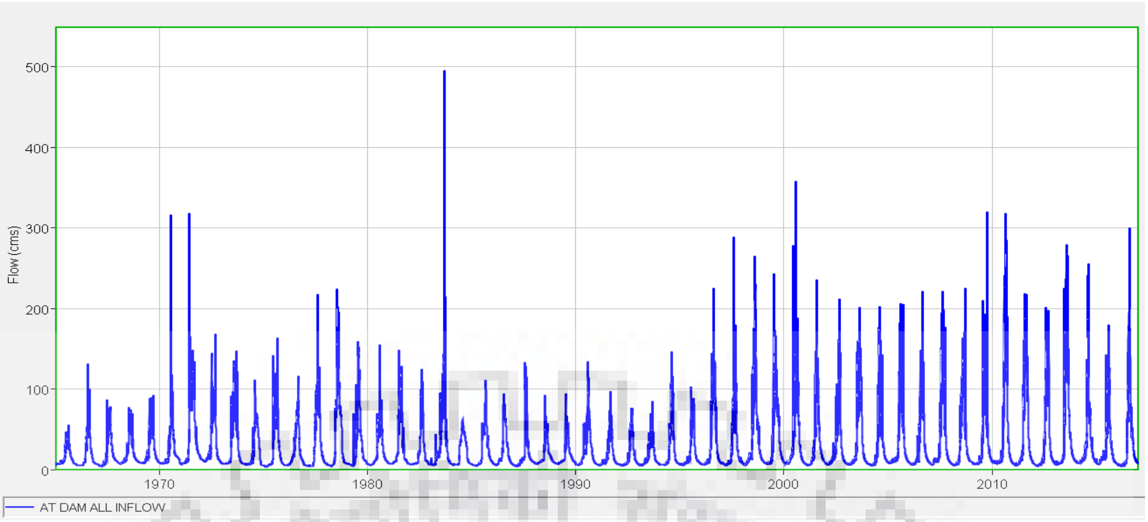


Figure 4. 11: Hydrograph of daily inflow at Nalgad reservoir

Physical data configuration for reservoir network

All physical data was defined in reservoir network module inside reservoir editor window. In reservoir editor window there are three main tabs such as physical, operations and observed data reservoir editor window shown in figure 4.12.

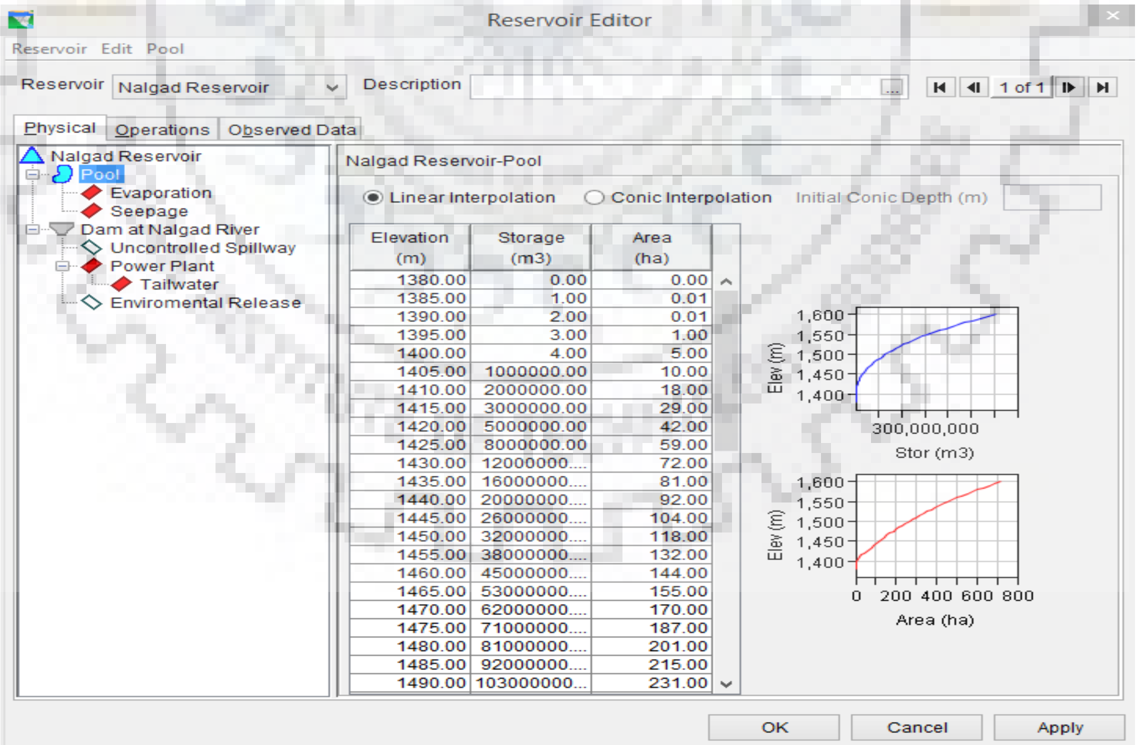


Figure 4. 12: Reservoir editor window for physical, operational and observed data input

Inside physical data tab there are major two physical parts for Reservoir and Dam. Reservoir pool is defined by Elevation–Area–Capacity relationship which is shown in figure 4.8. Inside pool tree there are two optional parameters such as evaporation and seepage. Graphical representation of defined evaporation is shown in figure 4.13 and seepage is taken as constant value 100 lps.

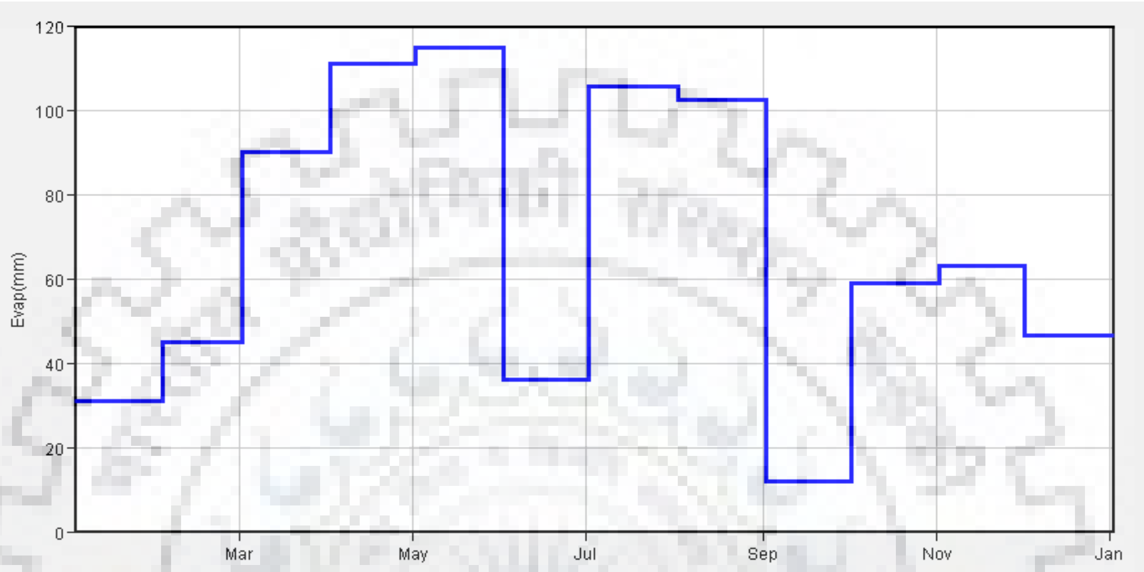


Figure 4. 13: Evaporation from Nalgad reservoir

Physical parameter of dam includes the controlled outlet, power plant, uncontrolled outlet, outlet groups, pump, pulse flow option, leakage and tail water elevation. But for this study controlled outlet, power plant and uncontrolled outlets are of major concerned. In this study intake rating curve, plant capacity (417MW), and station use (0) overall efficiency (87.8 %), hydraulic losses (as function of release) and tail water level (867.6 masl) are defined inside power plant. Two uncontrolled outlets are also assigned inside dam among them one is provided at full supply level of reservoir as uncontrolled spillway to release water when it reaches above FSL 1580 masl and next is provided as low level uncontrolled outlet for environmental release. Intake rating curve and spillway rating curve input in HEC-ResSim are shown in figure 4.14 & 4.15.

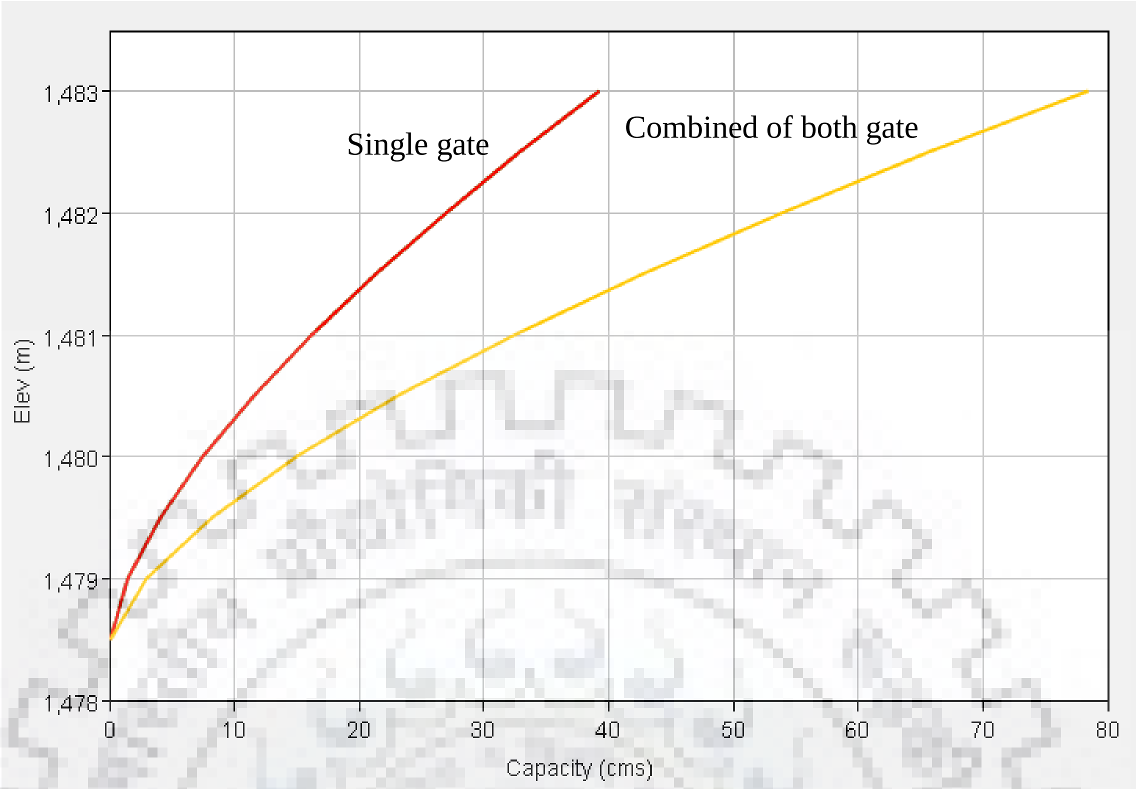


Figure 4. 14: Intake rating curve

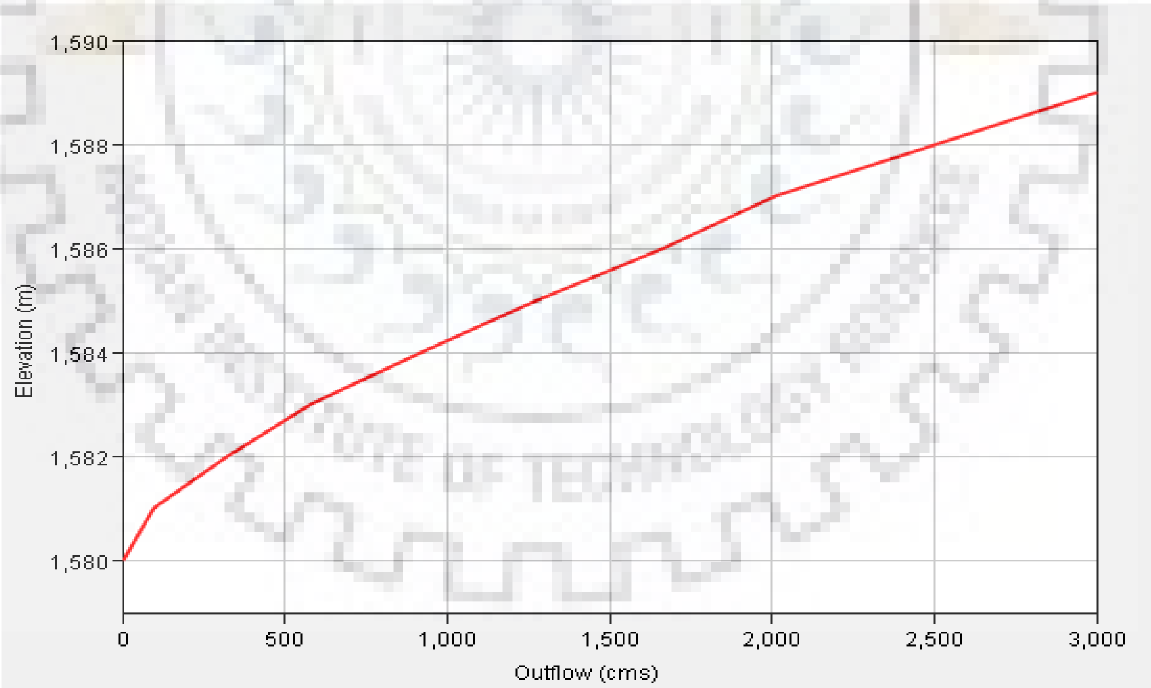


Figure 4. 15: Spillway rating curve

Operational data configuration for reservoir network

The operation rules are one of the most important elements of reservoir simulation models. The operation rule describes the logic used to decide whether to store or release water. The planning and operation of the dam requires decisions on the quantity and timing of the releases. The main anxiety in the operating process partly depends on the objectives of the project. That is, the rules that define the quantity of water stored in the reservoir. As a result, the generation of hydroelectric power is only one aspect of the operating rules developed in accordance with this decision.

Inside operation tab there are six menus such as Reservoir, Edit, Operations, Zones, Rule and IF_Block. Composition of zone and rule inside zone is called operation set which was assigned in each alternative to perform simulation. In Hec-ResSim there are three major zones such as Flood, Conservation and inactive zones. As Nalgad reservoir is for single purpose i.e. hydropower generation so conservation and inactive zones are considered here but food control is a obvious purpose for all storage project that's why it is also considered. Hydropower schedule rule and a release function rule are assigned inside conservation zone and no rules are applied in active zone. Each zones considered here are briefly described as below.

Flood control zone:

Flood control zone for temporary storage to absorb high flow to alleviating downstream flood damages. This space should be emptied as soon as possible to accommodate next flood. That's why this zone is assigned at elevation 1589 masl to spill excess flow as it reaches the elevation of 1580 masl to maintain the free board of 9m from top of conservation zone. No rules are assigned in this zone.

Conservation zone:

The maximum target elevation is assigned to conservation zone at elevation 1580 masl of top of maximum operating level of reservoir. The operation rule for the conservation zone is to set the target to fill the reservoir to the normal operating level of reservoir. The hydropower schedule rule is applied to this zone for various operational scenarios and sensitivity scenarios including the seasonal as well as hourly variation. Further to obtain better result and to make the better coordination of release with head causing power to generate target energy without any losses of flow, release function rule with maximum limit of release is used with second priority in present scenario to meet only power demand. But in future scenario if water supply is added as an additional purpose of reservoir, release function rule of higher priority and hydropower schedule rule with least priority are assigned as an operation set in each alternatives. Assign the trail operation set for each alternatives of operation scenarios considered and performed simulation for each alternatives repeat process till to obtained expected result and the optimum energy is selected based on the comparison of average energy generated per time step, total annual energy generation, optimum dry season energy generation with 90% reliability for different operation scenarios and generation patterns.

The hydropower rule is used to define regular monthly or user specified seasonally varying variable energy requirements. The different options in this rule editor allow us to define the energy requirement of each month (MWh or plant factor), as well as the hours of the day and the days of the week during which the plant generate. It consists of power generation pattern to which the peak pattern during specified hour of day or the 24-hour generation pattern can be applied. Power generation pattern of each day is separated into 24-hour values. Each value represents a weighting factor which is used to allocate energy requirement throughout the day and week. The default value for each hour of the day is 1.0, which evenly distributes the energy requirements throughout the day. However, if we want the plant to generate only part of the day, we can set the factor of these hours to 1.0 and all the others to 0. Basically, the values of 1.0 and 0.0 activate the hourly generation "ON" and "OFF". The weighting factor values comes into play when the values used in the model are not only 0 and 1, in other words, when the generation is not designed to be distributed evenly in the hours "in." The values of the weighting factor can be more of one and represents that it is generated with more than one capacity during that hour. (Source: HEC-ResSim User's Manual).

In this study there are five different operation scenarios are considered to develop optimal operation rule for reservoir operation in existing case and one additional scenario is considered as future scenario if water supply is added as a another purpose of reservoir with that four sensitivity scenarios are considered to analyse the sensitivity of energy generation due to change in inflow, environmental release and full supply level and reservoir storage loss due to sedimentation. For each operation scenario number of alternatives was created for different operation set as changing generation pattern, physical parameter and inflow time series etc. to select optimal operating policy/rule. Each considered scenarios with their various alternatives are briefly discussed in succeeding chapter 5 results and discussion.

Inactive zone:

This is also called dead storage zone. This is the lowermost zone where storage is expected to accumulate some of the sediment entering the reservoir. Storage in this zone is not likely to be released by the integrated output means. The minimum target elevation level is assigned to the inactive zone at elevation of 1498 masl at the top of the minimum operational level of the reservoir. No operation rules are assigned in this zone as no release is made from this zone. The inactive zone is a special zone in HEC-ResSim, because if it is deleted, it cannot be added later with its original function and this zone does not include as an additional rule.

4.8 Distribution of Sediment in the Reservoir

The storage capacity of the reservoir is progressively depleted due to sedimentation resulting in deviations in Elevation-Area-Capacity relationship. These curves are important for planners, designers and dam operators. Many empirical and semi-empirical methods were postulated to establish and predict these curves or relationship. In this study, Empirical Area Reduction Method Suggested by Borland and Miller in 1985 was used to establish the Elevation-Area -Capacity curve after 25, 50, 75 and 100 years from reservoir operation date. Later these developed revised Area-Elevation-Capacity curves are used in simulation study to analyse the effect of sedimentation on energy generation. The procedure followed for empirical area reduction method to establish the revised Elevation-Area-Capacity relationship due to sedimentation is descried below.

The reservoir surface is considered as conical in shape. when the sediment volume V_s is deposited progressively over a time ΔT, some part of the conical portion of the reservoir entirely filled up with sediment (Say up to height h_o above the original bed) and in the remaining portion the deposition will be on the surface and X-sectional area at any level will be diminished. Let the volume of sediment filled in the conical portion to depth of h_o = V_{so}.

Steps;

1. The elevation h_o relative to the reservoir original bed, up to the reservoir is completely filled up with the sediment, is assumed the top of this filled up portion is considered as the new bed level i.e. the new zero elevation. The area A_o at this depth is determined the value of P at this level $= P_o = h_o/H$

2. Now the total new depth of the reservoir $= H - h_o$

3. Volume of sediment to be distributed $= V_s - V_{so}$

4. The type classification of the reservoir is determined from table 2.1; here reservoir type is Type III (Hilly Region) and select the value of C, m_1 and n_1 for reservoir Type III from table 4.1.

Table 4. 1: Reservoir classification

Classification Number	Reservoir Type	Parameters		
		C	m_1	n_1
I	Lake	5.074	1.85	0.36
II	Flood plain, Foot-hill region	2.487	0.57	0.41
III	Hilly region	16.967	1.15	2.32
IV	Gorge	1.486	-0.25	1.34

5. Determine the value of dimensionless relative are Ap for various value of $P = h_o/H$ by using the equation as below.

$$Ap = C \times P^{m_1} \times (1-P)^{n_1}$$

Where, h= height above the reservoir bed to any given elevation in the reservoir and

H = Difference between the FRL and original bed of the reservoir

6. At $P = P_o$; $A_p = A_{po}$

7. Determine $K = A_o/A_{po}$

8. Calculate the sediment area A_s at any height h above the above the new bed level using the relation $A_s = A_p \times K$

9. Volume or sediment deposit (ΔV) between two consecutive height h_1 and h_2 above the new datum is determined as $\Delta V = (A_1+A_2)\times(h_2-h_1)/2$

10. Stored sediment at different elevations starting from the original bed level are now obtained.

11. The total sediment volume accumulated up to the reservoir top level, calculated in step 10, should be same as the given value of V_s. if the value obtained in step 10 differs from V_s significantly, say more than 2%, then repeat the entire procedure by assuming new value of h_o.

4.9 Rule Curve Development through Optimization Technique

Optimization technique is used to develop monthly reservoir operation policy to optimize the dry season energy generation by utilizing available inflow throughout the year. Monthly release R_t that optimize an objective function to maximize energy generation satisfying all the constraints is determined through optimization technique. The objective function is the function of release or reservoir storage. Mass conservation is a typical constraint in reservoir optimization model and other hydro -metrological and hydraulic constraints, minimum and maximum storage and release power generation limitations etc.

In this study, LINGO 17.0 was applied for the single–objective optimization and dry season energy generation was optimized by the model for 90% dependable flow year 1991. Dry season energy generation was optimized by limiting the maximum wet season release equal to release required for one hour operation. After that storage resulting from optimized release is used to develop the optimized rule curve for Nalgad reservoir operation for hydropower generation and compared this operation rule with that obtained through simulation model using HEC-ResSim then suggest the best operation rule curve to optimize the dry season energy generation and minimize the deficiency.

4.9.1 Optimization Problem Formulation

Objective Function

The main objective of this study is to optimize the dry season energy generation by utilizing the reservoir inflow. Hence objective function is to maximize the energy generation which can be written as in equation 4.1.

$$Z = \sum_{t=1}^{n} Et$$ ……………………………………………………eq. (4.1)

Where,

$E_t = 0.278*\eta*r*R_t* H_t = 0.278*0.878*9.81* R_t* H_t = 2.3944* R_t* H_t$………eq. (4.2)

$H_t = EL_t - TWL - 0.025*(EL_t - TWL)$…………………………………...……....eq. (4.3)

Where,

n= No. of time period here n= 12 month for 1 year period.

E_t = Energy generation in MWh during period t.

R_t = Release through turbine in Mm^3 during time period t.

H_t = Neat Head in m during time period t.

EL_t = Reservoir level during time period t. Initially it is assumed a certain suitable value to calculate evaporation and net head and finalized after optimization using optimized storage value.

TWL = Tail Water Level = 867.6 masl.

The inflow available to reservoir at beginning of any time step is considered as the state of system. The decision variable of the problem is release from the reservoir in simulation time step t (Month).

<u>System Constraints</u>

The objective function subjected to following system constraints.

Mass balance equation

$S_{t+1} = S_t + I_t - R_t - ER_t - E_t - Se_t - O_t$ ……………………………………………eq. (4.4)

Where,

S_t = Reservoir storage at time period t in (Mm3)

S_{t+1} = Reservoir storage at time period t+1 in (Mm3)

I_t = Reservoir inflow at time period t in (Mm3)

R_t = Release through turbine to generate power during time period t in (Mm3).

ER_t = Minimum environmental Release to D/S During time t in (Mm3).

E_t = Evaporation from reservoir loss during time period t in (Mm3).

Se_t = Seepage loss through dam during time period t in (Mm3).

O_t = Overflow through spill way during time period t in (Mm3).

Steady- state-condition

The reservoir storage volume during starting of initial time period and end of the last time period over the operation period must be equal which is written as in equation 4.5.

$\mathbf{S_1 = S_{t+1}}$ ……………………………………………………………………………….eq. (4.5)

Where,

S_1 = Reservoir storage at first time period (first month i.e. Jan)

S_{t+1} = Reservoir storage at last time period (last month i.e. Dec)

Storage bounds

The reservoir storage during operation time period should be within the range of minimum and maximum storage limits. Mathematically it is expressed as in equation 4.6.

$\mathbf{S_{min} \leq S_t \leq S_{max}}$ ……………………………………………………………..…..eq. (4.6)

Where,

S_{min} = Minimum reservoir storage (dead storage) = 123.8 Mm^3.

S_{max} = Maximum reservoir storage volume (reservoir capacity) = 474 Mm^3.

S_t = Storage Volume at the beginning of time period t Mm^3.

Release bounds

Release from reservoir should be greater than or equal to water required to generate minimum power and less than or equal to the turbine capacity. Mathematically it is expressed as in equation 4.7.

$\mathbf{R_{min} \leq R \leq R_{max}}$ ……………………………………………………………………..eq. (4.7)

$\mathbf{R_{min} = 3.6*P_{min}*T_t/(\eta *r*H_t)}$………...…………………..…………………… eq. (4.8)

P_{min} = Minimum power production limit Mw.

T_t = Total number of operation hour.

Overflow bounds

Water excess the reservoir storage capacity spill through emergency spill way otherwise overflow is zero i.e. no over flow. Mathematically it is expressed as in equation 4.9.

$\mathbf{O_t = 0 \quad If\ (S_t + I_t - R_t - ER_t - E_t - Se_t) \leq K}$ ....eq. (4.9)

$\mathbf{O_t = (S_t + I_t - R_t - ER_t - E_t - Se_t) - K \quad If\ (S_t + I_t - R_t - ER_t - E_t - Se_t) \geq K}$.. Eq. (4.10)

Where,

K = Reservoir Capacity = 474 Mm^3

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Reservoir Operation Simulation using HEC-ResSim

The reservoir simulation study was carried out for Nalgad Reservoir Project using the estimated long term daily inflow data of Nalgad reservoir at intake site for the period 1966 to 2016.The total storage zone was divided in to flood control, conservation zone and the inactive storage zone. The maximum operating levels considered in this study is full supply level at the elevation of 1580 masl which is set as top of conservation zone. The excess flow above that maximum operating level is spill through uncontrolled spillway. Minimum operating level is set at the top of inactive zone (1498 masl) which is the minimum drawdown level. The operation rule for the conservation zone is to set the target to fill the reservoir to that level. The power guide rule curve was applied to this level varying the hourly and seasonal generation pattern. The optimum energy is selected based on comparison of energy generated per time step, total annual energy generated, and annual dry season energy generation with 90% reliability and water level maintained in reservoir for different operation scenarios with different generation patterns. There are five different alternate operation scenarios with number of generation patterns are considered to develop optimal operation rule/policy. One operation scenario is considered for future with additional supply of drinking water to downstream municipality. Four sensitivity scenarios are also considered to analyse sensitivity to energy generation due to change in basin hydrology, environmental release, full supply level and reservoir sedimentation. Each of these operation scenarios results presented and described as below.

5.2 Considered Operation Scenarios

Various operation scenarios with different alternate for generation pattern considered for development of operation rules/ policies are summarised as in table 5.1.

Table 5. 1: Summary of details of considered operation scenarios with alternatives

Scenarios	Alternatives	Operation Zones	No. of turbine units are in operation	Generation Pattern		Simulation Time step
				Dry	Wet	
1	1	1498-1580 m	2	24	24	Daily
	2		3	24	24	Daily
	3*		4	24	24	Daily
2	1	1498-1580 m	4	24	24	Daily
	2		4	18	18	Daily
	3		4	12	12	Daily
	4*		4	8	8	Daily
	5		4	6	6	Daily
3	1	1498-1580 m	4	10	1	Daily
	2		4	10	4	Daily
	3*		4	11	1	Daily
	4		4	11	3	Daily
	5		4	12	1	Daily
	6		4	9	6	Daily
	7		4	8	7	Daily
4	1	1478.5-1580 m	4	9	1	Hourly
	2		4	9	2	Hourly
	3*		4	10	1	Hourly
	4		4	10	2	Hourly
	5		4	10	3	Hourly
	6		4	10	4	Hourly
	7		4	11	1	Hourly
5	1	1498-1580 m	4	9	4	Hourly
	2		4	9	5	Hourly
	3*		4	10	1	Hourly
	4		4	10	2	Hourly
	5		4	11	1	Hourly

*Selected alternative

5.2.1 Operation Scenario 1

The maximum and minimum target elevation level is assigned to conservation zone at elevation 1580 masl of top of maximum operating level of reservoir and inactive zone at elevation 1498 masl of top of minimum operating level of reservoir respectively and top of flood control zone is set at elevation 1589 masl. In this scenario the twenty-four hours generation pattern is assigned for all seasons. The power guide rule curve is not used here and the power generation is totally based on the variation of inflow throughout the year. It is further analysed by varying the number of turbine units in operation as two, three and four throughout the year. This operation scenario helps to select the number of turbine units to operate for maximum energy generation through power plant i.e. plant capacity is fixed through the analysis of result obtained from this operation scenario. The summary output for the different number of turbine unit in operation for operation scenario 1 is presented in table 5.2.

Table 5. 2: Summary report of HEC-ResSim for reservoir simulation with various turbine units for scenario 1.

Operating level (m)	No. of turbine unit in operation	Location/Parameter	Summary Output		
			Average	**Maximum**	**Minimum**
1498-1580	2	**Reservoir Summary Report**			
		Storage (Mm^3)	206.125	484.745	123.8
		Elevation (m)	1519.75	1581.7	1498
		Controlled Release (m^3/s)	23.89	39.2	2.51
		Uncontrolled Spill (m^3/s)	2.91	253.71	0
		Power Summary Report			
		Generation Efficiency	0.88	0.88	0.88
		Power Head (m)	652.15	714.1	630.4
		Hydraulic Losses (m)	17.7	17.7	17.7
		Energy Generated per Time Step (MWh)	3185.52	5004	318
		Power Generated (MW)	132.73	208.5	13.25
		Plant Factor	0.64	1	0.06
		Flow Power (m^3/s)	23.89	39.2	2.51
1498-1580	3	**Reservoir Summary Report**			
		Storage (Mm^3)	163.659	483.644	123.8
		Elevation (m)	1508.82	1581.5	1498
		Controlled Release (m^3/s)	25.61	58.8	2.51
		Uncontrolled Spill (m^3/s)	1.3	218.08	0
		Power Summary Report			
		Generation Efficiency	0.88	0.88	0.88
		Power Head (m)	623.52	696.2	612.7
		Hydraulic Losses (m)	17.7	17.7	17.7
		Energy Generated per Time Step (MWh)	3363.36	7506	318

		Power Generated (MW)	140.14	312.75	13.25
		Plant Factor	0.45	1	0.04
		Flow Power (m^3/s)	25.61	58.8	2.51
1498-1580	**4**	**Reservoir Summary Report**			
		Storage (Mm^3)	142.108	483.062	123.8
		Elevation (m)	1503.21	1581.4	1498
		Controlled Release (m^3/s)	26.3	78.4	2.5
		Uncontrolled Spill (m^3/s)	0.62	191.21	0
		Power Summary Report			
		Generation Efficiency	0.88	0.88	0.88
		Power Head (m)	617.91	696.1	612.7
		Hydraulic Losses (m)	17.7	17.7	17.7
		Energy Generated per Time Step (MWh)	3407.04	10008	318
		Power Generated (MW)	141.96	417	13.25
		Plant Factor	0.34	1	0.03
		Flow Power (m^3/s)	26.3	78.4	2.5

The best alternative for the twenty-four hour generation pattern throughout the year without using power guide rule curve is selected on the basis of comparison of the maximum average energy generated per time step (daily) for three alternatives above. The spill is minimum in third alternative with four turbine units are in operation. The third alternative with four turbine units in operation throughout the year gives the maximum average energy generation per time step. Therefore, Alternative 3 is considered the best alternative for operation scenario 1 with four turbine units are in operation for twenty-four hours' generation throughout the year without using power guide rule curve. The graphical representation of results of simulation of selected alternative 3 for twenty-four hours power generation pattern and four turbine units are in operation are shown in figure 5.1 to 5.5.

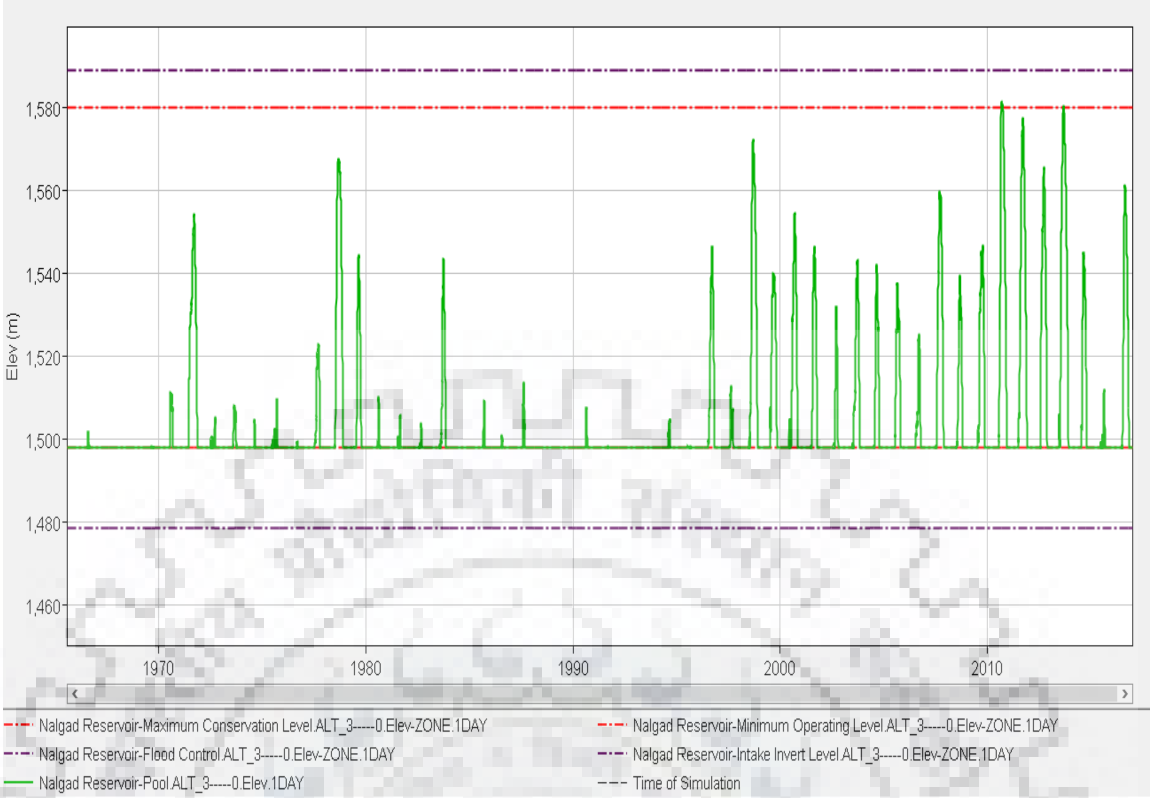


Figure 5. 1: Reservoir elevation for selected alternative 3 of scenario 1

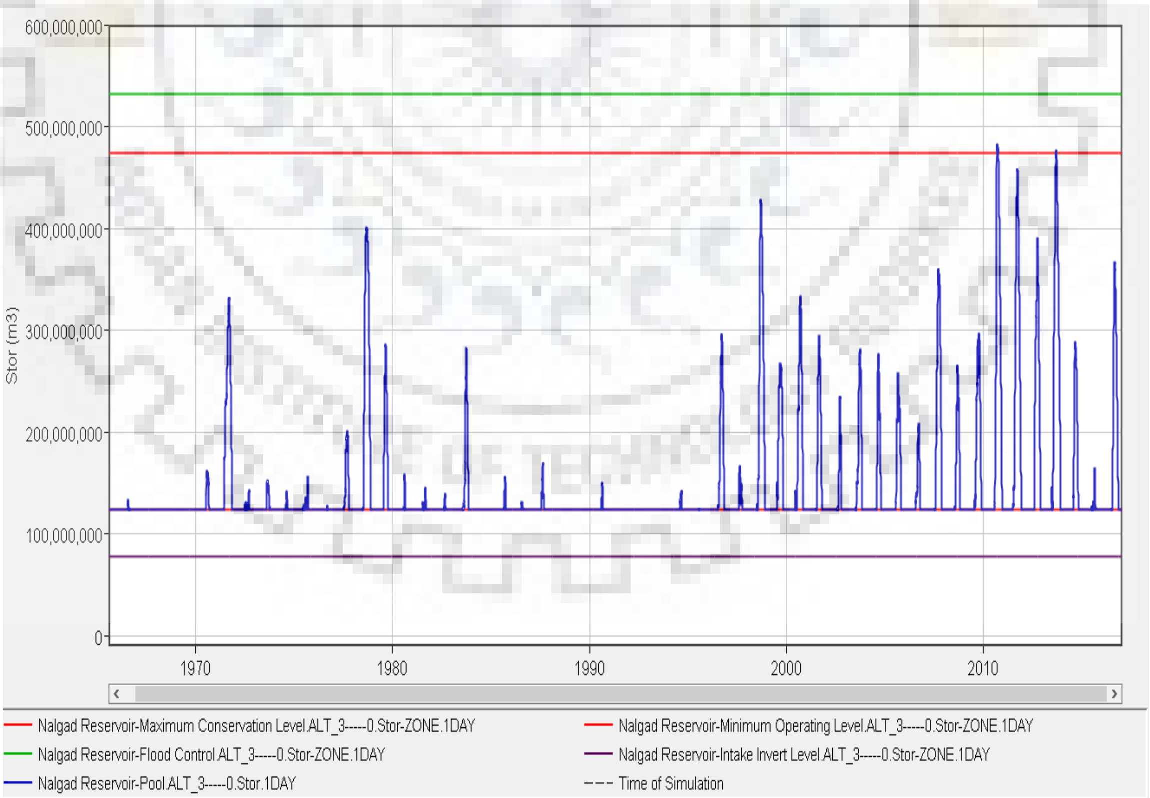


Figure 5. 2: Reservoir storage for selected alternative 3 of scenario 1

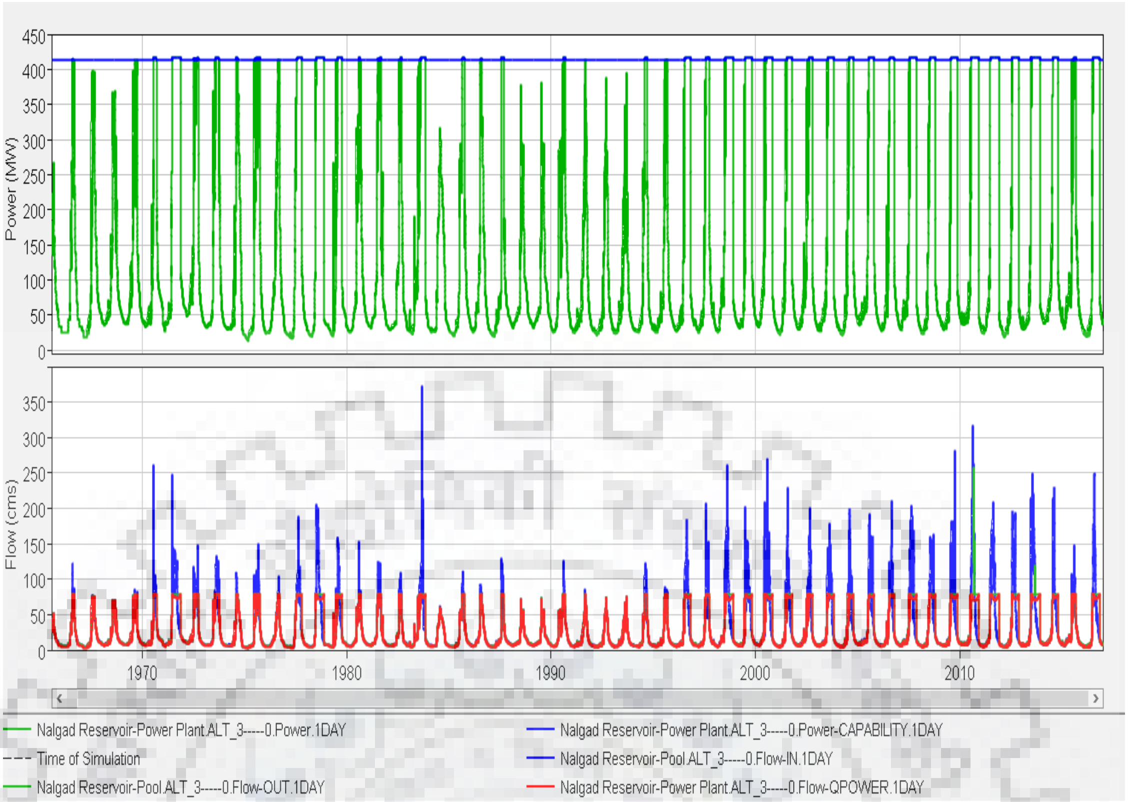


Figure 5. 3: Power generations, inflows and outflows for alternative 3 of scenario 1

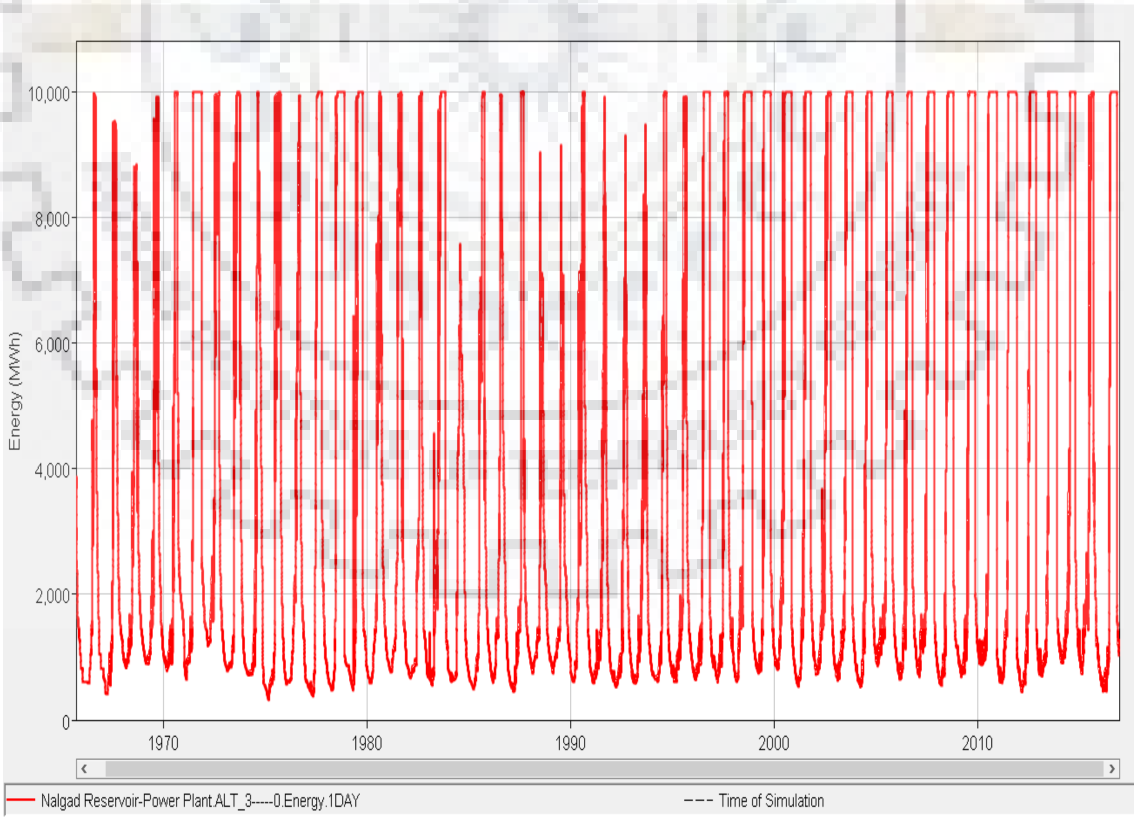


Figure 5. 4: Energy generation for selected alternative 3 of scenario 1

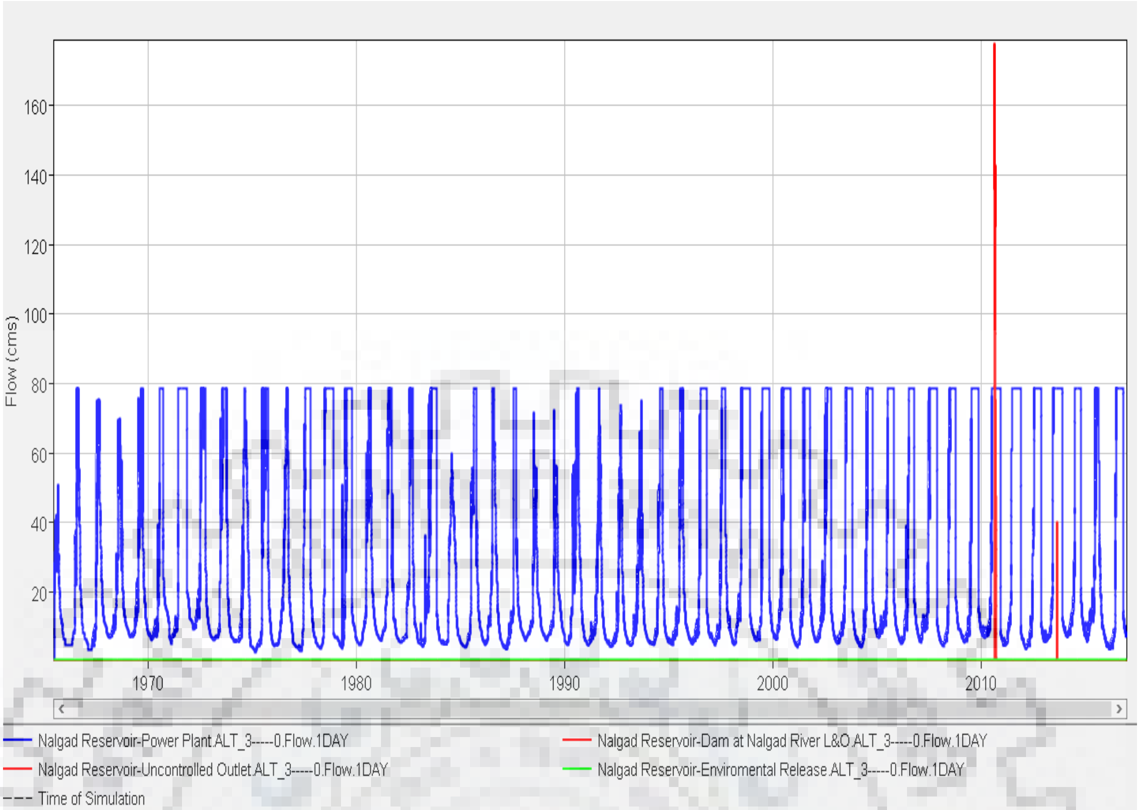


Figure 5. 5: Release from all controlled and uncontrolled outlets for alternative 3 of scenario 1

5.2.2 Operation Scenario 2

The maximum and minimum target elevation level is assigned to conservation zone at elevation 1580 masl of top of maximum operating level of reservoir and inactive zone at elevation 1498 masl of top of minimum operating level of reservoir respectively and top of flood control zone is set at elevation 1589 masl. This operation scenario includes twenty-four hours generation pattern throughout the year varying the minimum total daily energy requirement. The power guide rule curve used here is hydropower schedule rule. Five different alternatives were considered for the different minimum daily energy requirement such as one - fourth, one- third, one - half, three fourth and full energy of the maximum daily total energy generated. In this scenario HEC-ResSim try to meet the total daily energy requirement as daily time step was assigned for simulation. Details of simulation result obtained from selected alternative 4 of this scenario shown in table 5.3 and summary of result of each alternative shown in table 5.4

Table 5. 3: Summary report of HEC-ResSim for reservoir simulation of selected alternative 4 of operation scenario 2.

Month	Daily Energy Retirement (MWh/ Day)	Equivalent Operation Hours	Location/ Parameter	Summary Output		
				Avg.	**Max.**	**Min.**
ALTERNATE 4						
Jan	3336	8	**Reservoir Summary Report**			
Feb	3336	8	Storage (Mm^3)	288.973	485.759	123.8
Mar	3336	8	Elevation (m)	1541.01	1581.8	1498
Apr	3336	8	Controlled Release (m^3/s)	24.82	69.77	2.91
May	3336	8	Uncontrolled Spill (m^3/s)	1.04	211	0
Jun	3336	8	**Power Summary Report**			
Jul	3336	8	Generation Efficiency	0.88	0.88	0.88
Aug	3336	8	Power Head (m)	655.71	696.39	614.7
Sep	3336	8	Hydraulic Losses (m)	17.7	17.81	15.7
Oct	3336	8	Energy Generated per Time Step (MWh)	3480.72	10008	393.6
Nov	3336	8	Power Generated (MW)	145.03	417	16.4
Dec	3336	8	Plant Factor	0.34	1	0
Total	**40032**	**96**	Flow Power (m^3/s)	24.82	69.77	2.91
	Dry Season Energy Generated (GWh/year)			**515.088**		
	Wet Season Energy Generated (GWh/year)			**733.911**		
	Total Annual Energy Generated (GWh/year)			**1248.999**		
	Annual Energy Generation Reliability (%)			**87.34**		

Table 5. 4: Comparison of results of various competitive alternatives of scenario 2

Parameters		Alternatives				
Alternatives		**1**	**2**	**3**	**4**	**5**
Total daily Energy Requirement		100%	75%	50%	**33.33%**	25%
Equivalent Operation Hour		24	18	12	**8**	6
Average Energy Generated Per Time Step (MWh)		152.21	151.35	148.75	**145.03**	138.6
Dry Season Energy Generated (MWh/year)		193.33	277.527	429.129	**515.088**	451.057
Wet Season Energy Generated (MWh/year)		1141.00	1049.27	874.9	**733.911**	763.884
Total Annual Energy Generated (MWh/year)		1334.3	1326.8	1304.03	**1249.00**	1214.942
Spill (m^3/s)	Average	0.189	0.48	1.04	**1.85**	3.23
	Maximum	187	187	211	**239**	297
Annual Energy Generation Reliability (%)		15.26	34.46	57.1	**87.34**	98.84
Remarks					**Selected**	

In this operation scenario the maximum total annual energy generation is 1334.3 GWh/year when hydropower schedule rule with minimum daily energy requirement is equal to maximum total energy generation capacity i.e. total annual energy generation is maximum when the power plant operated /run for 24 equivalent hours. But as per the study objective maximum dry season energy generation is 515.088 GWh/year when the minimum daily energy requirement assigned is one-third that means dry season energy generation is maximum when power plant operated/run for 8 equivalent hours throughout the year. Hence from this scenario hydropower schedule rule with 8 hours energy generation pattern throughout the year is selected as best operation policy/rule to generate maximum dry season energy. There is large variation in reservoir level over the simulation period, during dry year reservoir is not filled to its full supply level and during wet year spill is very high and reservoir level not goes to its minimum draw down level even in dry period. Energy requirement is not meet out by system in 22 years out of 51 years of simulation period. As this power plant is planned as seasonal peaking plant for dry season so, seasonal variation in operation policy/rule should considered for system operation which is considered in succeeding operation scenario 3, 4 & 5. The graphical representation of simulation result of selected alternative 4 of operation scenario 2 are shown in figure 5.6 to 5.10.

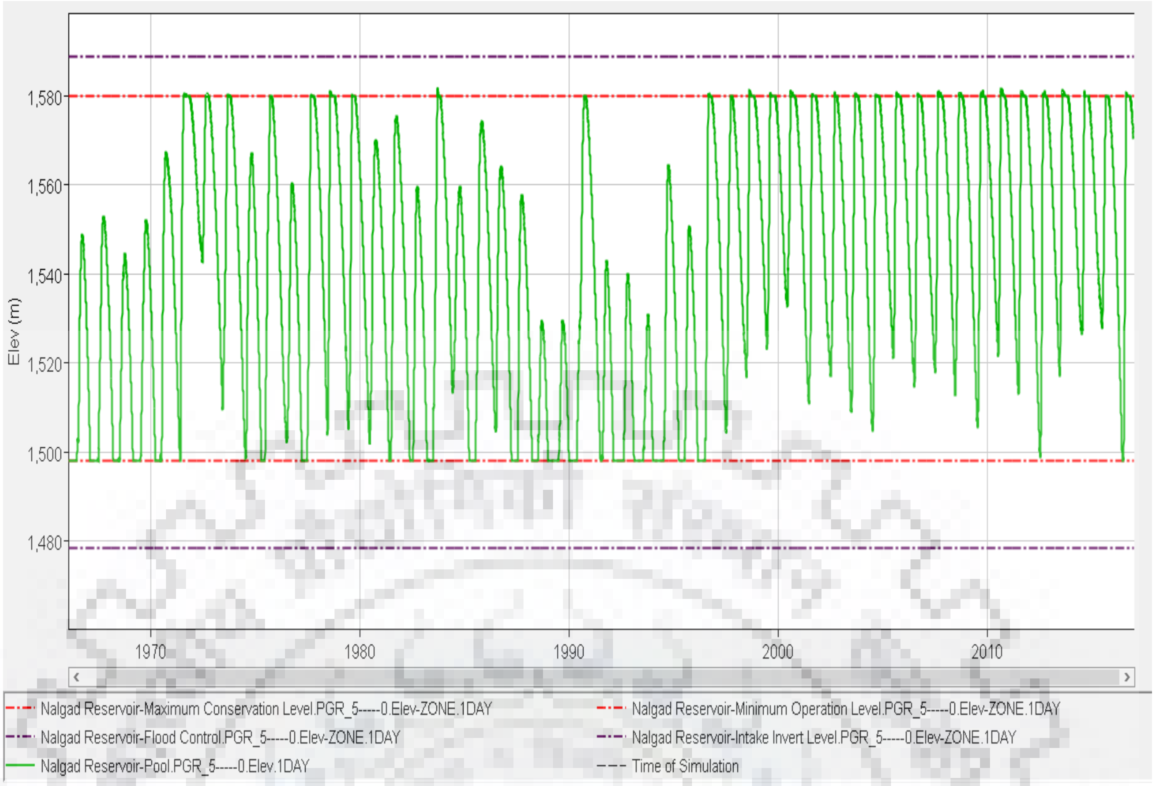


Figure 5. 6: Reservoir elevation for selected alternative 4 of scenario 2

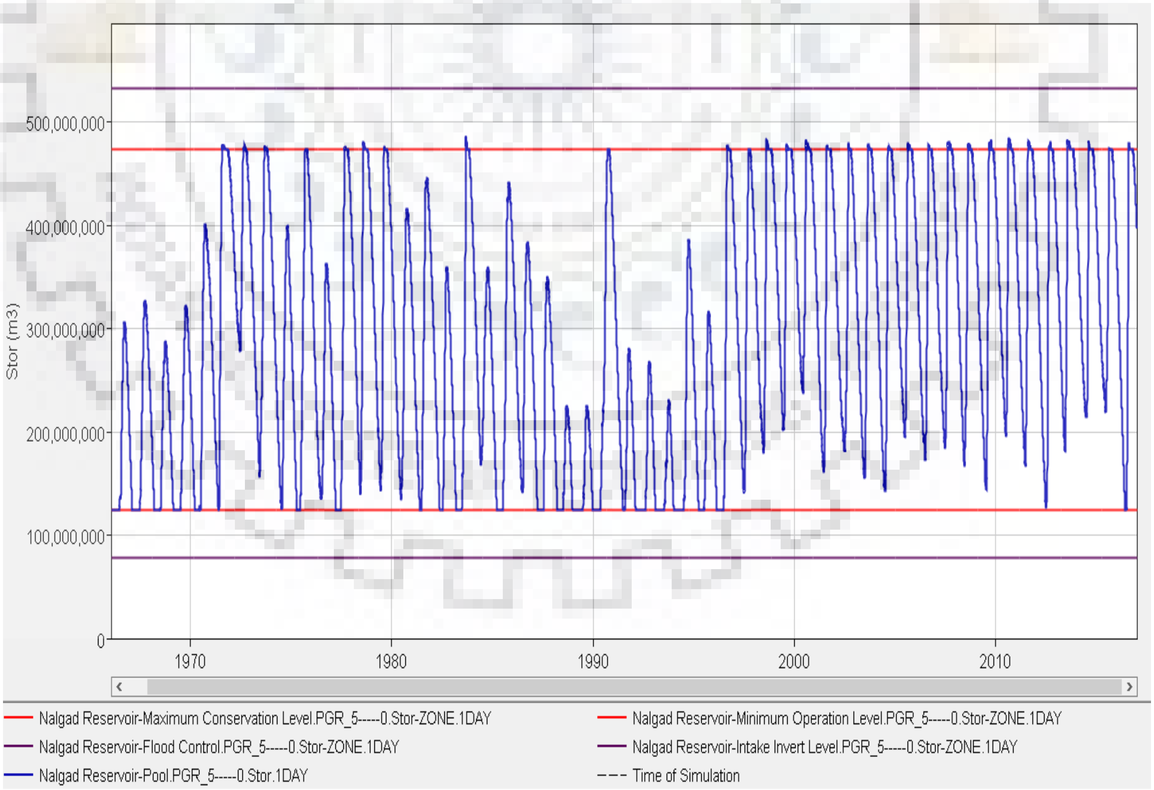


Figure 5. 7: Reservoir storage for selected alternative 4 of scenario 2

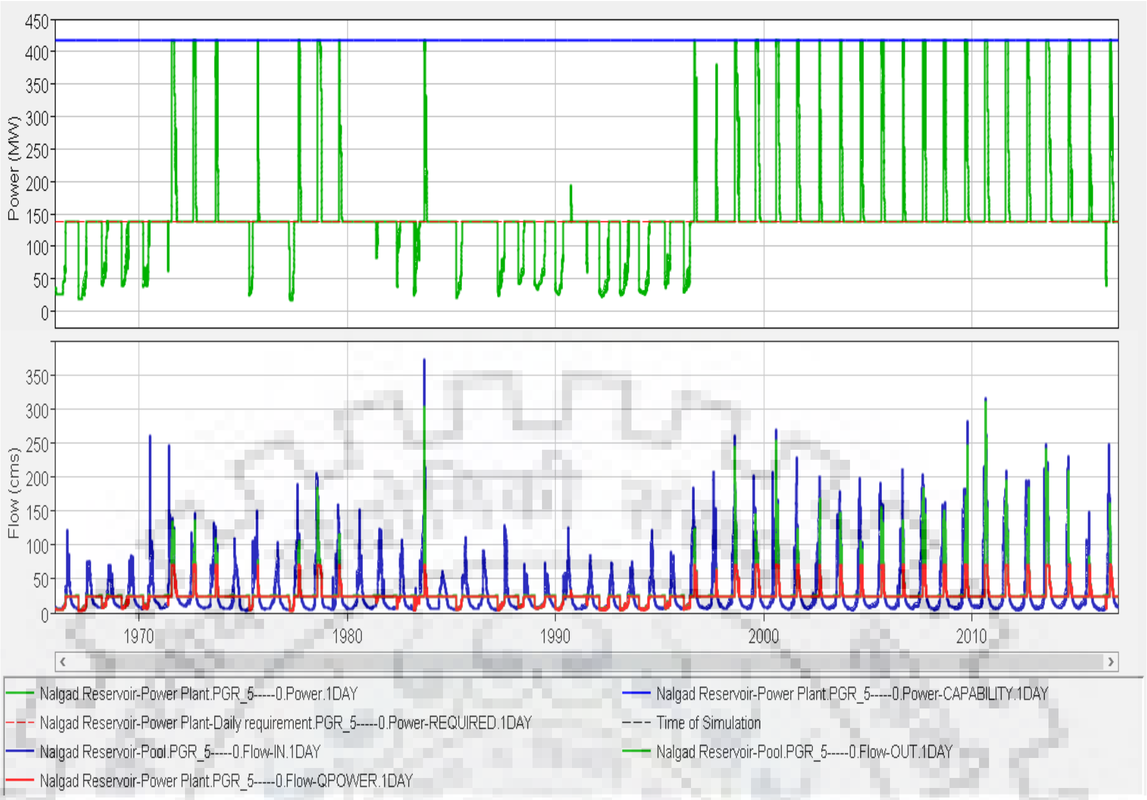


Figure 5. 8: Power generations, inflows and outflows for alternative 4 of scenario 2

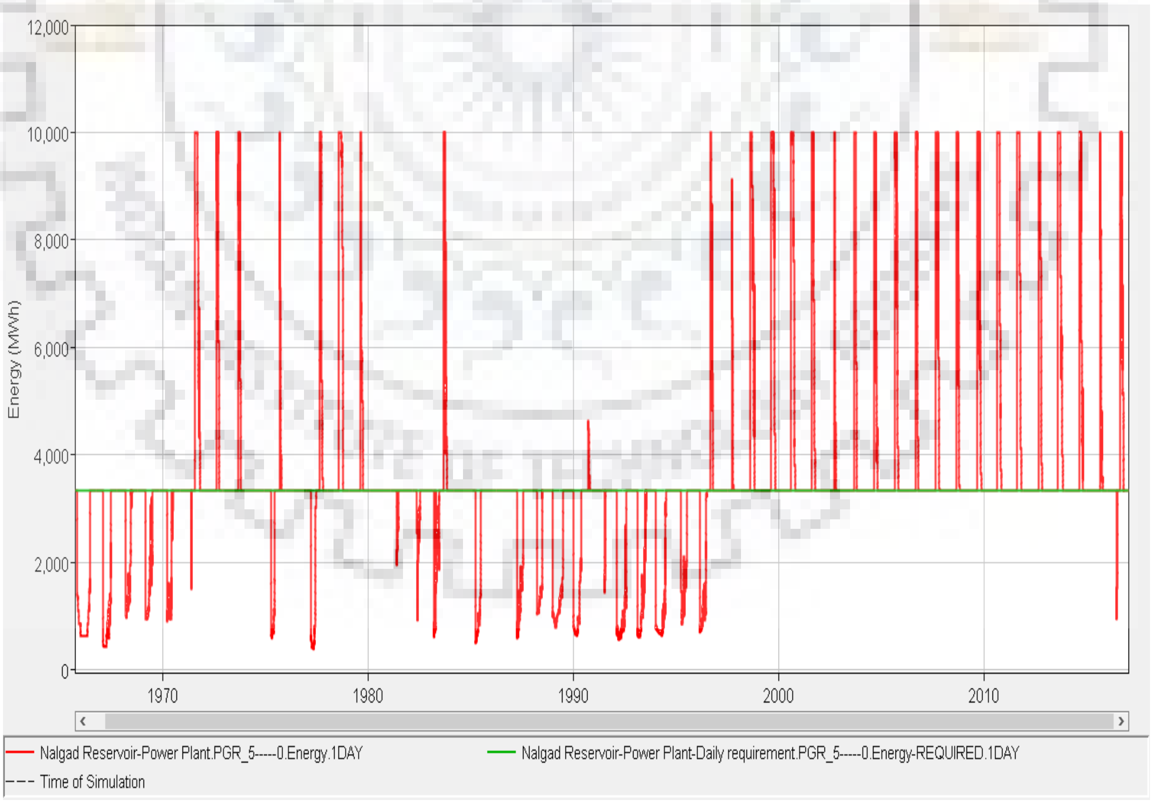


Figure 5. 9: Required and generated energy for selected alternative 4 of scenario 2

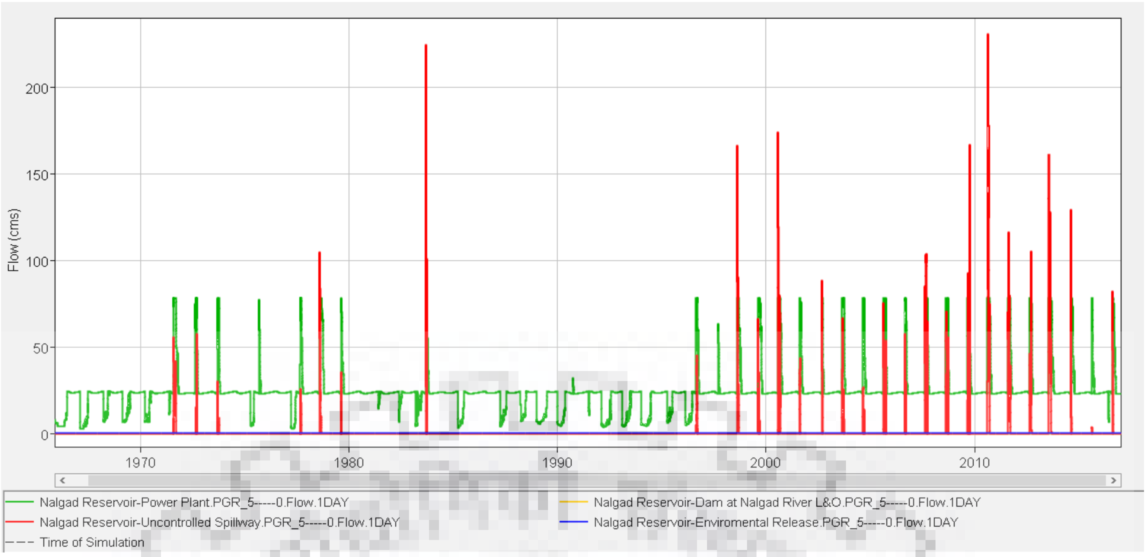


Figure 5. 10: Release from all controlled and uncontrolled outlets for selected alternative 4 of scenario 2

From energy duration curve we can obtain energy generation value corresponding to certain percentage of time. Here in this study energy corresponding to 90% probability (P_p) is considered as primary or firm energy and energy above that value is considered as secondary/spill energy. From figure 5.11 total annual average firm energy and dry season firm energy generation is 886.456 and 314.563 GWh/year respectively when hydropower schedule with energy generation pattern eight hours through out the year without seasonal variation was assigned as operation rule.

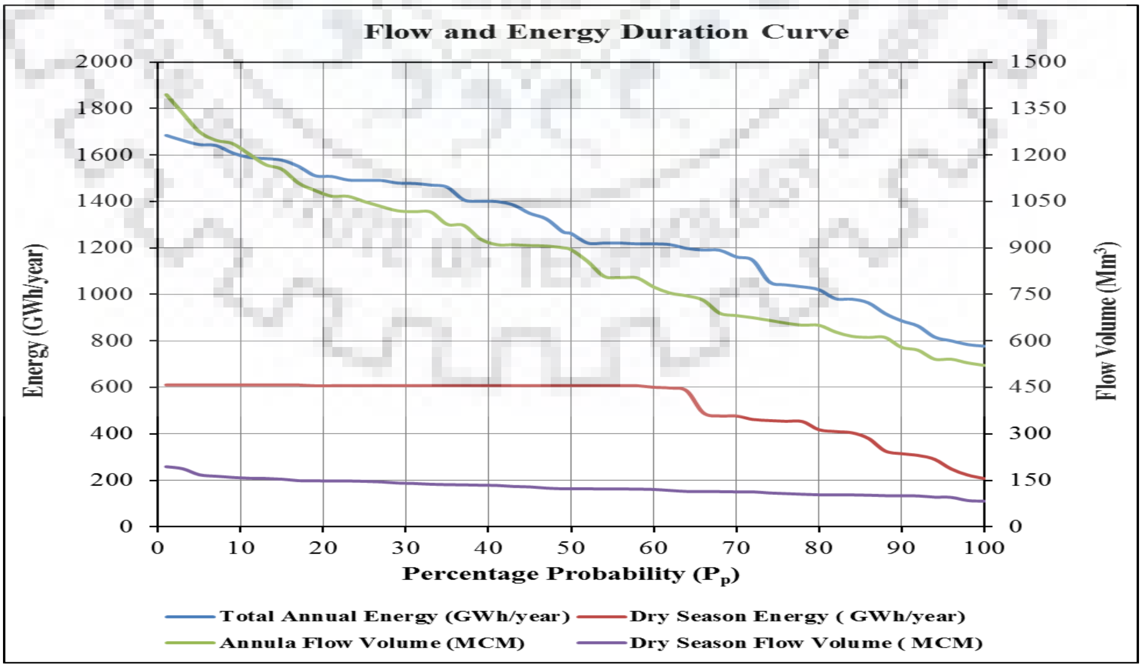


Figure 5. 11: Flow and energy duration curve for selected alternative 4 of scenario 2

5.2.3 Operation Scenario 3

The maximum and minimum target elevation level is assigned to conservation zone at elevation 1580 masl of top of maximum operating level of reservoir and inactive zone at elevation 1498 masl of top of minimum operating level of reservoir respectively and flood control zone is set at elevation 1589 masl. This operation scenario includes seven different generation pattern with seasonal and hourly variation in energy requirement. The power guide rule curve used here is hydropower schedule rule the amount of the daily energy requirement varies with season as dry season (Jan, Feb, Mar, Apr, May & Dec) and wet season (Jun, Jul, Aug, Sep, Oct & Nov). As daily time step was assigned for simulation in this scenario HEC-ResSim try to meet the total daily energy requirement. This scenario result gives the operation policy for maximum total annual energy generation, optimum dry season energy generation with 90 % reliability and reservoir level as in figure 5.12. Details of simulation result obtained from selected alternative 3 of this scenario shown in table 5.5 and summary of result of each alternative presented in table 5.6.

Table 5. 5 : Summary report of HEC- ResSim for reservoir simulation of selected alternate 3 of operation Scenario 3.

Month	Daily Energy Requirement (MWh/ Day)	Equivalent Operation Hours	Location/Parameter	Summary Output		
				Avg.	Max.	Min.
ALTERNATE 3						
Jan	4587	11	Reservoir Summary Report			
Feb	4587	11	Storage (Mm^3)	321.093	486.008	123.8
Mar	4587	11	Elevation (m)	1547.59	1581.9	1498
Apr	4587	11	Controlled Release (m^3/s)	24.28	69.77	2.97
May	4587	11	Uncontrolled Spill (m^3/s)	2.5	297	0
Jun	417	1	Power Summary Report			
Jul	417	1	Generation Efficiency	0.88	0.88	0.88
Aug	417	1	Power Head (m)	662.29	696.49	614.7
Sep	417	1	Hydraulic Losses (m)	17.7	17.81	15.7
Oct	417	1	Energy Generated Per Time Step (MWh)	3424.32	10008	393.6
Nov	417	1	Power Generated (MW)	142.68	417	16.4

Dec	4587	11	Plant Factor	0.34	1	0.03
Total	**30024**	**72**	Flow Power (m^3/s)	24.28	69.77	2.97
	Dry Season Energy Generated (GWh/year)			**742.727**		
	Wet Season Energy Generated (GWh/year)			**508.023**		
	Total Annual Energy Generated (GWh/year)			**1250.75**		
	Annual Energy Generation Reliability (%)			**92.67**		

Table 5. 6: Comparison of various competitive alternatives of scenario 3

Parameters		**Alternatives**						
Alternate		**1**	**2**	**3**	**4**	**5**	**6**	**7**
Daily total Energy Requirement (MWh/day)	Dry	4170	4170	**4587**	4587	5004	3753	3336
	Wet	417	1668	**417**	1251	417	2502	2919
Equivalent Operation Hour	Dry	10	10	**11**	11	12	9	8
	Wet	1	4	**1**	3	1	6	7
Energy Generated per Time Step (MWh)		3417.84	3459.36	**3424.32**	3452.4	3422.88	3466.32	3453.6
Dry Season Energy Generated (GWh/year)		731.917	699.167	**742.727**	726.036	743.021	617.286	552.522
Wet Season Energy Generated (GWh/year)		516.414	564.394	**508.023**	534.973	507.231	648.642	708.845
Total Annual Energy Generated (GWh/year)		1248.33	1263.56	**1250.75**	1261.009	1250.25	1265.93	1261.37
Annual Energy Generation Reliability (%)		97.8	92.42	**92.67**	90.47	88.07	90.81	91.1
Remarks				**Selected**				

From the results of this operation scenario, the maximum total annual energy generation is 1265.93 GWh/year when hydropower schedule rule with generation pattern nine-hour operation during dry season and six-hour operation in wet season is assigned. But as per the study objective maximum dry season energy generation is 742.727 GWh/year with 92.67 % reliability of total annual energy generation when the power plant operated/run for eleven hours during dry season and one hour during wet season. Hence from this scenario hydropower schedule rule with energy generation pattern as eleven-hour operation during dry season and one-hour operation during wet season is selected as best operation policy/rule to generate maximum dry season energy. Application of this operation rule resulting almost uniform reservoir level throughout the simulation period however the energy violation is much during dry as well as even in wet year also that's why it is necessary to consider reliability for dry season only because wet season energy requirement is meet out in all historical years and which is not much important for this project. The graphical representation of results of simulation of selected alternative 3 of this scenario are shown in figure 5.12 to 5.17

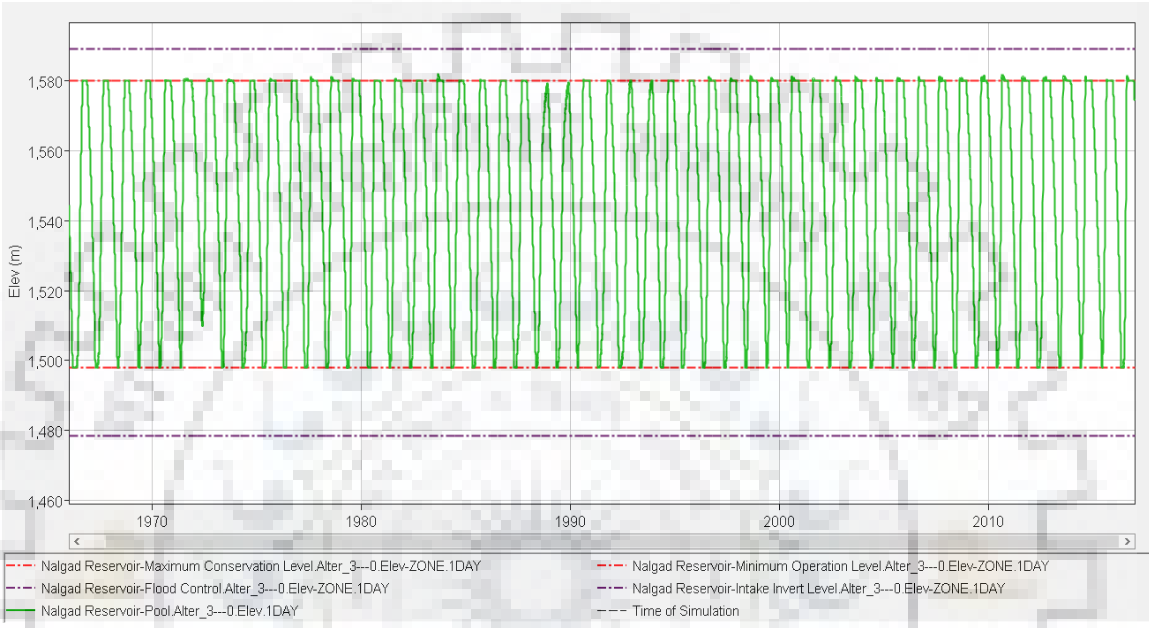


Figure 5. 12: Reservoir elevation for selected alternative 3 of scenario 3

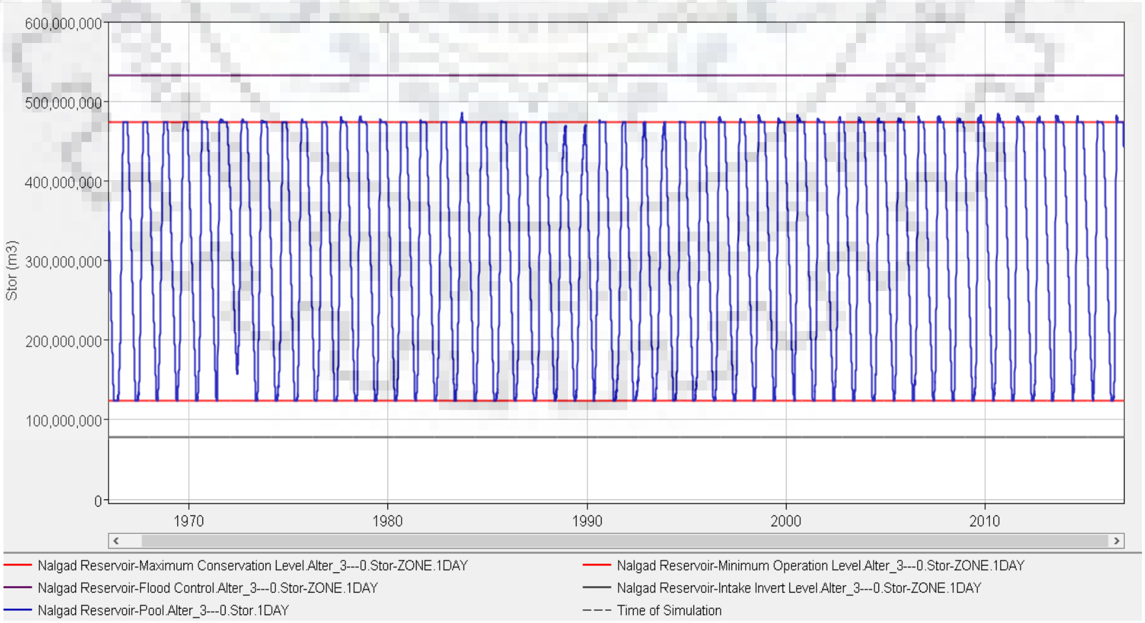


Figure 5. 13: Reservoir storage for selected alternative 3 of scenario 3

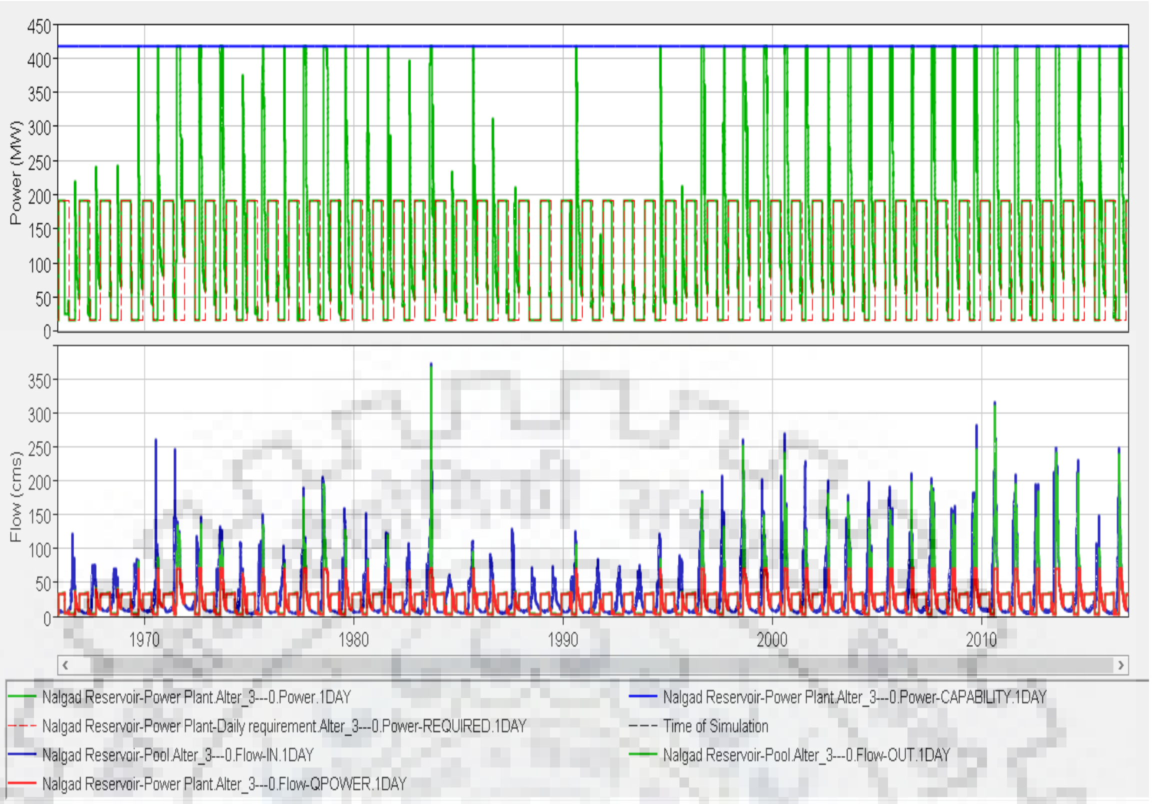


Figure 5. 14: Power generations, inflows and outflows for alternative 3 of scenario 3

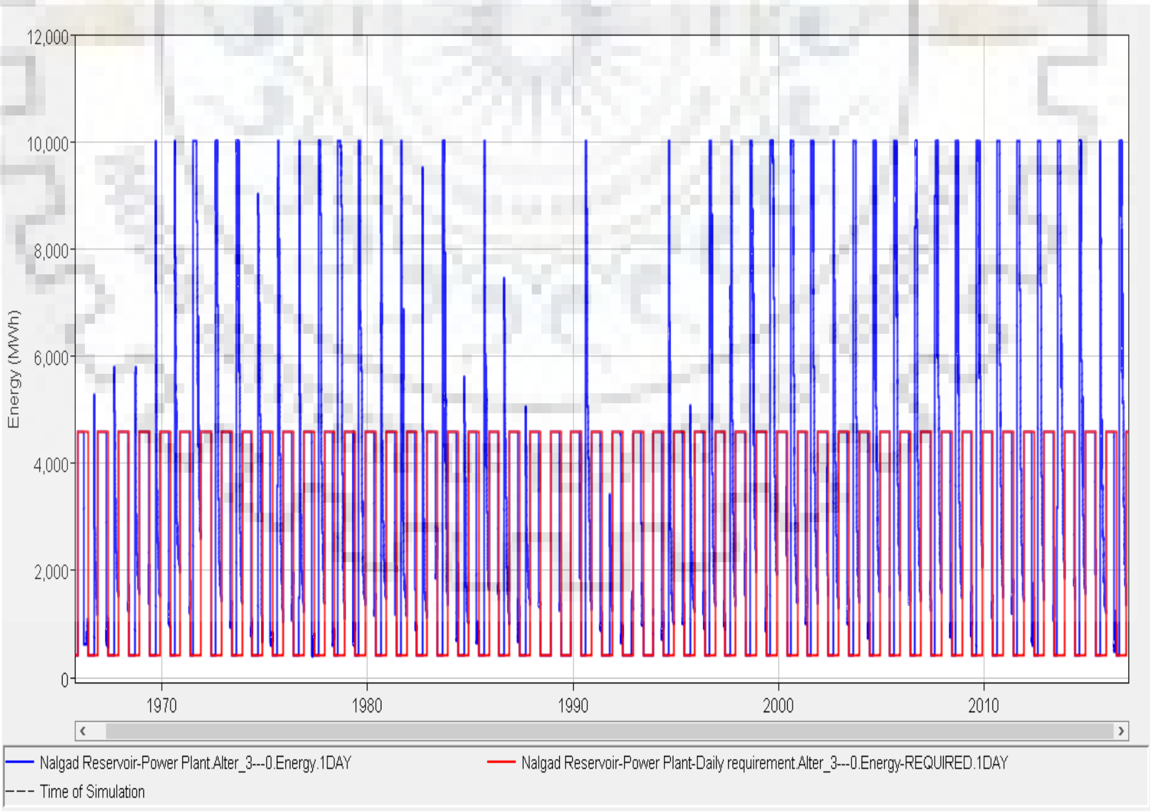


Figure 5. 15: Required and generated energy for selected alternative 3 of scenario 3

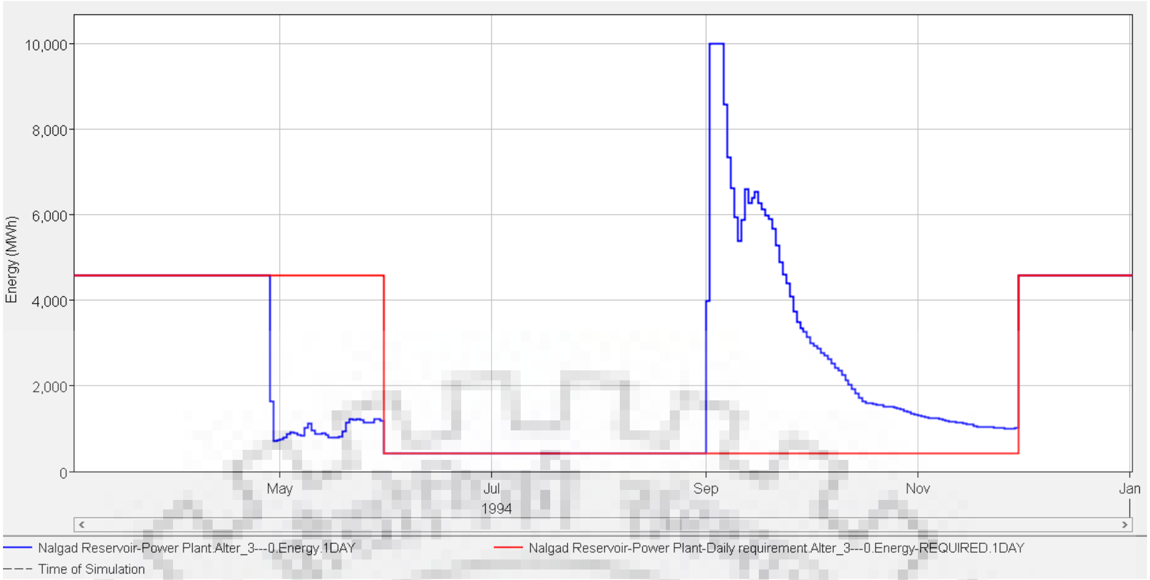


Figure 5. 16: Zoomed view of energy requirement and generation for selected alternative 3 of scenario 3

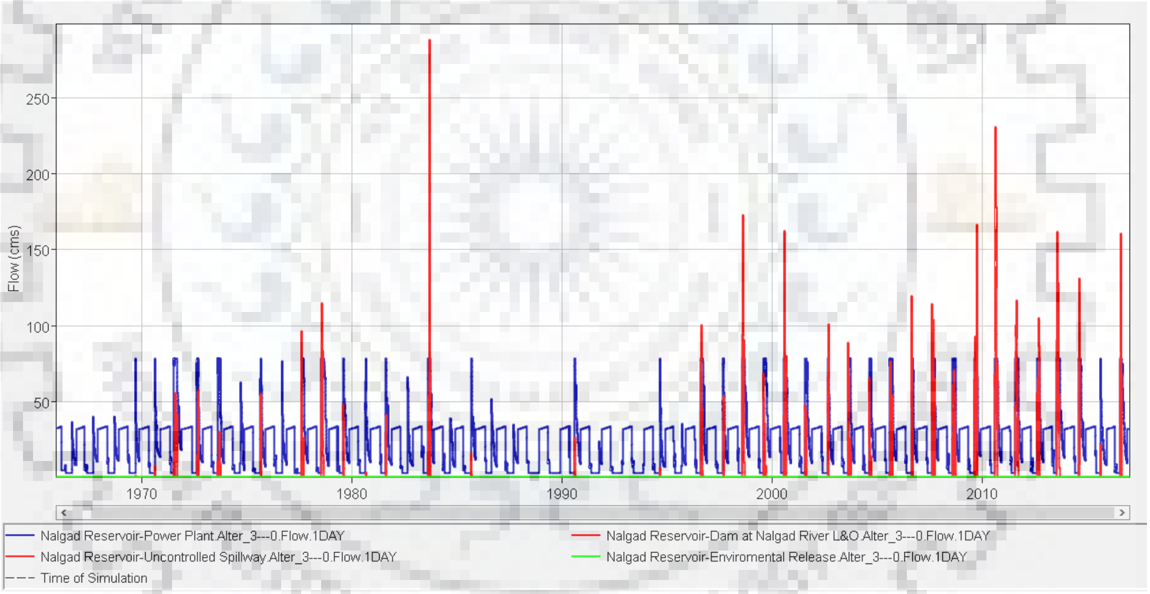


Figure 5. 17: Release from all controlled and uncontrolled outlets for selected alternative 3 of scenario 3

From energy duration curve we can obtain energy generation value corresponding to certain percentage of time. Here in this study energy corresponding to 90% probability (P_p) is considered as primary or firm energy and energy above that value is considered as secondary/spill energy. From figure 5.18 total annual average firm energy and dry season firm energy generation is 883.532 and 696.355 GWh/year respectively when hydropower schedule with energy generation pattern eleven hours during dry season and one hour during wet season with seasonal variation was assigned as operation rule.

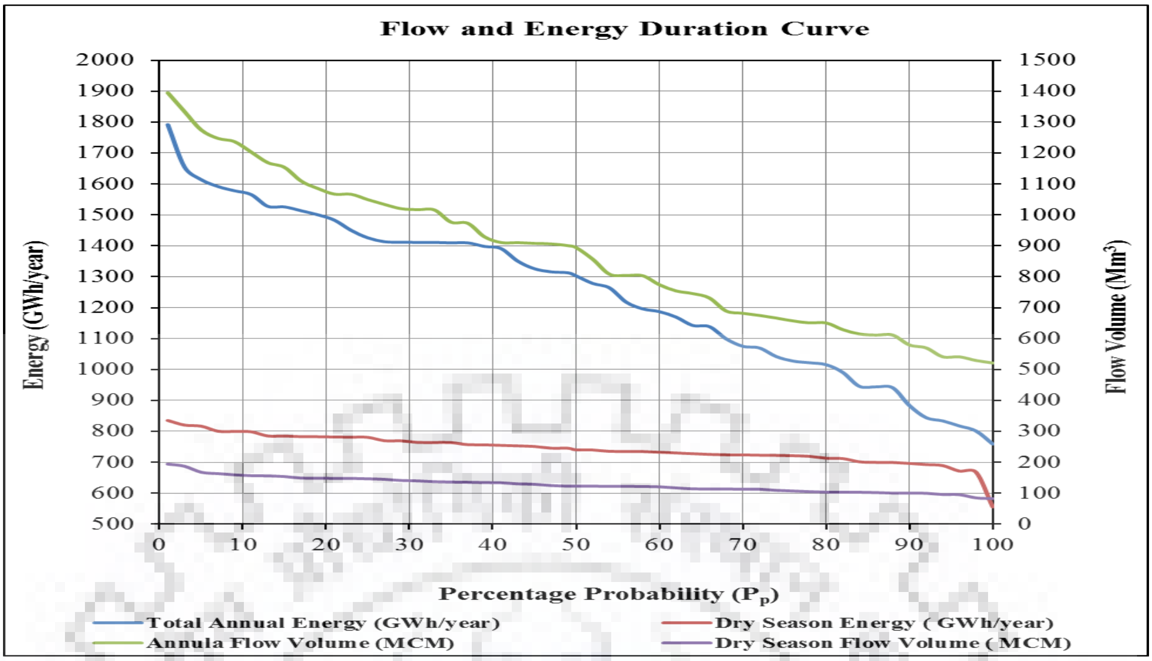


Figure 5. 18: Flow and energy duration curve for selected alternative 3 of scenario 3

5.2.4 Operation Scenario 4

The maximum and minimum target elevation levels are assigned to conservation zone at elevation 1580 masl of top of maximum operating level of reservoir and inactive zone at elevation 1478.5 masl of invert level of intake respectively and top of flood control zone is set at elevation 1589 masl. Here inactive zone is not defined in operation but it is taken as defined in physical parameter i.e. minimum drawdown level is now 1478.5 masl. In this operation scenario seasonal variation is considered, for that the whole year is divided in to two season as dry season (Jan, Feb, Mar, Apr, May & Dec) and wet season (Jun, Jul, Aug, Sep, Oct, Nov) according to inflow availability. The hydropower schedule rule used here is different monthly energy requirement generation pattern and the power generation is based on the seasonal variation of total monthly energy requirement pattern defined in hydropower schedule rule for each season. In this scenario HEC-ResSim try to meet monthly energy requirement as well as hourly energy requirement as defined in generation pattern. It is further analysed by summing and annualizing the generated energy and calculates dry season energy, wet season energy & the total energy generation in GWh/year and best alternative is selected based on the maximum total annual energy generation (GWh/year), maximum annual dry season energy (MWh/year) energy generation with reliability above 90%. Details of simulation result obtained from selected alternative 3 of this scenario shown in table 5.7 and summary of result of each alternative shown in table 5.8

Table 5. 7: Summary report of HEC- ResSim for reservoir simulation of selected alternate 3 of operation scenario 4.

Operating Option	**Altr_3**		
Maximum Operating Level (FSL)	1580 m		
Minimum Operating Level (MOL)	1478.5 m (Intake Invert Level)		
Operation Zone	Flood	Conservation	Inactive
	1589 m	1580 m	1478.5 m
Generation Pattern (Operation Hours)	Dry Season		Wet Season
	10		1
Output Summary From HEC-ResSim			
Location/Parameters	Summary Output		
	Average	Maximum	Minimum
Reservoir Summary Report			
Storage (Mm^3)	328.544	487.861	80.369
Elevation (m)	1549.43	1582.2	1479.7
Controlled Release (m^3/s)	24.26	74.98	0
Uncontrolled Spill (m^3/s)	2.52	371.9	0
Power Summary Report			
Generation Efficiency	0.88	0.88	0.88
Power Head (m)	664.09	696.79	594.48
Hydraulic Losses (m)	17.74	17.81	17.62
Energy Generated per Time Step (MWh)	142.62	417	0
Power Generated (MW)	142.62	417	0
Plant Factor	0.34	1	0
Flow Power (m^3/s)	24.26	74.98	0
Other parameters calculated as			
Parameters	Energy (GWh/year)	Rate(NRS/ KWh)	Value in Million (NRS)
Plant Capacity Factor Total Energy (%)	34.2		
Plant Capacity Factor Target Energy (%)	22.86		
Dry Season Target Energy (GWh/year)	758.94		
Wet Season Target Energy (GWh/year)	76.3	7.1	541.73
Total Dry Season Energy Generated (GWh/year)	754.14	12.4	9351.29
Total Wet Season Energy Generated (GWh/year)	496.06		
Total Spill Energy (GWh/year)	419.91	2.4	1007.79
Total Annual Energy Generation (GWh/year)	1250.20		10900.81
Reliability	97.38		

Table 5. 8: Comparison of results of different competitive alternatives of scenario 4

Parameter	**Generation Pattern**						
Operation Hours (Dry_Wet)	**9_1**	**9_2**	**10_1**	**10_2**	**10_3**	**10_4**	**11_1**
Energy Generated per Time Step (MWh)	140.9	141.45	**142.62**	143.11	143.68	144.25	143.74
Plant Capacity Factor Total Energy (%)	33.8	33.9	**34.2**	34.3	34.47	34.61	34.5
Plant Capacity Factor Target Energy (%)	20.7	21.13	**22.86**	24.95	27.03	29.13	24.95
Dry Season Target Energy (GWh/year)	683.046	683.046	**758.940**	758.940	758.940	758.940	834.834
Wet Season Target Energy (GWh/year)	76.300	152.622	**76.300**	152.622	228.933	305.244	76.310
Total Dry Season Energy Generated (GWh/year)	681.500	679.752	**754.136**	747.461	735.512	717.145	798.589
Total Wet Season Energy Generated (GWh/year)	553.661	560.192	**496.061**	507.045	523.985	547.331	461.444
Total Spill Energy (GWh/year)	477.378	407.645	**419.914**	354.423	296.691	242.087	385.925
Total Annual Energy Generation (GWh/year)	1235.16	1239.94	**1250.197**	1254.50	1259.49	1264.476	1260.03
Annual Energy Value (Million NRS)	10138.03	10490.87	**10900.81**	11204.32	11457.81	11640.82	11370.5
Dry Season Energy Generation Reliability (%)	99.67	99.01	**97.38**	94.11	92.15	89.21	85.94
Remarks			**Selected**				

From table 5.8 it is observed that the optimum dry season energy generation is 754.136 GWh/year with 97.38% reliability and total annual energy generation is 1250.197 GWh/year when the hydropower schedule rule with generation pattern as ten hour operation during dry season and one hour operation during wet season was assigned. Hence from this scenario hydropower schedule rule with energy generation pattern as ten hour operation during dry season and one hour operation during wet season is selected as best operation policy/rule to generate maximum dry season energy. But reservoir minimum drawdown level 1478.5 masl, physically defined here which is not practical because we have to maintain minimum certain dead storage above intake invert level to accommodate some portion of sediment that's why operation scenario 5 is considered to address this case. The graphical representation of simulation results of selected alternative 3 of this scenario are shown in figure 5.19 to 5.24.

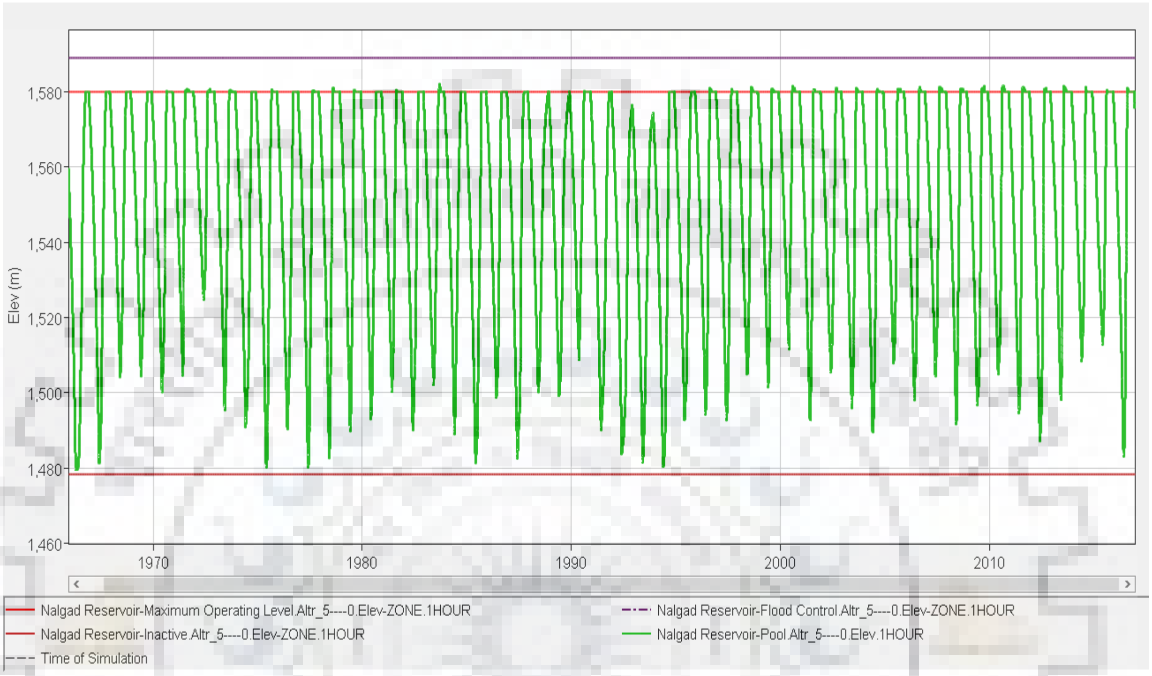


Figure 5. 19: Reservoir elevation for selected alternative 3 of scenario 4

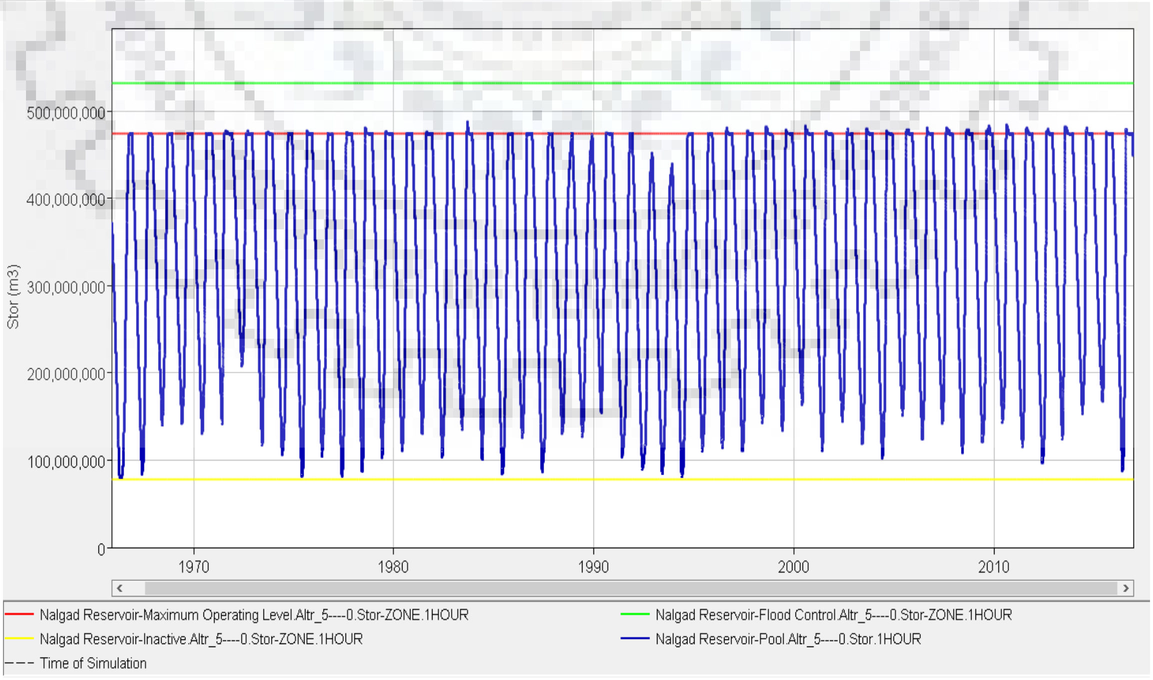


Figure 5. 20: Reservoir storage for selected alternative 3 of scenario 4

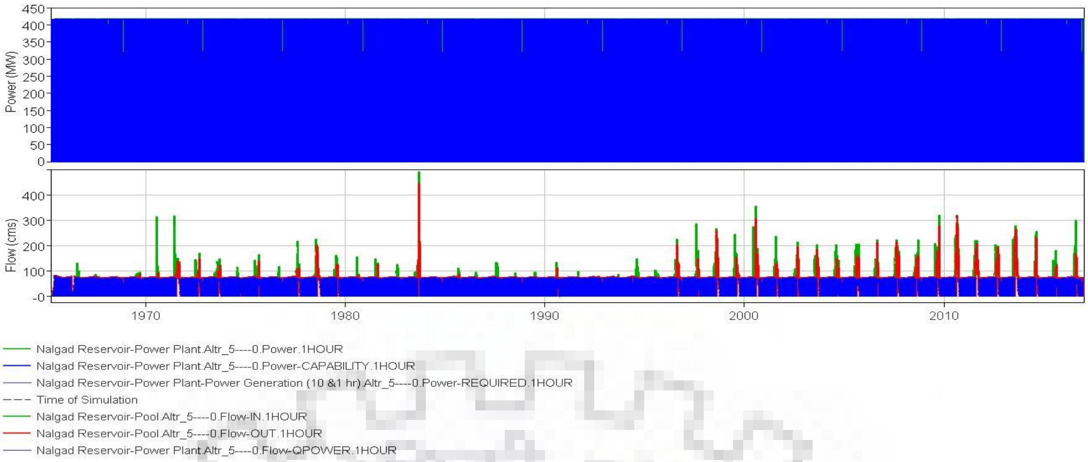


Figure 5. 21: Power generations, inflows and outflows for alternative 3 of scenario 4

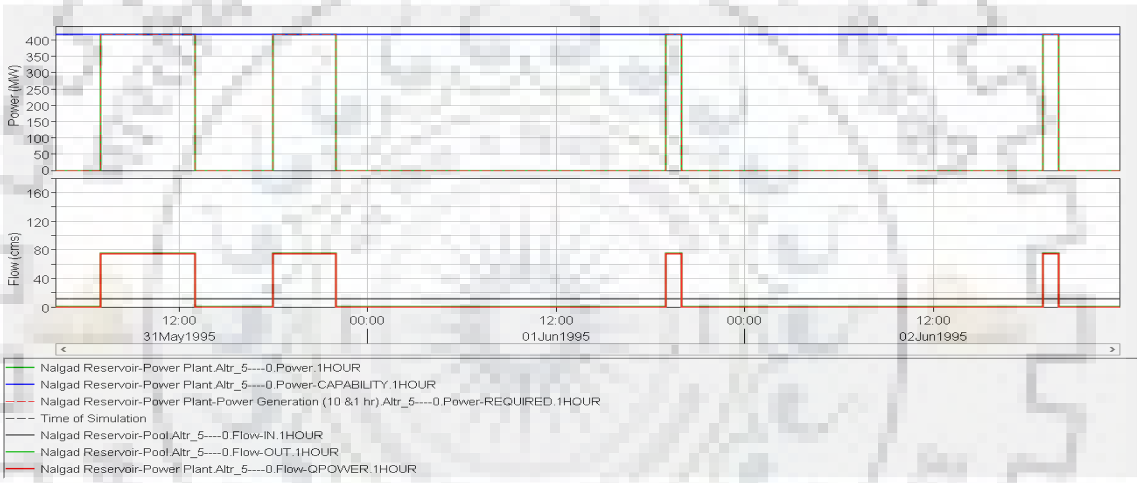


Figure 5. 22: Zoomed view of power generations, inflows and outflows for alternative 3 of scenario 4

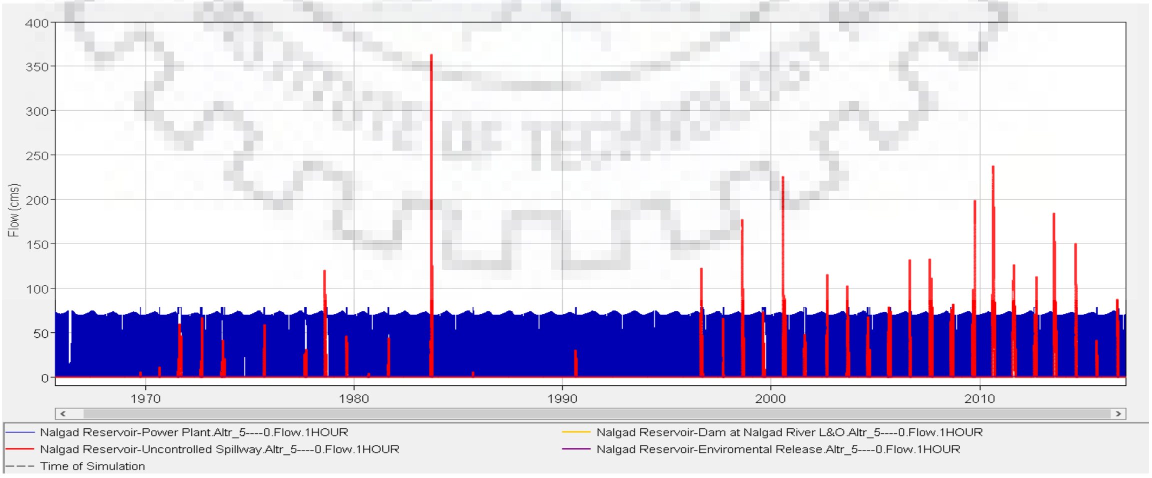


Figure 5. 23: Release from all controlled and uncontrolled outlets for selected alternative 3 of scenario 4

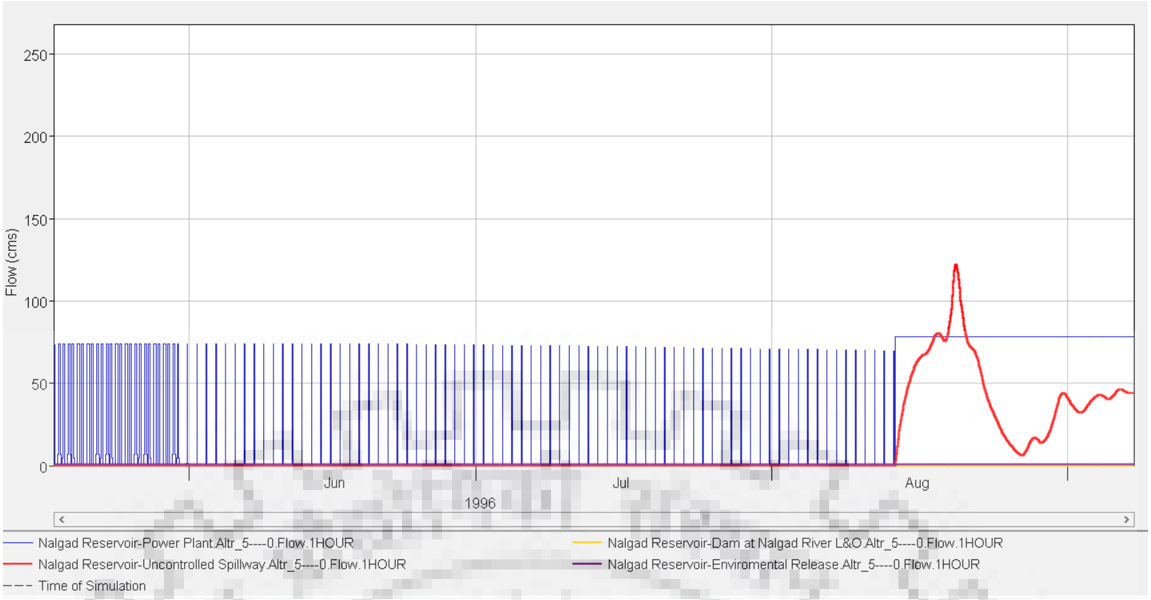


Figure 5. 24: Zoomed view of release from all controlled and uncontrolled outlets for selected alternative 3 of scenario 4

From energy duration curve we can obtain energy generation value corresponding to certain percentage of time. Here in this study energy corresponding to 90% probability (P_p) is considered as primary or firm energy and energy above that value is considered as secondary/spill energy. From figure 5.25 total annual average firm energy and dry season firm energy generation is 882.332 and 754.77 GWh/year respectively when hydropower schedule with energy generation pattern ten hours operation during dry season and one hour operation during wet season was assigned as operation rule.

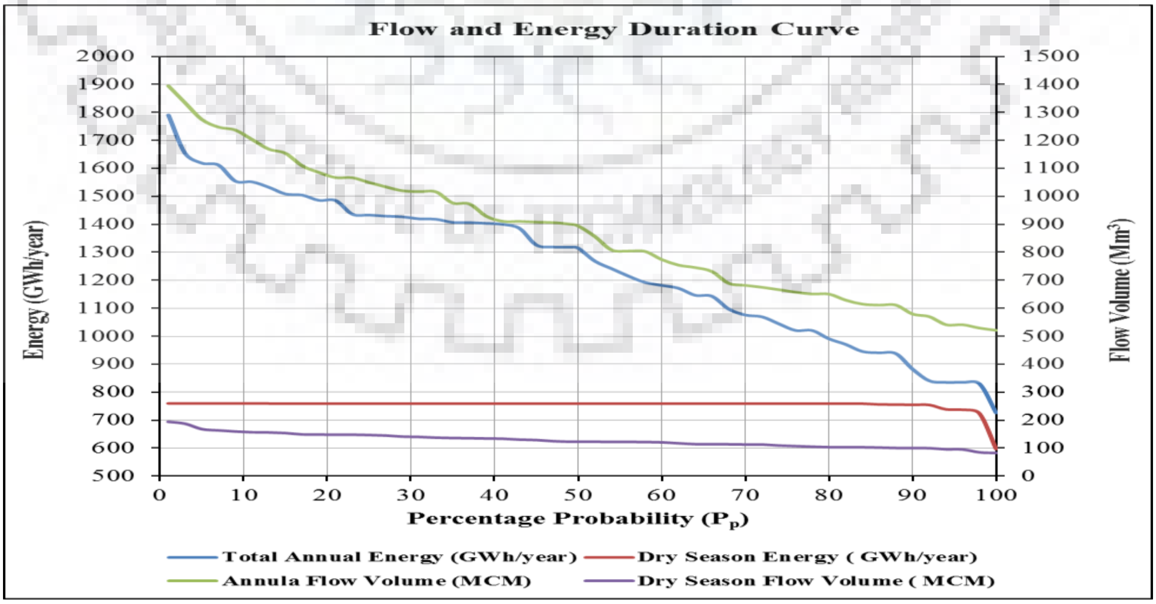


Figure 5. 25: Flow and energy duration curve for selected alternative 3 of scenario 4

5.2.5 Operation Scenario 5

The maximum and minimum target elevation levels are assigned to conservation zone at elevation 1580 masl of top of maximum operating level of reservoir and inactive zone at elevation 1498 masl top of minimum operating level respectively and top of flood control zone is set at 1589 masl. In this operation scenario seasonal variation is considered, for that whole year is divided in to two season as dry season (Jan, Feb, Mar, Apr, May & Dec) and wet season (Jun, Jul, Aug, Sep, Oct, Nov) according to inflow availability. This operation scenario includes seven alternatives for different generation pattern with seasonal and hourly variation in energy requirement. The power guide rule curve used here is hydropower schedule rule with seasonal and hourly variation in generation pattern. Hourly time step was assigned for simulation so that the HEC-ResSim distribute defined monthly total energy requirement in to each operation hours defined in hourly generation pattern. Hourly generation pattern is defined by putting 1 for operation hour and 0 for non-operation hour that means value 1 represent open gate to release water required to generate target energy and 0 represent close the gate no release.

It is further analysed by summing and annualising the generated energy and calculates dry season energy, wet season energy & the total energy generation in GWh/year and best alternative is selected based on the maximum annual dry season energy generation (MWh/year) with reliability above 90%. From this operation scenario we can select best operation policy to generate optimum dry season energy with reliability above 90% and to maintain certain target reservoir levels between minimum and maximum operating level throughout the year. Details of simulation result obtained for selected alternative 3 of this scenario shown in table 5.9 and summary of result of each alternative shown in table 5.10.

Table 5. 9: Summary report of HEC- ResSim for reservoir simulation of selected alternate 3 of operation scenario 5.

Operation Set	**Option_3**		
Maximum Operating Level (FSL)	1580 m		
Minimum Operating Level (MOL)	1498 m		
Operation Zone	Flood	Conservation	Inactive
	1589 m	1580 m	1489 m
Generation Pattern	Dry Season		Wet Season
	10		1
Output Summary From HEC-ResSim			
Location/Parameter	Summary Output		
	Average	Maximum	Minimum
Reservoir Summary Report			
Storage (Mm^3)	333.42	487.861	123.8
Elevation (m)	1550.83	1582.2	1498
Controlled Release (m^3/s)	24.18	74.06	0
Uncontrolled Spill (m^3/s)	2.62	371.9	0
Power Summary Report			
Generation Efficiency	0.88	0.88	0.88
Power Head (m)	665.5	696.79	612.83
Hydraulic Losses (m)	17.73	17.81	17.57
Energy Generated per Time Step (MWh)	142.34	417	0
Power Generated (MW)	142.34	417	0
Plant Factor	0.341	1	0
Flow Power (m^3/s)	24.18	74.06	0
Other Parameters Calculated			
Parameter	Energy (GWh/ year)	Rate(NRS/ KWh)	Value in Million (NRS)
Plant Capacity Factor Total Energy (%)	34.1		
Plant Capacity Factor Target Energy (%)	22.86		
Dry Season Target Energy (GWh/year)	758.94		
Wet Season Target Energy (GWh/year)	76.3	7.1	541.8
Total Dry Season Energy Generated (GWh/year)	735.04	12.4	9114.5
Total Wet Season Energy Generated (GWh/year)	512.68		
Total Spill Energy (GWh/year)	436.37	2.4	1047.29
Total Annual Energy Generated (GWh/year)	1247.72		10703.59
Reliability	90.19		

Table 5.10: Comparison of results of different competitive alternatives of scenario5

Parameter	Alternatives				
	1	2	3	4	5
Operation Hours (Dry_Wet)	**9_4**	**9_5**	**10_1**	**10_2**	**11_1**
Energy Generated per Time Step (MWh)	142.72	143.38	**142.34**	142.88	142.62
Plant Capacity Factor Total Energy (%)	34.24	34.38	**34.1**	34.2	34.2
Plant Capacity Factor Target Energy (%)	27.05	29.14	**22.86**	24.95	24.95
Dry Season Target Energy (GWh/year)	683.046	683.046	**758.94**	758.94	834.834
Wet Season Target Energy (GWh/year)	305.244	381.555	**76.31**	152.622	76.311
Total Dry Season Energy Generated (GWh/year)	660.454	640.184	**735.04**	728.8	746.202
Total Wet Season Energy Generated (GWh/year)	590.661	615.862	**512.68**	523.641	503.935
Total Spill Energy (GWh/year)	287.081	239.604	**436.37**	371.019	427.624
Total Annual Energy Generated (GWh/year)	1251.12	1256.05	**1247.72**	1252.44	1250.14
Annual Energy Value (Million NRS)	11045.85	11222.35	**10703.59**	11011.16	10820.98
Average Spill (m^3/s)	2.45	2.23	**2.62**	2.47	2.54
Dry Season Energy Generation Reliability (%)	92.48	87.58	**90.19**	88.56	78.1
Remarks			**Selected**		

Simulation result of this scenario shows that the optimum dry season energy generation is 735.04GWh/year with 90.19% reliability and total annual energy generation is 1247.72 GWh/year when hydropower schedule rule with generation pattern ten hours during dry season and one hour evening peaking in wet season is assigned. Hence from this scenario hydropower schedule rule with energy generation pattern as ten hour operation during dry season and one hour operation during wet season is selected as best operation policy/rule to generate maximum dry season energy. The graphical representation of simulation results of selected alternative 3 of this scenario are shown in figure 5.26 to 5.31.

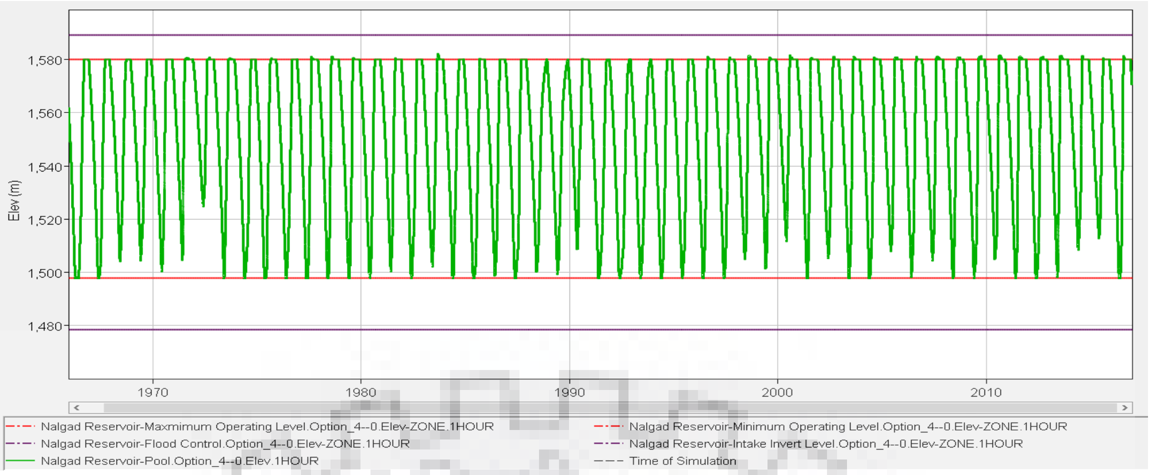


Figure 5. 26: Reservoir elevation for selected alternative 3 of scenario 5

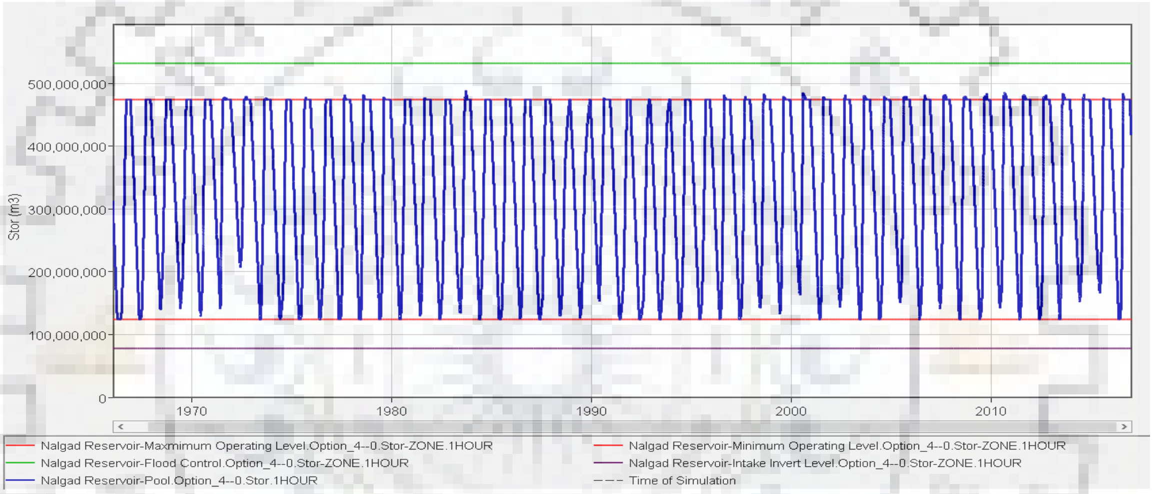


Figure 5. 27: Reservoir storage for selected alternative 3 of scenario 5

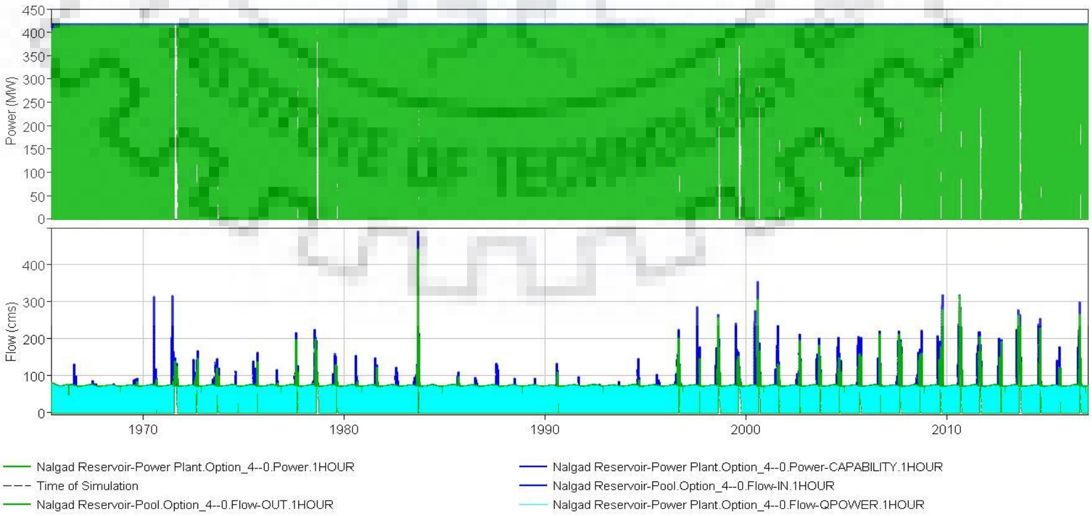


Figure 5. 28: Power generations, inflows and outflows for alternative 3 of scenario 5

Figure 5. 29: Zoomed view of power generations, inflows and outflows for alternative 3 of scenario 5

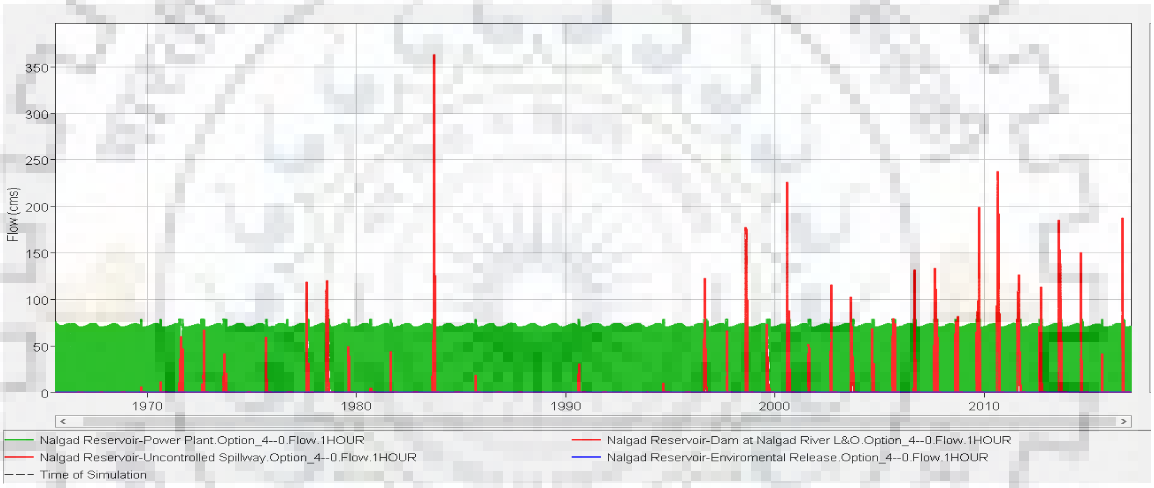


Figure 5. 30: Release from all controlled and uncontrolled outlets for selected alternative 3 of scenario 5

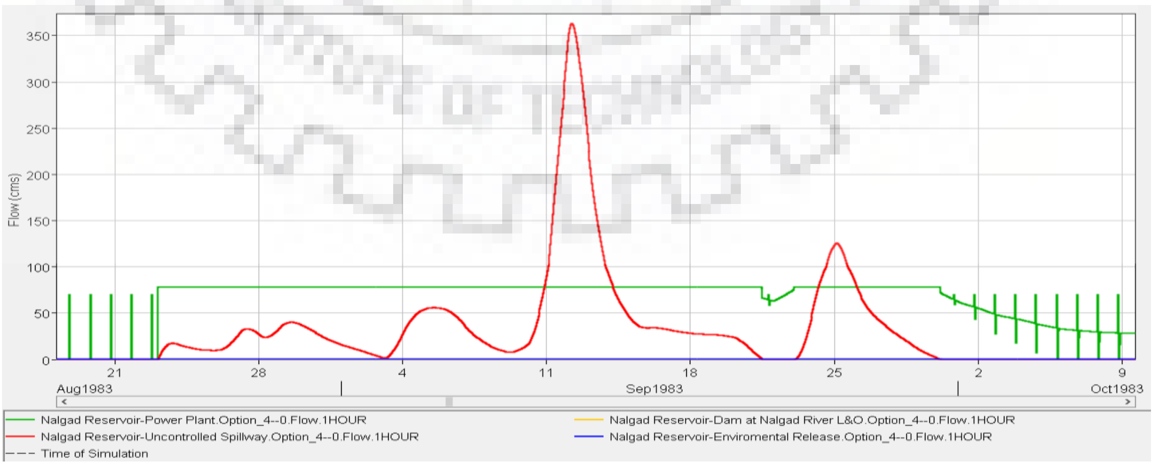


Figure 5. 31: Zoomed view of release from all controlled and uncontrolled outlets for selected alternative 3 of scenario 5

From energy duration curve we can obtain energy generation value corresponding to certain percentage of time.Here in this study energy corresponding to 90% probability (P_p) is considered as primary or firm energy and energy above that value is considered as secondary/spill energy. From figure 5.32 total annual average firm energy and dry season firm energy generation is 882.564 and 698.769 GWh/year respectively when hydropower schedule with energy generation pattern as ten hour operation during dry season and one hour operation during wet season was assigned as operation rule.

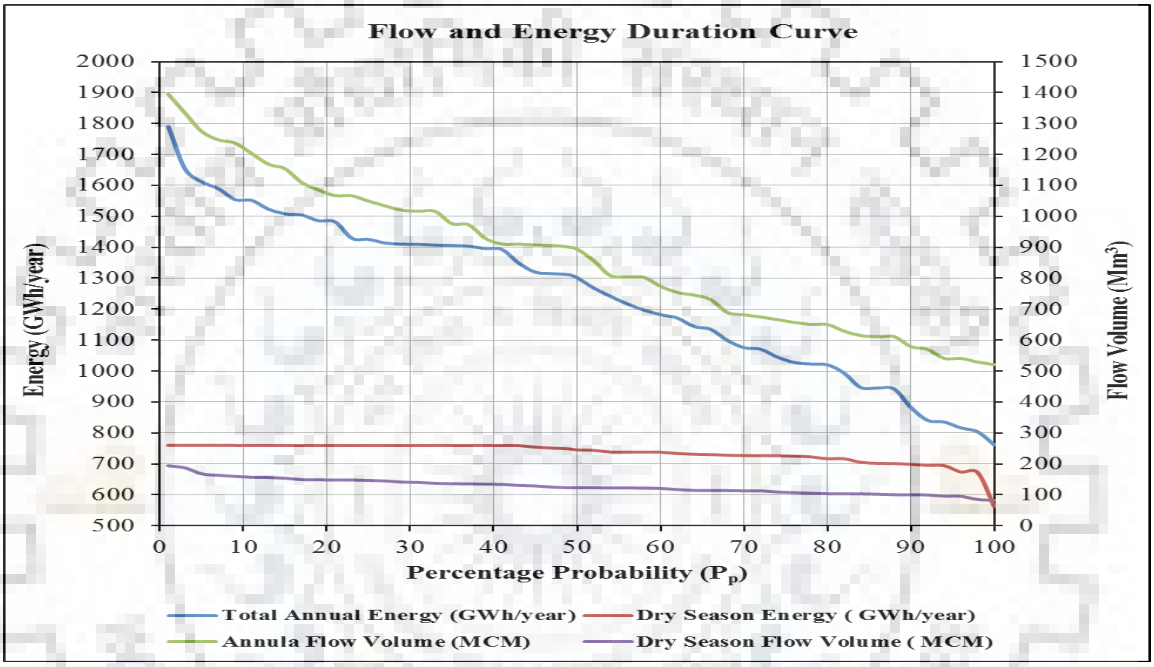


Figure 5. 32: Flow and energy duration curve for selected alternative 3 of scenario 5

5.3 Comparision of Selected Alternatives from Each Operation Scenarios

The summary of results of the best selected alternative from all considered five operation scenarios are summarized in table 5.11. From operation scenario1 it is observed that with the increases in number of turbines units, average energy generation per time step increases. However, the increment is small from three to four turbine units. Hence maximum output from power plant can obtain when four turbine units are in operation. The operation scenario 4 gives maximum dry season energy. However minimum operating level assigned in scenario 4 is equal to elevation of intake invert level 1478.5 masl. The minimum operating level considered in this scenario may not be practical as this MOL can't maintain minimum designed net head for power generation which resulted huge energy violation during dry season of dry year further dead storage from this MOL can't accommodate sufficient quantity of sediment which may causes huge reduction in energy generation after some years. Due to these reason the second option i.e. operation scenario 3 is preferred as it has second highest dry season energy generation. But in scenario 3 simulation time step is daily, that means HEC-ResSim try to meet daily energy requirement due to that power plant is not run in its full installed capacity during most of the hour of simulation period. So that the alternate selected from operation scenario 3 is also may not practical for operation of power plant. Hence to address all above mentioned practical problem obviously we have to go to selected alternative of scenario 5 which has dry season and annual average energy generation nearly equal to that in case of scenario 4 and scenario 3. As simulation time step is hourly, HEC-ResSim try to meet hourly energy requirement due to that power plant is run in its full installed capacity during all operation hour except available storage is less than required release. And MOL assigned in scenario5, 1498 masl is sufficient and practical as designed net head is maintained and most of sediment volume is accommodated with in the dead storage below MOL 1498 masl.

Table 5. 11: Comparison of selected alternatives from all five considered scenarios

Operation Scenarios		**1**	**2**	**3**	**4**	**5**
Operation Hours in season	Dry	24	8	11	10	**10**
	Wet	24	8	1	1	**1**
Simulation Time step		Daily	Daily	Daily	Hourly	**Hourly**
Number of turbine units in operation		4	4	4	4	**4**
Operating Zones (Elevation in m)	Max.	1580	1580	1580	1580	**1580**
	Min.	1498	1498	1498	1478.5	**1498**
Total Dry Season Energy Generated (GWh/year)		Selection of turbine unit based on max. avg. energy generation per time step	515.088	742.727	754.136	**735.04**
Total Wet Season Energy Generated (GWh/year)			733.911	508.023	496.061	**512.68**
Total Annual Season Energy Generated (GWh/year)			1248.999	1250.75	1250.2	**1247.72**
Spill (m^3/s)	Avg.		1.04	2.5	2.52	**2.62**
	Max.		211	297	371.9	**371.9**

From above discussion maximum dry season energy generated by utilizing the available water efficiently throughout the simulation period when operation rule/ policy used as in selected alternative of scenario 5. Hence the developed operation policy/rule for maximum dry season energy generation from Nalgad Hydropower Project is summarised as in table 5.12.

Table 5. 12: Developed reservoir operation rule/ policy

Power Guide Curve	Hydropower schedule rule
Generation Pattern	Dry season: 10 hours operation Wet Season: 1 hours operation
Flood control zone	1589 masl
Hydropower conservation Zone	1580 masl
Inactive Zone	1498 masl
Number of turbine units in operation	4 nos. (104.25 MW each)
Maximum release through turbine	78.4 m^3/s

The reservoir release rules for each time step are given below:

- Leakage and evaporation accounted for with first priority
- Environmental releases are made with second priority
- Release to generate in accordance with Hydropower Schedule Rule is made with third priority
- If the resulting end of day reservoir content would result in spill, the power plant is used to release water and generate secondary/Spill energy
- Lastly, spill is made to maintain the end of day reservoir content no greater than the reservoir volume corresponding to the FSL.

Application of the above operational rules results in a reservoir operational guide rule curve. Developed guide rule curve for each simulation years and for various dependable historical years are indicated in figure 5.33 and 5.34.

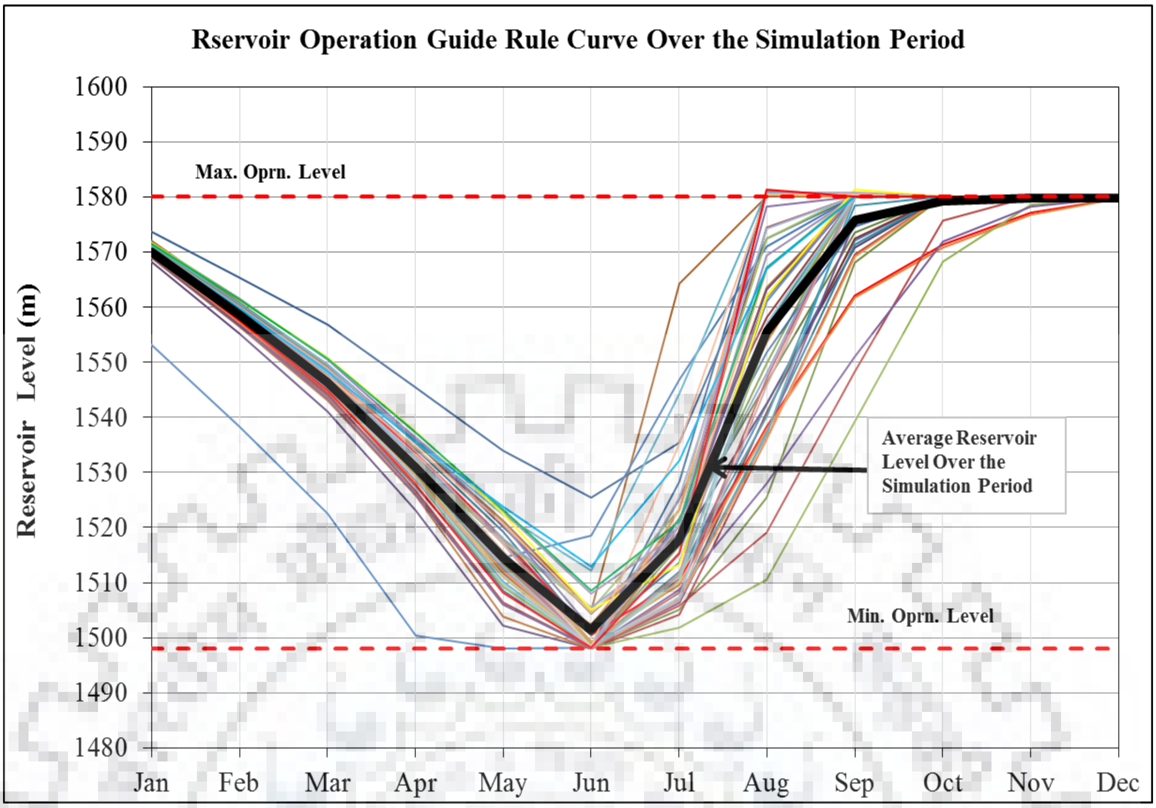


Figure 5. 33: Reservoir level over the simulation period

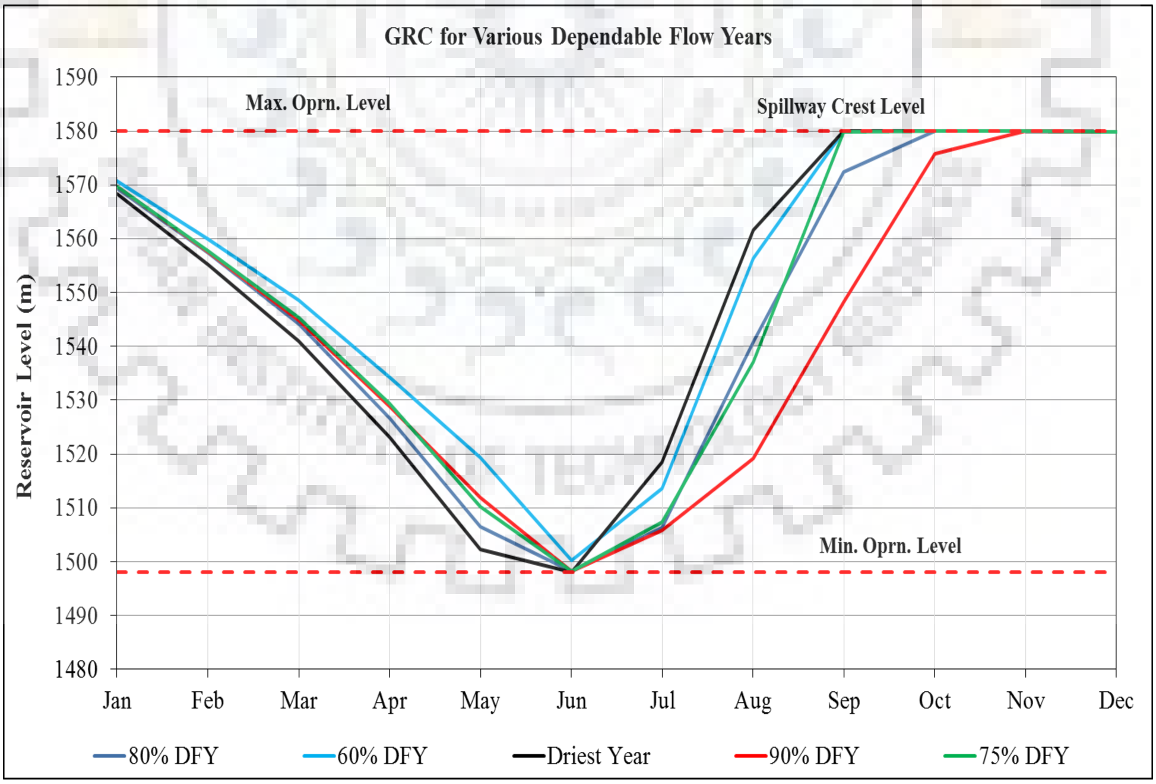


Figure 5. 34: Reservoir level in first day of each month for various dependable flow years.

5.4 Evaluation of Selected Operation Policy/Rule

As this project is at study phase we cant check the feasibility of developed operation rule in real field. when system output is unable to meet the specified target demand, then the unsatisfactory condition will occurs in the reservoir system that serve the puropse of hydropower demand. Various performance measure such as Realiability, Resiliency and Sustanability Index etc. are used to check the performance of developed operation policy. Among these realibility is most important performance parameter as it is simple and easy to understand.

To check the performance of developed operation rule find the critical historical years bsed on availabilty of water then check the reliability during such critical year individually. To find the critical water years first developed flow duration curve based on annual flow, lean period flow, monsoon period flow and normal period flow then find out the years corresponding to 100%, 90% and 80% dependable flow years as described in preceding chapter 4. Realibility of different critical years with date of unsatisfactory is shown in table 5.13.

Table 5. 13: Realibility during different dependable years with date of unsatisfactory

S.N.	Flow Dependability Condition	Year	Date of Unsatisfactory	Dry Season Energy Deficit (MWh/year)	Dry season Energy Reliability (%)	Remarks
1	100% dependable annual and monsoon flow year	1992	15-31 May	53464.4	91.2	
2	90% dependable annual and monsoon flow year	1991	21-31 May	32186.94	94.5	
3	80% dependable annual flow year	1968	31 May	3753	99.45	
4	100% dependable lean flow year	1975	7-31May	85012.24	86.81	Driest year

5	90% dependable lean flow & 80% dependable monsoon flow year	1987	13-31 May	57965.56	90.11	
6	80% dependable lean flow year	1974	23-31 May	28893.67	95.6	
7	100% dependable flow for normal month	1994	18-31 May	42264.51	92.85	
8	90% dependable flow for normal month	1979	21-31 May	32914.24	93.4	
9	80% dependable flow for normal month	1993	22-31 May	27813.15	94.5	

From table 5.13 it is seen that the unsatisfactory occurs during month of May in all critically dry dependable year. Hence from this study it can be suggest that Integrated Nepal Power System demand can't meet out from Nalgad hydropower project. Hence during the month of May deficit energy managed either from other power plant or from other source of energy and this power plant can operate as per developed guide rule curve during May month for better system performance and better utilization of available reservoir inflow.

Table 5. 14: Comparison of reservoir operation policy for dry, wet and normal years

Years	Operation Hours		Five years average Energy Generation (GWh/year)			Dry Season Energy Reliability (%)	Spill (m^3/s)	
	Dry	Wet	Dry Season	Wet Season	Total Annual		Avg.	Max.
Dry Year (1991-1995)	10	1	723.981	171.918	895.900	93.620	0.02	18.2
Normal Year (1972-1976)	10	3	725.662	506.816	1232.478	94.170	0.60	76.0
Wet Year (2008-2012)	10	8	705.877	884.383	1590.26	90	5.77	246.3

From table 5.14 it is appears that the reservoir operation policy for dry season in all hydrological condition is same but there is significant change in operation policy during wet season in all hydrological conditions. Hence from this analysis it can conclude that the reservoir operation policy developed in this study is best for optimum dry season energy generation through all hydrological condition over the simulation horizon.

5.5 Operation Rule Developed through Optimization Technique

Reservoir operation policy also can be developed by optimization technique. Here optimization problem of single objective function maximization of energy generation is formulated as described in preceding section 4.9.1 and reservoir operation policy was developed to optimize the dry season energy generation for 90% dependable historical year 1991.Comparison of result obtained from optimization and simulation study is presented as in table 5.15 in which it is appears that total annual, dry season energy generation reservoir storage, reservoir level; spill volume and energy reliability obtained from simulation and optimization technique is almost similar. Comparison of results obtained from simulation and optimization technique show that the simulation model is more effective tool for reservoir operation simulation model as it reflect the behavior of real system while optimization technique try to optimize the objective function to maximize the energy generation. Comparison of reservoir storage, levels and monthly energy generation obtained from both methods are presented in figure 5.35 and 5.36 respectively.

Table 5. 15: Comparison of results obtained through simulation and optimization model

Month	Simulated Result			Optimized Result		
	Storage (Mm^3)	Elevation (m)	Energy Generation (MWh/ month)	Storage (Mm^3)	Elevation (m)	Energy Generation (MWh/ month)
Jan	414.312	1569.7	129270	415	1570.0	129265.19
Feb	349.816	1557.6	116760	351.94	1558.4	116759.50
Mar	289.083	1544.8	129270	291.86	1545.5	129268.76
Apr	223.44	1528.8	125100	226.44	1530.4	125088.00
May	164.867	1511.9	97083.06	167.07	1513.8	103573.67
Jun	123.9	1498.2	12510	123.8	1498.0	12498.08
Jul	144.88	1505.8	12927	144.05	1505.4	12934.95
Aug	187.21	1519.2	12927	185.76	1518.5	12530.46
Sep	302.02	1548.3	12510	299.64	1547.4	12061.35
Oct	446.77	1576.0	58916.83	444.23	1575.0	57613.66

Nov	474	1580.0	45822.82	474	1580.0	46646.06
Dec	474	1579.9	129467.32	467.73	1579.0	121569.96
Total Annual Energy (MWh/year)			**882564.03**			**879809.62**
Dry Season Energy (MWh/year)			**726950.38**			**725525.07**
Target Dry Season Annual Energy (MWh/year)			**758940**			**758940**
Dry Season Energy Deficit (MWh/year)			**31989.62**			**33414.92955**
Dry Season Energy Deficit (%)			**4.21**			**4.6**

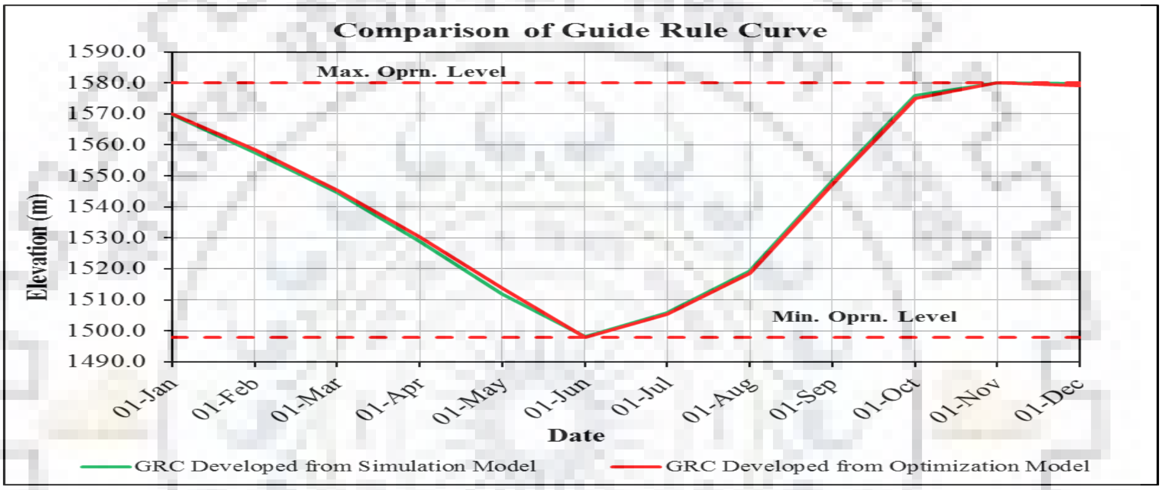


Figure 5. 35: Comparison of reservoir level obtained from simulation and optimization model

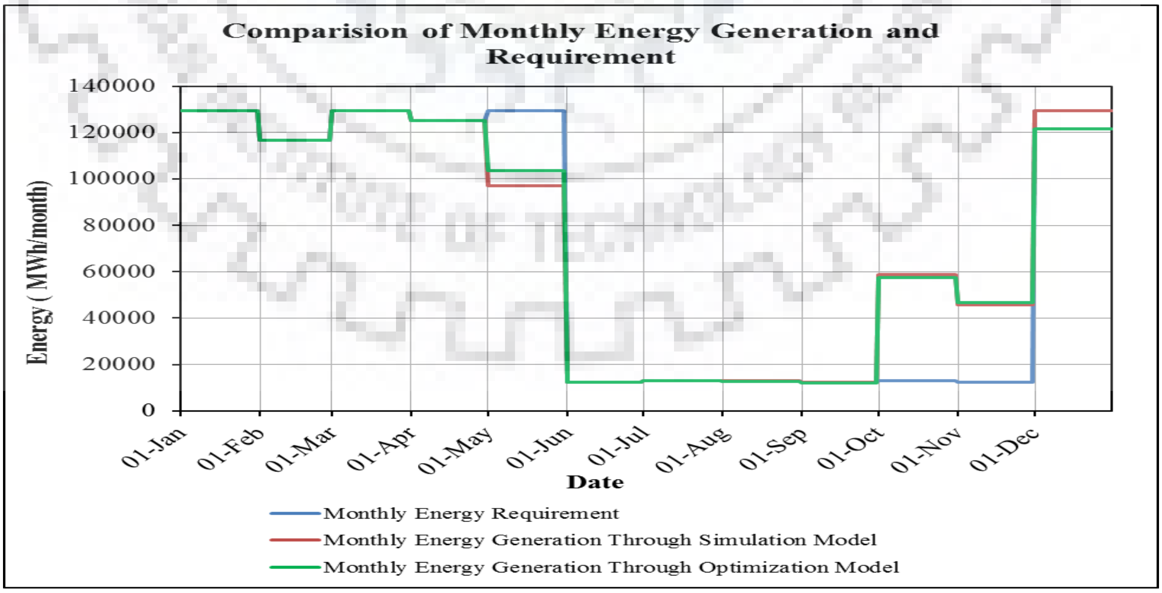


Figure 5. 36: Comparison of monthly energy generation obtained from simulation and optimization model and energy requirement.

5.6 Sensitivity Analysis

Three scenarios are considered here to analyse the sensitivity of energy generation due to change in inflow, environmental release and maximum operating level or full supply level. Operation rule assigned in all scenarios is same as that developed in present scenario of selected alternative 3 of operation scenario 5 above. Result obtained from different alternatives considered in each sensitivity scenarios are compared with the result of selected alternative 3 of operation scenario 5 as original case. This scenario also checks the feasibility of selected operation policy in different future scenarios if happened so. Result obtained from each scenario are analysed and presented as below.

5.6.1 Effect of Change in Inflow

In this scenario inflow data at intake site is increased by 10% and 20% using inflow multiplier as 1.1 and 1.2 and decreased by 10% and 20% using inflow multiplier as 0.9 and 0.8. This scenario aims to evaluate the change in energy generation form Nalgad hydropower project due to change in inflow. Comparison of result of all considered alternative are presented in table 5.16 and percentage change in annual energy generation is shown in figure 5.37. It is observed that there is less effect in dry season energy generation as compared to wet season energy generation. This happens due to fact that the dry season energy generation mainly depends up on controlled release from reservoir storage. However, wet season energy generation composed of both firm energy generation by release through intake (78.4 m^3/s) and spill energey generated by excess inflow to reservoir at maximum reservoir operating level. The firm energy generated for wet season in all cases are simillar. The reduction in dry season energy is about 6% for a 20% decrease in inflow and reduction in dry season energy generation relability is about 10% when inflow decreases by 20%. While incerase in dry season energy generation is about 2.5% and increase in dry season energy generation relability is about 6% when inflow increased by 20%.

Table 5. 16: Comparison of result of considered alternatives for various inflows

Parameters	Inflow Multiplier				
	0.8	**0.9**	**1**	**1.1**	**1.2**
Energy Generated per Time Step (MWh)	118.77	131.05	142.34	152.53	161.71
Plant Capacity Factor Total Energy (%)	28.5	31.44	34.1	36.66	38.8
Plant Capacity Factor Firm Energy (%)	22.86	22.86	22.86	22.86	22.86
Dry Season Firm Energy (GWh)	758.94	758.94	758.94	758.94	758.94
Wet Season Firm Energy (GWh)	76.311	76.31	76.311	76.311	76.311
Total Dry Season Energy Generated (GWh)	688.84	716.32	735.041	745.712	752.739
Total Wet Season Energy Generated (GWh)	352.26	432.39	512.682	591.319	664.787
Total Spill Energy (GWh)	275.95	356.08	436.371	515.008	588.476
Total Dry & Wet Season Energy Generated (GWh)	1041.1	1148.71	1247.72	1337.03	1417.52
Gross Return From Generated Energy in Million (Nrs)	9745.69	10278.74	10703.59	11024.63	11288.10
Percentage Change in Dry Season Energy Generation	-6.29	-2.55	0.00	1.45	2.41
Percentage Change in Dry Season Energy Generation	-31.29	-15.66	0.00	15.34	29.67
Percentage Change in Total Annual Energy Generation	-16.56	-7.94	0.00	7.16	13.61
Dry Season Firm Energy Reliability (%)	81.05	85.62	90.19	91.5	96.07
Remarks			**Base**		

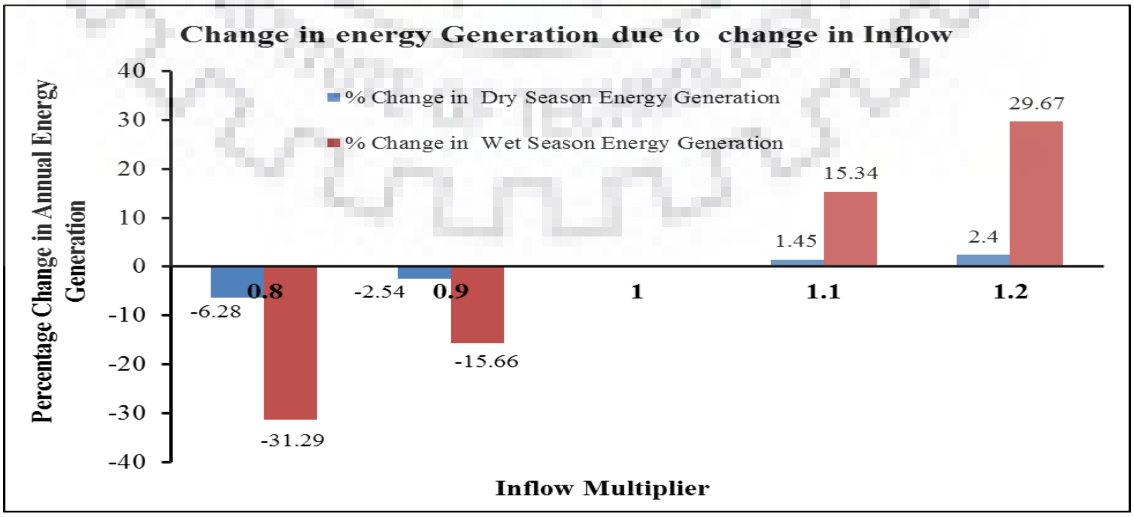


Figure 5. 37: Change in energy generation due to change in inflow

5.6.2 Variation of Environmental Release

In this scenario five different alternatives are considered for various environmental release such as no release i.e. 0, 1 m^3/s, 2 m^3/s, 3 m^3/s and 4 m^3/s while it was taken as 0.6 m^3/s in all prior scenario. Selected operation rule is used for reservoir operation and result is analysed based on the reduction in energy generation and total return from generated energy. Studies of this scenario will helps to adjust energy tariff if environmental release will be increase by certain amount due to some special reason and this gives the idea about the opportunity cost of increasing environmental release. Results of different alternatives considered in this scenario are presented in Table 5.17 and graphical representation of obtained result presented in figure 5.38. It is observed that the opportunity cost of increasing the environmental release by 1 m^3/s is in the range of 22 to 29 GWh/year for dry season energy and 17 to 24 GWh/year for wet season energy with total annual energy value of Nrs. 338 to 396 million per year.

Table 5. 17: Variation in dry season, wet season energy and total energy value in response to environmental release variation

Parameter	Environmental Release (m^3/s)					
	0	0.6	1	2	3	4
Energy Generated per Time Step (MWh)	145.55	142.34	140.27	134.99	129.62	124.19
Plant Capacity Factor Total Energy (%)	34.92	34.1	33.66	32.46	31.1	29.8
Plant Capacity Factor Firm Energy (%)	22.86	22.86	22.86	22.86	22.86	22.86
Dry Season Firm Energy (GWh/year)	758.94	758.94	758.94	758.94	758.94	758.94
Wet Season Firm Energy (GWh/year)	76.311	76.311	76.31	76.311	76.311	76.311
Total Dry Season Energy Generated (GWh/year)	756.265	735.041	727.80	705.102	678.448	650.451
Total Wet Season Energy Generated (GWh/year)	519.598	512.682	501.77	478.18	457.79	438.145
Total Spill Energy (GWh/year)	443.353	436.371	425.46	401.869	381.479	361.838
Total Annual Average Energy Generated (GWh/year)	1275.86	1247.72	1229.57	1183.28	1136.24	1088.6
Decreases in Dry	NA	21.2241	28.47	22.69	26.6539	27.9974

Season Energy Generation (GWh/year/year)						
Decreases in Wet Season Energy Generation (GWh/year/year)	NA	6.98216	17.82	23.60	20.3893	19.6449
Decreases in Total Annual Energy Generation (GWh/year/year)	NA	28.1403	46.29	46.29	47.0432	47.6423
Gross Return From Generated Energy in (Million Nrs/year)	10983.54	10703.59	10587.59	10249.54	9870.11	9475.80
Decrease in Total Annual Energy Value (Million Nrs/year)	NA	279.95	395.95	338.05	379.43	394.31
Dry Season Energy Reliability (%)	98.69	90.19	87.58	83.33	79.41	75.16

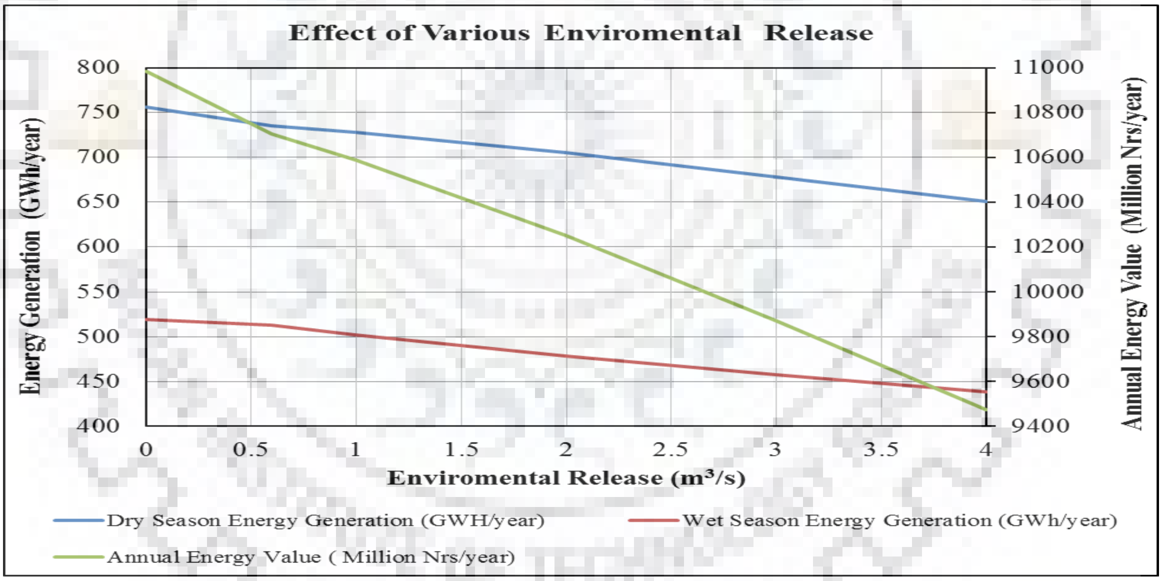


Figure 5. 38: Variation in dry season, wet season energy and total energy value in response to environmental release variation

5.6.3 Effect of Various Full Supply Level

In this scenario six alternatives are considered for different maximum conservation level as 1550 masl, 1560 masl, 1570 masl, 1580 masl, 1590 masl and 1600 masl at top of full supply level of reservoir and minimum conservation level is assigned at top of inactive zone (minimum operating level) at elevation 1498 masl and the selected operation rule from above scenario 5 is applied for simulation and simulated results for each alternative are analysed and check the suitability of selected FSL whether it is logical or not. Comparison of result of each candidate FSL presented in table 5.18 and figure 5.39. It may be noted that dry season energy generation, total annual energy generation and annual energy value is increase lineraly from FSL 1550 to 1580 masl above that FSL there is small increment in energy generation and energy value. This would suggest that FSL 1580 might be a logical FSL selection. Hence there is no need of revision of the developed operation policy/rule.

Table 5. 18: Variation in dry season, total annual average energy and total energy value in response to various FSL.

Parameter	FSL (m)					
	1550	1560	1570	1580	1590	1600
Energy Generated per Time Step (MWh)	132.29	135.33	138.85	142.34	144.11	145.34
Plant Capacity Factor Total Energy (%)	31.74	32.46	33.31	34.1	34.5	34.87
Plant Capacity Factor Firm Energy (%)	22.86	22.86	22.86	22.86	22.86	22.86
Dry Season Firm Energy (GWh)	758.94	758.94	758.94	758.94	758.94	758.94
Wet Season Firm Energy (GWh)	76.311	76.31	76.311	76.31	76.311	76.311
Total Dry Season Energy Generated (GWh)	470.821	553.90	645.788	735.04	755.218	755.227
Total Wet Season Energy Generated (GWh)	688.761	632.38	571.319	512.68	507.977	518.78
Total Spill Energy (GWh)	611.548	556.07	495.008	436.37	431.666	442.469
Total Annual Energy Generation (GWh)	1159.58	1186.28	1217.11	1247.72	1263.2	1274.01
Incremental Value of Dry Season Energy (GWh/year)	NA	83.08	91.89	89.25	20.18	0.01
Change in Value of Wet Season Energy (GWh/year)	NA	-56.38	-61.06	-58.64	-4.70	10.80
Incremental Value of Total Annual Energy (GWh/year)	NA	26.70	30.82	30.62	15.47	10.81
Gross Return From Generated Energy (Million (Nrs/year)	7847.68	8744.72	9737.57	10703.59	10942.49	10968.5
Dry Season Firm Energy Reliability (%)	41.5	53.26	70.91	90.19	99.34	99.34

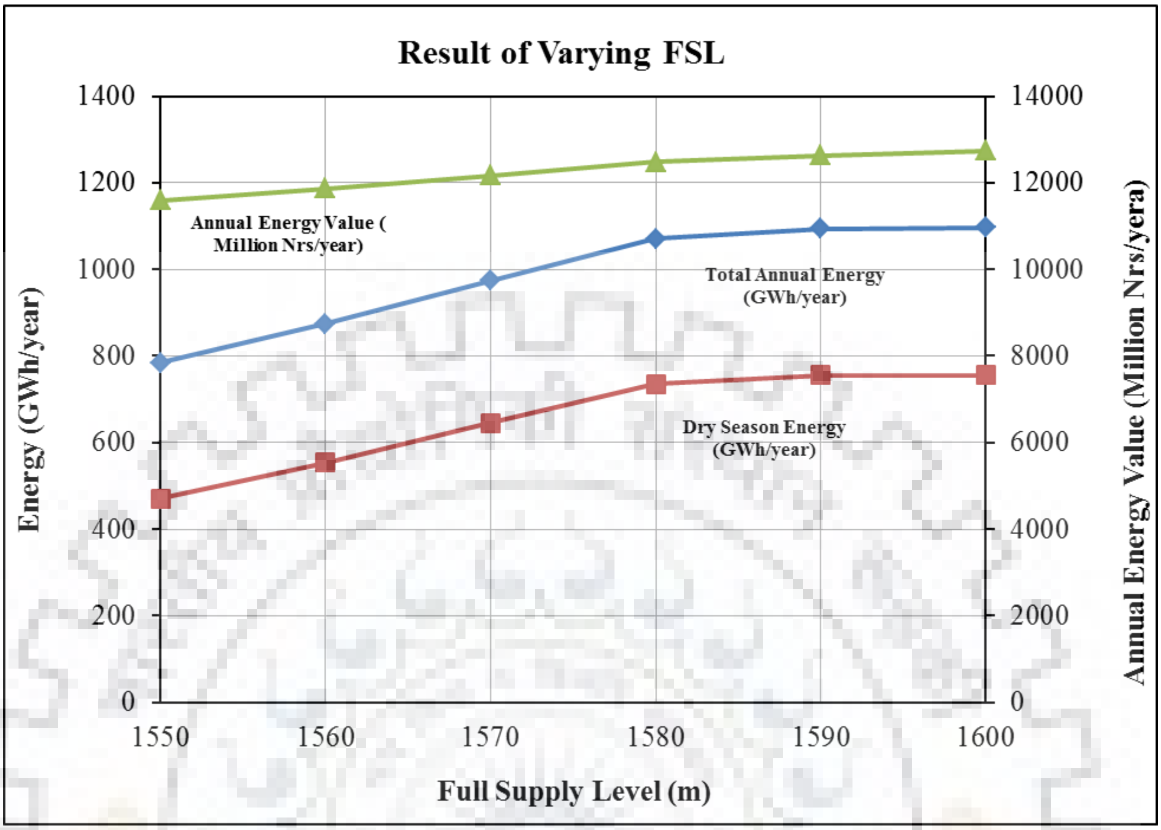


Figure 5. 39: Variation in dry season, total annual average energy and total energy value in response to various FSL.

5.7 Effect of Reservoir Sedimentation

Major reservoir physical data Elevation-Area-Capacity relationship changes due to reservoir sedimentation hence in this scenario revised Elevation- Area- Capacity curve after 25 years, 50years, 75 years and 100 years was developed as shown in figure 5.40 to 5.43 are used for simulation study. All other physical input data are same as in scenario 5 and hydropower schedule rule with generation pattern 10 hours operation during dry season and 1 hour evening peak operation during wet season is used as operation rule for this scenario. This scenario aims to evaluate the effect of reservoir sedimentation on energy generation. Comparison of result of each alternative considered are presented table 5.19.

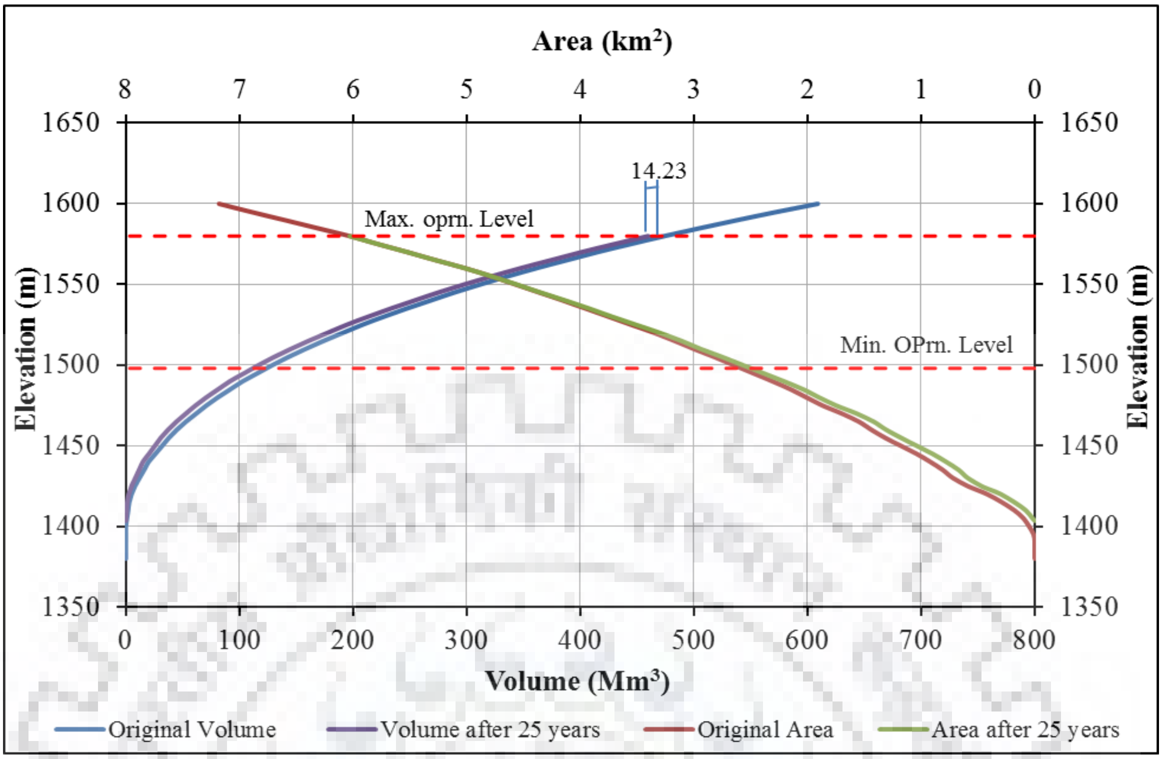


Figure 5. 40: Revised Elevation-Area-Capacity curve after 25 years

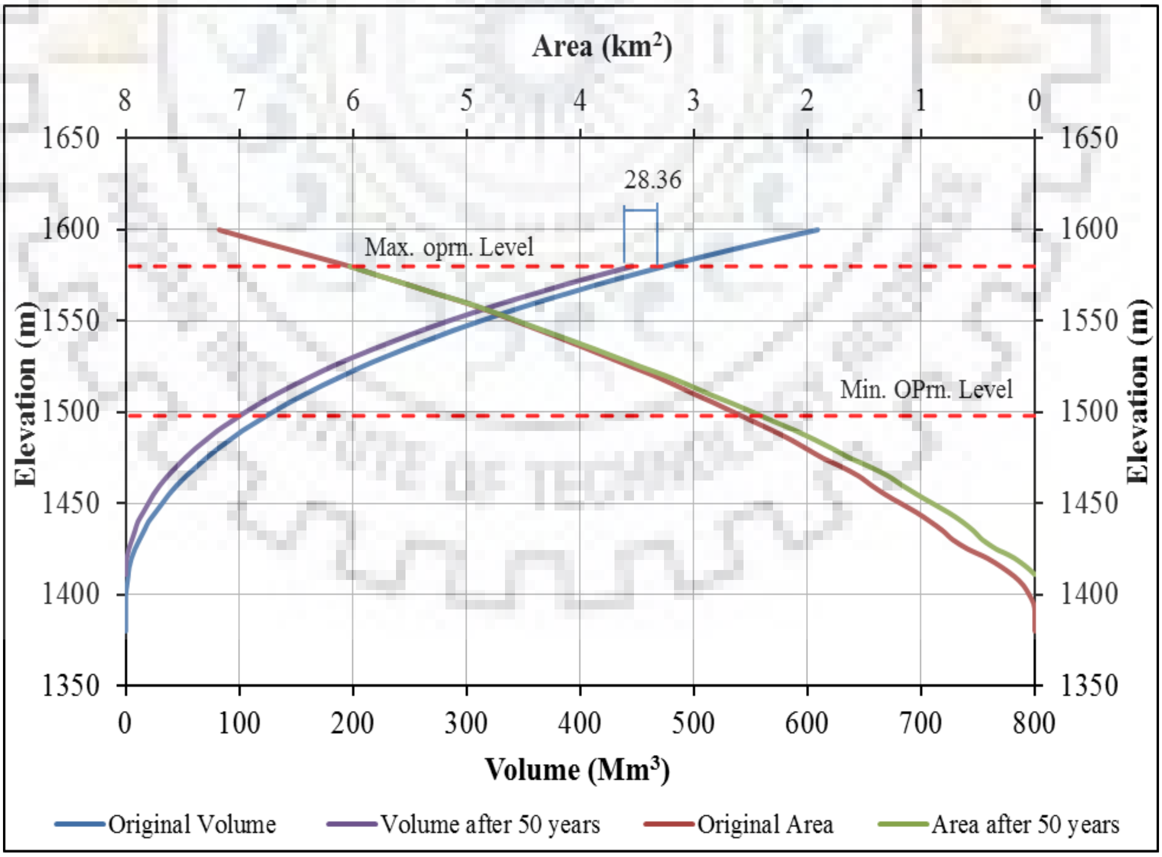


Figure 5. 41: Revised Elevation-Area-Capacity curve after 50 years

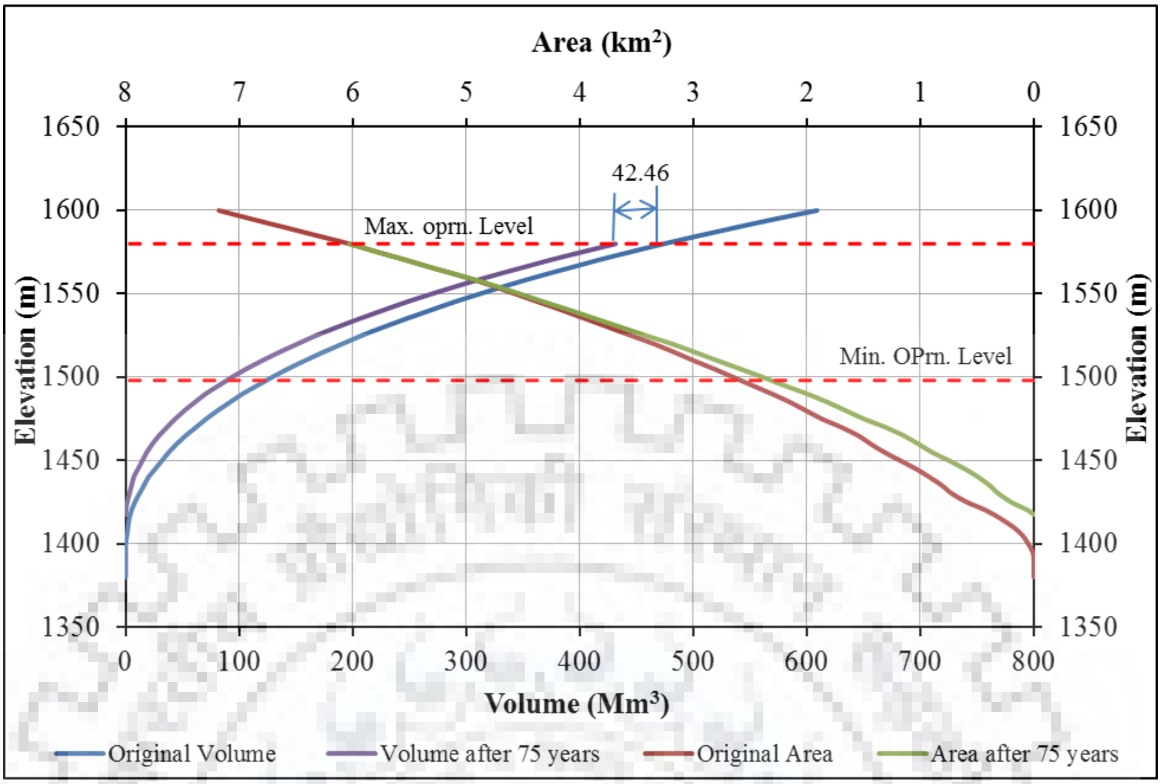


Figure 5. 42: Revised Elevation-Area-Capacity curve after 75 years

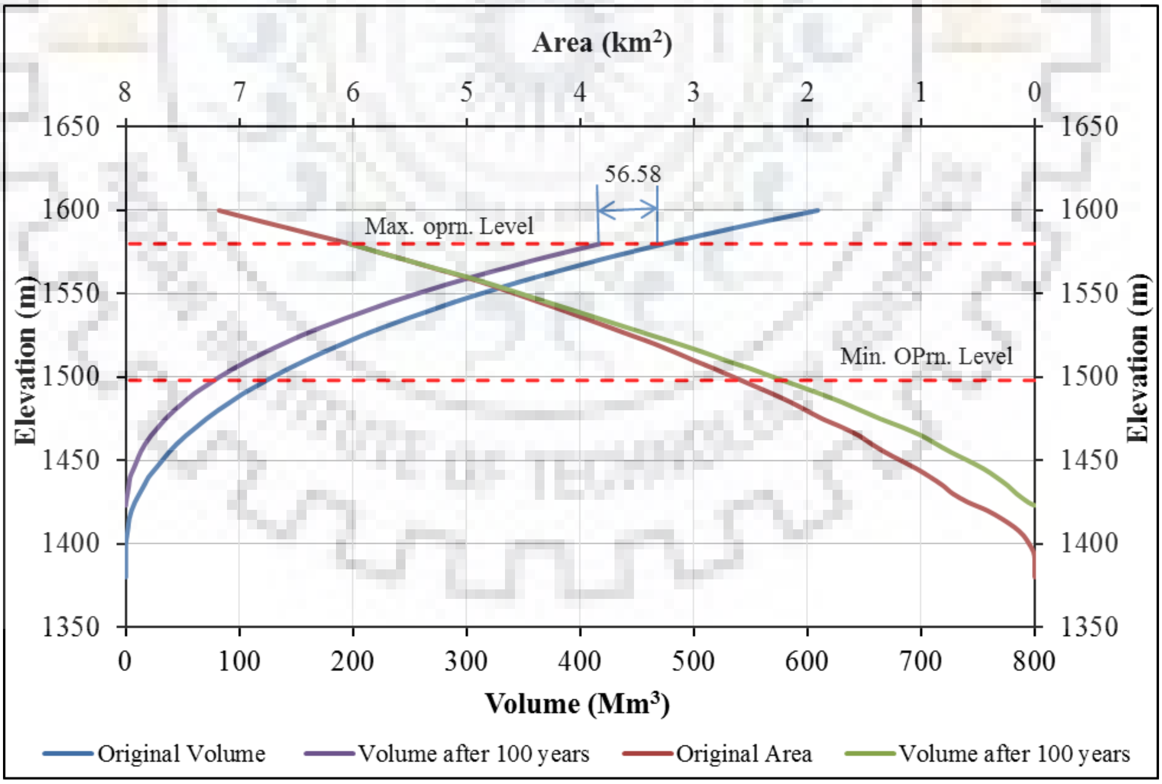


Figure 5. 43: Revised Elevation-Area-Capacity curve after 100 years

Table 5. 19: Summary of effect of sedimentation in energy generation

Alternate	Parameter	Pool Volumes (Mm^3)			Energy Generation (GWh/year)	
		Total	**Dead**	**Live**	**Total**	**Dry Season**
1	**Pre-impoundment**	474.000	123.000	351.000	1247.723	735.041
	After 25 years	459.770	111.798	347.972	1247.700	733.307
	Difference	**14.230**	**11.202**	**3.028**	**0.023**	**1.734**
2	**Pre-impoundment**	474.000	123.000	351.000	1247.723	735.041
	After 50 years	445.640	100.278	345.362	1247.668	731.020
	Difference	**28.360**	**22.722**	**5.638**	**0.055**	**4.021**
3	**Pre-impoundment**	474.000	123.000	351.000	1247.723	735.041
	After 75 years	431.540	89.000	342.540	1247.489	728.174
	Difference	**42.460**	**34.000**	**8.460**	**0.234**	**6.867**
4	**Pre-impoundment**	474.000	123.000	351.000	1247.723	735.041
	After 100 years	417.420	77.690	339.730	1247.188	725.072
	Difference	**56.580**	**45.310**	**11.270**	**0.535**	**9.969**

From table 5.19 it is appear that there is very less or negligible decreases in annual average total and dry season energy generation due to sedimentation even after 100 years due to the fact that there is very less sediment yield in this catchment. Moreover, minimum drawn down level (minimum operation level) chosen during feasibility study is sufficient to accommodate the sediment within inactive pool that's why simulation study shows major storage loss about 80% of total storage loss is from dead pool which is not used for power generation in any time. From above table it has been seen that the dry season energy loss is about only 1 % while storage loss from live/conservation pool is about 20% this occurs actually due to fact that the energy generation loss due to reservoir storage loss is makeup by increase in head due to sedimentation. Further as seen in above table, a decline in live storage has almost no impact on total energy. However, there is a roughly linear relationship between live storage loss and dry season energy generation. Each 1 Mm^3 loss of live storage will reduce dry season energy by about 0.57- 0.9 GWh/year after 25 years to 100 years.

The number of deficit years at various interval of percentage energy deficit due to sedimentation is given in table 5.20. The total simulation is carried out for 51 years. It may be observed that due to sedimentation zero deficit years decreases from 22 years in normal conditions to 14 years due to sedimentation after 100 years. The deficit years for

5-10% energy deficit are almost doubled after sedimentation of 50 years shown in figure 5.44.

Table 5. 20: Number of deficit year due to sedimentation

Percentage Energy Deficit	Number of deficit year				
	Normal	25	50	75	100
0	22	19	18	15	14
0.1-5	18	20	16	17	17
5.1-10	8	9	14	14	14
>10	3	3	3	5	6

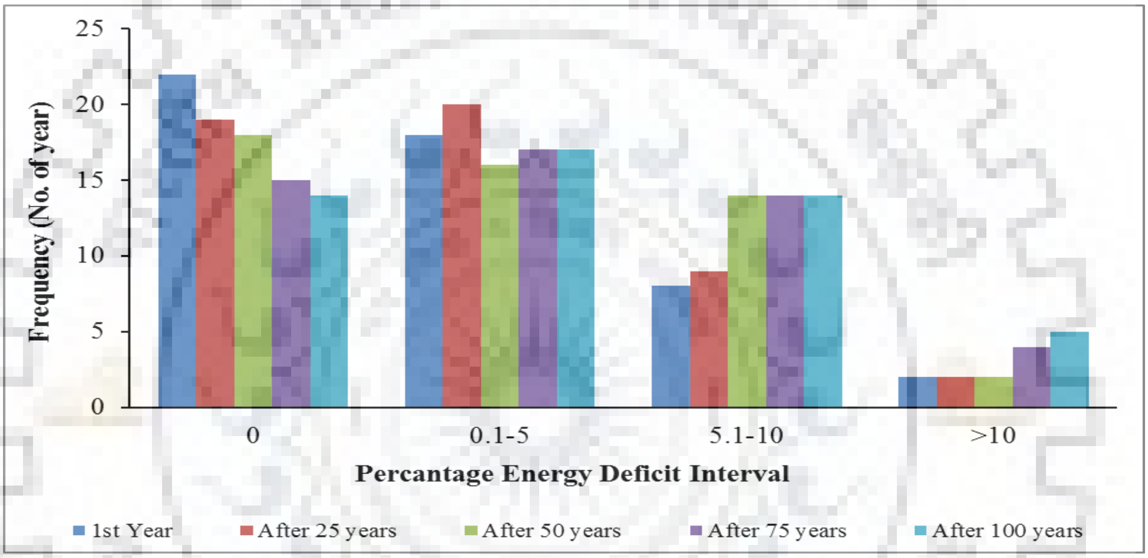


Figure 5. 44: Histogram of energy deficit year due to sedimentation after various years.

5.8 Future Operation Scenario with Muncipal Water Demand

The project is primarily planned for single purpose to generate hydropower. However, considering rapid growth of population and urbanization, in future water supply demand may not be meet from the existing water source. In such situation drinking water may be supplied from this project hence this scenario is considered as future scenario to supply future drinking water demand of about 2.5 m^3/s water to downstream municipality such as Nalgad, Athbiskot, Bheri and Chaurjhari. Here in this scenario water allocated for drinking purpose as well as hydropower purpose for that add a low level gated outlet at elevation 1450 masl to release drinking water and all other operational zones are as same in present scenarios considered above. Release function rule to release drinking water for 24 hour throughout the year with first priority and hydropower schedule rule with generation pattern ten hour operation during dry season and one hour operation during wet season with least priority is assigned and simulation was performed for assigned operation set then the result is compared with the result obtained from application of selected operation policy in existing scenario above. Summary report of HEC-ResSim for reservoir simulation of considered operation policy in this scenario is shown in table 5.21.

Table 5. 21: Summary report of HE- ResSim for reservoir simulation of alternate considered in future operation scenario with water supply.

Operation Set	**Option_1**		
Maximum Operating Level (FSL)	1580 m		
Minimum Operating Level (MOL)	1498 (MOL)		
Operation Zone	Flood	Conservation	Inactive
	1589 m	1580 m	1489 m
Release Function Rule	Constant release of 2.5 m^3/s		
Generation Pattern	Dry Season	Wet Season	
	10	1	
Output Summary From HEC-ResSim			
Location/Parameter	Summary Output		
	Average	Maximum	Minimum
Reservoir Summary Report			
Storage (Mm^3)	352.665	487.861	123.8
Elevation (m)	1555.71	1582.2	1498
Controlled Release (m^3/s)	22.39	78.4	0
Uncontrolled Spill (m^3/s)	2.28	369	0
Power Summary Report			
Generation Efficiency	0.88	0.88	0.88
Power Head (m)	670.39	696.79	612.86
Hydraulic Losses (m)	17.72	17.81	17.54
Energy Generated per Time Step (MWh)	129.21	417	0
Power Generated (MW)	129.21	417	0
Plant Factor	0.3	1	0
Flow Power (m^3/s)	22.39	78.4	0
Other Parameters Calculated			
Parameters	Energy (GWh/ year)	Rate(NRS/ KWh)	Value in Million (NRS)
Plant Capacity Factor Total Energy (%)	31		
Plant Capacity Factor Firm Energy (%)	22.86		

Dry Season Firm Energy (GWh/year)	758.94		
Wet Season Firm Energy (GWh/year)	76.3	7.1	541.8
Total Dry Season Energy Generated (GWh/year)	676.84	12.4	8392.76
Total Wet Season Energy Generated (GWh/year)	455.76		
Total Spill Energy (GWh/year)	379.45	2.4	910.68
Total Annual Energy Generation (GWh/year)	1132.60		9845.24
Dry season energy Generation Reliability (%)	79.1		
Water supply Reliability (%)	99.73		

In above alternative 1 operation policy applied for hydropower generation is same as that applied for selected alternative of scenario 5 which is final operation policy. So that the result obtained from alternative 1 of this secenario is comaperd with result of selected alternative 3 of operation scenario 5. Comparison of obtained result is summerised in table 5.22.

Table 5. 22: Comparision of result obtaine from existing scenario and future scenario.

Parameters	Existing scenario (power demand only)	Future scenario (W/S and Power demand)	Difference
Total Dry Season Energy Generated (GWh/year)	735.041	676.836	58.205
Total Wet Season Energy Generated (GWh/year)	512.682	455.764	56.918
Total Spill Energy (GWh/year)	436.371	379.453	56.918
Total Dry & Wet Season Energy Generated (GWh/year)	1247.723	1132.599	115.124
Average Spill (m3/s)	2.62	2.280	0.34
Dry Season Firm Energy Reliability (%)	90.19	79.10	11.09
Water supply Reliability (%)	NA	99.73	

From table 5.22 it is seen that when 2.5 m^3/s water is release to meet the drinking water demand of downstream municipality nearby dam, decrease in total annual energy generation is 115.124 GWh/year, decrease in dry season energy generation is 58.2 GWh/year and dry season energy generation reliability decreased to 79.1% from 90.19%.

Comparison of annual dry season energy generation with and without considering water supply demand over the simulation period is presented in figure 5.45.

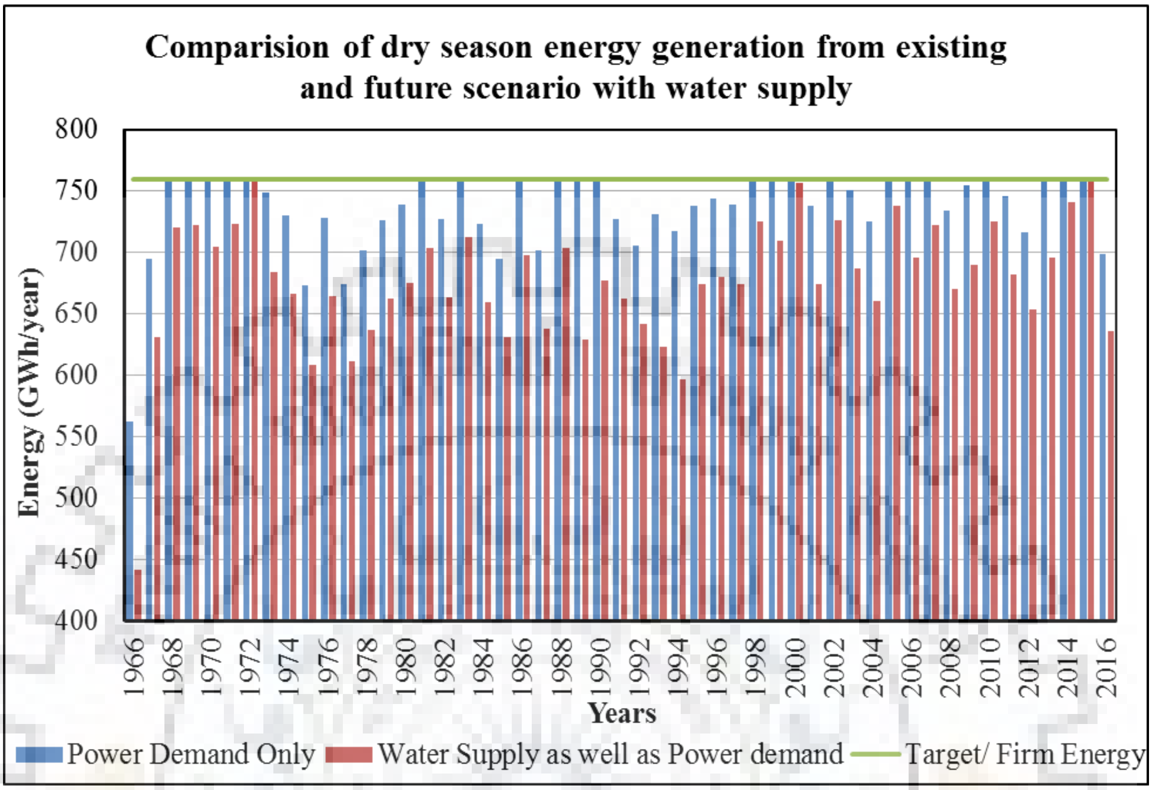


Figure 5. 45: Comparison of dry season energy generation with and without water supply demand.

From above discussion and figure 5.45 it is clear that there is large energy violation when release function rule with constant release 2.5 m^3/s through out the year and hydropower schedule rule with generation patten ten hour operation during dry season and one hour operation during wet season is assigned together. Hence it is necessary to curtailed release for hydropower demand and release drinking water with 100% relability. For that various alternatives are considered by changing the energy generation pattern in hydropower schedule rule. Summary report of HEC-ResSim for reservoir simulation of selected alternative 2 of this scenario is shown in table 5.23.

Table 5. 23: Summary report of HEC -ResSim for reservoir simulation of selected alternative 2 of future operation scenario with water supply demand.

Operation Set	**Option_2**		
Maximum Operating Level (FSL)	1580 m		
Minimum Operating Level (MOL)	1498 (MOL)		
Operation Zone	Flood	Conservation	Inactive
	1589 m	1580 m	1489 m
Release Function Rule	Constant release of 2.5 m^3/s		
Generation Pattern	(9 hrs) Dry Season	(1 hr) Wet Season	
Output Summary From HEC-ResSim			
Location/Parameter	Summary Output		
	Average	Maximum	Minimum
Reservoir Summary Report			
Storage (Mm^3)	348.792	487.861	123.8
Elevation (m)	1554.84	1582.2	1498
Controlled Release (m^3/s)	21.89	78.08	0
Uncontrolled Spill (m^3/s)	2.36	369	0
Power Summary Report			
Generation Efficiency	0.88	0.88	0.88
Power Head (m)	669.5	696.79	612.8
Hydraulic Losses (m)	17.74	17.81	17.6
Energy Generated per Time Step (MWh)	128.82	417	0
Power Generated (MW)	128.82	417	0
Plant Factor	0.3	1	0
Flow Power (m^3/s)	21.89	78.08	0
Other Parameters Calculated			
Parameters	Energy (GWh/ year)	Rate(NRS/ KWh)	Value in Million (NRS)
Plant Capacity Factor Total Energy (%)	30.98		
Plant Capacity Factor Firm Energy (%)	20.78		
Dry Season Firm Energy (GWh/year)	683.046		
Wet Season Firm Energy (GWh/year)	76.3	7.1	541.8
Total Dry Season Energy Generated (GWh/year)	661.903	12.4	8207.59
Total Wet Season Energy Generated (GWh/year)	467.33		
Total Spill Energy (GWh/year)	391.02	2.4	938.44
Total Annual Energy Generation (GWh/year)	1129.23		9687.83
Dry season energy Generation Reliability (%)	90.52		
Water supply Reliability (%)	100%		

From this scenarios result maximum total annual average energy generation is 1129.23 GWh/year, maximum dry season energy generation is 661.903 GWh/year with 90.52% dry season energy generation reliability and water supply reliability is 100% throughout the simulation period when the release function rule with constant release of 2.5 m^3/s and hydropower schedule rule with generation pattern Nine hours operation in dry season and One hour operation in wet season is assigned hence this operation policy is selected from this scenario. The graphical representation of simulation results of selected alternative 2 of this scenario are shown in figure 5.46 to 51.

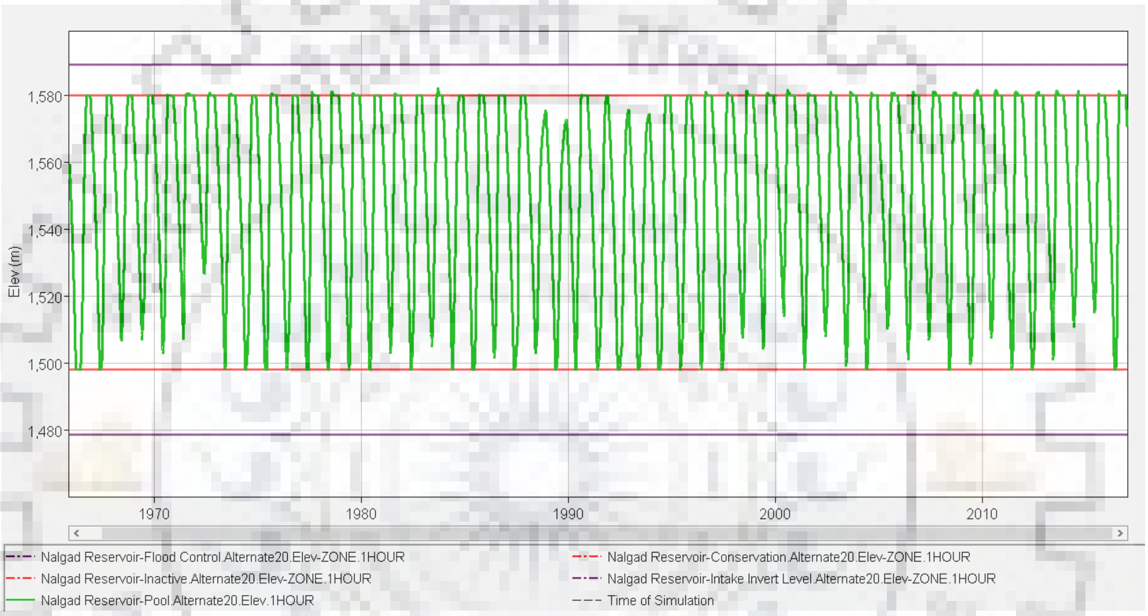


Figure 5. 46: Reservoir elevation for selected alternative 2 of future scenario

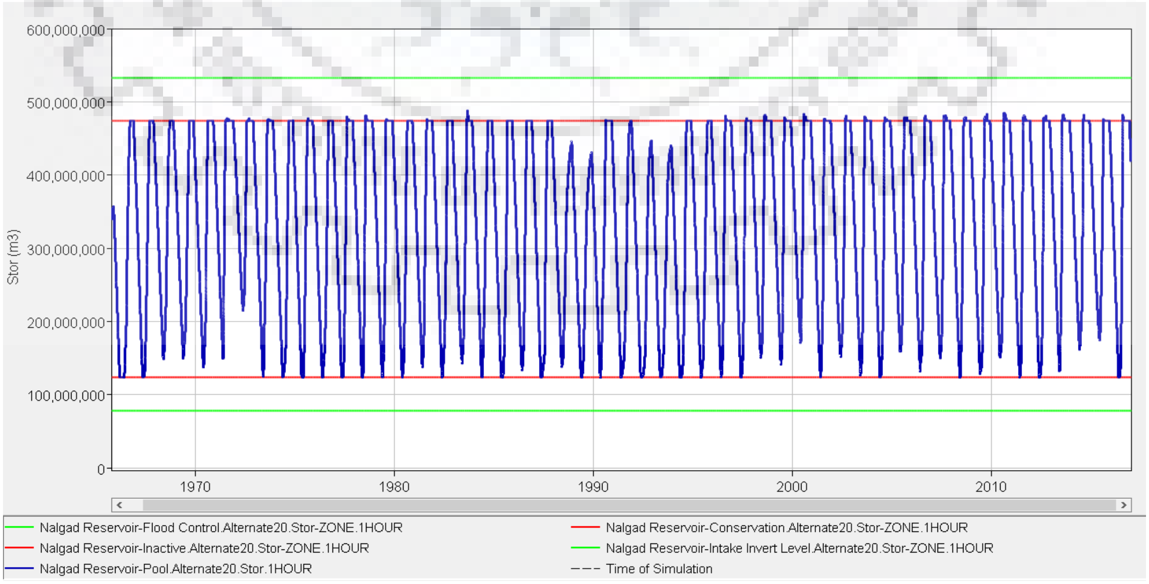


Figure 5. 47: Reservoir storage for selected alternative 2 of future scenario

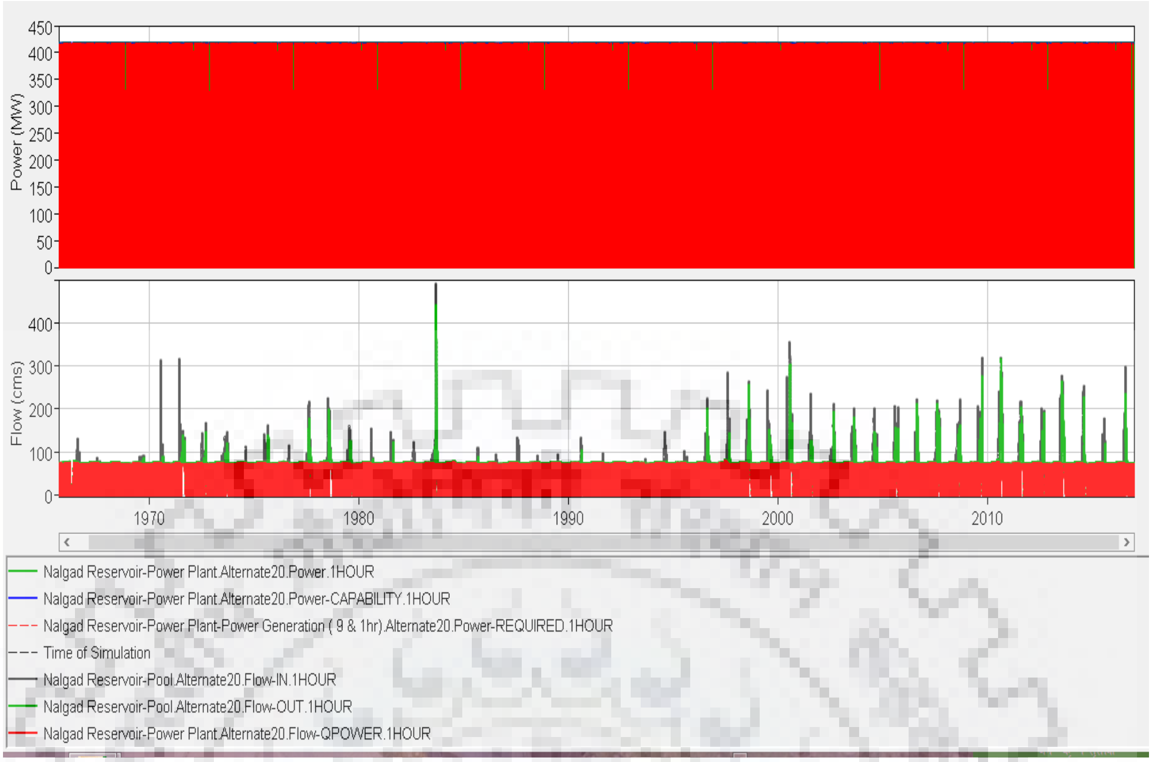


Figure 5. 48: Power generations, inflows and outflows for selected alternative 2 of future scenario

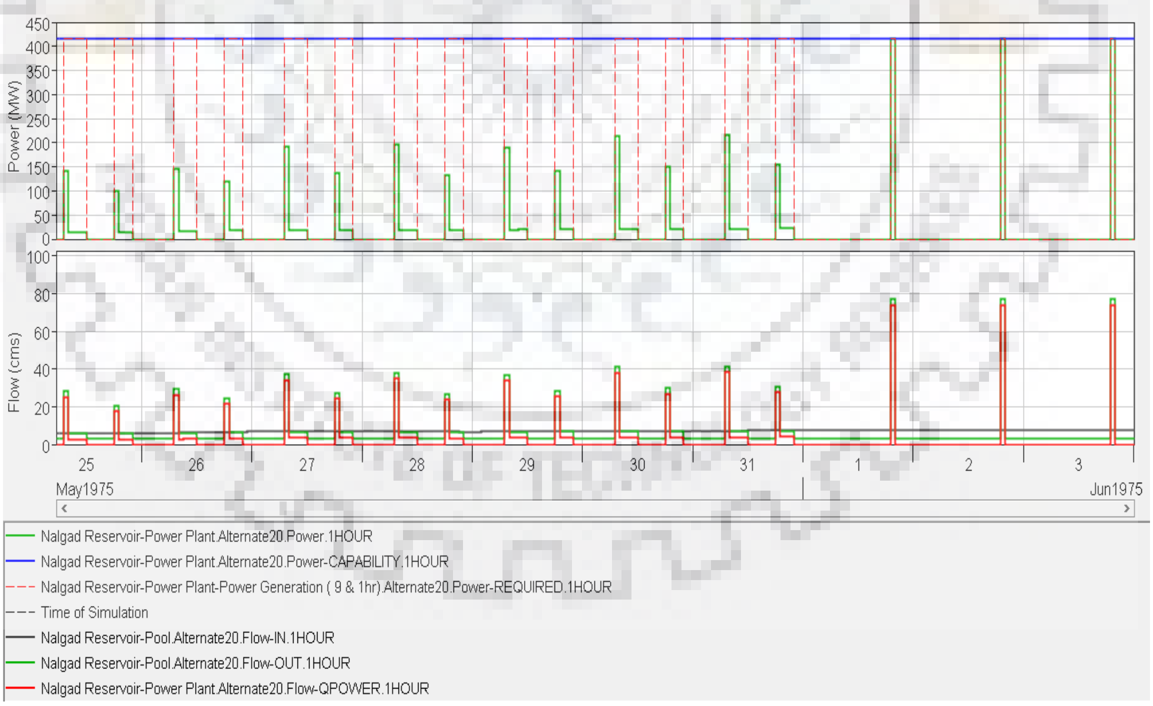


Figure 5. 49: Zoomed view of power generations, inflows and outflows for selected alternative 2 of future scenario

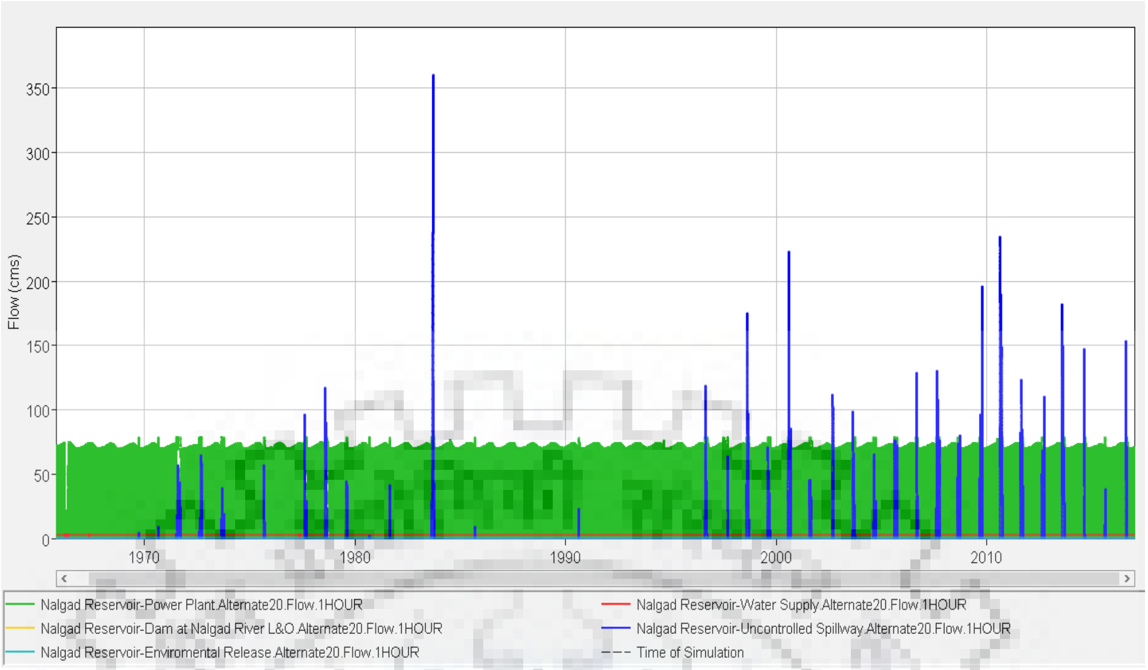


Figure 5. 50: Release from all controlled and uncontrolled outlets for selected alternative 2 of future scenario

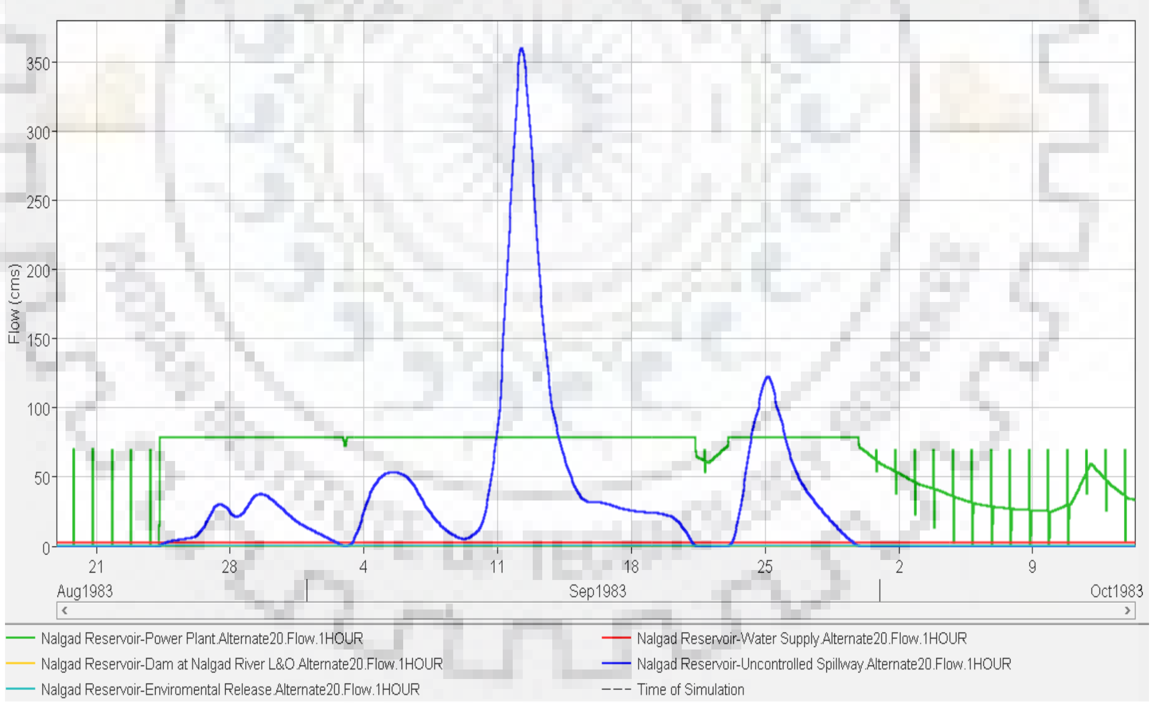


Figure 5. 51: Zoomed view of release from all controlled and uncontrolled outlets for selected alternative 2 of future scenario

From figure 5.52 total annual average firm energy and dry season firm energy generated is 759.356 and 630.696 GWh/year respectively when release function rule with constant realse of 2.5 m^3/s for water supply and hydropower schedule with energy generation pattern nine hours operation in dyr season and one hour operation in wet season for power generation was assigned as operation rule.

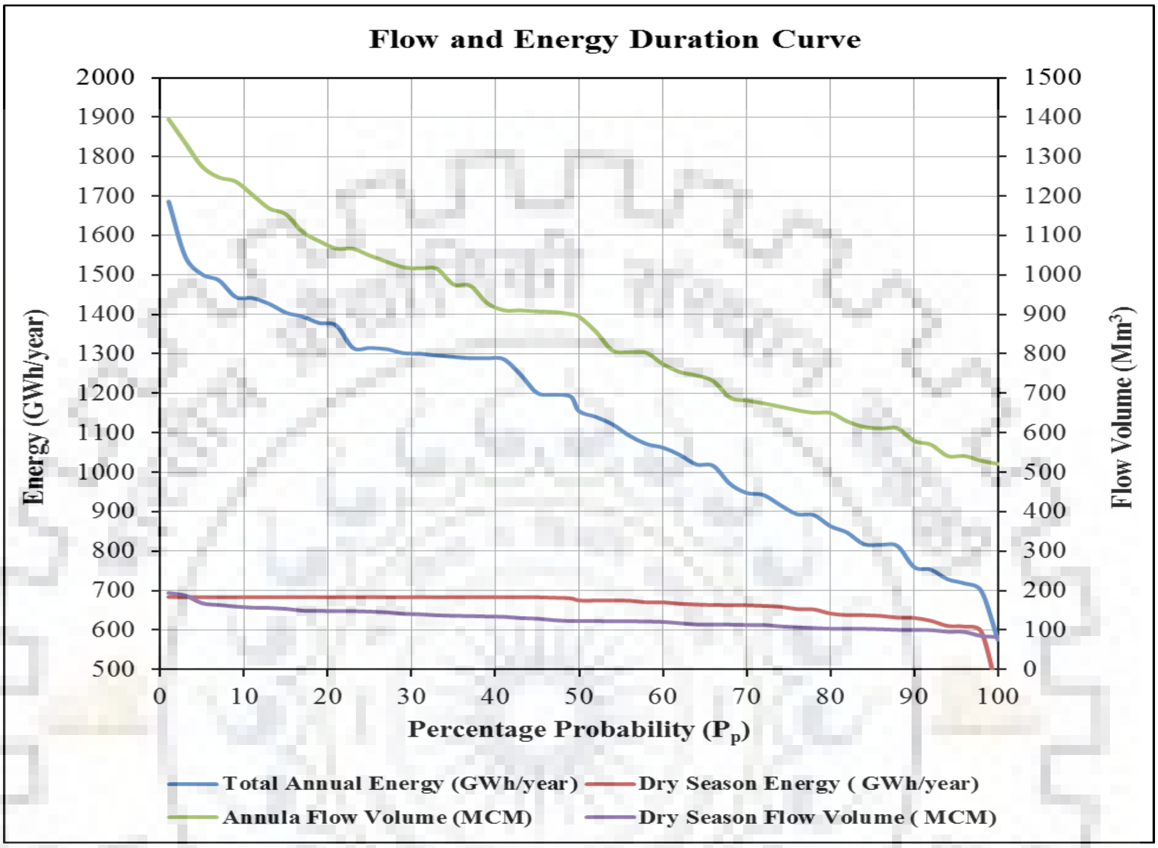


Figure 5. 52: Flow and energy duration curve for selected alternative 2 of future scenario

5.8.1 Operation Rule for Muncipal and Hydropower Demand

With addational release of 2.5 m^3/s for municipal water demand with first priority the reliability of dry season energy generation decreased from 90.19% to 79.1%. Hence, it is proposed to change the generation pattern to 9 hours from 10 hours operation during dry season (Dec to May) and 1 hour operation during wet season (Jun to November) having second priority. The 1 hour reduction in operating hour will reduce the energy generation by 73.138 GWh/year, while maintaining the reliability of dry season energy above 90%.

CHAPTER 6: SUMMARY AND CONCLUSION

In spite of harbouring a huge hydropower potential, Nepal has unable to meet its own domestic electricity demand with its resources. As a result, the country is currently going through an unadorned energy crisis. Recently, Nepal is focusing highly on development of hydropower to fulfil its ever increasing demand of energy for economic development of the country. There is a need to use latest tools and methodologies for design and operation of such hydropower projects to maximize its benefits. Optimal use of available water resources is an essential part in estimating parameters of a storage energy system. An oversized facility will not be able to fully utilize its design capacity due to lack of sufficient water during the dry season and will generate abundant spill energy during the wet season. Moreover, the power station will cause a loss of precious water for an undersized installed capacity. Both scenarios will have a negative impact on the economic parameters of the power project. Hence, the importance of reservoir simulation is obvious for such storage projects. This study aims at to build a simulation model of the proposed Nalgad dam reservoir operation for hydropower generation in Nepal using HEC-ResSim. The historical daily discharge data for the period 1966 to 2016 are used for simulation. Five different operation scenarios with number of alternatives are considered to develop reservoir operation policy for hydropower generation. Among these five scenarios, first scenario (scenario1) is used to select number of turbine units to be in operation for maximum energy generation and other four scenarios are used to select optimal generation pattern for maximum dry season energy generation. Further, monthly reservoir operation policy for 90% dependable historical year is also developed through optimization technique and the results are compared with that obtained from simulation model for same historical year. Simulation is also carried to analyse the effect of change in inflow, environmental release and variation of FSL on sensitivity on annual energy generation. Effect of reservoir sedimentation after 25, 50, 75 and 100 years after reservoir operation is also considered to assess decreases in reservoir storage and resulting change in energy generation. Future, operation scenario with municipal water demand in addition to hydropower demand is considered to suggest future operation policy when existing source of drinking water are unable to meet the municipal water demand due to rapid growth of population and urbanization.

The optimum reservoir operation rule to utilize the available inflow to reservoir for hydropower generation is developed through simulation study in HEC ResSim using long term estimated daily inflow series for the period 1966 to 2016. It is observed that the optimum dry season energy generation is 735.04 GWh/year with 90.19% reliability and total annual average energy generation is 1247.72 GWh/year when hydropower schedule rule with energy generation pattern as ten hours peaking in dry season and one-hour evening peaking in wet season is employed. The operation rule/policy for optimum power generation from Nalgad reservoir is suggested with operation of reservoir using Hydropower–Schedule–Rule through generation pattern as ten hours peaking in dry season and one hour in wet season with four turbine units. On evaluating the reliability of the reservoir system to meet the specified hydropower targets, it is found that system is in unsatisfactory condition for 9.81% of dry season time period (306 month). That unsatisfactory condition occurs mostly during dry season month of May and in case of some critical water year's unsatisfactory condition also occurs in dry season month of March, April and even in December. However, this unsatisfactory condition exists for very few times.

Monthly reservoir operation policy is also developed by using the liner programming optimization technique solved using LINGO model for 90% dependable historical year. The results are compared with that obtained from simulation model for same historical year. It is observed that the energy generation, reservoir storage and reservoir elevation, spill etc. obtained from both methods is almost similar. However, the simulation model is more effective tool for analyzing reservoir operation simulation as it reflects real system behavior. The optimization model tries to maximize the objective function of energy generation which may not real representation of behavior of system.

Sensitivity of energy generation due to change in inflow, environmental release and maximum operating level or full supply level are analysed. It is observed that the effect of change in inflow on dry season energy generation is very less in comparision to wet season energy generation. This happens due to the fact that the dry season energy generation mainly depends up on controlled release from reservoir storage, where as wet season energy generation composed of both firm eneregy generation by release through intake (78.4 m^3/s) and spill energey generated by excess inflow to reservoir at maximum reservoir operating level. The firm energy generated for wet season in all cases are simillar. The reduction in dry season energy is about 6% for a 20% decrease in inflow. It is observed that when minimum environmental release is increased by 1 m^3/s, the average annual dry season energy generation decreases in the range of 22-29 GWh/year with total annual opportunity cost of Nrs. 338 -396 Million per year. From the analysis of various FSL it is found that the annual average total and dry season energy generation and gross return from energy linearly increases from FSL 1550-1580 masl. After this level there is negligible increment in energy generation. Hence the selected FSL at breakeven point i.e. 1580 masl is justified.

The storage capacity of the reservoir gradually reduced due to sedimentation. The Empirical Area Reduction Method was used to develop Elevation-Area-Capacity curve after 25, 50, 75 and 100 years from reservoir operation date. The decrease in total storage volume after 25, 50, 75 and 100 years of sedimentation are estimated to be 14.23 MCM, 28.36 MCM, 42.46 MCM and 56.58 MCM respectively. However, the reduction in live storage is about 20% of the total loss. Reservoir simulation shows that that there is very less or negligible decreases in annual average total and dry season energy generation due to sedimentation even after 100 years as there is only 2% decrees in live storage capacity. Moreover, there is very less sediment yield in this catchment and the minimum drawn down level adopted during design is sufficient to accommodate the sediment within inactive pool. Linear relationship is observed between live storage loss and reduction in dry season energy generation. Each 1 Mm^3 loss of live storage will reduce dry season energy by about 0.57- 0.9 GWh/year after 25 years to 100 years. Further the number of deficit years due to sedimentation is also analysed for simulation period of 51 years. It is observed that due to sedimentation zero deficit years decreases from 22 years in present conditions to 14 years due to sedimentation after 100 years. Moreover, the 5-10% energy deficit years are almost doubled after sedimentation of 50 years.

The drinking water may supply from this project to downstream municipality such as Nalgad, Athbiskot, Bheri and Chaurjhari is forecasted to be about 2.5 m^3/s. For this scenario optimum total annual average energy generation is 1129.23 GWh/year and optimum dry season energy generation 661.903 GWh/year with 90.52% dry season energy generation reliability. The water supply reliability is nearly equal to 100% throughout the simulation period when the release function rule with constant release 2.5 m^3/s and hydropower schedule rule with generation pattern Nine-hour operation in dry season and One-hour operation in wet season is assigned. It may be noted that to fulfil the municipal water demand of about 2.5 m^3/s there will be reduction in dry season energy in the order of 73.138 GWh/year.

6.1 Limitations

- The reservoir simulation using HEC-ResSim is carried out at hourly time step and the optimum operating hour are found to be ten hours in dry season and one hour during wet season. However, daily inflow data series was available. More accurate calculation might have been made with availability of hourly inflow data.
- While developing the operation rule, the stochastic nature of the flow is not considered. The developed rule curve can be further improved by incorporating flexibility for both inflow and energy demand.

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