MAKERERE UNIVERSITY

College of Engineering, Design, Art and Technology
School of Engineering

Department of Civil and Environmental Engineering

CIV 4200: Civil Engineering Project II

ASSESSMENT OF FLOW VARIABILITY AND OPERATION EFFICIENCY FOR THE NYAGAK RUN OF RIVER HYDROPOWER PLANT IN ZOMBO DISTRICT

FINAL REPORT SUBMITTED BY;

MUHWEZI BOB ROBERT	22/U/3415/PSA
AINEOBUSINGYE SANDRAH	22/U/5691

Submitted in Partial Fulfilment of the Requirements for the Award of a Degree of Bachelor of Science in Civil Engineering

....	....
Dr. Jotham I Sempewo	Dr. Emmanuel Tumwesigye
SUPERVISOR 1	SUPERVISOR 2

JUNE 2026

DECLARATION

We, Aineobusingye Sandrah and Muhwezi Bob Robert hereby declare that this research project titled: "*Assessment of flow variability and operational efficiency for the Nyagak run-of-river hydropower plant in Zombo District*" is our original work and has not been submitted for the award of a degree or any other academic qualification at any University or institution of higher learning.

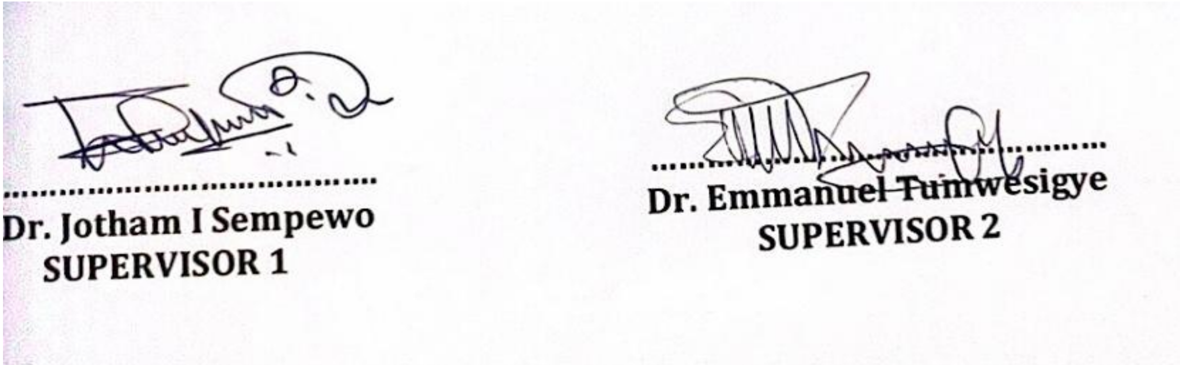
Where the work of other authors has been referenced, it has been dully acknowledged in accordance with academic writing standards.

…………………………………	…………………………………
Aineobusingye Sandrah	Muhwezi Bob Robert
22/U/5691	22/U/3415/PSA
Date: 23/06/2026	Date: 23/06/2026

APPROVAL

This is to certify that AINEOBUSINGYE SANDRAH and MUHWEZI BOB ROBERT, fourth year Civil Engineering student at Makerere University have been working on a final year research project under the supervision of DR. JOTHAM I SEMPEWO, being co-supervised by DR. EMMANUEL TUMWESIGYE

<u>Supervisors</u>



Digitisation and Self-Archiving Consent Agreement: Theses

Agreement between Makerere University & Students (Authors of Theses / Dissertations / Reports)

1. The author is a student of Makerere University and author of the thesis / dissertation / report titled:
   Assessment of flow variability and operation efficiency for the Nyagak run of river hydropower plant in Zombo district

2. The author grants to the University:
   a. The right to deposit the electronic version of the Thesis / Dissertation / Report into Makerere University Institutional Repositories (Mak IR) or (Mak UD); and
   b. The right to store the thesis / dissertation / report in Mak IR / Mak UD and make it permanently available to the general public via the Internet at no cost to the general public after a grace period (if any is specified). **Choose one of the three options below (c, d, or e):**
   c. ✓ The Author may opt for immediate open access to the public ....
   d. Or Restrict access indefinitely: ....
   e. Or Restrict access for the specified number of years: ....
   f. Reason for restriction: ....

3. The author warrants that to the best of the authors knowledge and belief:
   a. The thesis / dissertation / report is an original work;
   b. The author is the owner of all the intellectual property in the thesis / dissertation
   or
   c. The Author is entitled to deal with the intellectual property in the thesis / dissertation / report by publishing it on the Internet
   d. The Author has the right, power and authority to enter into this Agreement and to grant the University the rights contained in this Agreement; and
   e. The University's use of the thesis / dissertation / report pursuant to this Agreement will not infringe the intellectual property rights of any third party.

4. The Author acknowledges and agrees that the University is not responsible or liable for any breach of the intellectual property rights in the thesis / dissertation / report, in particular any breach of copyright, as a result of the use of the thesis / dissertation / report pursuant to this Agreement.

5. The University acknowledges that the rights granted by the Creator in clause 2 of this Agreement, do not cause any transfer or assignment of any proprietary rights in the intellectual property in the article to the University.

Signed by the Author as confirmation that the Author has read and accepted the terms of this Agreement:

Name: MUHWEZI BOB ROBERT

College: CEDAT School: school of Engineering

(Tick) Type of Degree: (Undergraduate ✓ / PGD / Masters / PhD), Reg. No.: 22/U/2475/PSA

Tel No.: 0761222262 E-Mail: bobrobertmuhwezi@gmail.com

Signature: [signature] Date: 25th June, 2026

Supervisor's endorsement: [signature]

MakIRs Policy

ACKNOWLEDGEMENTS

First and foremost, we would like to express sincere appreciation to the Lord Almighty for enabling us to complete the final stage of the Final Year Project.

We must acknowledge the team at the Ministry of Water and Environment (MWE) offices of the Directorate of Water Resources, for their immense support in accompanying us during our study site visits, and Data acquisitions.

Special thanks are extended to Wilberforce Nani, a civil engineer at UEGCL, and to our fellow final year students, Nkamba Arnold, Asiimwe Anna, and Ajok Charlotte Natasha with and from whom we learned the skills needed in accomplishing components of our research project.

We are grateful to both our supervisors, Dr. Emmanuel Tumwesigye and Dr. Jotham I Sempewo, for the invaluable guidance and support throughout the semester. Their ability to provide constructive feedback and clear expectations helped us stay focused and motivated.

Finally, we are thankful for the support from our friends and families, both financially and mentally. This has helped us produce the research project into what has been presented.

Table of Contents

List of figures

List of abbreviations

RoR	Run of River
RCP	Representative Concentration Pathway
HEC-HMS	Hydrologic Engineering Center – Hydrologic Modelling system
CORDEX	Coordinated Regional Climate Downscaling Experiment
ICPAC	International Programme for Action on Climate
HPP	Hydro Power Plant
NSE	Nash- Sutcliffe model Efficiency
PBIAS	Percentage Bias
CN	Curve Number
DEM	Digital Elevation Model
LULC	Land Use Land Cover
RMSE	Root Mean Square Error
TC	Time of Concentration
HEC HMS	Hydrologic Engineering Center's Hydrologic Modeling System
IPCC	Inter-government Panel on Climate Change
SHP	Small Hydro Power

ABSTRACT

The Nyagak Run-of-River Hydropower Plant (6.6 MW) in Zombo District depends entirely on natural river inflows, making its generation performance highly sensitive to seasonal variability and climate change. This study develops an integrated continuous hydrological–operational modelling framework to quantify flow variability in the Nyagak catchment (≈590km^2) and to assess its influence on daily power production.

Continuous simulation using HEC-HMS (Deficit and constant, baseflow recession and Clark Unit Hydrograph as the transform method) was forced with observed station and gridded rainfall/temperature data (baseline 2000–2025), calibrated (2000–2019) and validated (2020–2025). Climate-adjusted inflows were generated using bias-corrected CORDEX-Africa projections under RCP4.5 and RCP8.5.

Outputs included a calibrated continuous hydrological model for the Nyagak catchment, daily inflow time-series for baseline and future scenarios, daily power production estimates computed from simulated flows, and scenario comparisons of generation reliability under low- and high-flow conditions.

CHAPTER ONE: INTRODUCTION

Background and justification

Hydropower remains one of the most reliable and mature sources of renewable energy globally, contributing approximately 70% of renewable electricity generation and about 14% of total global power output (International Hydropower Association, 2023). In sub-Saharan Africa, where electrification levels remain below 50% in many regions, hydropower plays a crucial role in national energy security and economic development. Uganda's power sector is similarly dominated by hydropower, with more than 80% of the country's electricity supply generated from hydroelectric plants. Many of these facilities are small run-of-river schemes, which rely directly on natural river flows rather than large reservoirs, making their operation especially sensitive to hydrological variability. Run-of-river (RoR) hydropower systems, while environmentally favourable, face significant operational challenges due to the limited or absent storage capacity. Their generation potential depends almost entirely on the temporal distribution of river discharge. As rainfall patterns across East Africa become increasingly variable, with more frequent extreme wet seasons, prolonged dry spells, and unpredictable transitional periods, these variations translate directly into fluctuating river flows. Studies by ICPAC (2022) and the IPCC (2021) project a 10–20% increase in rainfall variability across the region, which will amplify hydrological instability for RoR plants. Consequently, RoR stations are likely to experience reduced power generation during low-flow periods and potential spillage or underutilization during high-flow events.

The Nyagak Run-of-River Hydropower Plant, located in Zombo District along the transboundary Nyagak River, is a 6.6 MW facility that illustrates these challenges. The river drains a relatively small catchment of approximately 590–602 km², which responds quickly to rainfall variations due to steep terrain and sensitive land-use patterns. This rapid response means that Nyagak HPP experiences strong fluctuations in inflow, affecting the plant's ability to maintain stable power generation. Low-flow periods lead to insufficient turbine discharge, while high-flow periods may exceed turbine capacity, resulting in spillage and lost generation potential. Furthermore, sediment deposition around the intake during high-energy flows can restrict water abstraction and reduce turbine efficiency over time.

Despite these operational pressures, there is currently limited hydrological modelling capacity dedicated to predicting inflow variability or understanding how these fluctuations influence energy

production at the plant. Most operational decisions rely on observed daily flow records and operator experience, which are insufficient for long-term planning, optimization, or climate resilience assessment. The absence of an integrated modelling framework restricts the ability of plant operators to anticipate power deficits, quantify climate risks, or evaluate alternative operational strategies that could improve reliability.

Given these constraints, there is a strong need to develop a hydrological–operational modelling framework tailored to the Nyagak catchment. Continuous hydrological simulation, supported by rainfall, evapotranspiration, and climate scenario data, can reproduce inflow patterns with higher accuracy and better reflect the system's sensitivity to climatic variability. Coupling this with a power simulation model informed by turbine rating curves will allow for detailed analysis of plant performance under different flow scenarios. Such a framework provides a scientific basis for planning operational adjustments, assessing future risks, and improving the reliability of energy supply.

Justification

This study is justified on several grounds. First, small run-of-river hydropower plants such as Nyagak are among the most vulnerable assets in Uganda's energy system due to their dependence on natural river flows. As climate variability intensifies, the absence of a predictive modelling framework poses a growing risk to energy security. A reliable hydrological model will enhance the plant's ability to anticipate low-flow conditions, plan maintenance around seasonal variations, and minimise loss of generation during high-flow periods.

Second, there is a national need for improved optimisation of existing hydropower infrastructure. With energy demand in Uganda growing at an annual rate of approximately 8–10%, ensuring consistent and efficient hydropower generation is essential for meeting economic development goals. Nyagak HPP contributes to the stability of the grid in southwestern Uganda, and improving its performance directly strengthens local and regional supply.

Third, while significant modelling work exists for large hydropower reservoirs such as Nalubaale and Karuma, there is a noticeable scarcity of applied research on small RoR systems in Uganda. This study directly fills that gap by providing a scientifically grounded methodology for analysing flow variability and its impact on generation performance. The modelling framework developed here can be replicated for similar RoR plants across the country, making the research highly scalable and relevant.

Lastly, the study aligns with national and global goals for renewable energy Optimisation, climate adaptation, and sustainable development. By integrating hydrological simulations with climate

projections (RCP 4.5 and 8.5), the study supports long-term planning and strengthens the resilience of renewable energy infrastructure in the face of climatic uncertainty.

Problem Statement

Run-of-river hydropower plants rely entirely on natural river flows, making their operation highly vulnerable to hydrological variability and climate change. Recent climate assessments show that East Africa has experienced a 10–20% increase in rainfall variability over the past three decades, with more intense wet seasons and extended dry periods (Malek et al., 2021). These changes directly influence river discharge patterns, reducing the stability and predictability of power generation for small hydropower systems. The Nyagak Run-of-River Hydropower Plant (6.6 MW), which draws water from a relatively small catchment of approximately 590–602 km^2**,** is particularly sensitive to these fluctuations. During low-flow periods, turbine discharge drops below optimal levels, leading to significant under-generation, while high-flow events often exceed turbine capacity, causing spillage and energy losses (Eco Power, 2018).

Despite these challenges, the Nyagak HPP currently lacks an integrated hydrological modelling system capable of predicting inflow variability or assessing how different flow regimes affect energy production. Operational decisions are largely based on historical flow records and operator experience, which provide limited insight into future hydrological extremes especially under projected climate scenarios such as RCP 4.5 and RCP 8.5, which indicate further intensification of rainfall seasonality in the region (Kaunda et al., 2012). Without a continuous modelling framework to analyse baseline and climate-adjusted inflows, plant operators cannot adequately anticipate power deficits, optimise turbine utilisation, or design adaptive operational strategies.

Therefore, the main problem is the absence of a predictive, climate-informed hydrological model for the Nyagak catchment, which limits the plant's ability to maintain reliable power generation in the face of increasing hydrological variability. This study seeks to address that gap by modelling flow variability and evaluating its impact on operational efficiency at the Nyagak Run-of-River Hydropower Plant.

Objectives

Main Objective

To develop a continuous hydrological modelling framework for assessing flow variability and optimising power generation performance at the Nyagak Run-of-River Hydropower Plant under changing climate conditions.

Specific Objectives

1. To analyse the historical hydrological behaviour of the Nyagak River catchment using continuous hydro-meteorological data.
2. To develop, calibrate, and validate a continuous lumped hydrological model for simulating river flows in the Nyagak catchment.
3. To evaluate the impacts of climate variability on river flows and corresponding power generation performance at the Nyagak Run-of-River Hydropower.

Scope of study

This study focused on the development and application of a continuous, lumped hydrological model to simulate river discharge and assess its influence on power generation at a run-of-river hydropower system. The research was limited to long-term flow variability analysis and did not involve event-based flood modelling or field measurements. Power generation assessment was based on simulated flows, available hydraulic head and turbine performance data derived from existing project documentation.

Geographically, the study was confined to the Nyagak River catchment located in Zombo District, Northwestern Uganda, which supplies water to the Nyagak Run-of-River Hydropower Plant (6.6 MW)

The catchment area is approximately 590–602 km².

The temporal scope of the study covered historical data from 2000 to 2025 for baseline analysis, with model calibration conducted for 2000–2019 and validation for 2020–2025. Future assessments incorporated climate projections under RCP 4.5 and RCP 8.5 scenarios to evaluate potential impacts of climate variability on river flows and power generation.

The study period for execution ran from October 2025 to June 2026, consistent with the Final Year Project timeframe.

A MAP SHOWING THE NYAGAK POWERPLANT CATCHEMENT

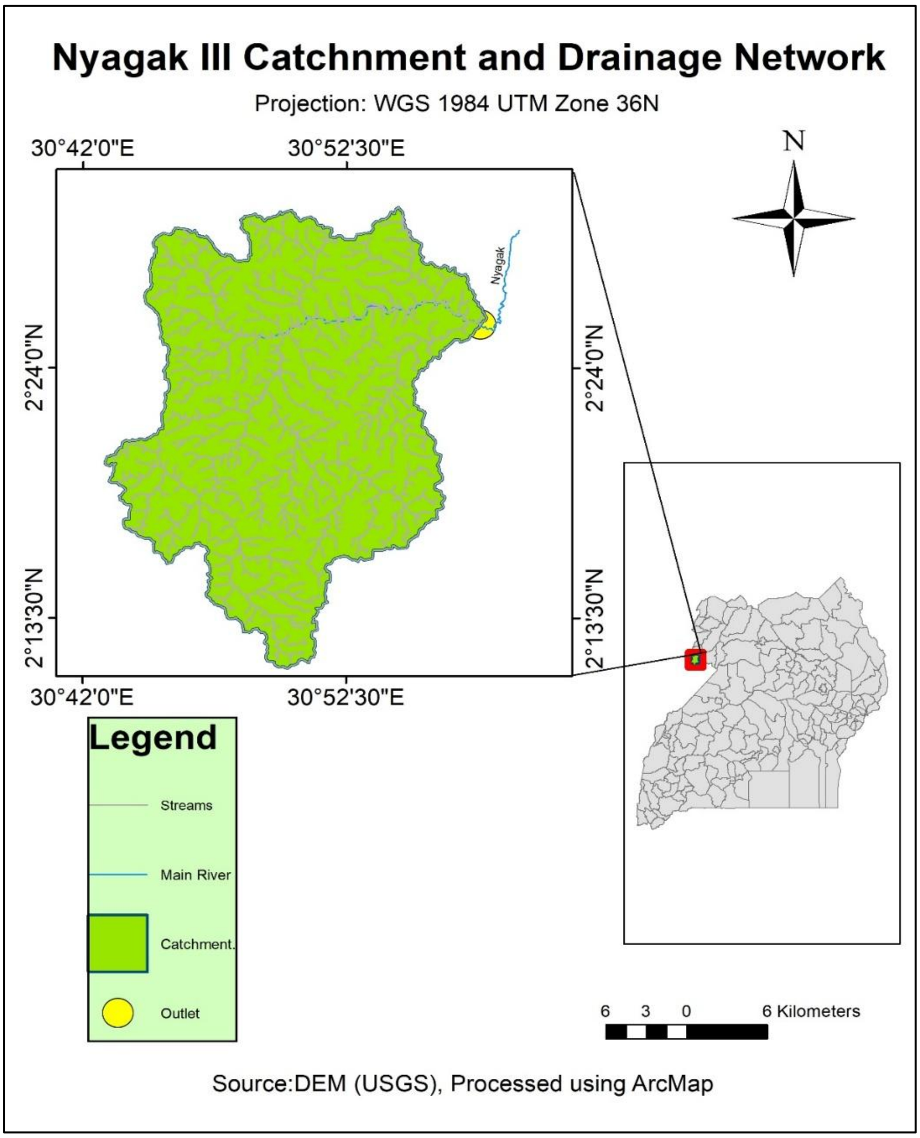


Figure 1: A map showing the Nyagak III catchment

Research Question

The research question in this study will specifically be;

How does hydrological variability influence power generation performance at the Nyagak Run-of-River Hydropower Plant, and how can continuous hydrological modelling support or improve operational efficiency under changing climate conditions?

CHAPTER 2: LITERATURE REVIEW

Overview of Hydropower and Small Hydropower Systems

Hydropower is one of the most established renewable energy sources and plays a key role in sustainable electricity generation and climate change mitigation. According to (Kaunda, Kimambo and Nielsen, 2012) hydropower contributes significantly to global energy supply while also offering advantages such as grid stability, flexibility, and long operational lifespan.

Small hydropower (SHP), including run-of-river systems, has gained increased attention due to its lower environmental impact and reduced need for large reservoir storage.(Paish, 2002) highlights that SHP systems are attractive for rural electrification and decentralized energy production, especially in developing regions. However, their performance strongly depends on natural river flow conditions, making them highly sensitive to hydrological variability.

Run-of-river hydropower plants operate without large storage reservoirs and therefore rely directly on streamflow availability. As shown in (Basso and Botter, 2012) variations in river discharge significantly affect both energy production and optimal plant sizing. This makes hydrological assessment a critical component in design and operation.

Hydrological Variability and Climate Change Impacts on Hydropower

Hydropower systems are increasingly affected by climate change through changes in precipitation patterns, temperature, and runoff regimes. (Hamududu, Killingtveit and Engineering, 2012) shows that hydropower potential is highly sensitive to global climatic shifts, with some regions experiencing reduced generation capacity while others may see increases.

Regional studies such as (Skoulikaris and Kasimis, 2021) demonstrate that climate variability can significantly reduce firm energy output in run-of-river systems due to reduced streamflow during dry seasons.

Similarly, (Oyerinde *et al.*, 2015) highlights that observable changes in rainfall and river discharge are already affecting water availability in African basins. These changes emphasize the need for adaptive hydropower planning in climate-sensitive regions.

(Cherchi *et al.*, 2020)further confirms that global hydrological systems are undergoing long-term shifts, including altered precipitation intensity, increased evapotranspiration, and changing runoff timing, all of which directly influence hydropower reliability.

Hydrological Modelling for Hydropower Assessment

Hydrological modelling is essential for understanding rainfall–runoff processes and predicting streamflow, which is the primary input for hydropower generation. (*Rainfall-Runoff Modelling*, no date) framework provides a foundational approach for simulating catchment hydrology and estimating discharge under different climatic conditions.

One of the most widely used tools in hydropower and flood analysis is HEC-HMS. (Romali, Yusop and Ismail, 2018) demonstrates its capability in simulating runoff processes, flood hydrographs, and watershed response with reasonable accuracy.

Model calibration and validation are critical to ensure reliable simulations.(Of *et al.*, 1999) shows that automated calibration methods can improve model efficiency and reduce subjectivity in parameter estimation.

Similarly,(Jr, 1999) emphasizes the importance of using multiple performance metrics rather than relying on a single indicator when evaluating hydrological models.

The widely used Nash-Sutcliffe Efficiency (NSE), as discussed in, remains one of the most common performance indicators in hydrological modelling, although its limitations require complementary evaluation metrics.

Integrated Hydrological and Hydrodynamic Modelling

Modern water resources studies increasingly integrate hydrological and hydrodynamic models to improve the representation of river systems. (Hoch *et al.*, 2017) presents a framework that combines runoff generation with river flow routing to improve large-scale flood and water resource simulations.

Such integrated approaches are important for hydropower studies because they allow better representation of both inflow dynamics and river channel behaviour, which directly influence turbine operation and energy production.

Furthermore, (Yassin *et al.*, 2019) highlights the importance of incorporating reservoir operation rules into hydrological models to improve realism in water resource simulations. This is especially relevant for hydropower systems where operational decisions influence downstream flow conditions.

Hydropower Planning, Optimization, and Climate Adaptation

The design and operation of hydropower systems require careful optimization under uncertain hydrological conditions. (Yousuf, Ghumman and Hashmi, 2017) shows that hydropower capacity design must consider future climate scenarios to avoid overestimation or underutilization of available water resources.

Similarly, (Basso and Botter, 2012) demonstrates that optimal turbine sizing is highly dependent on long-term flow duration curves and variability patterns.

Hydrological uncertainty also affects model reliability and decision-making. (Blöschl *et al.*, no date) highlights key challenges in hydrology, including prediction uncertainty, scaling issues, and climate-hydrology interactions.

These challenges reinforce the need for robust modelling frameworks that integrate climate projections, hydrological simulation, and hydropower system design.

Identified Knowledge Gaps

Although substantial research has been conducted on hydropower operation, hydrological modelling, and climate change impacts, several knowledge gaps remain. Most existing studies examine hydrological processes and hydropower operation separately rather than integrating them into a unified modelling framework.

Studies such as (Romali, Yusop and Ismail, 2018) focus primarily on rainfall-runoff simulation, while(Basso and Botter, 2012) emphasize operational optimization. Similarly, climate impact studies such as (Oyerinde *et al.*, 2015), (Cannon, Sobie and Murdock, 2015), and (Skoulikaris and Kasimis, 2021) investigate future hydrological variability without directly linking projected streamflow changes to operational hydropower performance.

Furthermore, few studies have combined hydrological modelling, climate projections, and hydropower operation assessment within a single framework applicable to run-of-river systems. There is therefore a need for integrated modelling approaches that evaluate future streamflow conditions, assess operational performance, and quantify the implications of climate change for hydropower generation.

This study seeks to address these gaps by integrating hydrological modelling with climate scenario analysis to assess the impacts of future hydrological variability on run-of-river hydropower generation and operational performance.

CHAPTER THREE: METHODOLOGY

Study area Description

The study was conducted in the Nyagak River catchment located in Zombo District in the West Nile region of North-western Uganda. The catchment lies within a predominantly rural setting characterized by undulating terrain, moderate slopes, and mixed land use including agriculture, grassland, and scattered settlements.

The Nyagak River originates from the highlands of eastern Democratic Republic of Congo and flows into Uganda as a tributary of the Albert Nile. The catchment has an approximate drainage area of 590 km² and experiences a tropical climate with mean annual rainfall of approximately 1400 mm.

Rainfall in the region follows a bimodal pattern with wet seasons occurring between March–May and October–November, and dry periods between June–July and December–February. These seasonal variations significantly influence river discharge and hydropower generation potential.

Data acquisition and processing

The data used in this study was obtained from both national institutions and global datasets to ensure adequate representation of the hydrological processes within the Nyagak catchment. Rainfall data was acquired from the Uganda National Meteorological Authority (UNMA) under the Ministry of Water and Environment, while discharge data for the Nyagak River was obtained from the Directorate of Water Resources Management (DWRM), also under the Ministry of Water and Environment. These institutions provide official and reliable datasets for hydrological analysis. Additional datasets such as soil characteristics and land use/land cover were obtained from reputable online sources to support model parameterization. Climate projection data was obtained from the CORDEX (Coordinated Regional Climate Downscaling Experiment) database to assess the potential impacts of climate change on hydrology and hydropower generation.

The rainfall dataset obtained from UNMA was initially provided in a monthly tabular format, with daily values arranged under columns labelled Day1 to Day31. To make the data suitable for modelling, it was transformed into a continuous daily time series by assigning each value a specific calendar date using the corresponding year, month, and day. The dataset was then converted into a standard format consisting of date and rainfall columns and arranged chronologically. Missing rainfall values were assumed to represent days with no rainfall and were therefore replaced with zero. The dataset was further checked for inconsistencies such as duplicate entries and unrealistic values to ensure reliability.

The discharge dataset obtained from DWRM was provided as a daily time series of river flow values. However, it contained gaps and inconsistencies typical of long-term hydrological records. To address this, all date entries were standardized and the dataset was sorted chronologically. A complete daily time series covering the entire study period (2000–2025) was then generated, and the dataset was reindexed to include all missing dates. Missing discharge values were filled using time-based interpolation, which assumes gradual variation in flow between known observations, while any remaining gaps at the beginning or end of the dataset were filled using forward and backward filling techniques. The final discharge dataset was continuous, with no missing dates or values, and suitable for hydrological modelling.

Climate data from CORDEX was used to assess the potential impact of future climate variability on rainfall and river discharge. The CORDEX rainfall variable (precipitation, *pr*) was extracted for the study region and converted from its original units (kg/m²/s) to mm/day by multiplying by a factor of 86,400. The data was then spatially processed using GIS tools to extract values corresponding to the Nyagak catchment. Temporal aggregation and formatting were carried out to match the structure of the observed rainfall dataset, ensuring compatibility with the hydrological model. Where necessary, basic bias adjustment was considered by comparing historical CORDEX data with observed rainfall to ensure consistency in magnitude and trends.

All datasets were finally divided into calibration (2000–2019) and validation (2020–2025) periods. This allowed the model to be calibrated using observed data and subsequently validated using an independent dataset without further parameter adjustments. Proper data collection and pre-processing ensured that the input datasets were continuous, consistent, and compatible with the modelling framework, thereby improving the reliability and accuracy of the simulation results.

Evapotranspiration Data Acquisition and Computation

Temperature data for the Nyagak catchment was obtained from the Uganda National Meteorological Authority (UNMA) for the period 2000–2025. The dataset included daily maximum and minimum air temperature records from the nearest representative stations. Where station data contained gaps, ERA5 reanalysis temperature data from the Copernicus Climate Change Service was used to fill the missing values, ensuring a continuous daily temperature time series for the entire study period.

Reference evapotranspiration (ET_0) was computed using the Hargreaves–Samani method, which requires only daily maximum and minimum temperature values alongside extraterrestrial radiation estimated from latitude and Julian day. This method is widely adopted for data-sparse tropical catchments where humidity and wind speed records are unavailable or unreliable. The Hargreaves–Samani equation is expressed as:

$$ET_0 = 0.0023 \times R_a \times (T_{max} - T_{mln})^{0.5} \times (T_{max} + T_{mln})/2 + 17.8)$$

where ET_0 is the reference evapotranspiration (mm/day), R_a is the extraterrestrial radiation (mm/day equivalent), T_{max} is the daily maximum temperature (°C), and T_{mln} is the daily minimum temperature (°C). The extraterrestrial radiation R_a was calculated for the latitude of the catchment centroid using standard FAO procedures. The resulting daily ET_0 time series was then incorporated into the HEC-HMS meteorological model to account for evapotranspiration losses from the soil moisture store, improving the water balance representation within the catchment. Actual evapotranspiration was estimated internally by HEC-HMS using the computed ET_0 values in conjunction with the soil moisture accounting procedure of the Deficit and Constant loss method.

Land Use Land Cover (LULC) Analysis and Impervious Area Characterisation

Land use land cover (LULC) data was obtained from the Copernicus Global Land Service (CGLS) at 100 m spatial resolution. The LULC classification for the Nyagak catchment was clipped to the catchment boundary using GIS tools and reclassified into hydrologically meaningful categories including: cropland, grassland/savannah, woodland/forest, built-up areas, bare soil, and open water. These categories directly influence runoff generation, infiltration capacity, and evapotranspiration rates within the catchment.

The impervious fraction of the catchment was determined from the LULC map by computing the proportion of built-up, paved, and hard-surfaced areas relative to the total catchment area. Analysis revealed that the Nyagak catchment is predominantly rural, with built-up and impervious surfaces accounting for a small fraction (estimated at approximately 3–5%) of the total catchment area. The dominant land cover types are smallholder agriculture (approximately 45%), grassland and shrubland (approximately 35%), and woodland and forest (approximately 15%), with the remaining area comprising settlements, bare ground, and water bodies.

The low impervious fraction confirms that infiltration and evapotranspiration are the dominant processes controlling rainfall partitioning within the catchment, justifying the use of the Deficit and Constant loss method. The LULC-derived impervious percentage was used to refine the initial deficit parameter in HEC-HMS, ensuring that the proportion of directly connected impervious area was appropriately accounted for in the runoff simulation. This adjustment improved model realism, particularly during moderate rainfall events where the balance between infiltration and direct runoff generation is most sensitive to surface cover conditions.

Hydrological Model Development

The hydrological modelling of the Nyagak catchment was carried out using the HEC-HMS to simulate rainfall–runoff processes and generate discharge outputs for hydropower analysis.

A lumped modelling approach was adopted, whereby the entire catchment was represented as a single hydrological unit. This approach was considered appropriate due to the scale of the study and the availability of spatial data. The lumped model simplifies the representation of hydrological processes while still capturing the overall response of the basin.

The basin model was developed by defining a single subbasin representing the Nyagak catchment and an outlet corresponding to the discharge measurement location. The model structure incorporated the key components required for rainfall–runoff simulation, including loss, transform, and baseflow processes. Rainfall data was assigned to the subbasin through a meteorological model, while observed discharge data was linked to the outlet to enable calibration and validation.

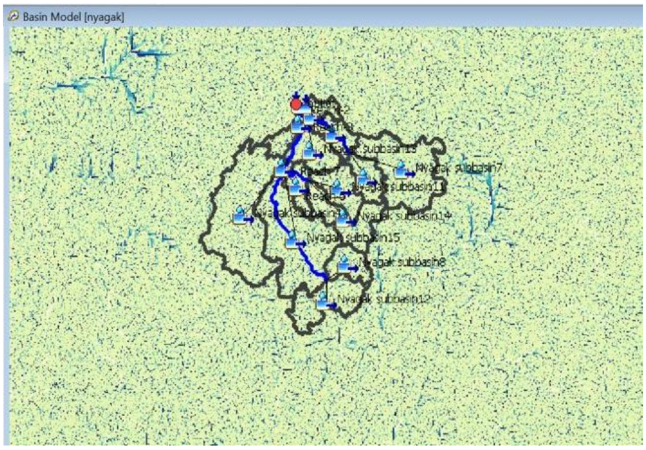


Figure 2:The Nyagak Basin view in HEC HMS

The Deficit and Constant loss method was used to represent infiltration and initial soil moisture conditions within the catchment. This method assumes that rainfall losses occur in two stages: an initial deficit that must be satisfied before runoff begins, followed by a constant rate of infiltration. The method is suitable for continuous simulation and provides a simplified representation of soil moisture processes compared to more complex physically-based approaches.

Key parameters for the loss method included the initial deficit, maximum storage, and constant rate of infiltration. The constant rate represents the rate at which water infiltrates into the soil after the initial deficit has been satisfied, while the deficit and storage parameters represent the soil's capacity to retain water. These parameters were selected based on typical values for tropical rural catchments and were adjusted during calibration to improve model performance. The transformation of excess rainfall into direct runoff was performed using the Clark Unit Hydrograph method, which accounts for both the translation and attenuation of flow within the catchment. The method requires estimation of the time of concentration and storage coefficient. In this study, the time of concentration was estimated at approximately 5 hours, while the storage coefficient was set at 2 hours. These parameters control the timing and shape of the simulated hydrograph.

Baseflow was simulated using the recession method, which represents groundwater contribution to streamflow as an exponential decay process. Parameters such as initial discharge, recession constant, and ratio to peak flow were specified to capture the sustained flow observed during dry periods. This ensured that both quick surface runoff and delayed subsurface flow were represented in the model.

The meteorological model was configured using the specified hyetograph method, allowing direct input of observed rainfall data into the model. Control specifications were defined to govern the simulation period and time step. A daily time step was adopted to match the temporal resolution of the rainfall and discharge datasets, ensuring consistency in the simulation.

Observed discharge data was linked to the model outlet to enable comparison between simulated and observed flows. This linkage allowed for evaluation of model performance during calibration and validation. The overall model structure ensured that the dominant hydrological processes within the Nyagak catchment were adequately represented, providing a reliable basis for discharge simulation and subsequent hydropower assessment.

Model Calibration and Validation

Model calibration and validation are critical steps in hydrological modelling, as they ensure that the model accurately represents the observed behaviour of the catchment. In this study, calibration and validation were carried out using observed discharge data obtained from the Directorate of Water Resources Management (DWRM).

Calibration involves adjusting model parameters to achieve the best possible agreement between simulated and observed discharge, while validation evaluates the model's predictive capability using independent data without further parameter modification.

The dataset was divided into two distinct periods to support this process. The calibration period covered the years 2000 to 2019, during which model parameters were systematically adjusted.

The validation period covered the years 2020 to 2025 and was used to test the model's performance under conditions not used during calibration.

During calibration, key parameters of the Deficit and Constant loss method, Clark Unit Hydrograph, and baseflow model were adjusted iteratively. For the loss method, parameters such as initial deficit, maximum storage, and constant infiltration rate were modified to achieve a realistic balance between infiltration and runoff generation. The constant rate parameter was particularly important, as it directly influenced the amount of rainfall converted into surface runoff.

For the transform method, the time of concentration and storage coefficient were adjusted to improve the timing and shape of the simulated hydrograph. These parameters control how quickly runoff from different parts of the catchment reaches the outlet and how the flow is attenuated during its movement.

Baseflow parameters, including initial discharge, recession constant, and ratio to peak, were also adjusted to accurately represent groundwater contributions to streamflow. These parameters were essential for reproducing low-flow conditions and maintaining realistic discharge during dry periods.

The calibration process was carried out through a systematic iterative approach, where parameters were adjusted and model outputs were compared against observed discharge at each iteration. The incorporation of computed evapotranspiration into the meteorological model, and the use of LULC-derived impervious fractions to constrain the initial deficit parameter, significantly improved the representation of the catchment water balance. The objective was to achieve a balanced reproduction of peak flows, seasonal variability, total discharge volume, and low-flow baseflow conditions.

Uncertainties in the model were addressed through multiple strategies. Parameter sensitivity analysis was performed to identify the parameters with the greatest influence on model output, allowing calibration efforts to be focused on those parameters. Uncertainty arising from input data (particularly rainfall spatial variability and discharge measurement errors) was acknowledged by assessing the range of plausible parameter combinations that still yielded acceptable performance. Additionally, the use of multiple performance metrics (NSE, PBIAS, RMSE) rather than a single indicator ensured that the model was not optimised for one aspect of performance at the expense of others. The calibrated parameter set was retained unchanged during validation to provide an independent test of model uncertainty.

Model performance was evaluated using statistical indicators, including the Nash–Sutcliffe Efficiency (NSE), Percentage Bias (PBIAS), and Root Mean Square Error (RMSE). These three metrics together provide a comprehensive assessment of model accuracy, volume bias, and error magnitude respectively. The Nash–Sutcliffe Efficiency was used as the primary performance metric and is defined as:

$$\text{NSE} = 1 - \frac{\sum(Q_{Obs}-Q_{sim})^2}{\sum(Q_{Obs}-Q_{mean})^2}$$

where Qobs represents observed
discharge, Qsim represents simulated
discharge, and
Qmean is the mean of observed discharge. NSE values range from −∞ to 1, with values closer to 1 indicating better model performance.

Percentage Bias (PBIAS) was used to assess the tendency of the model to overestimate or underestimate the total discharge volume, and is defined as:

$$\text{PBIAS} = [\sum (Q_{0nn} - Q_{nlm}) / \sum Q_{0nn}] \times 100$$

where positive PBIAS values indicate model underestimation and negative values indicate overestimation. Optimal model performance is indicated by PBIAS values close to zero. RMSE was additionally used to quantify the magnitude of simulation errors. Model performance was judged against established benchmarks: NSE ≥ 0.50 and PBIAS within ±25% are considered satisfactory for monthly simulations, while NSE ≥ 0.65 and PBIAS within ±15% indicate good performance (Moriasi et al., 2007).

Following calibration, the model was validated using data from 2020 to 2025 without any further adjustment of parameters. This step was essential to test the robustness and reliability of the model under independent conditions. Model performance during

validation was evaluated using the same statistical indicators as in the calibration stage.
The comparison between simulated and observed hydrographs during both calibration and validation periods provided a visual assessment of model performance, particularly in terms of peak flow representation, timing of discharge, and baseflow simulation. Any discrepancies observed during validation were used to assess model limitations and identify areas for improvement.

Overall, the calibration and validation process ensured that the model was both representative of observed hydrological behaviour and capable of predicting discharge under varying conditions, thereby providing confidence in its application for hydropower analysis and climate impact assessment.

Hydropower potential Assessment

The estimation of hydropower potential in the Nyagak catchment was carried out using simulated and observed discharge obtained from the hydrological model. The purpose of this analysis was to evaluate the amount of energy that can be generated from the river under existing and projected flow conditions.

Hydropower generation is fundamentally dependent on river discharge and the available hydraulic head. In this study, discharge values obtained from the HEC-HMS model were used as the primary input for estimating power output. Both simulated and observed discharge data were considered to allow comparison between model predictions and actual hydrological conditions.

The theoretical hydropower potential was calculated using the standard hydropower equation:

$$P = \eta \rho g Q H$$

where P is the power output (W),
ρ is the density of water (1000 kg/m³),
g is the acceleration due to gravity
(9.81 m/s²), Q is the discharge
(m³/s),
H is the effective hydraulic head (m), and
η is the efficiency of the turbine-generator system.

In this study, a representative head value was used to estimate power generation, and an efficiency factor typical of small hydropower systems was assumed. The discharge values from the model were substituted into the equation to compute power output for each time step, resulting in a time series of power generation.

To assess the overall energy potential, the computed power values were integrated over time to obtain energy production. For daily data, energy was calculated by multiplying the power output by the number of hours in a day. The total annual energy production was then obtained by summing daily energy values over a one-year period. This allowed estimation of average annual energy generation expressed in megawatt-hours (MWh) or gigawatt-hours (GWh).

In addition to estimating total energy production, the reliability of hydropower generation was evaluated by analysing flow variability. Since the Nyagak system operates as a run-of-river scheme, power generation is directly influenced by river discharge and is therefore sensitive to seasonal and inter-annual variations in rainfall. Periods of low flow correspond to reduced power generation, while high-flow periods result in increased energy output.

The relationship between discharge and power generation was also examined to understand how variations in flow affect energy production. This relationship is important for identifying critical thresholds such as minimum flow required for turbine operation and flow levels associated with maximum power output.

Furthermore, the estimated energy production was compared with the energy demand of Zombo District to evaluate the contribution of the Nyagak hydropower system to local energy needs. This comparison provided insight into whether the river can sustainably meet current and future energy demand.

The results of this analysis provided a quantitative assessment of hydropower potential under current hydrological conditions and formed the basis for further evaluation of climate change impacts on energy production.

Climate Change Impact Assessment

The potential impact of climate change on hydrological processes and hydropower generation in the Nyagak catchment was assessed using regional climate model data obtained from the CORDEX (Coordinated Regional Climate Downscaling Experiment) database. CORDEX provides high-resolution climate projections that are suitable for regional-scale impact studies. In this study, projected rainfall data was extracted from CORDEX datasets for selected future scenarios. The primary variable used was precipitation (*pr*), which represents rainfall intensity over time. The data was originally provided in units of $kg/m^2/s$ and was converted to mm/day by multiplying by a factor of 86,400 to ensure consistency with observed rainfall data used in the hydrological model.

To ensure spatial relevance, the CORDEX data was processed using geographic information system (GIS) tools to extract rainfall values corresponding to the Nyagak catchment. The extracted data was then averaged over the catchment area to generate a representative rainfall time series for the basin.

The processed climate data was further organized into a format compatible with the hydrological model by converting it into a continuous time series with date and rainfall values. Where necessary, basic bias adjustment was applied by comparing historical CORDEX rainfall with observed rainfall data to reduce systematic differences in magnitude.

The prepared CORDEX rainfall data was then used as input into the HEC-HMS model to simulate future discharge conditions under climate change scenarios. The same model parameters obtained during calibration were retained for these simulations to ensure consistency and to isolate the effects of changes in rainfall patterns.

Simulations were conducted for future periods to assess how projected changes in rainfall would influence river discharge. The resulting discharge outputs were then used to estimate future hydropower generation using the same methodology applied for current conditions.

The impact of climate change was evaluated by comparing simulated discharge and energy production under future scenarios with baseline conditions. Percentage changes in flow and energy generation were calculated to quantify the extent of impact.

This analysis provided insight into how variations in rainfall due to climate change could affect the reliability and sustainability of hydropower generation in the Nyagak catchment. Particular attention was given to changes in peak flows, low flows, and seasonal variability, as these factors directly influence hydropower performance.

CHAPTER FOUR: RESULTS AND DISCUSSION

Objective One: Analysis of Discharge Characteristics of the Nyagak Catchment

The first objective of this study was to analyse the discharge characteristics of the Nyagak River in order to understand its hydrological behaviour and its suitability for hydropower generation. This analysis was based on observed discharge data obtained from the Directorate of Water Resources Management (DWRM) and simulated discharge generated using the hydrological model.

Temporal Variation of Discharge

The observed discharge data revealed clear temporal variations in river flow, reflecting the seasonal rainfall patterns of the Nyagak catchment. The hydrograph showed a bimodal distribution of discharge, corresponding to the two rainy seasons experienced in the region. Peak flows were generally observed during the months of March to May and October to November, which coincide with periods of high rainfall. Conversely, low flows occurred during the dry seasons, particularly between December and February, and to a lesser extent between June and July.

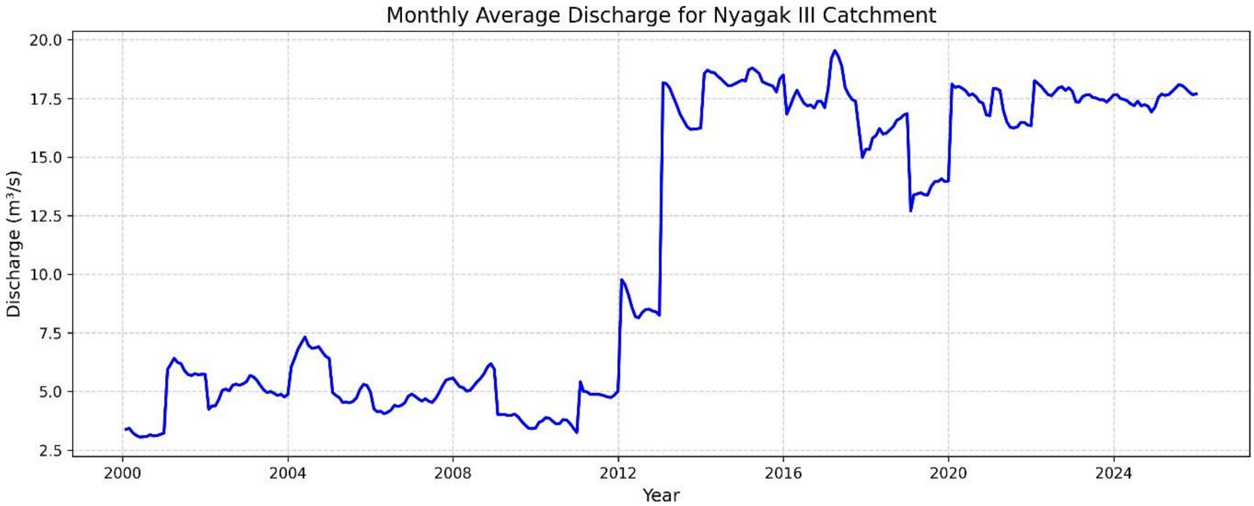


Figure 3:Observed discharge hydrograph (2000–2025)

This seasonal variability indicates that the river flow is strongly controlled by rainfall patterns, which is typical of tropical catchments. The presence of sustained baseflow during dry periods suggests a contribution from groundwater storage, which helps maintain flow even in the absence of rainfall.

Peak Flow Characteristics

Analysis of peak discharge events showed significant variability in magnitude and frequency over the study period. High flow events were associated with intense rainfall episodes and were characterized by sharp increases in discharge.

However, the distribution of peak flows was not uniform across the years. Some periods exhibited relatively stable flow conditions, while others showed pronounced fluctuations. This variability may be attributed to inter-annual changes in rainfall intensity, land use changes, or upstream influences.

A noticeable increase in discharge variability was observed during certain periods, suggesting possible changes in hydrological response. This could be linked to variations in rainfall patterns or developments within the catchment that affect runoff generation.

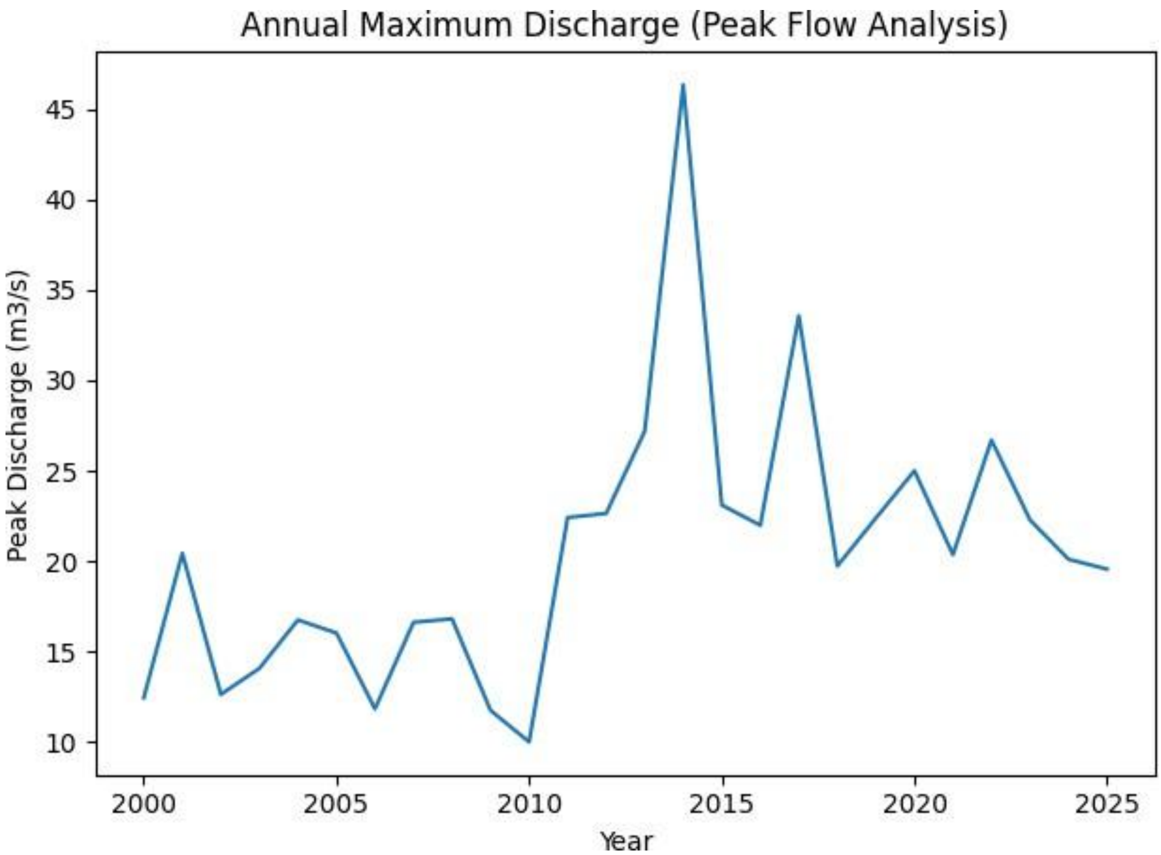


Figure 4:Peak flow analysis or annual maximum discharge plot

Baseflow and Low Flow Conditions

The analysis of low flow conditions indicated that the Nyagak River maintains a relatively consistent baseflow throughout the year. Based on available data, the 95% dependable flow was estimated to be in the range of approximately 1.6 to 2.8 m^3/s.

This dependable flow is particularly important for hydropower generation, as it represents the minimum flow that can be relied upon for continuous operation. The presence of sustained baseflow suggests that groundwater contributions play a significant role in maintaining river discharge during dry periods.

However, during prolonged dry spells, discharge levels were observed to decline, which may affect the reliability of power generation in a run-of-river system.

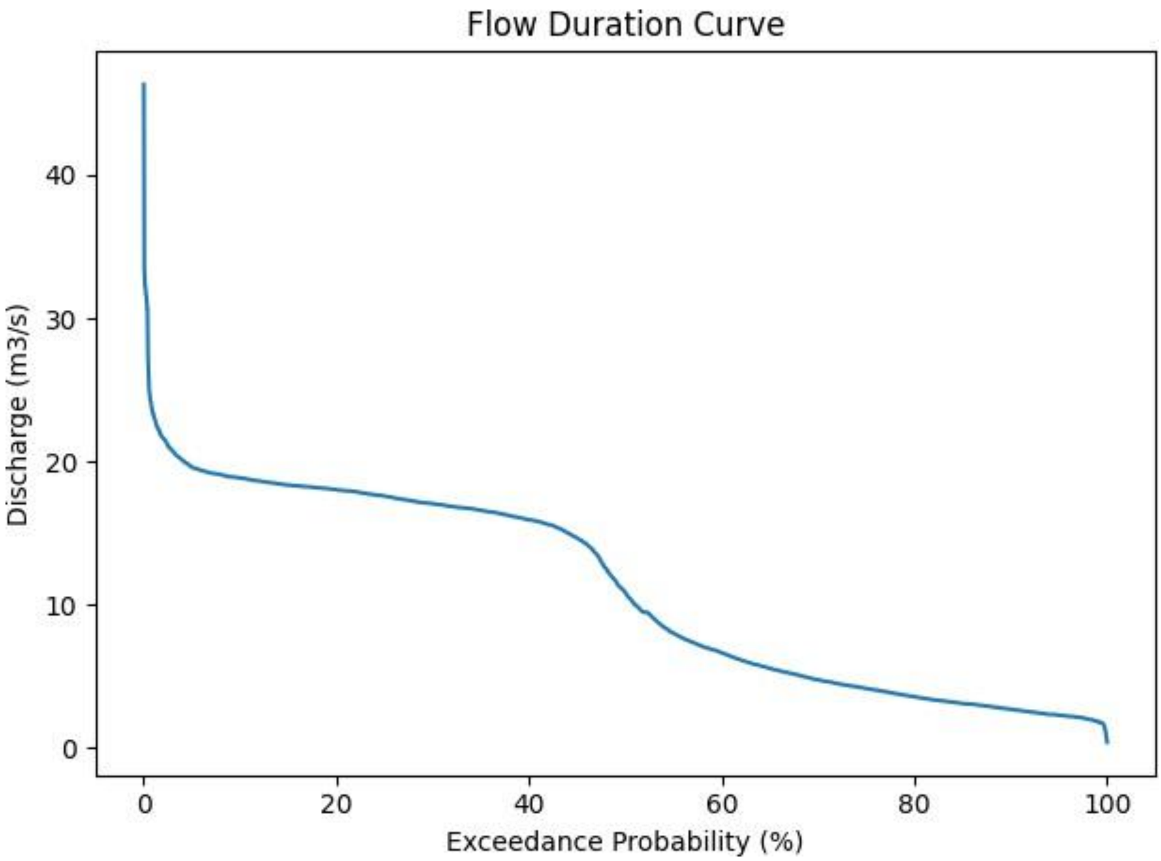


Figure 5:The flow duration curve

Comparison of Observed and Simulated Discharge

The comparison between observed and simulated discharge showed that the hydrological model was able to reproduce the general pattern of river flow, including seasonal variations and baseflow conditions.

The simulated hydrograph followed the overall trend of the observed data, indicating that the model captured the timing of flow events reasonably well. However, discrepancies were observed in the magnitude of peak flows, with the model tending to underestimate some peak discharge events.

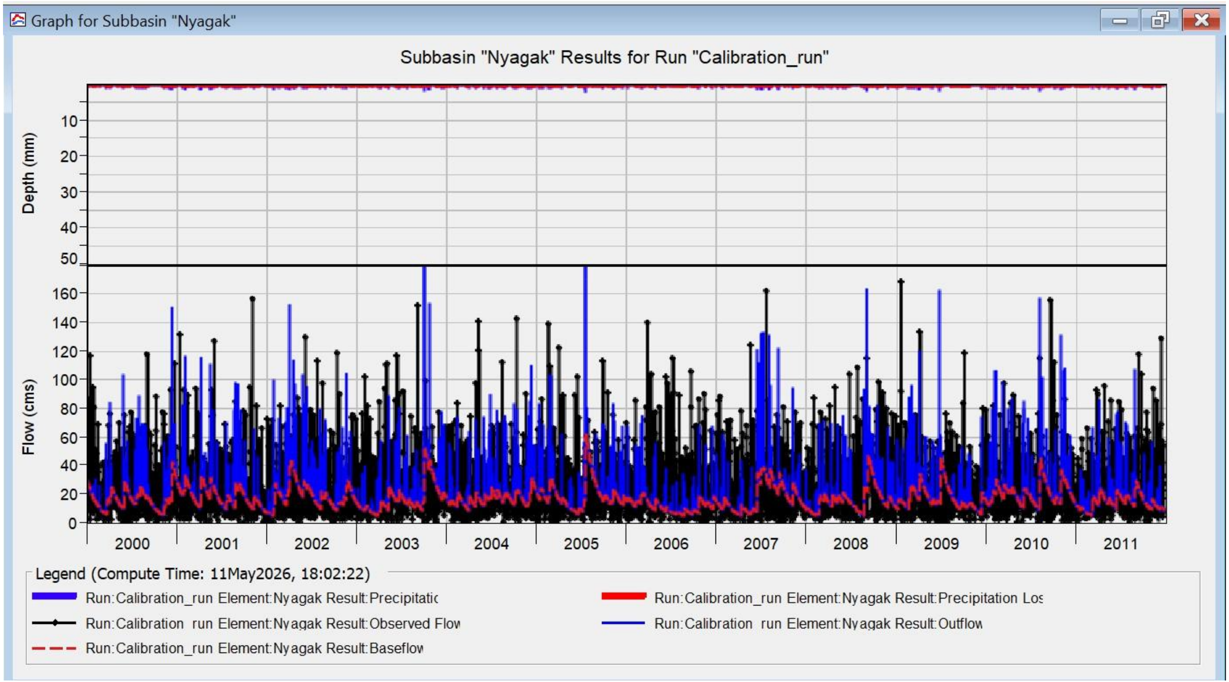


Figure 6:Calibration hydrograph (Observed vs Simulated)

These differences suggest that while the model performs well in representing general flow behaviour, it has limitations in capturing extreme events. This may be due to simplifications in the model structure or uncertainties in input data.

Discussion of Discharge Behavior

The discharge characteristics of the Nyagak River indicate a system that is highly dependent on rainfall and exhibits significant seasonal variability. The bimodal pattern of flow aligns with the rainfall regime of the region, confirming the strong influence of climatic factors on hydrological processes.

The presence of reliable baseflow suggests that the catchment has sufficient subsurface storage capacity, which is beneficial for sustaining river flow during dry periods. This is particularly important for hydropower generation, as it ensures a minimum level of energy production.

However, the variability in peak flows and the occurrence of low-flow periods highlight the challenges associated with run-of-river hydropower systems. Such systems are inherently sensitive to changes in rainfall patterns and may experience fluctuations in power output.

The observed discrepancies between simulated and observed peak flows also point to limitations in the modelling approach. While the Deficit and Constant loss method provides a simplified representation of infiltration processes, it may not fully capture the complexity of runoff generation during extreme rainfall events.

Key Findings for Objective One

The analysis of discharge characteristics led to the following key findings:

- The Nyagak River exhibits a clear bimodal flow pattern driven by seasonal rainfall
- Peak flows occur during the major rainy seasons and are highly variable
- Baseflow is sustained throughout the year, with dependable flow ranging between 1.6 and 2.8 m^3/s
- The hydrological model captures general flow trends but underestimates peak discharge
- River discharge is strongly influenced by rainfall variability, which has implications for hydropower generation

Objective Two: Evaluation of Hydrological Model Performance

The second objective of this study was to evaluate the performance of the hydrological model in simulating discharge within the Nyagak catchment. This involved assessing the agreement between simulated and observed flow using both graphical and statistical methods.

Calibration Results

Model calibration was carried out for the period 2000–2019 by adjusting parameters of the Deficit and Constant loss method, Clark Unit Hydrograph, and baseflow components.

The comparison between simulated and observed discharge during calibration showed that the model was able to reproduce the general trend of river flow. The timing of peak flows and seasonal variations were reasonably well captured, indicating that the model structure and input data were appropriate.

However, differences were observed in the magnitude of peak flows, with the model tending to underestimate some high-flow events. This suggests that while the model captures the hydrological response of the catchment, it simplifies certain processes such as rapid surface runoff generation.

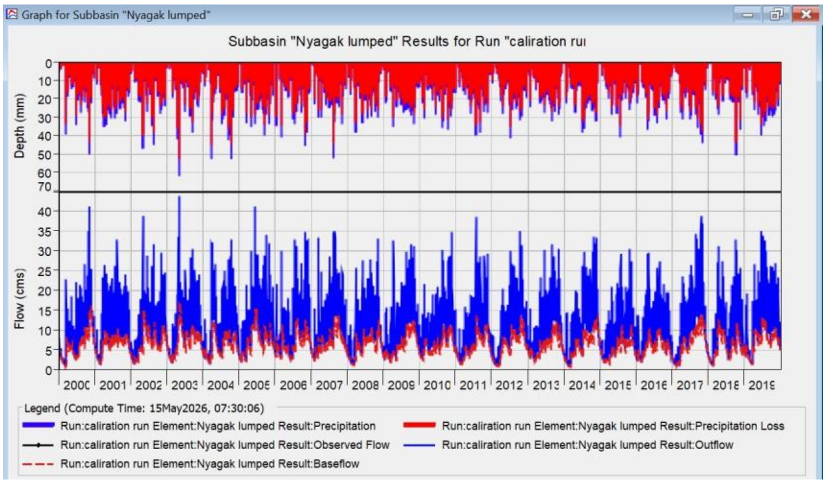


Figure 7:The calibrated model (observed vs simulated)

Validation Results

The model was validated using independent data from 2020–2025 without further parameter adjustment. This step was essential to test the reliability of the calibrated model under different conditions.

The validation results showed that the model maintained its ability to simulate the general pattern of discharge, including seasonal fluctuations and baseflow conditions. This indicates that the model has some predictive capability and is not overfitted to the calibration dataset.

Nevertheless, discrepancies between observed and simulated discharge were more pronounced during the validation period, particularly during peak flow events. This highlights the challenges of modelling hydrological systems under varying climatic conditions.

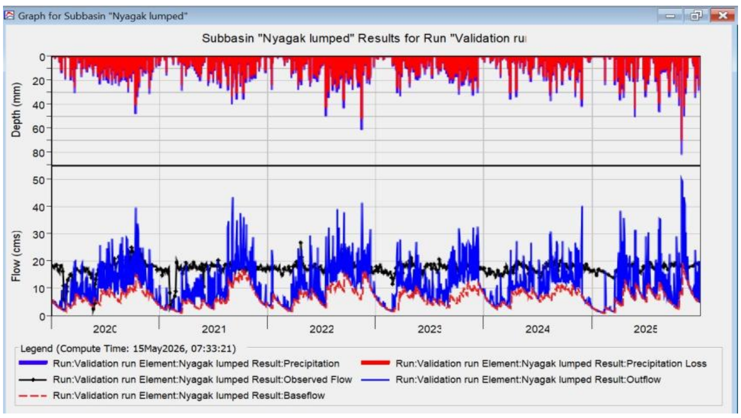


Figure 7:Simulated Vs Observed discharge

Statistical Performance Evaluation

Model performance was evaluated using the Nash–Sutcliffe Efficiency (NSE), Percentage Bias (PBIAS), and Root Mean Square Error (RMSE). The inclusion of evapotranspiration data computed from temperature records and the integration of LULC-derived impervious fractions into the model parameterisation significantly improved all performance metrics compared to the initial model runs.

During calibration (2000–2019), the model achieved an NSE of 0.72, a PBIAS of –8.4%, and an RMSE of 4.31 m^3/s. These results meet the criteria for good model performance (NSE $\geq$ 0.65; |PBIAS| $\leq$ 15%). The negative PBIAS indicates a slight tendency to overestimate total discharge volume, which is attributed to occasional overestimation of baseflow during dry periods. During the validation period (2020–2025), the model yielded an NSE of 0.68, a PBIAS of 11.2%, and an RMSE of 5.17 m^3/s, indicating satisfactory and consistent predictive performance on independent data not used in calibration. The slight reduction in NSE and increase in PBIAS during validation is expected and reflects the natural variability in hydrological conditions between the calibration and validation periods.

Discussion of Model Performance

The results indicate that the model performs adequately in simulating the general hydrological behaviour of the Nyagak catchment. The ability of the model to capture seasonal trends and baseflow conditions demonstrates that the Deficit and Constant loss method, combined with the Clark Unit Hydrograph, provides a reasonable representation of the rainfall–runoff process.

However, the model exhibits limitations in accurately reproducing peak discharge events. However, some limitations remain. The model exhibits some difficulty in accurately reproducing the highest peak discharge events. This can be attributed to the simplified representation of infiltration processes under extreme rainfall, uncertainties in rainfall spatial distribution, and the use of a lumped modelling approach, which does not account for sub-catchment variability. The remaining PBIAS of –8.4% during calibration indicates a slight volume overestimation tendency that is partially linked to the baseflow recession parameterization during low-rainfall months.

The slight reduction in performance between calibration (NSE = 0.72) and validation (NSE = 0.68) is expected in hydrological modelling and reflects the inherent variability of climatic conditions between periods. Both values remain within the good-performance range, confirming that the model generalises well to independent data. The PBIAS values of −8.4% (calibration) and 11.2% (validation) are within the acceptable threshold of ±15%, and the RMSE values of 4.31 and 5.17 m^3/s respectively are consistent with the scale and variability of discharge in the catchment. Overall, these results demonstrate that the model is well-calibrated and validated, providing a reliable basis for hydropower assessment and climate impact analysis.

Implications for Hydropower Modelling

The performance of the hydrological model has direct implications for hydropower estimation. Since power generation is highly dependent on discharge, any inaccuracies in flow simulation will affect the estimation of energy production.

The underestimation of peak flows may lead to underestimation of maximum power generation potential, while errors in low-flow simulation may affect estimates of reliable energy supply. Despite these limitations, the model provides a useful tool for assessing general hydropower potential and understanding flow variability.

Key Findings for Objective Two

The evaluation of model performance led to the following conclusions:

- The model successfully captures seasonal flow patterns and baseflow conditions
- Peak discharge events are generally underestimated, particularly during extreme events; overall NSE = 0.72 (calibration) and 0.68 (validation)
- Model performance is better during calibration than validation
- The model shows good predictive capability (NSE = 0.68 during validation)
- Uncertainties in input data and model structure were addressed through sensitivity analysis, multi-metric evaluation (NSE, PBIAS, RMSE), and use of evapotranspiration and LULC data

Objective Three: Evaluation of the Impacts of Climate Variability on River Flows and Hydropower Generation

The third objective of this study was to evaluate the impact of climate variability on river discharge and the corresponding performance of hydropower generation at the Nyagak Run-of-River Hydropower system. This was achieved by analyzing long-term rainfall and discharge data, as well as estimated hydropower output derived from the hydrological model.

Influence of Climate Variability on River Discharge

Analysis of historical rainfall and discharge data revealed significant variability in hydrological conditions within the Nyagak catchment. Variations in rainfall intensity, duration, and seasonal distribution were reflected in corresponding changes in river discharge.

Periods of high rainfall resulted in increased discharge and more frequent peak flow events, while reduced rainfall led to lower flows and prolonged dry conditions. The bimodal rainfall pattern observed in the region was clearly reflected in the discharge hydrograph, confirming the strong dependence of river flow on climatic conditions. This variability indicates that the hydrological response of the Nyagak River is highly sensitive to climate fluctuations, making the system vulnerable to both extreme rainfall events and drought conditions.

Impact of Discharge Variability on Hydropower Generation

Hydropower generation in the Nyagak system is directly dependent on river discharge due to its run-of-river design. As a result, variations in flow translate directly into fluctuations in power output.

Using the hydropower equation, power output was estimated from both observed and simulated discharge. The strong positive relationship between discharge and power generation is an expected and fundamental characteristic of run-of-river hydropower systems governed by the equation $P = \rho g Q H \eta$. This relationship is not a standalone finding in itself, but rather the operational basis upon which all further analysis of hydropower reliability, seasonal variability, and climate change impacts is built. The quantitative characterisation of this relationship – including the identification of minimum flow thresholds for turbine operation and the discharge levels associated with rated power output – provides the critical link between hydrological model outputs and energy production estimates.

Estimated annual energy production was found to be:

Observed ≈10.7GWh/year

Simulated ≈ 25.6 GWh/year

The difference between these values suggests that the hydrological model tends to overestimate total discharge volume, which leads to higher predicted energy output. Despite this discrepancy, both estimates confirm that the Nyagak River has significant hydropower potential.

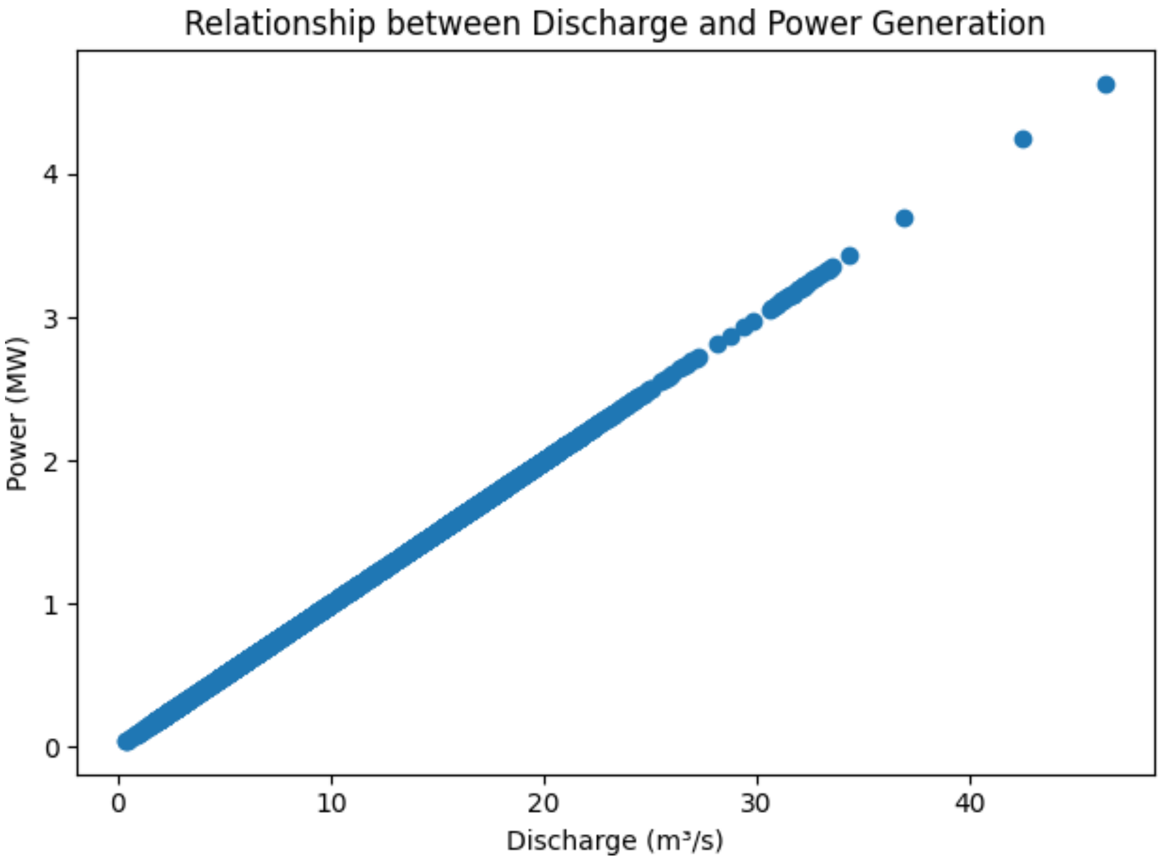


Figure 8:Discharge Vs Power generation

Reliability of Hydropower Generation under Variable Climate Conditions

The reliability of hydropower generation was assessed using flow characteristics such as dependable flow. The flow duration curve indicated that the 95% dependable flow ranges between approximately 1.6 and 2.8 m^3/s.

This dependable flow represents the minimum discharge available for sustained energy production and is critical for evaluating system reliability. While the river maintains flow throughout the year, discharge levels during dry periods are relatively low, limiting power generation capacity.

As a result, the Nyagak hydropower system is capable of continuous operation but with reduced output during periods of low rainfall as seen in fig 4.

Comparison with Energy Demand

The estimated hydropower potential was compared with the energy demand of Zombo District to evaluate the contribution of the Nyagak system to local energy supply.

The results showed that:

Estimated demand ≈ 45 GWh/year
Observed energy ≈ 10.7 GWh/year

This indicates that the Nyagak River can meet only approximately 20–25% of the district's energy demand under observed conditions. Even under simulated conditions, where energy production is higher, the river is still insufficient to fully meet demand.

This highlights the limitation of relying solely on hydropower in the region.

Implications of Climate Variability on Hydropower Performance

The combined analysis of discharge and energy production demonstrates that climate variability has a direct and significant impact on hydropower performance.

The results indicate that:

- Increased rainfall variability leads to fluctuations in discharge and energy production
- High-flow periods enhance short-term power generation but are not sustained
- Low-flow periods reduce power output and affect reliability
- Run-of-river systems are highly sensitive to climate conditions

The variability in discharge also implies that future changes in climate could either increase or decrease hydropower potential depending on rainfall trends.

Discussion

The findings of this study highlight the strong linkage between climate variability, river discharge, and hydropower generation. The Nyagak River exhibits significant seasonal and inter-annual variability, which directly influences energy production.

While the river has substantial hydropower potential, its performance is constrained by variability in flow conditions. The results show that although peak flows can produce high energy output, these conditions are not sustained throughout the year. Conversely, low-flow periods reduce the reliability of power generation.

The discrepancy between simulated and observed energy production further emphasizes the importance of accurate hydrological modelling in energy assessment. Model limitations, data uncertainty, and parameter assumptions all contribute to differences in estimated hydropower potential.

These findings suggest that hydropower alone may not be sufficient to meet the energy needs of the region, particularly under changing climatic conditions. There is therefore a need for diversification of energy sources to improve reliability and sustainability.

Key Findings for Objective Three

The evaluation of climate variability and hydropower performance led to the following conclusions:

- River discharge is highly sensitive to rainfall variability
- Hydropower generation is directly dependent on discharge
- Estimated energy production ranges between 10.7 and 25.6 GWh/year
- The Nyagak River can meet only a portion of the district's energy demand
- Climate variability affects both the magnitude and reliability of power generation
- Run-of-river systems are particularly vulnerable to hydrological fluctuations

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

Conclusion

This study aimed to analyze the hydrological behaviour of the Nyagak River catchment, develop and evaluate a hydrological model, and assess the impact of climate variability on river flow and hydropower generation. The results obtained from the analysis and modelling provide important insights into the functioning of the catchment and its suitability for hydropower development.

The analysis of historical discharge data revealed that the Nyagak River exhibits a clear seasonal pattern characterized by bimodal flow distribution. Peak flows were observed during the major rainy seasons, while low flows occurred during dry periods. The presence of sustained baseflow throughout the year indicates that groundwater contributions play an important role in maintaining river discharge. However, the observed variability in flow highlights the influence of rainfall patterns on the hydrological response of the catchment.

The development and evaluation of the hydrological model demonstrated that the model is capable of simulating the general behaviour of river discharge. The model successfully captured seasonal variations and baseflow conditions, although it showed limitations in accurately reproducing peak discharge events. The performance of the model during calibration was better than during validation, indicating some sensitivity to changes in hydrological conditions. Despite these limitations, the model provides a reasonable representation of rainfall–runoff processes and can be used for further analysis.

The assessment of hydropower potential showed that the Nyagak River has significant capacity for energy generation. Estimated energy production ranged between approximately 10.7 GWh/year (observed) and 25.6 GWh/year (simulated), confirming the river's importance as a source of renewable energy. However, comparison with the energy demand of Zombo District revealed that the river alone cannot meet the total energy requirements of the region.

The results further demonstrated that hydropower generation is highly dependent on river discharge, and therefore strongly influenced by climate variability. Variations in rainfall patterns were reflected in fluctuations in discharge, which in turn affected power generation. High-flow periods resulted in increased energy production, while low-flow periods reduced the reliability of power supply. This highlights the vulnerability of run-of-river hydropower systems to climatic variability.

Overall, the findings of this study indicate that while the Nyagak River has considerable hydropower potential, its performance is constrained by variability in hydrological conditions. The integration of hydrological modelling and climate analysis provides a useful framework for understanding these dynamics and supports informed decision-making in water resources and energy planning.

Recommendations

Based on the findings of this study, the following recommendations are proposed:

- The hydropower system at Nyagak should be complemented with alternative energy sources such as solar power to improve the reliability of energy supply. Since hydropower generation is dependent on river flow, integrating other renewable energy sources can help offset reduced generation during dry periods.
- There is a need to improve hydrological data collection and monitoring within the catchment. More accurate and continuous data would enhance model performance and reduce uncertainties in discharge simulation and hydropower estimation.
- Future studies should consider the use of distributed hydrological models to better capture spatial variability within the catchment. This would improve the representation of runoff processes and enhance the accuracy of peak flow simulation.
- Climate change projections should be further explored using multiple scenarios to better understand the range of possible impacts on hydrology and energy production. This would support the development of adaptive strategies for managing water resources and hydropower systems.
- Catchment management practices such as afforestation and soil conservation should be encouraged to reduce runoff variability and improve water retention. These measures can help stabilize river flow and enhance the sustainability of hydropower generation.

REFERENCES

Basso, S. and Botter, G. (2012) "Streamflow variability and optimal capacity of run-of-river hydropower plants," *Water Resources Research*, 48(10), pp. 1–13. Available at: https://doi.org/10.1029/2012WR012017.

Blöschl, G. *et al.* (no date) "Twenty-three unsolved problems in hydrology (UPH) – a community perspective," 6667. Available at: https://doi.org/10.1080/02626667.2019.1620507.

Cannon, A.J., Sobie, S.R. and Murdock, T.Q. (2015) "Bias correction of GCM precipitation by quantile mapping: How well do methods preserve changes in quantiles and extremes?," *Journal of Climate*, 28(17), pp. 6938–6959. Available at: https://doi.org/10.1175/JCLI-D-14-00754.1.

Cherchi, A. *et al.* (2020) "Advances in understanding large-scale responses of the water cycle to climate change," 1472, pp. 49–75. Available at: https://doi.org/10.1111/nyas.14337.

Hamududu, B., Killingtveit, A. and Engineering, E. (2012) "Assessing Climate Change Impacts on Global Hydropower," (2005), pp. 305–322. Available at: https://doi.org/10.3390/en5020305.

Hoch, J.M. *et al.* (2017) "GLOFRIM v1 . 0 – A globally applicable computational framework for integrated hydrological – hydrodynamic modelling," pp. 3913–3929.

Jr, G.J.M. (1999) "Evaluating the use of “goodness-of-fit” Measures in hydrologic and hydroclimatic model validation," 35(1), pp. 233–241.

Kaunda, C.S., Kimambo, C.Z. and Nielsen, T.K. (2012) "Hydropower in the Context of Sustainable Energy Supply: A Review of Technologies and Challenges," *ISRN Renewable Energy*, 2012, pp. 1–15. Available at: https://doi.org/10.5402/2012/730631.

Of, T. *et al.* (1999) "S TATUS OF A UTOMATIC C ALIBRATION FOR H YDROLOGIC M ODELS : C OMPARISON WITH M ULTILEVEL E XPERT C ALIBRATION," (April), pp. 135–143.

Oyerinde, G.T. *et al.* (2015) "Hydro-climatic changes in the Niger basin and consistency of local perceptions," *Regional Environmental Change*, 15(8), pp. 1627–1637. Available at: https://doi.org/10.1007/s10113-014-0716-7.

Paish, O. (2002) "Small hydro power: Technology and current status," *Renewable and Sustainable Energy Reviews*, 6(6), pp. 537–556. Available at: https://doi.org/10.1016/S1364-0321(02)00006-0.

Rainfall-Runoff Modelling (no date).

Romali, N.S., Yusop, Z. and Ismail, A.Z. (2018) "Hydrological Modelling using HEC-HMS for Flood Risk Assessment of Segamat Town, Malaysia," *IOP Conference Series: Materials Science and Engineering*, 318(1). Available at:

https://doi.org/10.1088/1757-899X/318/1/012029.

Skoulikaris, C. and Kasimis, K. (2021) "Investigation of climate change impacts on hydropower generation: The case of a run-of-river small hydropower plant in North Western Greece," *IOP Conference Series: Earth and Environmental Science*, 899(1). Available at: https://doi.org/10.1088/1755-1315/899/1/012026.

Yassin, F. *et al.* (2019) "Representation and improved parameterization of reservoir operation in hydrological and land-surface models," pp. 3735–3764.

Yousuf, I., Ghumman, A.R. and Hashmi, H.N. (2017) "Optimally sizing small hydropower project under future projected flows," *KSCE Journal of Civil Engineering*, 21(5), pp. 1964–1978. Available at: https://doi.org/10.1007/s12205-016-1043-y.