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APPLICATION OF HYPE MODEL FOR RESERVOIR OPERATION OPTIMIZATION: A CASE STUDY OF KOKA RESERVOIR, AWASH BASIN, ETHIOPIA

BY

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ABSTRACT

Water scarcity increasingly threatens agricultural productivity in Ethiopia, exacerbated by ineffective reservoir operation policies that contribute to the misuse of available water resources. The suboptimal operating policy of the Koka Reservoir represents a critical and common challenge. The developed Et-HYPEv2.0 model demonstrated good and satisfactory performance during calibration and validation, as measured by the Nash-Sutcliffe Efficiency (NSE) and Relative Volume Error (RE%).This thesis focuses on optimizing the operation of the Koka Dam Reservoir within the Awash Sub-Basin, Ethiopia, through the application of the Et-HYPEv2.0 model. The model is built using daily inflow data from two stations (Hombole and Mojo River), daily precipitation, water Storage data, monthly reservoir surface evaporation, and physical characteristics of the Koka Dam and Reservoir, spanning a twenty-one-year period (1990-2010) for inflow and precipitation at the reservoir surface. A monthly reservoir optimization strategy, implemented to prioritize irrigation demands, significantly altered seasonal flow patterns to achieve a stable, year-round downstream release. The optimized operation reduced the average wet-season flow by 27% (from 62.25 m^3/s to 45.4 m^3/s) and increased the average dry-season flow by 46% (from 31 m^3/s to 45.4 m^3/s) there by improving year round flow stability. This balanced approach effectively mitigates extreme seasonal variations, providing reliable water availability for multiple downstream uses including irrigation and power generation. The total area currently located downstream of Koka Reservoir under irrigation encompasses 715.894 km^2. The annual water requirements for the monoculture optimization scenario were calculated as 957.49 MCM for sugarcane and 287.62 MCM for wheat. Under the multi-crop optimization scenario, the total annual water requirement was estimated at 449.05 MCM.

Keyword: IWR, HYPE, Optimization, Reservoir, Operation, Rule Curve

DECLARATION AND COPYRIGHT

I, Melese Gosalo Gorata, declare that this is my own original work and that it has been presented and will not be presented to any other University for similar or any degree award.

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LIST OF ABBREVIATION

CCNLP	Chance-Constrained Nonlinear Programming
CWR	Crop Water Requirement
DEM	Digital Elevation Model
EEPC	Ethiopian Electric Power Corporation
EFR	Environmental Flow Requirement
ETO	Reference Crop Evapotranspiration
EWS	Early warning system
Evt	Evaporation
GPS	Global Positioning System
HYPE	Hydrological Prediction for the Environment
It	Inflow volume of the reservoir during time t,
IWR	Irrigation Water Requirement
LP	Linear Programming
MAR	Mean Annual Rainfall
MoA	Ministry of Agriculture
MoWR	Ministry of Water Resources
MGC	Multi-Gauge Calibration
NH	Niger HYPE
NMA	National Metrology Agency
OWWDSE	Oromia Water Work Design and Supervision Enterprise
Pot	Potential Evaporation
Prec	Precipitation as Provided
QGIS	Quantum Geographical Information System
Qt	Out flow from reservoir
RBM	River Basin Model

Rt	Released volume of the reservoir during time t.
SLAPIS	Sirba River Local Alert and Information System
Sml3	Soil Moisture Third Soil Layer
Soim	Computed Soil Moisture
SSD	Sum of Squared Deviation
St	Storage volume in the reservoir at time t,
St+1	Storage at the end of a time.
Temp	Temperature
Tred A and B	Two other land use soil temperature evap.
Upepot	Upstream Catchment Average Pote
Upevap	Upstream Catchment Average Evap
Upsmfp	Upstream Soil Moisture as Fraction of Por
Upcprc	Upstream Catchment Average Prec
Wcep1	Effective porosity as a fraction, for uppermost soil layer
Wcwp1	Wilting point as a fraction, for uppermost soil layer
Wcfc	Fraction of soil available for evapotranspiration
W0REF	Relative difference to the threshold of outlet 1
WWH	World-Wide HYPE

1. INTRODUCTION

Ethiopia is recognized for its extensive water resources, often referred to as the water tower of East Africa, featuring a complex hydrological system characterized by 12 major river basins, numerous lakes, and substantial groundwater potential. The average annual river runoff is estimated at 122 billion cubic meters, further augmented by a groundwater potential estimated between 2.6 and 6.5 billion cubic meters. Research by the Water Resources Institute (WRI) consistently highlights the imbalance between water supply and demand coupled with rapid urbanization and industrialization as critical factors driving water stress across Ethiopian river basins, notably the Awash. Understanding and effectively managing this abundance is crucial for the nation's socio-economic progress. The Koka Reservoir is a vital water resource infrastructure in Ethiopia, plays a crucial role in supporting various sectors including hydropower generation and irrigation demand water supply (Merga, 2020). Optimizing the reservoir's operation is essential to ensure its sustainable management and meet the growing demands for water resources (Giuliani et al., 2021). The primary focus of this study is the Et-HYPEv2.0 model's utility for reservoir operation and optimization specifically at Koka Reservoir in the Awash Basin, Ethiopia.

The Koka Reservoir is one of Ethiopia's oldest and most significant dam’s faces increasing pressure from growing water demands, sedimentation and the uncertainties introduced by climate change. Traditional reservoir operation strategies often rely on historical data and rigid rule curves which may not adequately account for dynamic hydrological conditions or evolving water needs. This can lead to inefficient water allocation, missed opportunities for maximizing benefits and increased vulnerability to water related hazards.

The HYPE model is a flexible and comprehensive tool capable of simulating complex hydrological processes including rainfall-runoff, groundwater flow and reservoir dynamics. By incorporating relevant hydrological data and calibrating the model to local conditions the HYPE model provides valuable insights into the reservoir's behavior under different scenarios (Pechlivanidis & Arheimer, 2015). The model code is open source and describes hydrological processes in different sub basins, although the algorithms are not purely based on physical laws but of more conceptual nature. It is meant to be applied in a multi-basin manner to achieve high spatial distribution of flow paths in the landscape. It can be evaluated against point measurements in the river network and against spatially distributed observations, such as Earth Observations or interpolated products from in-situ monitoring.

Ethiopian Irrigation Policy enhance greater participation by the Regional and Federal Governments in the development of large scale irrigated farms in high water potential basins, but with low population density (Ethiopian Water Sector Policy, 2001).To foster the development of irrigated agriculture, it is essential to dedicate a reasonable percentage of committed resources, specifically targeting capacity building and the improvement of infrastructure. Furthermore, it is crucial to promote decentralization and user based management of irrigation systems, ensuring that the unique needs of rural women are particularly considered. A clear hierarchy of priority schemes should also be established, with foundational considerations being national food requirements, the needs of the national economy and demands for raw materials, among other vital needs.

Beyond strategic allocation and prioritization, the practical enhancement of existing traditional irrigation systems is paramount. This involves upgrading water intake methods, improving conveyance infrastructure and increasing the overall efficiency of water application. Effective management of irrigated water also demands a dual approach actively preventing its degradation while simultaneously implementing mitigation strategies to maintain a suitable quality for agricultural use. Moreover, a robust framework for water allocation and prioritization must be developed, one that seamlessly integrates social equity, economic efficiency, and environmental sustainability as harmonized requirements. Finally, a non-negotiable aspect of all irrigated agriculture schemes is the mandatory establishment of appropriate drainage facilities to ensure long-term viability and prevent waterlogging or salinization. According to (MoWIE & MoANR, 2016) the principal objective of the irrigation development strategy was to exploit the agricultural production potential of the country to achieve food self-sufficiency at the national level, including export earnings, and to satisfy the raw material demand of local industries, but without degrading the fertility and productivity of the country’s land and water resources base. With respect to irrigation development the strategy was directed to expand irrigated agriculture, improve irrigation water use efficiency and thus the agricultural production efficiency, develop irrigation systems that are technically and financially sustainable, and address water logging problems in irrigated areas and implement measures to secure long-term viability and sustainability of irrigation schemes. Furthermore, enhancing the adoption of improved agricultural practices based on detailed agronomic and agricultural studies of crops, soils, farming practices, efficient irrigation methodology, etc. that will contribute to improved irrigation systems management.

The Federal Democratic Republic of Ethiopia's Central Statistical Agency (CSA) conducted its Agricultural Sample Survey (AgSS) for the 2019/20 agricultural year. This comprehensive survey aims to collect fundamental quantitative information on the country's agriculture, which is vital for effective planning, policy formulation, and ensuring food security. The AgSS is structured into four main components: The Crop Production Forecast Survey, the Meher Season Survey (which includes Farm Management Practices), the Livestock Survey, and the Belg Season Survey. Data pertaining to the application and quantities of fertilizer, improved seed, irrigation and pesticides used within private peasant holdings were collected, processed and summarized as part of the survey.

The survey findings highlight that the adoption of irrigation practices across the country needs substantial development to realize its full potential. Specifically, the total irrigated crop area within private peasant holdings was estimated at approximately 211,047 hectares, utilized by about 1.3 million farmers. Maize, sorghum, and teff accounted for the largest portions of this irrigated land, with estimated areas of 53,670 hectares for maize, 19,619 hectares for sorghum, and 7,708 hectares for teff, respectively.

The Agricultural transformation from subsistence agriculture to commercialization has given a top priority in the development agenda of the Government of Ethiopia. Consequently, fostering market driven irrigated farming, especially the cultivation of high value crops under irrigation, holds substantial promise for transitioning smallholder subsistence farming towards commercial agriculture. Thus, Agriculture plays Lion Share on reduction of rural poverty and can make an important contribution to achieve the country’s vision to be a middle income country in the coming 20-30 years.

1.1. Statement of the Problem

Water stored in the Koka reservoir has competing demands for hydropower, irrigation, drinking water and flood control. The Wonji sugar cane irrigation command area (6000 ha), located 12 km downstream from the dam, is entirely dependent on releases from the Koka Reservoir (Reis et al., 2011). Lack of efficient management of the reservoir is one possible explanation for the reservoir operating below its optimum capacity(Fanta et al., 2023).

Climatic variations and increased sedimentation in the Koka reservoir cause hydrologic variability in river flow, hindering the current water management's ability to meet existing and future irrigation demands (Tajin et al., 2016).

According to the analysis output of Fanta et al.(2023) the higher optimized power capacity of the Koka reservoir isn't being realized in observed power output due to the current operation trend. To address the challenges and enhance water management within the region, this research developed a Hydrological Predictions for the Environment (HYPE) model based reservoir operation optimization. This study addresses the research gap created by the current suboptimal operating policy of the Koka Reservoir, which is a significant factor in the mismanagement of available water resources and subsequent risk to agricultural productivity in the downstream of Koka dam irrigation area. Operational optimization is required to manage the 27% shortfall in average year-round wet-season flow. This strategy is essential for minimizing losses from reservoir spillage and power generation shortfalls, while simultaneously balancing the critical needs of downstream irrigation during the dry season and the prevention of flood problems.

1.2. Research questions

- How accurate is the calibrated Et-HYPEv2.0 model for simulating Koka Reservoir inflow?
- How much do HYPE derived optimal rule curves improve the multi-objective performance of Koka Reservoir?
- What operational rule curves maximize the irrigation water delivery reliability from Koka Reservoir?

1.3. Research Objective

General Objective

The overall objective of this study is to develop an integrated hydrological and operational rule curve using the HYPE model for the Koka reservoir, aimed at optimizing water resource management to meet irrigation demands through accurate inflow estimation, reservoir operation strategies and adaptive crop Scenarios

Specific Objectives

- Develop catchment-based hydrological model in HYPE for accurate and reliable estimation of reservoir inflow
- Develop reservoir operation and optimization model in HYPE
- Develop crop scenarios and align Koka Reservoir operations with irrigation water needs.

1.4. Scope of the Study

This thesis focuses on applying the Et-HYPEv2.0 model for the optimization of Koka Reservoir operations within the Awash Sub-Basin. The thesis directly addresses critical challenges of inefficient water use, scarcity, and uneven distribution within the project area.

This thesis begins by meticulously collecting and analysing historical hydrological and meteorological data. This includes comprehensive records of inflow, outflow and storage, which establish a robust foundation for understanding the Koka Reservoir system's behaviour. This extensive dataset is then critical for the subsequent calibration and validation of the Et-HYPEv2.0 model, ensuring its accuracy and reliability.

The Et-HYPEv2.0 model has been developed to accurately simulate the hydrological processes within the reservoir system. This model integrates essential components such as rainfall runoff modelling, reservoir routing and water balance calculations. Through rigorous calibration and validation, the thesis ensures the model's reliability and predictive capabilities, making it a dependable tool for estimating reservoir inflow.

Et-HYPEv2.0 based model for reservoir operation and optimization has been formulated. This model considers multiple objectives, including maximizing reservoir release and effectively meeting irrigation demands, while minimizing water shortages. It incorporates crucial constraints such as reservoir capacity limits and operational rules to ensure feasible and sustainable solutions.

Finally, this thesis utilizes the Et-HYPEv2.0 model to simulate and evaluate a wide range of operational scenarios, considering diverse hydrological conditions and water demand patterns. By systematically exploring the crop selection and proportion based scenarios, strategies have been developed and evaluated to enhance Koka Reservoir operation, optimizing irrigation water requirements and other competing demands. This thesis ultimately identified the optimal operating strategies that maximize benefits while minimizing potential risks.

1.5. Organization of the Chapters

This study presents the reservoir operation modeling with the frame work of Et-HYPEv2.0 model application of Koka reservoir for safe operation and optimal use of water for irrigation and Hydropower. The study considers Koka reservoir inflow source options and a number of interrelated activities.

The remainder of this thesis is structured into five distinct chapters. Chapter 1 provides the background, problem statement, research objectives, and the scope of the study. Chapter 2 follows with a comprehensive and critical review of the existing literature relevant to hydrological modeling, reservoir operation optimization and water management in the Awash Basin. Subsequently, Chapter 3 details the study area, the general materials (data sources) and the specific methodology employed for data analysis, model setup, calibration and validation of the Et-HYPEv2.0 model. Chapter 4 then presents a detailed analysis and interpretation of the findings, including the developed optimized reservoir operating strategies and their implications for water resource management in the Koka Reservoir system. Finally, Chapter 5 summarizes the main findings, states the key conclusions drawn from the research and provides actionable recommendations for future study and implementation.

1.6. Significance of Research

Optimizing dam reservoir operations is essential for maximizing revenue and minimizing costs, risks, and inefficiencies (Lai et al., 2022). This thesis holds significant importance for the optimized regulation of the Koka Reservoir. By thoroughly applying the Et-HYPEv2.0 model to optimize reservoir water release operations, this research offers a crucial and necessary step toward improving current water management practices. Ultimately, this work will contribute to enhanced reservoir regulation, leading to more efficient and sustainable water resource management in the study area. The thesis findings contribute to the development of strategies aimed at enhancing reservoir operation efficiency, advancing sustainable hydropower production and satisfying the irrigation water requirements within the scheme's command area.

Koka dam reservoir like many regions in Ethiopia faces water scarcity challenges (Adeba et al., 2015). This study demonstrates the application of Et-HYPEv2.0 model to optimize reservoir regulation systems efficiency. The study can contribute to more sustainable water management practices in the region.

This research explores the application of the Et-HYPEv2.0 model to optimize reservoir operations at the Koka Dam. Strategies aimed at minimizing water waste and balancing hydropower generation with irrigation demands are crucial for enhancing reservoir management and optimizing resource utilization. The bathymetric survey report indicates that the reservoir experiences a high volume of average annual spillage, for instance, as illustrated in Table 1.

The research offers a crucial path to tangible benefits which directly addressing both societal needs and scientific advancement. By establishing and implementing optimal operation rules, this study ensures a more efficient and dependable water supply to the downstream irrigation command area. This directly supports agricultural productivity and significantly enhances local food security, particularly during the critical dry season. The approach developed in this research serves as a transferable template for optimizing management at other multi-purpose dams in the region, promoting sustainable management of water scarcity and competing resource demands.

Therefore, the findings of this research can be utilized to prevent this unnecessary water loss via the spillway and contribute to the expanding knowledge base on utilizing the Et-HYPEv2.0 model. This research can pave the way for further advancements in water management strategies, particularly in regions facing water scarcity and competing demands for water resources.

2. LITERATURE REVIEW

Hydrological modelling plays a crucial role in understanding and managing water resources. The HYPE model is a widely used tool for hydrological prediction and has been applied in various regions worldwide. This literature review will focus on eight key areas:

2.1. Overview of Surface Water Availability

Sok & Oeurng, (2016) state that surface water is very important for numerous purposes. For instance, it serves for a sustainable environment, ecology, productive agriculture, industry and public purpose. Therefore, determining surface water resources is a key aspect of water resource assessment. Information of water resource is very important for every development sector. Since water problems are not the same over time and space, it is important to make a comprehensive assessment of surface water availability of rivers to manage the resources for both ecologies and to utilize the potential of the river efficiently by building well organized infrastructure (Sok & Oeurng, 2016). Constantly increasing population in countries increases the demand for irrigated agriculture to produce more food and pure water supply, especially in view of Awulachew et al., (2007) the two to three times greater productivity of irrigated agriculture than rain fed agriculture. Consequently, efforts must be directed towards enhancing the efficiency and productivity of existing water resources for irrigation (Berhe et al., 2013).

Ethiopia has twelve major river basins in which all of them are under the control of Ministry of Water and Energy of the country. Though the country has a large amount of water resource, very little of it has been developed for agriculture, water supply, hydropower and other purposes. The principal water resources issue facing the nation is the heterogeneous spatial and temporal patterns of their occurrence and allocation. The western and southwestern regions of Ethiopia are rich in water resources with the Abay (Blue Nile), Tekeze, Baro Akobo and Omo Gibe river basins accounting for a substantial 80-90% of the country's total. Interestingly, this water abundant area is relatively less populated, housing only 30-40% of Ethiopians. In contrast, the more densely populated eastern and central river basins, such as the Awash, have considerably less water availability, representing just 10-20% of the national total (MoWR, 2012).

2.2. Integrated Water Resources Management

The concept of integrated water resources management (IWRM) provides ideas to consider how it can best make social choices about water allocation and access as well as the sustainability of water resources and the infrastructure used to manage those resources (Giordano & Shah, 2014). Integration in water resource management is the most effective approach to the sustainable use and management of water resources. Because of the significant role that water plays in human livelihoods. IWRM is a critical way to reduce rural poverty, mainly in developing countries (Mulwafu & Msosa, 2005). Ethiopia has established a water resources management policy in 1998 and the policy has an overall goal to enhance and promote all national efforts towards the efficient equitable and optimum utilization of the existing water resources of Ethiopia for substantial socio-economic development on a sustainable basis (MoWR, 2012).

The Ministry of Water Resources in Ethiopia has established comprehensive objectives for the nation's water resource management policy. These objectives aim to develop Ethiopia's water resources equitably and sustainably ensuring widespread economic and social benefits for its citizens. A key principle involves optimizing water distribution through integrated frameworks which is crucial for efficient use, fair access and the long-term sustainability of this vital resource. Furthermore, the policy emphasizes proactive strategies for managing and combating droughts and other slow-onset disasters by efficiently allocating, redistributing, transferring, storing and utilizing water resources. It also focuses on preventing and regulating floods through sustainable mitigation, prevention, rehabilitation and other practical measures. Finally, the policy is committed to sustainably managing water resources and the entire aquatic environment through concerted conservation, protection, and enhancement efforts.

According to Ethiopian Water Sector Policy, (2001) the water allocation first priority is provided for drinking and sanitation purposes then proceeded by water requirements for livestock. The remaining will be assigned to the uses yielding the highest socio-economic benefits.

2.3. Applications of HYPE

Applications of HYPE models in hydrological modelling, including flood forecasting, drought analysis, water balance assessment and climate change impact assessment is summarized below.

According Ogliari et al.(2020) the HYPE Hydrological Model and Neural Network proposes a hybrid approach to enhance the accuracy of energy forecasts for runoff the river hydroelectric power plants. The core of the method involves combining the strengths of the HYPE hydrological model and neural networks. The HYPE model is utilized to simulate hydrological processes and providing essential input data for the neural network. The neural network is trained on historical data and then learns complex patterns and relationships between hydrological variables and power generation. By integrating these two powerful techniques the hybrid method aims to improve the reliability and precision of energy forecasts enabling better decision making and resource management for hydroelectric power plants.

The HYPE model can provide reliable hydrological forecasts enabling the optimization model to make informed decisions about water releases, energy generation and flood control ultimately enhancing the overall performance of the reservoir system.

The study conducted by Pechlivanidis & Arheimer (2015) modifies the Prediction in ungagged basin (PUB) recommendations to improve the model's calibration and validation. By incorporating these modifications, the India-HYPE model demonstrates its ability to accurately represent complex hydrological systems including river flows, water storage and evapotranspiration. The findings of this study provide valuable insights into the potential of HYPE for large scale hydrological modeling and can inform future applications in water resources management and climate change impact assessments. The outflow from lakes is determined by a general rating curve unless a specific one is given or if the lake is regulated. Regulated lakes and manmade reservoirs are treated equally but a simple regulation rule can be used, in which the outflow is constant or follows a seasonal function (as it is often the case with hydropower) for water levels above the threshold**.**

2.4. Reservoir water operation optimization

This section explores studies that employ optimization methods to improve reservoir operations, with a focus on enhancing water management for hydropower generation, irrigation, and flood control.

The Salwey et al. (2024) study approach involves simulating various operating strategies under different hydrological scenarios to evaluate their performance in terms of water supply reliability, flood control, and environmental flow requirements. By optimizing the reservoir operation rules, the model achieves a balance between these competing objectives. The study emphasizes the importance of considering uncertainties in hydrological forecasts and water demand to develop adaptive operating rules. By incorporating these principles into the optimization framework, it is possible to improve the efficiency and sustainability of water resource management.

The application of metaheuristic algorithms, such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Differential Evolution (DE), are employed to find optimal reservoir release policies that maximize hydropower generation, irrigation supply, and flood control, while considering various constraints like reservoir capacity, inflow variability and water quality. By systematically searching the solution space, these algorithms can identify efficient operation strategies that balance competing objectives and improve overall reservoir performance. The study demonstrates the effectiveness of metaheuristic algorithms in addressing the complexities of reservoir operation optimization (Lai et al., 2022)**.**

The Giuliani et al.(2021) study techniques aim to balance multiple conflicting demands, such as hydropower generation, irrigation, flood control, and environmental flow requirements. The review highlights the importance of considering uncertainties in hydrological inputs, water demand, and climate change impacts. By integrating advanced optimization algorithms, such as stochastic dynamic programming, robust optimization, and machine learning, it is possible to develop more resilient and adaptive reservoir operation strategies.

The Birhanu et al.(2014) study addresses the challenge of optimizing reservoir operation under uncertainty. This research introduces a chance constrained nonlinear programming

(CCNLP) model designed to establish optimal reservoir release strategies. The model aims to find a balance between providing irrigation water, generating hydropower, and mitigating flood risks. To account for the inherent uncertainty in water inflows, the CCNLP framework utilizes probabilistic distributions and integrates chance constraints, thereby ensuring a specified level of dependability in fulfilling water requirements. The primary objective of the study was to optimize the operational policy of the Koga Irrigation Dam in the Abay Basin to enhance water resource management and overall system performance. The analysis was conducted using five distinct operational scenarios (I, II, III, IV and V), each representing different water allocation priorities and constraints imposed on the dam. The core finding was the ideal planned irrigation deficit needed to achieve optimal system performance, defined by the lowest Water Shortage Duration (SSD), lowest vulnerability and greatest volumetric reliability.

The results showed that the required deficit varied significantly based on the scenario's constraints: Scenario I, representing the least constrained operational policy, achieved optimality with a 20% irrigation deficit. Scenarios II, III, and V, which modelled intermediate operational constraints or demands, required a moderate 30% deficit. Scenario IV, representing the most constrained policy due to the mandatory inclusion of compensation releases (environmental flows) for the downstream environment, necessitated the highest deficit of 40% to maintain optimal performance. This comparative analysis provides essential guidance for water managers to implement tailored operational rules at the Koga Dam. The current water allocation practices are unsustainable and may lead to water scarcity in the future. Considering the water demand and supply scenarios in the region, the article offers relevant information that can be applied to the optimization of reservoir operations in the Koka Dam, located in the Awash Basin, Ethiopia.

A notable disparity exists in Ethiopia's water resource distribution, with the central, western and south western regions possessing ample supplies, in contrast to the comparatively dry north eastern and eastern parts of the country, which face substantial hurdles in their sustainable utilization (Seleshi et al., 2007). This article explores the current state of water resources and irrigation development in Ethiopia, highlighting the country's efforts to address water scarcity, improve agricultural productivity and promote equitable access to water.

2.5. Reservoir operation policy

Reservoir operation is the most important method in water resource management and used to allocate water that is stored in the reservoir among different upstream and downstream users. Reservoir operation takes into account the water uses for power generation, water supply, irrigation and releases for downstream ecosystem and the needs of aquatic habitats. These large numbers of complex and interrelated activities may create a demand conflict that requires an optimal operation rule and strong decision support system (Charalampos Skoulikaris, 2008).

A reservoir operating policy can be understood as a set of rules that govern water releases over time (such as on a monthly basis). These rules are formulated based on the prevailing conditions of the reservoir system at the beginning of each operational period, primarily the stored water volume and the concurrent inflow.

An operating plan or release policy is a set of guidelines for determining the quantities of water to be stored and to release or withdraw from a reservoir. Operating decisions involve allocation of storage capacity and water releases between project purposes, between water uses and between time periods. A release plan includes a set of quantitative criteria within which significant flexibility exists for qualitative judgment. Growing management complexity and objectives require optimized operation rule curves to effectively guide reservoir personnel in managing water supply and power generation (Rong et al., 2024)

2.6. Existing Koka Reservoir characteristics

Ethiopian electric power corporation (EEPC) is a governmental organization which runs Koka hydropower station including the reservoir. Operational rules adopted by EEPC require spillway discharge at reservoir levels above 1588.4 m a.s.l. if the reservoir level is increasing at a rate of 30 cm/day or more. In principle, if the extrapolated reservoir rise is not completed by the end of the spill period (18 August to 18 September), spill is released to achieve that end. The purpose is largely to avoid flooding problems at Wonji which begin at river discharges over 300 m^3/s and become extensive at flow exceeding 500 m^3/s (Halcrow,1989). Following the study of the Awash Basin by Halcrow (1989), EEPC employs the rule curve established from that study shown in Figure 1. The historical releases and the reservoir levels as a function of time were examined to see the effectiveness of those operations. One can observe that, for some years the reservoir was not full at the end of the wet season which may result in shortage of water both for hydropower and irrigation purposes. This problem may arise as a result of excess amount, of water released through the spillway. If water had been saved from spillage, then it would have been probable that the reservoir would be full at the end of the wet season. But this assertion is not necessarily true because for a low wet season enough water may not inflow in to the reservoir which can fill the reservoir at the end of the wet season.

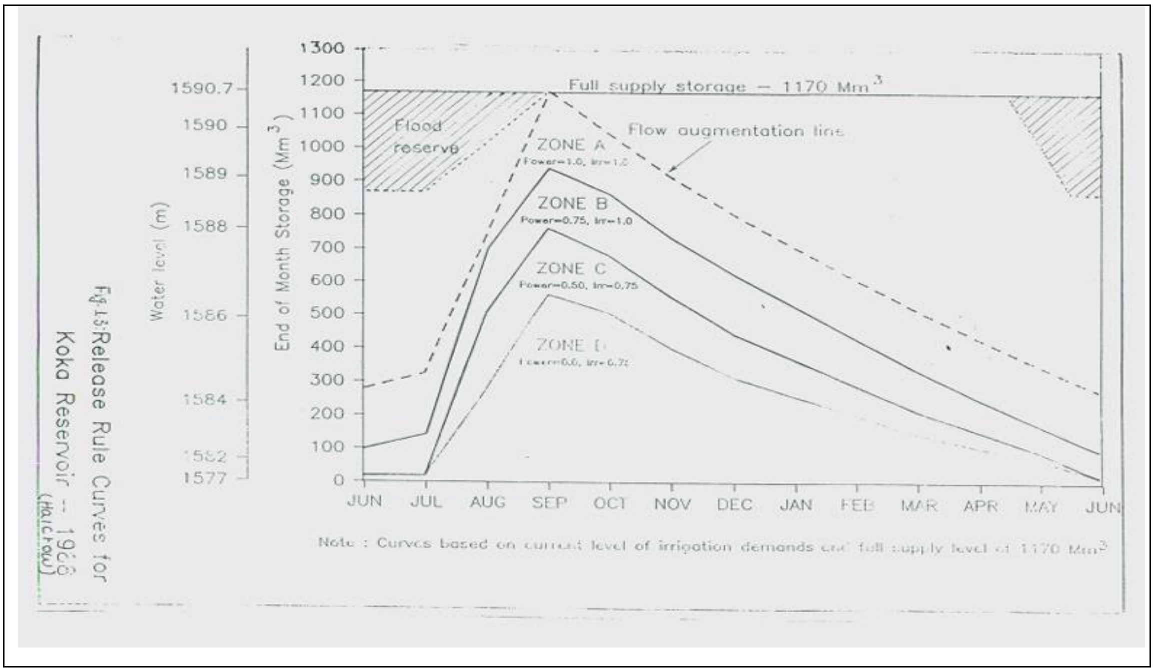

Figure 1: Reservoir Operation Practices(source: EEP,1997)

These techniques require a good quality historical and real time hydro meteorological data, suitable simulation and optimization models and qualified personnel to run and interpret them. The implementation of this system on all single and multipurpose reservoirs in Ethiopia is highly important to effectively use water resources while protected against flood. Since the 1996 flooding, a committee under the title Koka Technical Committee has been established comprising professionals from the Ministry of Water and Energy (MoWE), EEPC and other concerned parties and good initiatives have been taken to operate the reservoir in a more scientific way.

Table 1: Historical water release through the spillway for wet seasons (source: EEP,1997)

Year	Spillage(MCM)
1988	91.3
1989	144
1990	164
1991	129
1992	0
1993	762
1994	20.3
1995	0
1996	>1500

The Hydropower house is constructed below the dam with runner center elevation of 67.5 m.a.s.l. (reduced level) and the installed capacity of 14.4 MW/unit; there are three unites in the power house with combined installed capacity of 42.3 MW. The relationship between elevation and maximum capacity for the powerhouse outlet has been determined. The capacity at various elevations was calculated using the standard outlet formula.

$$Q = C_d * A * \sqrt{2} * g * H$$

Where:

- ✓ Cd = Coefficient of discharge
- ✓ A = Area of pressure tunnel (m2)
- ✓ g = gravitational acceleration (m/s2)
- ✓ H = Elevation (m)

Tail water arises both due to hydropower outlets and spillway but in a different elevation and location according to dam topography. It can be natural channel or concert channels. Design of the tail water is important because of the risk for cavitation that can damage the system when sub critical water condition arises. The reference water elevations to be added to simulate water level before print out or the minimum operating level of hydropower is 100.4m adopted from the hydrographic survey study document data obtained from ministry of water and energy (MoWE). The hydropower plant at Koka has turbines designed to handle a specific maximum flow rate, which is the primary limiting factor for full capacity discharge. Each turbine has a rated discharge, measured in cubic meters per second (m^3/s). Another important factor is the hydraulic head, which is the difference in water elevation between the reservoir level and the turbine outlet (tailrace). A higher head allows for greater power generation from the same volume of water, and this head varies with the reservoir's water level. The reservoir level is also significant, as when the reservoir is at its maximum operating level (or full supply level), the hydraulic head is also at its maximum, enabling the greatest potential power generation at full turbine discharge. It's important to note that while the dam has other outlets, such as spillways and sluices, full capacity discharge in the context of power production specifically refers to the water passing through the turbines.

The power generated by the Koka Reservoir's hydropower plant, like any other, is calculated using the formula:

$$P = \rho * g * Q * H * e$$

Where:

- ✓ P is power (Watts),
- ✓ ρ is the density of water (kg/m^3),
- ✓ g is the acceleration due to gravity (m/s^2),
- ✓ Q is discharge (m^3/s),
- ✓ H is hydraulic head (m), and
- ✓ e is the efficiency of the turbine and generator.

Actual discharge for power generation at Koka Reservoir typically deviates from full turbine capacity due to operational adjustments based on electricity demand, water inflow, downstream needs (e.g., irrigation), reservoir storage and flood control.

Table 2: Storage capacity of the Koka reservoir at different levels (source: Bathymetry survey report,1999)

Reservoir level		Volume (MCM)	Remark
m.a.s.l	Reduced level		
1578	97.6	0.02	Minimum operating level is 104.4m
1579	98.6	0.2	
1580	99.6	1.6	
1581	100.6	8.11	
1582	101.6	34.25	
1583	102.6	91.83	
1584	103.6	176.24	
1585	104.6	282.16	Storage capacity at full supply level of 110.3m is 1186.2 MCM
1586	105.6	404.8	
1587	106.6	542.61	
1588	107.6	639.14	
1589	108.6	859.3	
1590	109.6	1045.41	
1591	110.6	1246.5	

The bathymetric survey report for Koka Reservoir presents a revised elevation capacity curve, indicating a storage of 1186 MCM at the full supply level of 110.3m. This revised capacity accounts for a total silt deposition of 470 MCM observed up to the commencement of 1999.

In this research, the reservoir optimization operation is determined in the model LakeData.txt file by the following equation, which describes a rating curve used to calculate discharge (Q) from water level (W).

$$Q = gratk * (W - W_O)^{gratp}$$

Where:

- ✓ Q is discharge (m³/s),
- ✓ gratk is rating curve coefficient,
- ✓ gratp is rating curve exponent,
- ✓ W is water level from reference level (m), and
- ✓ W_O is water level from reference level of Zero water flow (m)

3. MATERIAL AND METHODOLOGIES

3.1. MATERIAL

The construction of the Et-HYPEv2.0 model begins with the model software HYPE itself, specifically the background map files Geoclass and Geodata model text files. Once these foundational files are prepared, the model requires essential forcing data to operate: a key input is the CHIRPSv2.0 rainfall dataset (available via the Climate Hazards Centre). This highly detailed meteorological input provides comprehensive rainfall data at a 5-kilometer grid resolution, spanning from 1981 to the present. Finally, the model utilizes a specific grid cell parameter file which contains all necessary configuration values. By integrating these three components the internally generated files, the external CHIRPSv2.0 rainfall data, and the grid cell parameter file the Et-HYPEv2.0 model is fully developed and operational. In this study, 250m × 250m resolution soil map of the study area catchment was accessed from Africa soil information service(AFSIS) coverage of Africa(https://africasoils.info/) and near east used for study area basin pre-processing such as stream and sub-basin delineation, perform spatial analysis and watershed characteristic under QGIS 3.32 tool.

Land use and land cover (LULC) data for the study were sourced from the Water Productivity Open Access Portal (WaPOR), an initiative of the Food and Agriculture Organization (FAO) of the United Nations. Specifically, the WaPORv2.0 (https://wapor.apps.fao.org/.) LULC map was utilized in this study.

The study area was delineated based on the location of existing gauging stations and their historical data, which provided the necessary inputs for computed streamflow generation and the initialization of the Et-HYPEv2.0 model. All processes such as study area basin characteristics, metrological inputs and background map file were done in Et-HYPEv2.0 model. The GeoClass.txt and GeoData.txt files are the essential static inputs for the HYPE model, defining the watershed's structure. GeoClass.txt details the properties of the Hydrological Response Units (HRUs) (land/soil classes) where modeling occurs, while GeoData.txt provides sub basin characteristics (like area and class fractions) and the flow connections that route water through the river network.

Table 3: Data source and description

SN	Data type	Data source	Description
1	Historical flow data	MOWE	14 years daily data(2000-2013)
2	Meteorological Data	CHIRPS v2.0	Gridded data since 1981 up to Present with 5KM resolution
3	land use ,land cover map	WaPORv2.0 classification source for the year 2024.	Coverage of Africa and the Near East with 250 m * 250 m resolution
4	Thematic Soil Map	Africa soil information service(AFSIS) for the year 2024.	Coverage of Africa and near east with 250 m* 250 m resolution

3.2. Study Area Description

The Awash River basin represents a nationally critical river system due to its substantial economic and socio-economic contributions. However, the basin is experiencing severe and ongoing environmental degradation, posing a significant and persistent threat to its sustainability and functionality. Currently, water scarcity is an issue at many points in the River system particularly in the dry seasons. Hence, Integrated and multi-purpose and demand driven approach responses are necessary to address the threats in the River basin, to address their underlying causes and optimize the land and water resources of the Basin.

Rising from the highlands close to Addis Ababa at an elevation of 2300 meters, the Awash River traverses a distance of 1200 kilometers in a southerly direction before its terminus below sea level in Lake Abbe, situated in the Danakil Desert. The Koka dam is located 90 kilometers south of Addis Ababa at an elevation of 1600 meters and its reservoir covers approximately 200 square kilometers and has a storage capacity of 1.65 billion cubic meters. The dam is managed by the Ethiopian Electric Power Corporation (EEPC), though the Ethiopian Ministry of Water Resources (MWR) maintains overall responsibility for the reservoir and its operations, including the input data used for hydrological modelling (Reis et al., 2011).

The Upper and Middle Awash study area watershed, a part of the Awash River basin in the Northwest Rift Valley of central Ethiopia, is geographically situated between 38.978°

– 40.1819° East longitude and 9.0773° – 9.0045° North latitude. This study area encompasses a total area of 21,144.2 km², with elevations ranging from 2577.91 meters to 132.54 meters above mean sea level. Within this area lies the Koka reservoir, located between 8.005° to 8.008056° North latitude and 39.00°to 39.0028° East longitude. The reservoir has a total storage capacity of 1651.9 million cubic meters (MCM) and a usable head of 10.86 meters. The power plant associated with the reservoir has firm and installed capacities of 43.2 Megawatts (MW) and 34.5 MW at working heads of 32 meters and 40 meters, respectively. The study area is characterized by large-scale mechanized and private irrigated agricultural farms in both the Upper and Middle Awash watershed (Reis et al., 2011). The 2024 Land Cover Land Use and soil combination data, derived from WaPORv2.0 SLC classification, indicated that agriculture comprised 76.13% of the watershed's land area. Soil data analysis, based on the FAO soil classification system, indicates that 43.98% of the watershed is covered by moderately fine soils, while moderately coarse soils constitute the smallest portion at 1.14%.

The Et-HYPEv2.0 model employs daily data on inflow, precipitation, water level, reservoir surface evaporation, and the physical characteristics of the Koka dam and reservoir. Inflow data from two stations, Hombole and Mojo, are used for reservoir operation modelling.

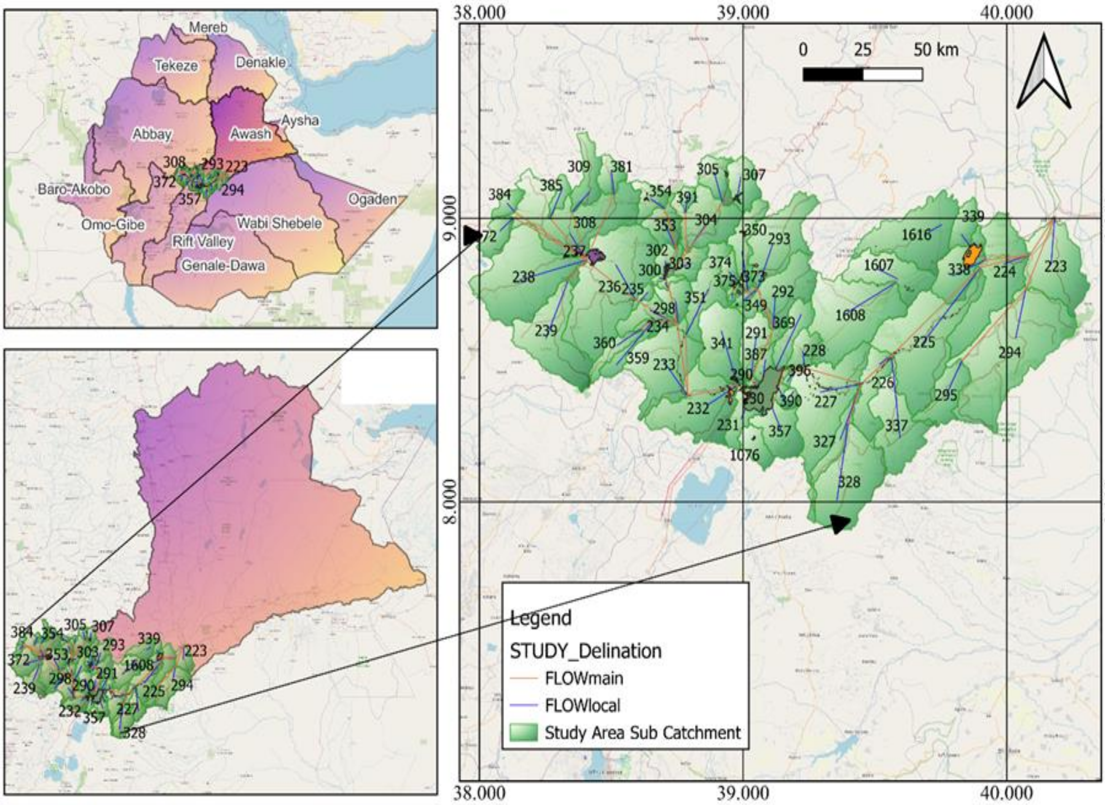

Figure 2: Maps of Study Area

A) Land Use Land Cover

The land cover of the study area catchment is primarily characterized by Agriculture (Rain fed), which dominates the landscape, covering approximately 73% of the total catchment area. Other land cover types present include irrigated farmland, various forest types (closed and open), shrub land, and grassland. While specific percentages for each of these other categories are provided in the Table 4, it's clear that their combined extent is significantly less than that of rain fed agriculture. Water bodies such as lakes (Olake and Ilake) and main rivers have a negligible presence within the study area.

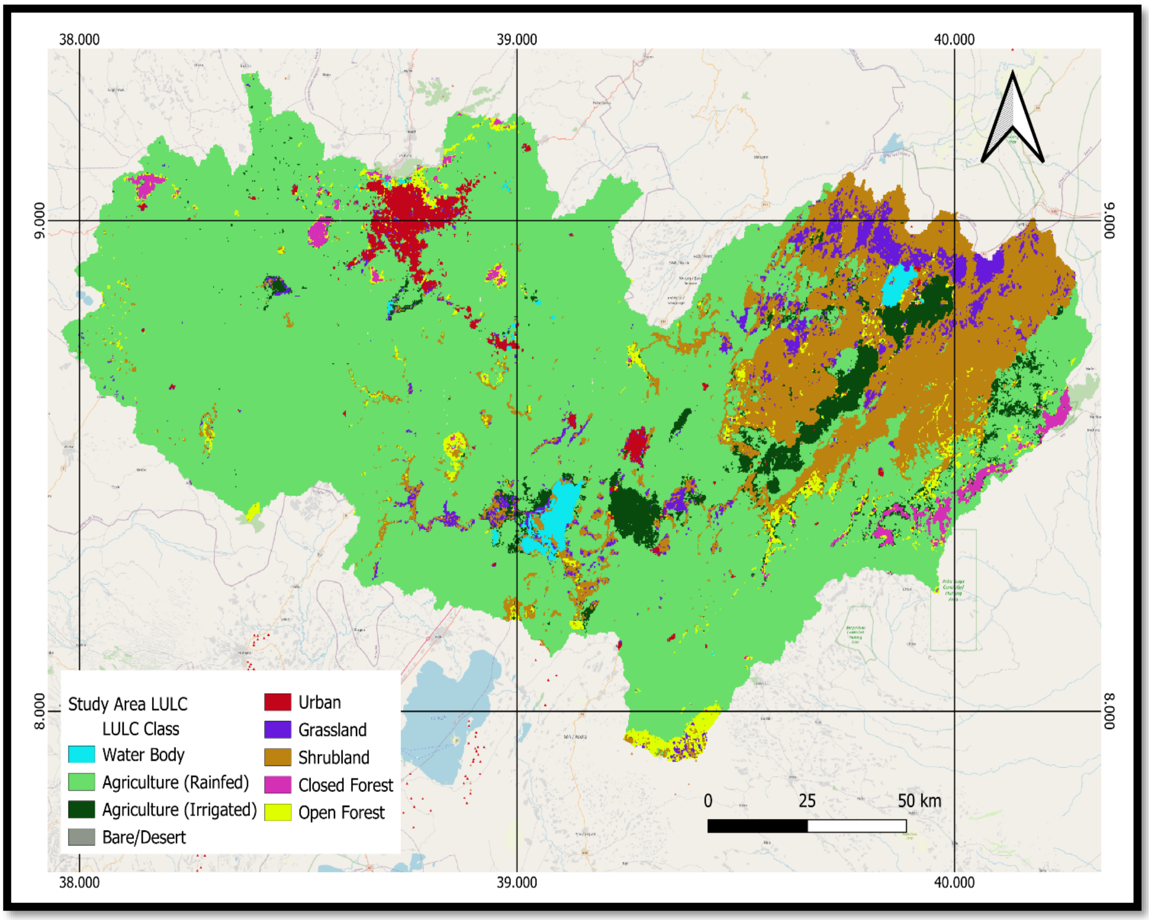

Figure 3: Land use land cover map of the study area.

Table 4: Land use Land cover property of the study area

Agriculture (Rain fed)	Agriculture (Irrigated)	Bare/Desert	Urban	Grassland	Shrub land	Closed forest	Open forest	O lake	I lake	Main river
landuse_1	landuse_2	landuse_3	landuse_4	landuse_5	landuse_6	landuse_7	landuse_8	landuse_9	landuse_10	landuse_11
73%	3%	0%	4%	3%	9%	1%	2%	4%	1%	0%

B) Soil

Soil is one of the essential input parameters for a hydrologic model to determine the water yield estimation of a given catchment. In this study, 250m × 250m resolution soil map was accessed from Africa soil information service(AFSIS) coverage of Africa and near east used for study area basin preprocessing such as stream and sub-basin delineation, perform spatial analysis and watershed characteristic under QGIS 3.32 tool.

The study area is characterized by different soil types. The major soil types in the area are moderately fine, Medium and moderately coarse.

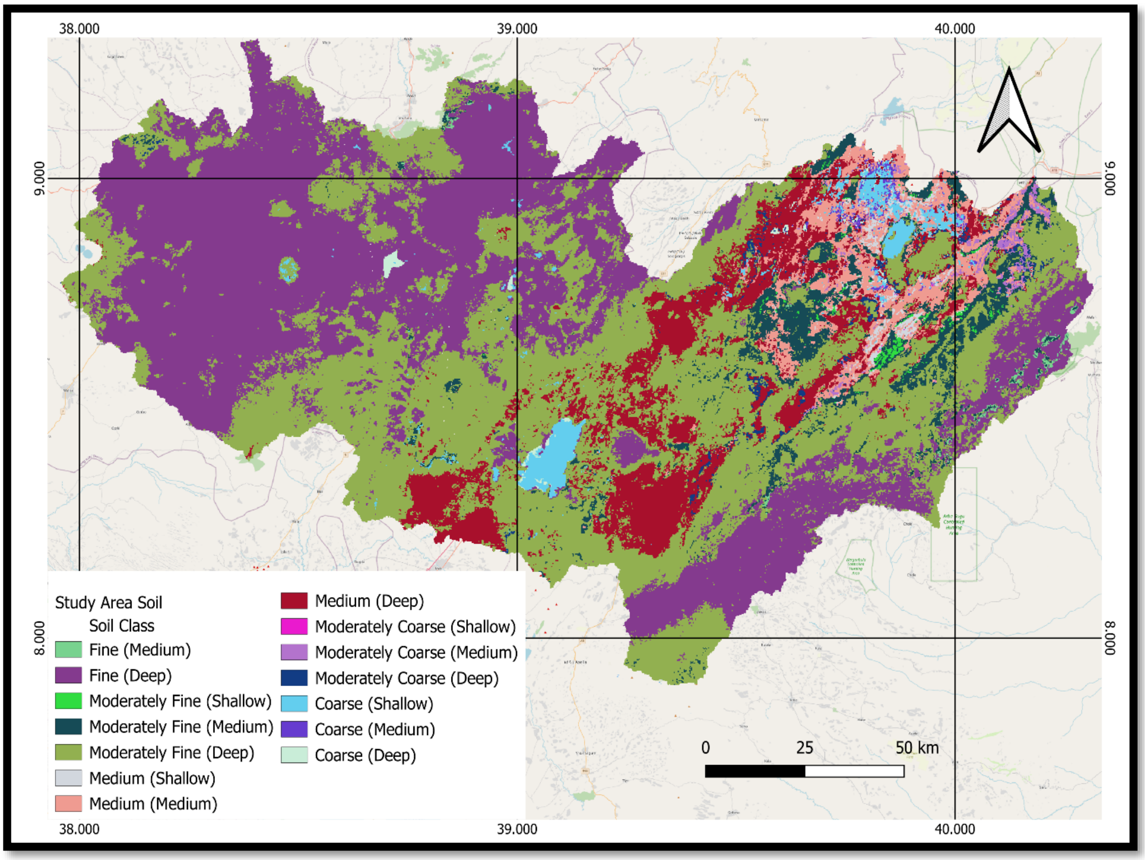

Figure 4: The soil texture variations within the study area.

Table 5: The soil texture variations within the study area

-	Fine	Moderately Fine	Medium	Moderately Coarse	Coarse
soil_0	soil_1	soil_2	soil_3	soil_4	soil_5
1%	47%	44%	6%	0%	2%

3.3. Methodology

The overall methodology of this study is summarized in Figure 5, which illustrates the relationship between the data sources, the analysis techniques, and the result.

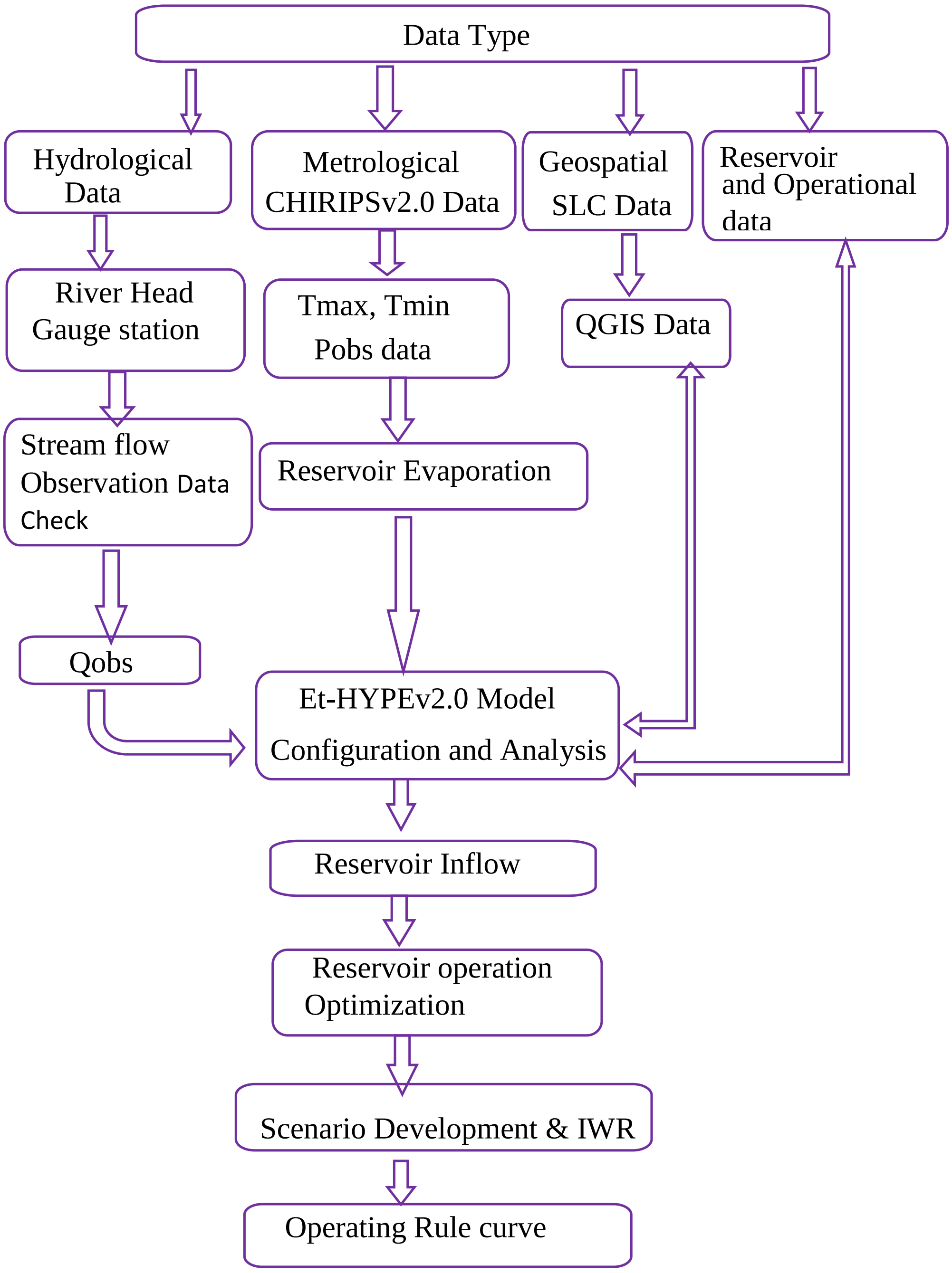

Figure 5:The general frame work of the methodology

3.3.1. HYPE Model Configuration

The HYPE model's configuration is a detailed and hierarchical process that transforms a real world river basin into a structured computational environment for hydrological simulation. This transformation begins with Spatial Discretization, where the large Catchment is systematically divided. The first level of partitioning is into a cascade of interconnected Sub-basins, which are delineated based on the local topography and the river network's structure. These sub-basins establish the hydrological routing pathways, dictating how water and substances flow from upstream to downstream. The second, more granular level of discretization involves dividing each sub-basin into Hydrological Response Units (HRUs). These HRUs represent the fundamental computational cells for land-based processes, defined by unique combinations of soil type and land-use/land-cover. By linking a large portion of the model's process parameters to these specific soil and land-use classes, HYPE effectively captures the physical heterogeneity of the landscape, allowing for realistic spatial variation in processes as indicated in Table 6. Finally, the entire simulation is driven by continuous Input Data, or forcing data, supplied at the sub basin level, which includes essential time series of Precipitation and Air Temperature.

Table 6: Physical Characteristics and Process Parameters

Component	Physical Input Data	Parameterization Detail
Soil/Land	Soil maps (depth, texture), Land-use maps.	Parameters control water holding capacity in different soil layers, flow partitioning (surface vs. macro pore flow), and recession rates for sub-surface flow and groundwater.
Reservoir/Lake	Area-Volume curve (storage capacity), operational rules (if modelled).	Parameters define evaporation loss, surface area, and routing coefficients for the water body.
River Routing	River geometry (length, slope), Sub-basin connectivity.	Parameters define the flow velocity or routing time step for translating upstream discharge to downstream points.

The HYPE model is a hydrological simulation model primarily used to generate the reservoir inflows and assess the impacts of reservoir release decisions. The algorithm configuration is defined by the choice and structure of the equations, which are highly flexible and driven by various input files and parameters. Water Balance equation is the fundamental principle in mass conservation. For any storage compartment (like a soil layer or a lake), the change in storage($\frac{Ds}{dt}$) is the difference between inflows and outflows.

$$\frac{Ds}{dt} = \text{Inflows - Outflows}$$

- Inflows include precipitation and influx from other SLC
- Outflows include evapotranspiration, percolation, and runoff.

Rainfall and Snowfall Separation is the partition of precipitation into rain and snow which is calculated based on air temperature (T) a threshold temperature (ttmp) and a transition interval (ttpi).

- If T ≤ ttmp - ttpi, precipitation is 100% snow.
- If T ≤ ttmp + ttpi, precipitation is 100% rain.(for the case of these study)

For intermediate temperatures, it is a mixture of liquid and solid forms, calculated as a linear or non-linear fraction (based on specific parameter choices). Potential Evapotranspiration (PET) is calculated for each SLC based on land use and atmospheric variables. HYPE offers different models (0-5) for PET calculation. Models (0-2) primarily use air temperature (T) and Models (3-5) is Modified Hargreaves-Samani approach uses a short wave radiation (radext) and minimum or maximum daily air temperature, incorporating parameters like the crop coefficient (kc) and turbidity (turbidity). The PET rate is then adjusted by a seasonal factor (cseason), which is often sinusoidal.

Runoff Generation processes (surface, interflow, base flow) are simulated as flow from soil layers. The amount of flow depends on soil moisture content and soil dependent parameters of Field capacity (wcfc) is Water available only for evapotranspiration and Effective porosity (wcep) is Water available for evapotranspiration, percolation and flow. The parameters that determine the configuration of these equations are stored in input files like par.txt, with specific values assigned to different Soil and Land-use Classes (SLCs) or applied generally across the catchment.

The Koka Dam reservoir operation optimization problem is mathematically defined by employing advanced computational techniques, such as Dynamic Programming (DP), Genetic Algorithms (GA), or Various Hybrid approaches. The entire problem centres on the Objective Function (H), which is the singular mathematical criterion that the chosen algorithm seeks to maximize or minimize over the planning horizon. The entire problem centres on the Objective Function (F), which is the singular mathematical criterion that the chosen algorithm seeks to maximize or minimize over the planning horizon.

The constraint that ensures the mathematical fidelity of the dynamic system is the water balance equation, which is a direct application of the Law of Mass Conservation to the reservoir's change in storage over time.

$$s_{t+1} = s_t + I_t - R_t - E_t - O_t$$

Where:

- ✓ s_{t+1} is the final storage volume at the end of period t.
- ✓ s_t is Storage Volume at the Start of Period t
- ✓ E_t is the loss due to evaporation during period t.
- ✓ O_t is the spill / overflow (uncontrolled release) during period t.
- ✓ R_t is Controlled Release (released through the dam out let) during period t.
- ✓ I_t is Inflow (Total water entering to the reservoir) during period t.

The optimization of reservoir operations is fundamentally governed by constraints, which represent the essential physical and operational limits that must be satisfied by the system at every time step(t). These boundaries define the feasible solution space and are typically categorized into two primary types: Storage Constraints and Release Constraints. Storage Constraints ensure that the reservoir volume (s_t) is continuously maintained within the design capacity, bounded by a minimum operational volume (Smin) and a maximum physical capacity (Smax), formalized as Smin $\leq s_t \leq$ Smax. Release Constraints impose two conditions on the controlled outflow (R_t) must be non-negative ($R_t \geq 0$) and it must not exceed the maximum flow capacity of the outlet works, such as penstock ($R_t \leq$ Rmax), where Rmax is often dependent on the current storage level.

The optimization algorithms that find an optimal release R_t at every time step, the HYPE model uses a simplified parametric regulation scheme (a release rule) for simulating regulated reservoirs. This rule defines the outflow (Qout) based on the water level or storage and a set of parameters including seasonal variation.

The general formula for the regulated outflow (Qregu in m^3/s) in HYPE often combines a seasonal target flow with an unregulated overflow based on a rating curve. The specific regulation parameters found in LakeData.txt file are used to define the seasonal target flow (Qtarget) component us illustrated in the Table 7.

Table 7: Seasonal target flow (Qtarget) component in Lake data txt file

Parameter	Description
Q_{PROD1}	Base Production/Target flow (m³/s).
Q_{PROD2}	Amplitude of a second, Sinusoidal target flow (m³/s).
QAMP	Amplitude of a sinusoidal flow variation, used if Q_{PROD1} is a median inflow.
QPHA	Phase Shift (in days) for the Seasonal Variation.

The most common HYPE regulation rule aims to maintain steady target outflow (Qreg) over the season, which is calculated as a base flow (QPROD1) modified by a sinusoidal (seasonal) component.

$$Q_{reg(t)} = Q_{PROD1} + \quad Q_{PROD2} * \sin\left(\frac{2\pi * (\text{day of year} + \text{QPHA})}{365}\right)$$

Where:

- ✓ $Q_{reg(t)}$ is the total target flow for the day t.
- ✓ Q_{PROD1} is the base flow
- ✓ $Q_{PROD2}$is the Amplitude of the seasonal variation and
- ✓ QPHA is the Phase Shift in days,

The actual reservoir outflow is then calculated by considering the available water (based on the water balance) and an unregulated flow component (like the overflow from the dam, Qunreg), which is often calculated using a rating curve (RATE and EXP in the file). The regulation scheme forces the outflow to be close to regulated flow (Qreg) as long as the water level is between the maximum and minimum regulation levels (defined by parameters like DATUM1 and DATUM2).

The system's uncontrolled discharge (Q_{unreg}) is quantified using a standard Rating Curve model, a nonlinear empirical relationship that correlates water storage volume to flow rate. The specific parameters required for this governing equation are contained within the provided lakedata.txt file.

$$Q_{unreg(t)} = RATE * (W_t - W_0 RFF)^{Exp}$$

Where:

- ✓ $Q_{unreg(t)}$ is the unregulated outflow(m^3/s)
- ✓ W_t is the instantaneous water level.

- ✓ W_0RFF is the minimum water level for outflow.
- ✓ $RATE$ is the discharge coefficient
- ✓ Exp is the exponent

3.3.2. Monte Carlo and HYPE Optimization Integration

This research utilizes a coupled Monte Carlo (MC) simulation and HYPE optimization framework to derive robust operating policies for a regulated reservoir system. The core principle of this integration is the use of the Monte Carlo method to generate a large ensemble of stochastic inflow scenarios and which accounts for the inherent hydrological uncertainty. The HYPE model then functions as a high-fidelity system simulator to test the performance of candidate operating policies against these diverse scenarios to ensuring the final robust policy.

The HYPE model serves as the system simulator and responsible for calculating the water balance and system performance metrics. Critically, the model's LakeData.txt input file defines the specific physical and operational structure of the reservoir. This file stores essential geometric properties (e.g. elevation-storage relationship) and most importantly provides the mechanism to define the reservoir as a regulated water body. This allows the candidate operating policy, parameterized by the vector (R) to be directly implemented and tested, linking the reservoir's simulated state (water level/storage) to the controlled outflow calculation during the simulation.

The overall simulation-optimization framework systematically searches for the optimal set of policy parameters (R) that govern the reservoir releases and aiming to maximize the objective function (F) across the range of simulated conditions. This process is formalized by the optimization statement:

Optimize F [R (MC Inflows, HYPE) LakeData.txt].

The process begins with the formulation of a specific objective function (F), such as maximizing the (P) reliable hydropower generation and the generation of candidate policy parameters (R) by an optimization algorithm.

The subsequent steps involve a critical loop. First, the Monte Carlo method generates synthetic inflow time series by capturing the statistical variability of the natural inputs. Second, the HYPE model is executed number of iteration for a single policy (R) with the policy parameters loaded via LakeData.txt in each run to simulate the resulting regulated outflow for each inflow scenario. Third, the resulting performance metrics (F) are aggregated to calculate a single robust fitness of annual cumulative volume inflow and release. Finally, this aggregated value of annual cumulative volume is used by the optimization algorithm to iteratively adjust and refine the policy parameters (R). This sequence repeats until the policy converges to an optimal set of operating rules that provides the best balance of performance and risk management across the spectrum of potential hydrological futures.

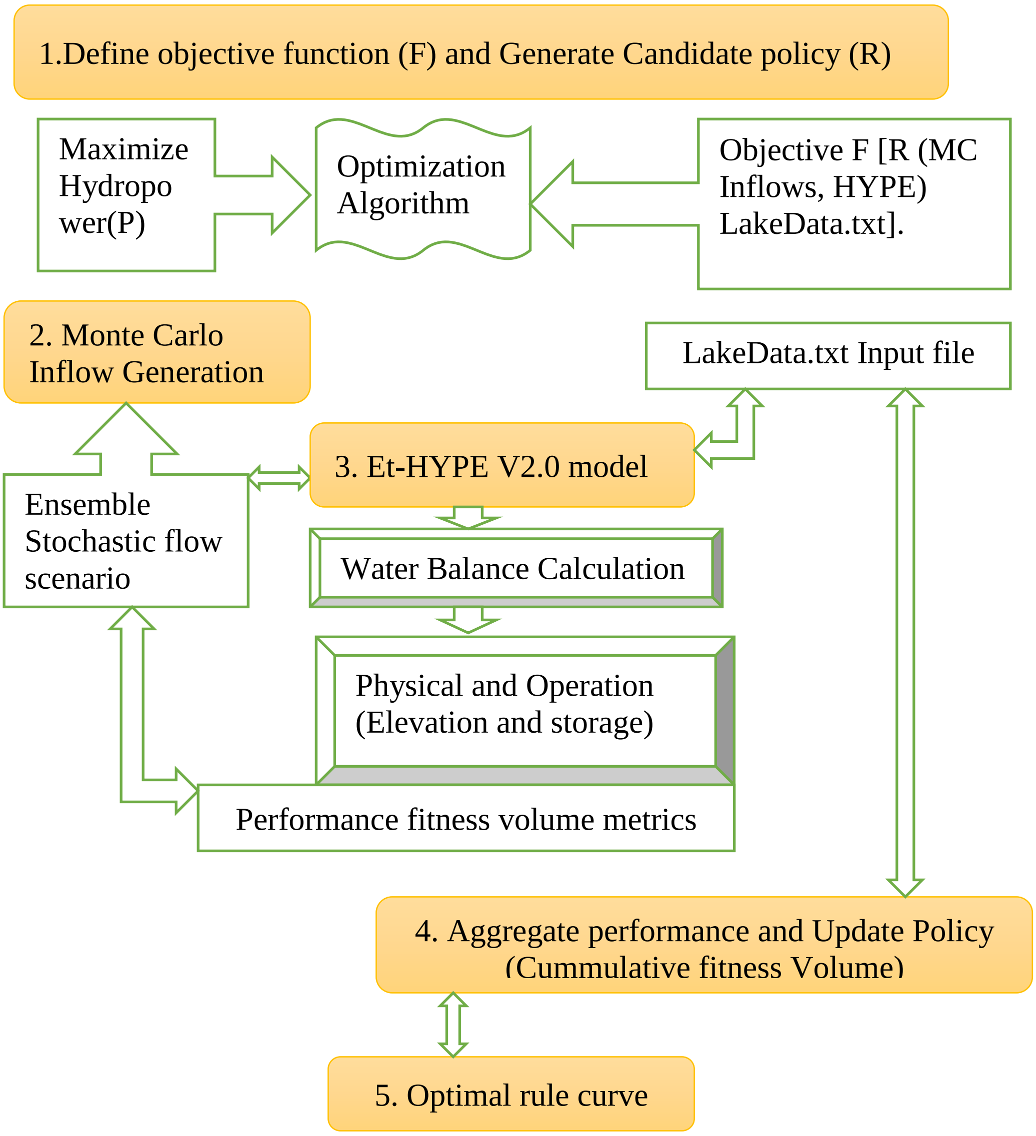

Figure 6:Optimizing and irrigation objective frame work methodology

3.3.3. Et-HYPEv2.0 Model Setup

The Et-HYPEv2.0 model a national setup of the HYPE model for Ethiopia. In this study, the Et-HYPEv2.0 model was chosen for several key reasons. Firstly, all necessary spatial and non-spatial data are readily available at the required resolution for the study area.

Secondly, the HYPE model and its manual are non-commercial, making it an accessible and cost-effective choice. Furthermore, its continuous time-based properties also provide the flexibility to predict runoff at any user defined temporal resolution. Ultimately, the Et-HYPEv2.0 model represents a strategic and highly advantageous framework, and its adoption is expected to significantly enhance the quality and impact of thesis research conducted at Addis Ababa University.

The Et-HYPEv2.0 model, applied across the entire study area, further classifies sub-basins into homogeneous units termed CLASSES. These classes, inherent to the HYPE model framework, are uniquely defined by specific combinations of land cover and soil type (The HYPE wiki pages [HYPE Model Documentation]).Drawing from the data sources the model incorporates eleven distinct land cover types namely Agriculture (Rain fed), Agriculture (Irrigated), Bare/Desert, Urban, Grassland, Shrub land, Closed Forest, Open Forest, Lake (distinguishing between Olake and Ilake), and Main river. Additionally, five primary soil types Fine, Moderately Fine, Medium, Moderately Coarse, and Coarse have been identified and integrated into the Et-HYPEv2.0 model for comprehensive hydrological simulation.

The HYPE model was employed to simulate the streamflow dynamics at the Hombole and Mojo stations. This modeling effort included calculating the aggregated sub-catchment contributions from the 69 delineated sub-catchments within the study area to determine the overall inflow to the Koka Reservoir.

3.3.4. Streamflow Data Analysis

Prior to any reservoir simulation or optimization study, it is essential to first acquire and validate a comprehensive set of input data. This fundamental step ensures the proper and accurate modeling of reservoir operations, laying the groundwork for a reliable and effective optimization strategy. These data were collected from different agencies and organizations. CHIRPSv2.0 Site Light Meteorological and MoWE hydrological flow data, and the time series data were also used for prediction of stream flow calibration and validation purpose.

LU/LC map, Soil map, stream flow, physical and operational data of the Koka reservoir and Awash were the main data used for this study. The LU/LC, soil, and meteorological data were integrated within the Et-HYPEv2.0 model. The stream flow data were obtained from the Ministry of Water and Electricity of Ethiopia. The primary water sources of Koka reservoir are Mojo and Hombole rivers. The Mojo and Hombole gauging stations, responsible for measuring the stream flow of their respective rivers, are situated at a distance of 42 km and 35 km from the Koka reservoir's inflow point, and no other tributary contributes water in between.

To estimate inflow to the Koka Reservoir from the two rivers, daily observed flows at Hombole (QHombole) and Mojo (QMojo) were utilized. These observed flows were then used to calibrate the Et-HYPEv2.0 model, with the model's computed flow subsequently serving as the estimated inflow. Upon the successful calibration and validation of the Et-HYPEv2.0 Model, the model was subsequently run over a 21-year period to generate the long-term average hydrological predictions for the study area.

3.3.5. Streamflow Data Outlier Test

The determination of outliers in gaged river stream flow is crucial for assessing fluctuations in river flow patterns. Given the global concern regarding water resource availability, it is essential to address uncertainties in these resources. The Water Resources Council recommends that adjustments be made for outliers, defined as data points that significantly deviate from the overall trend of the dataset. The decision to retain or eliminate these outliers can markedly influence the statistical parameters derived from the data, particularly in small samples.

Procedures for outlier detection necessitate careful judgment that encompasses both mathematical and hydrological considerations. According to the Water Resources Council (1981), when the station skew exceeds +0.4, priority should be given to testing for high outliers. Conversely, if the station skew falls below -0.4, the focus should shift to identifying low outliers. In cases where the station skew lies between -0.4 and +0.4, it is advisable to conduct tests for both high and low outliers before making any decisions about their removal from the dataset. This approach is essential for ensuring the integrity of the observed stream flow data series used in subsequent analyses.

The model performance was computed using 10 years (from 2000 to 2009) of stream flow data during the model calibration and 4 years (from 2010-2013) validation phases, respectively. The widely used objective functions, the relative Volume error (RE%) and Nash Sutcliffe Efficiency (NSE) were used for evaluation.

3.4. Calibration and Validation

3.4.1. Calibration

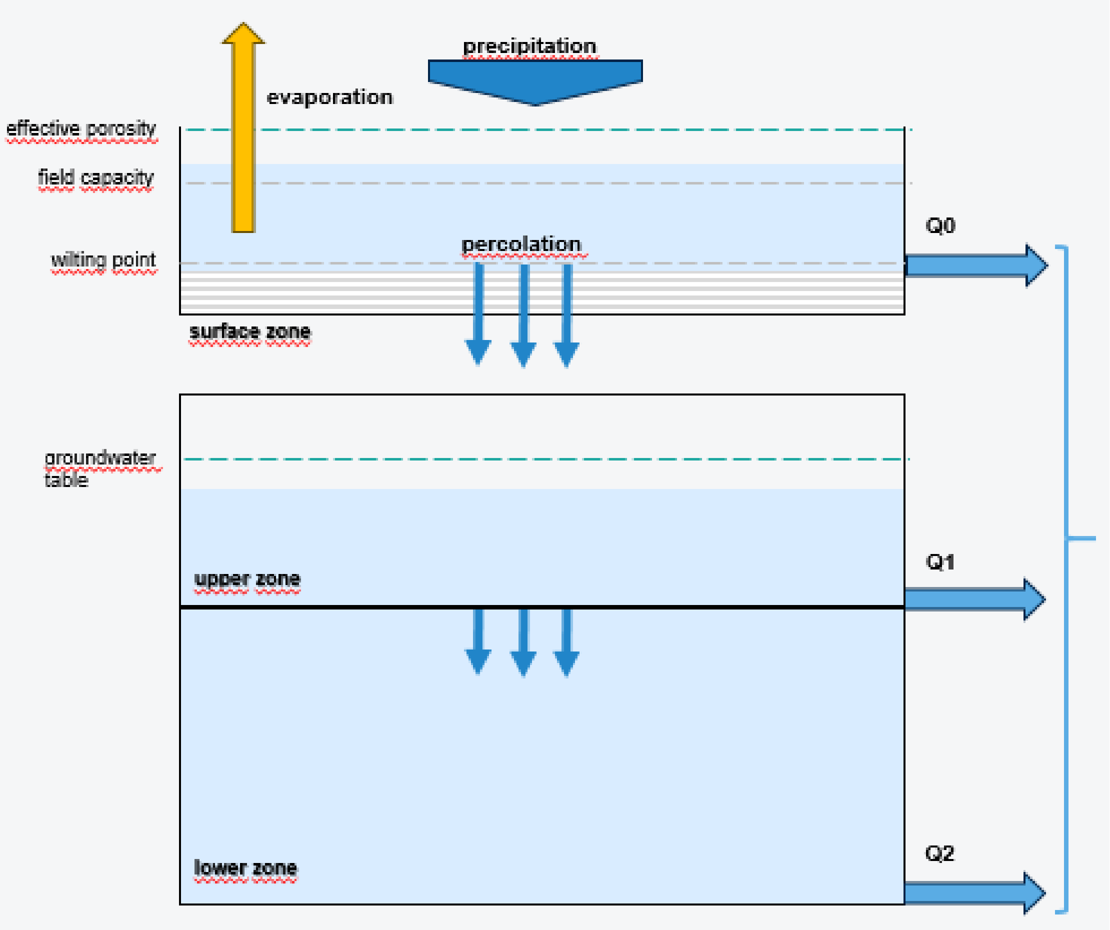

Figure 7: The general frame work of the HYPE model Local runoff from one SLC class

The HYPE model is a powerful tool for simulating water flow and substance transport in different environments. However, to ensure its accuracy for a specific area, calibration is essential. The model calibration involves systematically adjusting model parameters to optimize the agreement between simulated and observed hydrological processes (Massazza et al., 2020). The Calibration involves adjusting model parameters to minimize the difference between simulated and observed data. In the case of Et-HYPEv2.0, this typically means comparing simulated streamflow with observed streamflow data from gauging stations.

The Et-HYPEv2.0 model has been calibrated based on the 14 years (2000-2013) daily average flow measured at two gauging stations on inflow streams of Koka reservoir (Hombole and Mojo).

3.4.2. Validation

For this research, a temporal split-sample approach was applied to the collected 14 years of hydrological data obtained from various gauge stations. Specifically, 10 years of this dataset were allocated for the model calibration phase, allowing for a thorough optimization of the hydrological model's parameters across a representative range of conditions. Subsequently, the remaining 4 years of independent data were reserved for validation. This distinct delineation facilitated an impartial assessment of the calibrated model's performance and its capacity to accurately simulate hydrological processes when presented with previously unseen data, thereby ensuring a reliable evaluation of the model's predictive capabilities across the different gauge stations.

3.5. Hydrology

The Koka Reservoir (upper valley) receives an average annual runoff of roughly 1,660 MCM. Notably, the period from July to September accounts for approximately 90% of this total. By the time the water reaches the Awash station in the middle valley, the mean annual runoff is reduced to around 1,390 MCM, primarily as a consequence of water withdrawals for irrigation in the upper valley and losses associated with the Koka Reservoir. (Y., 2011)

According to MoWE, (2005) scenario the total run off generated from Awash River is 4527.1MCM/annum. A large amount of this is lost to seepage, evaporation and evapotranspiration from open water surfaces and wetlands. Annually, the rivers and streams feeding directly into Koka reservoir, along with the tributaries located upstream of the dam, supply a combined volume of 1650.9 MCM. The Koka Reservoir experiences substantial water losses due to seepage and evaporation, totaling over 400 MCM annually. Consequently, the mean annual runoff immediately downstream of the dam is reduced to 1248.3MCM (Birhanu.A, 2008)

The main tributaries of Awash River, up stream of Koka dam, are Akaki and Mojo rivers. Akaki River starts from the mountainous areas of the northern part of Addis Ababa and goes to the main Awash River Kunture and finally joins the Hombole gauging stations. Mojo River, the other main tributary to Awash, originates from the high lands northeast of

Addis Ababa. It drains a catchment area close to 1,900 km^2 and travels a total length of about 105 km before joining Awash. (Halcrow,1989).

3.5.1. Metrology

Climate Hazards Group InfraRed Precipitation with Station data version 2.0(CHIRPSv2.0) is a quasi-global, high-resolution (approximately 5 km) gridded precipitation product, which is designed to address data scarcity in regions with limited ground gauge networks. The estimation process for CHIRPS v2.0 blends three core data sources: InfraRed (IR) Satellite Data, which uses Cold Cloud Duration (CCD) estimates from geostationary satellites to provide high spatial and temporal resolution; in-situ rain gauge station data, which is incorporated to correct for systematic biases in the satellite-derived estimates; and the Climate Hazards Group Precipitation Climatology (CHPclim), which provides a long term average rainfall distribution to enhance the blending process. This synthesis yields a continuous long term daily gridded precipitation time series, which is then spatially aggregated and formatted to correspond to the delineated sub basins of the Et-HYPEv2.0 model domain. The weather Variables used in this study are daily precipitation, minimum and maximum air temperature for the period 1990 – 2010 of Daily meteorological data set.

A) Temperature

The study area experiences a tri-seasonal climate. The primary wet season, locally referred to as Kiremt, occurs during the summer months, specifically from July to September. A subsequent catchment-based analysis of the Mojo and Hombole sub-catchment river basin identified a significant dry period, locally termed Bega, which characteristically runs from March to June. This bega season is significant in the region as it coincides with the main harvest. Finally, a period of shorter rainfall, locally called belg, spans from March to May. In this study CHIRIPSv2.0 meteorological data with daily temporal resolution were used. As shown in Figure 7 below the maximum and minimum temperature in the upstream sub catchments of Mojo and Hombole station ranges from 17.5206 °C to 21.902 °C respectively.

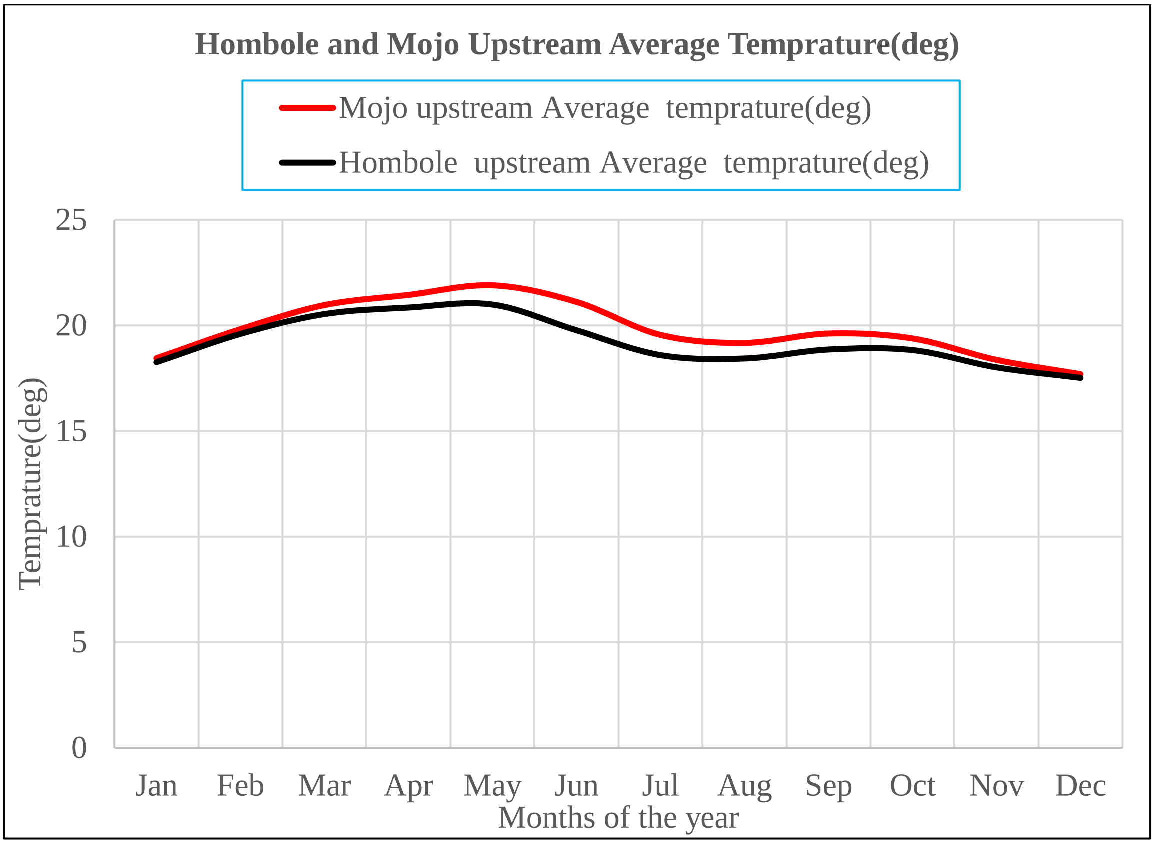

Figure 8: Average Monthly temperature of Hombole and Mojo station upstream (1990-2010)

B) Precipitation

The Monthly rainfall derived from a 21-year analysis of daily CHIRPSv2.0 satellite meteorological data range from 0 mm to 160 mm across the upstream sub-catchments of the Mojo and Hombole gauging stations. An analysis of the Average monthly rainfall as illustrated in Figure 8 from upstream of meteorological gauging station data, reveals a peak in precipitation within the study area Mojo and Hombole gauging stations during the months of July, August, and September, which corresponds to the region's characteristic wet season. whereas there is less rainfall for the month of October to February and it shows slightly moderate rainfall in the month of March to June in the small rainy season.

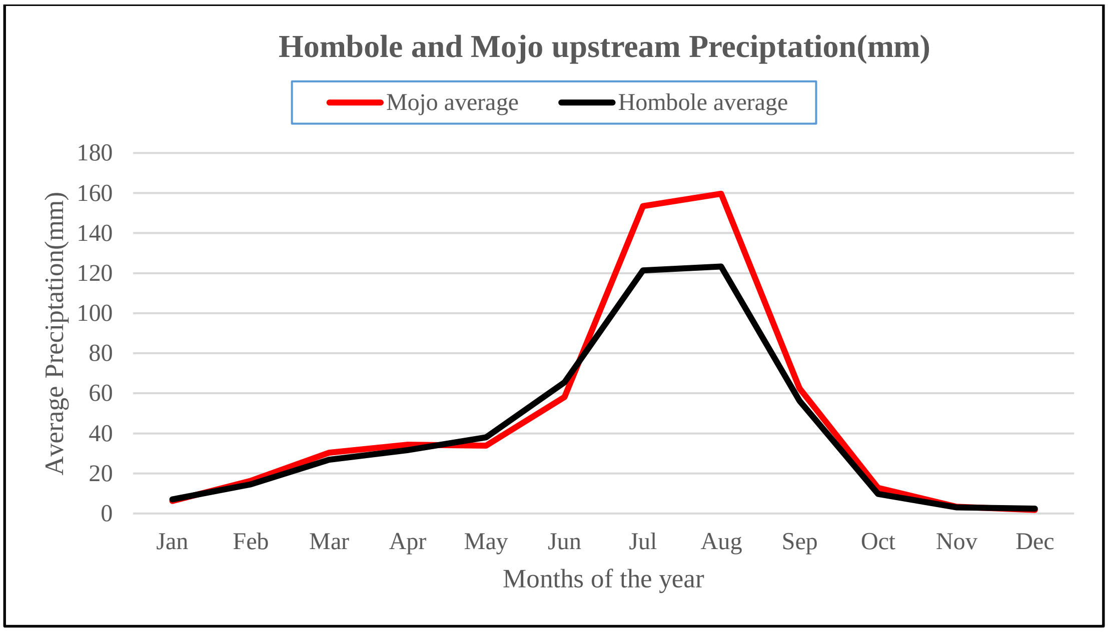

Figure 9: Average Monthly precipitation of Hombole and Mojo station upstream(1990-2010)

3.5.2. Surface water resources

Surface water is one of the key variables to determine the water resource availability of a given stream. Hombole catchment is characterized by high surface water resources potential. This is due to the high rainfall in the upstream area. The catchment has only one outlet in which Hombole river flows through and joined the main channel of awash river and joined the Koka reservoir.

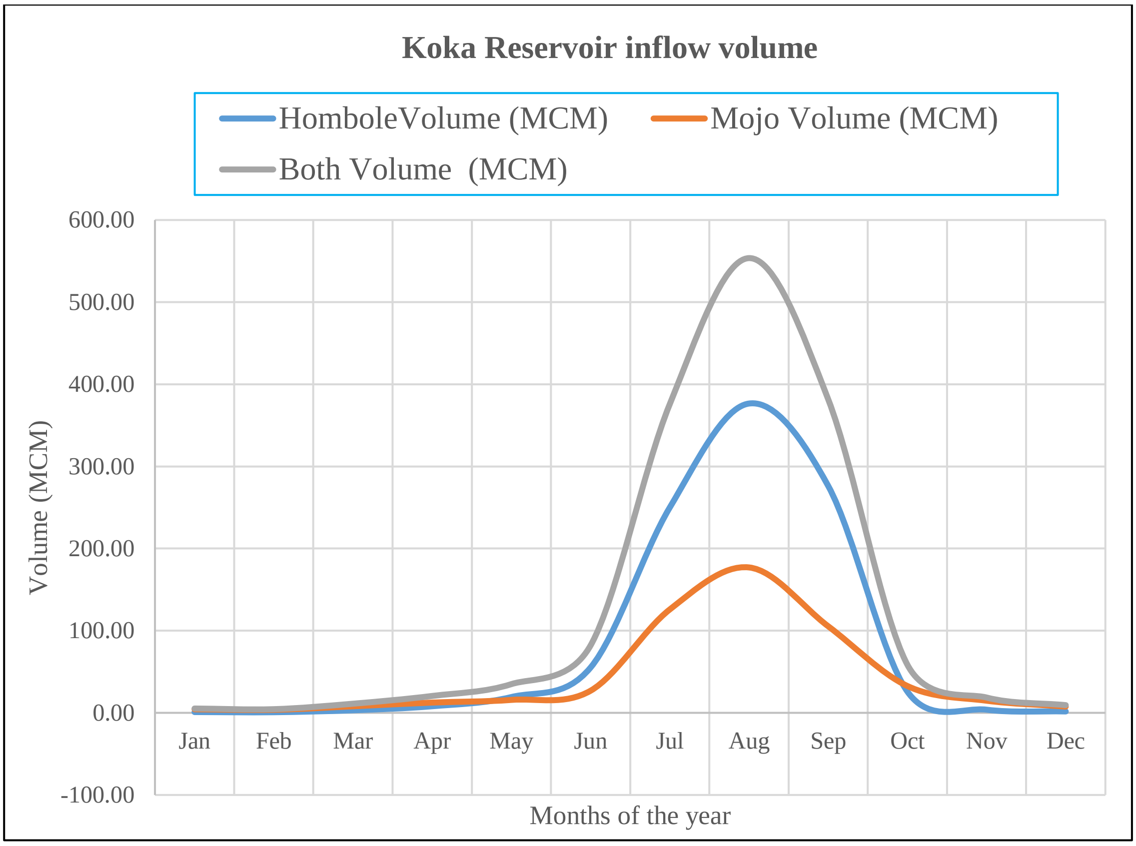

Figure 10: Average monthly inflow volume of Hombole and Mojo (1990-2010)

Leveraging the RGB concept, a comparative analysis of soil texture and agricultural classification reveals a strong similarity between Sub-basin awash Awash (ID 223) and Sub-Basin Below koka (ID 229) within the Awash River Basin. Specifically, both sub-basins exhibit characteristics consistent with moderately fine soil textures and a reliance on rain-fed agricultural practices. This established homogeneity suggests that the hydrological parameters calibrated and validated at the Awash Awash gauging station (linked to Sub-basin ID 223) can be reasonably transferred and considered representative for the upstream of below koka gauging station (associated with Sub-basin ID 229).

3.6. Representative Gauging Basin (RGB) classification

This study introduces an RGB classification approach, leveraging satellite imagery, to map and analyze SLC patterns within the study area. Specifically, this study utilizes the concept of Sub-Basin Identification (sub-basin ID) within Et-HYPEv2.0 model framework to delineate hydrological units that serve as the spatial basis for the classification. By integrating the Et-HYPEv2.0 model's sub-basin ID concept with RGB classification, the study aims to enhance the accuracy and relevance of SLC mapping for hydrological modeling and environmental assessments in the study area of the irrigation water requirement. This approach will allow us to assess the spatial distribution of key SLC categories, such as agriculture, urban areas, and forests, and their potential impacts on water resources and ecosystem services.

The methodological framework for this study area utilizes high-resolution modeling, specifically within the Et-HYPEv2.0 model environment. This approach prioritizes regional homogeneity over site-specific optimization. Data from multiple locations are incorporated to delineate broad hydrological patterns, acknowledging a potential trade-off in localized accuracy. Parameterization within the Et-HYPEv2.0 model is primarily dependent on land use and soil type classifications, rather than discrete, location-based calibration. This assumes that variations in these physical characteristics are representative of corresponding variations in hydrological processes. The avoidance of individual catchment calibration, or location-based fitting, is a deliberate strategy to enhance the model's robustness and predictive capacity, particularly in ungauged basins. This design choice aims to produce a model that is less reliant on site-specific observations and more capable of generalized prediction, which is considered advantageous for regional-scale hydrological assessments.

To analyze the water demands within the study area, this research initially delineates between rain-fed and irrigated agricultural practices. This fundamental distinction provides the framework for developing comparative scenarios that quantify water requirements under each agricultural system. Subsequently, the study investigates water use patterns in relation to the total reservoir discharge and specifically examines the volumes allocated for irrigation, considering the potential irrigable command area based on varying reservoir release amounts.

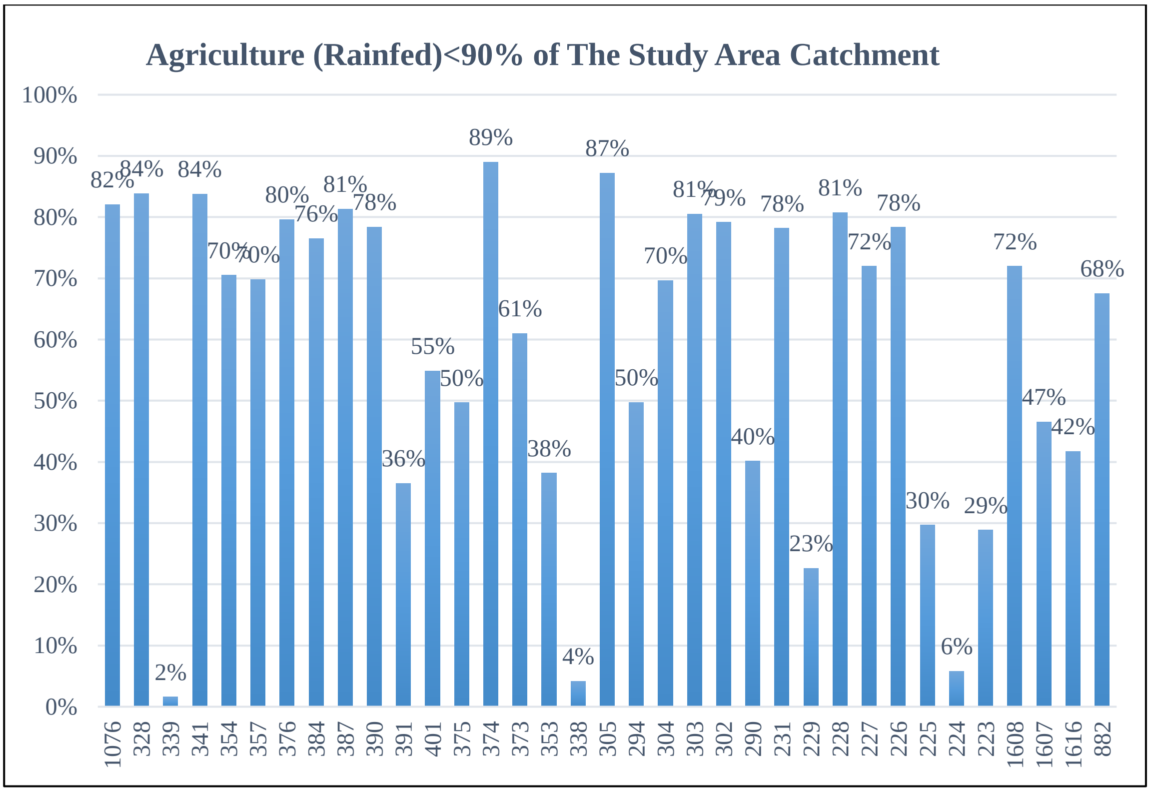

Figure 11: land use land cover of Rain fed agricultural < 90% of area chart

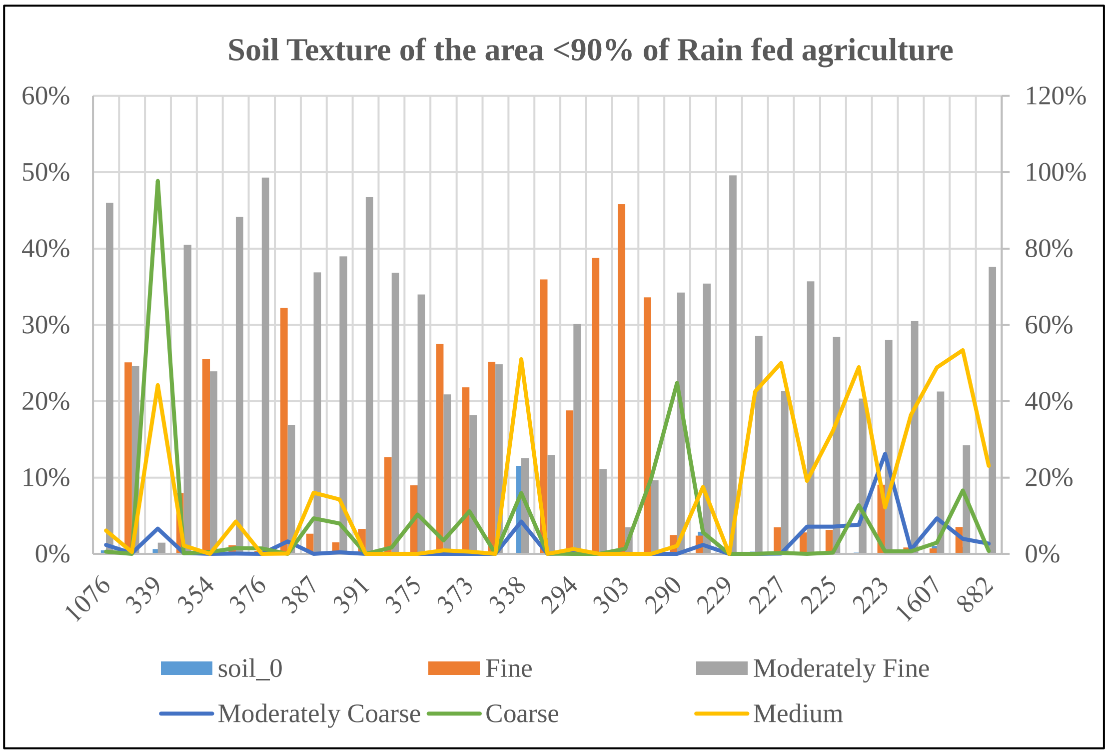

Figure 12: Soil texture of Rain fed agricultural < 90% area chart

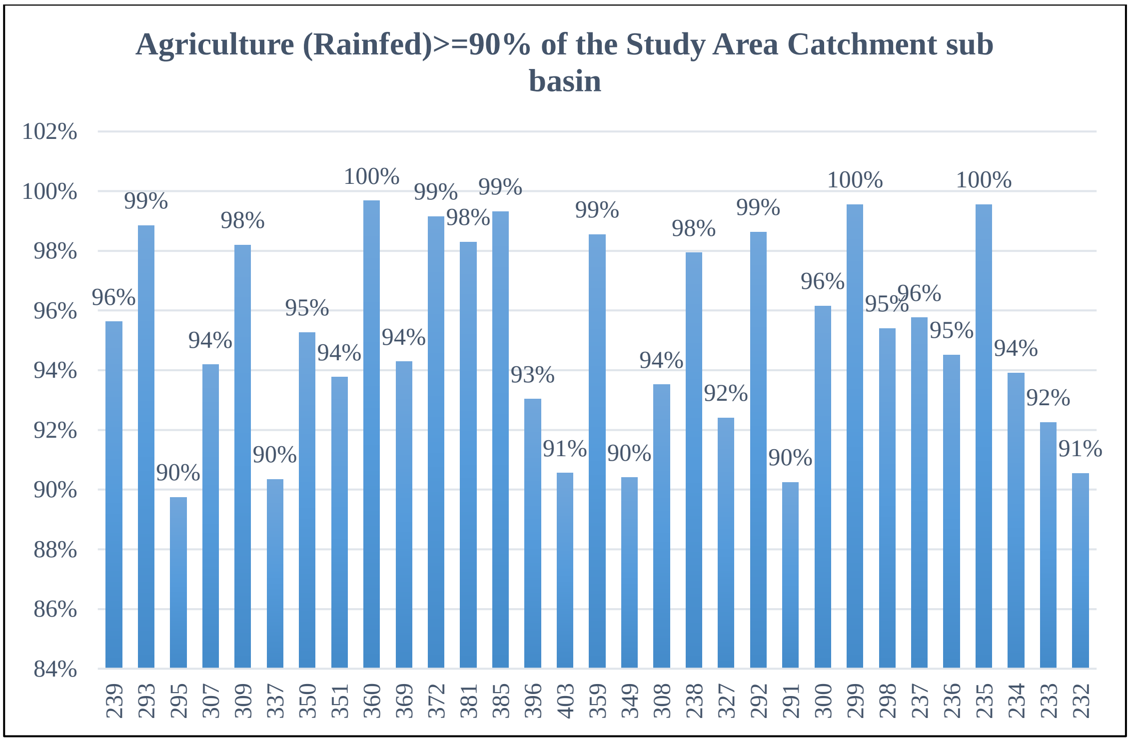

Figure 13: land use land cover of Rain fed agricultural >= 90% of area chart

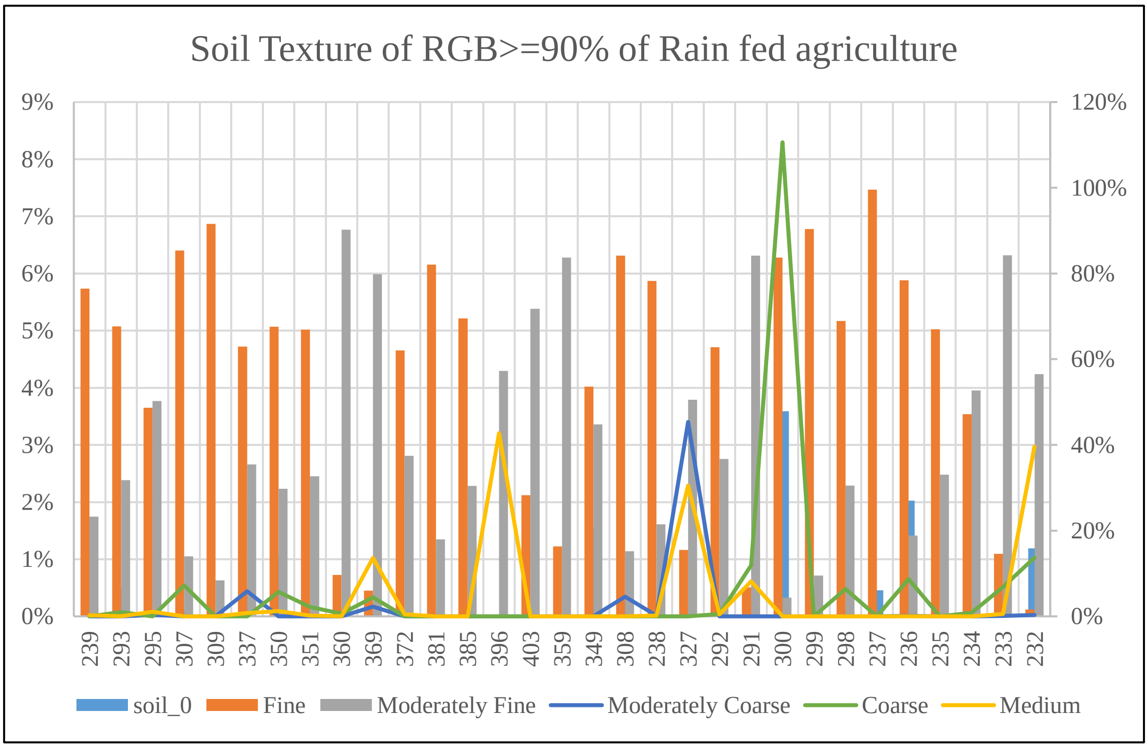

Figure 14: Soil texture of Rain fed agricultural >=90% area chart

In order to establish representative gauging basins for this research, the study area was systematically divided into 69 sub-catchments within the Et-HYPEv2.0 model framework.

This delineation, inherent to the model's structure, facilitated a consistent assessment of land use characteristics across the region. Aligning with our large-scale approach, we prioritized regional homogeneity over site-specific optimization. Consequently, 31 sub-catchments were identified as having a dominant land use of rain fed agriculture, exceeding 90% of their respective areas, there by capturing the prevalent agricultural patterns. Conversely, 35 sub-catchments, while also featuring rain fed agriculture, exhibited a lower proportional coverage, falling below 90%. These sub-catchments offer a contrast, highlighting the variability in agricultural land use across the broader study area. Finally, the remaining 3 sub-catchments, classified as Olake within the Et-HYPEv2.0 model, indicate the presence of water bodies, contributing to the region's overall hydrological diversity. This structured sub-catchment classification, based on land use and hydrological characteristics, supports the selection of gauging basins that are representative of the diverse conditions within the study area region, crucial for the application of our large scale, high-resolution modeling approach. By linking parameters primarily to land use and soil type, and avoiding individual calibration, we aim to enhance the model's robustness and predictive capacity, particularly in ungauged basins.

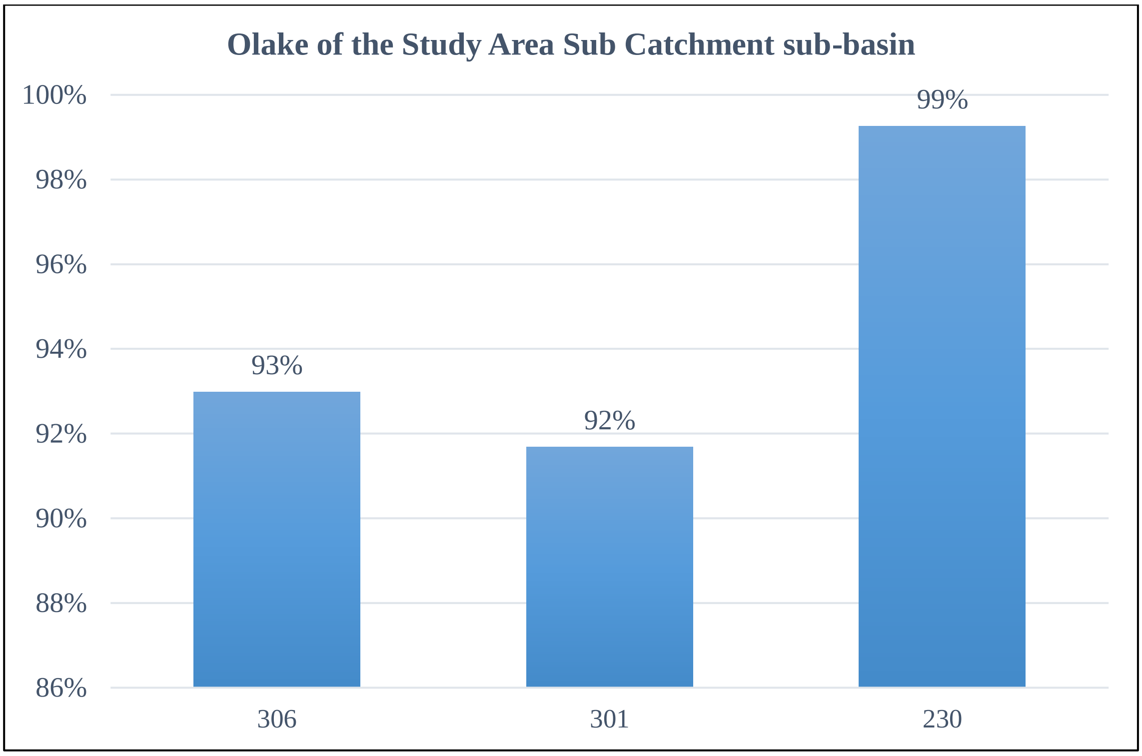

Figure 15: Olake of study area >=90% area chart

To establish representative gauging basins for calibration, sub-basin ID 233 was selected, representing sub-catchments with rain fed agriculture exceeding 90% coverage, and sub-basin ID 292 was chosen to represent those with rain fed agriculture below 90%. Calibration of these basins was performed, aiming to achieve Nash-Sutcliffe Efficiency (NSE) and Relative Error (RE) values within acceptable ranges.

3.7. Crop Selection and Scenario Development

This research explores improvements in Koka Reservoir operations through scenario-based crop selection, aiming to optimize water resource management. Building on the 2024 East Shoa Zone Modern Irrigation Inventory report, this research analyzes current agricultural data to determine optimal crop selection and proportions in the case of multi-crop scenario. The findings offer actionable recommendations to improve modern farming practices in the region. The core premise is that by strategically aligning crop choices with anticipated water availability scenarios, the reservoir's release patterns can be better managed to meet agricultural demands while also considering other operational objectives and creating a more holistic and responsive system.

The classification of irrigation command areas within a study region is crucial for effective water resource management and agricultural planning. This process involves delineating areas that are currently irrigated or have the potential for irrigation development. A key factor in this classification is the analysis of existing agricultural practices, specifically the distribution of rain-fed and irrigated agriculture, in conjunction with land use and land cover (LULC) maps.

The approach to developing and analyzing reservoir operation scenarios involves considering both monoculture and multi-crop systems water requirements within the study area. This method allows for the exploration of improvements in reservoir management, aiming to optimize irrigation water supply while simultaneously maximizing hydropower generation.

A) Multi-crop

In the Multi-crop scenario this research considered 10 crops to calculate the demand of water required for the cultivation in the 715.894 km2 irrigated agricultural field. Multi-crop production is currently a major aspect of agriculture in the Middle Awash, known for its significant presence in the irrigated agricultural system. A key horticultural crop in the region, benefiting from the favourable growing conditions and irrigation practices.

Multi-crop irrigation scenario was a carefully constructed plan defining exactly which crops would be grown (the crop portfolio) and how much land each one would take up (proportional area coverage). The proposed crop selections were outlined in the rigorous 2024 East Shoa Zone Modern Irrigation Inventory report. This initial data helps to select a diverse and important mix of crops for the region, ranging from essential staples for food security like teff, maize, and wheat, to profitable cash crops such as cotton, sugarcane, and mango.

To turn this theoretical proposal into a trustworthy field-based model, two-part validation methodology was implemented. First, we conducted extensive field investigations, walking the ground to see if the selected crops were truly a good fit for the Middle Awash's specific soils and local weather patterns. Second, conversations with the people who manage the system, the key administrative and technical staff at the Middle Awash Irrigation Infrastructure Administration Office. These interviews were the human element, essential for confirming the real-world market demand, social acceptance and operational viability of our crop distribution plan. This careful foundational scenario was strong and realistic setting for the proposed multi-Crop scenario from.

B) Monoculture

The first alternative investigated is the Monoculture Scenario, which is strategically cantered on sugarcane cultivation. This choice is highly relevant because sugarcane is recognized as the maximum water-consuming crop in the region, making it a critical test case for assessing the system's hydrological capacity and management limits. In contrast, the second key alternative examined is the Wheat Import Substitution Scenario. This scenario is developed in direct alignment with the Agricultural Transformation Institute's Agricultural transformation institute (ATI) national import substitution policy, which aims to reduce reliance on foreign grain. Therefore, the promotion and substantial expansion of wheat cultivation is modelled as a distinct and strategically important scenario, offering a direct assessment of how the irrigation system could support national food security objectives.

3.8. Irrigation Water Requirement

CLIMWAT 2.0 serves as a crucial climatic database specifically designed for seamless integration with the CROPWAT 8.0 software packages, particularly in the context of irrigation management (Gaddikeri et al., 2024).This database provides long-term monthly averages of essential meteorological parameters from over 5,000 weather stations across the globe. These parameters, which include mean daily maximum and minimum temperatures, mean relative humidity, mean wind speed, mean sunshine hours per day, mean solar radiation, monthly rainfall, and calculated monthly effective rainfall and reference evapotranspiration (ETo) using the Penman-Monteith method, form the fundamental climate input for CROPWAT. By offering readily available and formatted climate data, CLIMWAT 2.0 eliminates the need for extensive manual data collection and processing, streamlining the initial steps of crop water requirement and irrigation scheduling analyses within the CROPWAT environment.

The Cropwat8.0 software can directly import data for selected stations from the CLIMWAT 2.0 database. This allows users to define the climatic conditions relevant to their specific irrigation project location. CROPWAT2.0 then uses this historical climate data, in conjunction with user-defined crop and soil characteristics, to perform a comprehensive water balance. This balance enables the software to calculate crucial irrigation-related parameters such as crop water requirements (CWR), net and gross irrigation requirements, and to develop optimized irrigation schedules. By integrating CLIMWAT 2.0's long term climate averages, CROPWAT facilitates the development of robust irrigation strategies that account for typical climatic conditions and rainfall patterns, ultimately supporting efficient water use and maximizing crop productivity under irrigated agriculture.

The monthly irrigation water demand was computed using CLIMWAT 2.0 for CROPWAT and Cropwat8.0 software using irrigation area, soil, climate, and crop in formation. Crop water requirement (CWR) refers to the total amount of water needed by a crop to grow normally and achieve its full yield potential under specific environmental conditions. It encompasses the water lost through evapotranspiration (ETc), which is the sum of water transpired by the plant and evaporated from the soil surface around it. CWR is typically expressed in units of depth (millimetres) over a specific period (daily, monthly, or per growing season). Understanding CWR is fundamental for effective irrigation planning and management.

The water needs of a crop are influenced by several key factors. Climate plays a significant role, as environmental elements like temperature, solar radiation, humidity, and wind speed directly impact evapotranspiration rates and consequently, the crop water requirement (CWR). Hot, sunny, dry, and windy conditions all contribute to higher water demands. Crop type and its growth stage are also crucial; different crops have unique physiological characteristics and water usage patterns. Moreover, the water needs of a single crop fluctuate throughout its life cycle, typically increasing during vegetative growth and peak flowering/fruiting, then gradually decreasing as the crop approaches maturity. Soil type is another important determinant, as soil texture and structure dictate how much water the soil can hold and how readily it's available to plants. It shows that, sandy soils have a lower water holding capacity than clayey soils, necessitating more frequent irrigation. Finally, agronomic practices like planting density, mulching, and tillage can indirectly affect CWR by influencing soil evaporation.

Estimating CWR typically involves calculating or determining the reference evapotranspiration (ETo), which represents the evapotranspiration rate from a standardized vegetated surface (usually grass) under well-watered conditions. This ETo value is then adjusted by a crop coefficient (Kc) that accounts for the specific crop type and its growth stage. The formula is:

$$\mathrm{ET_C} = \mathrm{k_C} * \mathrm{ET_0}$$

Various methods are used to estimate ETo, ranging from direct measurements using lysimeters to estimations based on meteorological data using formulas like Penman-Monteith, which is widely considered the most accurate. Crop coefficients (Kc) are empirically derived values that vary with the crop and its developmental stage and are often available in guidelines published by organizations like the Food and Agriculture Organization of the United Nations (FAO).

For irrigation planning, it's also important to consider effective rainfall, which is the portion of rainfall that is actually available to meet the crop's water needs. The irrigation water requirement is then the difference between the CWR and the effective rainfall, adjusted for irrigation efficiency.

3.9. Rule Curve

Operating multipurpose reservoirs effectively for both flood mitigation and drought management necessitates the use of reservoir rule curves as essential guidelines. These curves ensure sufficient water storage for the subsequent dry season by strategically controlling water levels, aiming for maximum storage capacity at the conclusion of the rainy period. The Et-HYPEv2.0 reservoir simulation model served as the core analytical tool for this research, enabling the detailed simulation of various operating policies. The goal was to derive optimized operating rules that specifically lead to an improved water conservation strategy, allowing the reservoir to achieve and sustain the maximum permissible storage capacity at the close of the rainy season. The present and future inflow was used to evaluate the efficiency of the newly obtained rule curves. To evaluate performance, this study utilized the conditions of water scarcity and surplus, alongside the volume of stored water at the close of the wet season.

The Rule Curve aims to meet the required releases during these scarcer months. In the present work Cropwat8.0 is adopted for estimating the water requirement for selected crops water requirement. It is based on soil, climate and type of the crop. It can also be used in development of irrigation schedules for supplying water for varying crop patterns.

4. Result and Discussion

4.1. Model Calibration and Validation

The hydrological model's performance was rigorously assessed across three key gauging stations within the study area: Awash Awash, Hombole, and Mojo. This evaluation employed widely accepted metrics, including the Nash-Sutcliffe Efficiency (NSE), Correlation Coefficient (CC), and Relative Error (RE%), covering both calibration and independent validation periods.

The performance of hydrological and reservoir simulation models is rigorously assessed using established metrics, primarily the Nash-Sutcliffe Efficiency (NSE) and the Relative Volume Percentage (RE), also known as Percent Bias (PBIAS). The NSE is a widely used normalized statistic, developed by Nash and Sutcliffe in 1970, that assesses a model's performance relative to observed data by comparing the residual variance of the model to the variance of the measured data. Its values range from to 1.0, where 1.0 indicates a perfect match and 0 means the model performs no better than using the observed mean. Based on established hydrological criteria (Daniel N. et al., 2015) , an NSE value greater than 0.80 is classified as Very Good, while values between 0.70 and 0.80 are considered Good. Complementarily, the Relative Volume Percentage (RE) quantifies the overall volume error or bias, measuring the model's tendency to consistently over- or under-estimate the total water volume over the study period. An RE of 0% signifies a perfect volume balance, while positive or negative values denote over- or under-estimation, respectively. For flow simulation, an RE/PBIAS value within pm 10% is categorized as Very Good, and values within pm 15% are classified as Good.

At the Awash Awash gauging station (ID:223), the model exhibited satisfactory to good performance during calibration. An NSE of 0.53 and a CC of 0.74 indicated a reasonable ability to capture the observed flow dynamics and hydrograph shape. Furthermore, a relative Volume error (RE%) of -11.43% suggested a slight, yet acceptable, underestimation of flow volume. Crucially, the model's performance improved notably during the validation period, achieving an NSE of 0.65 and an excellent CC of 0.80. The most striking improvement was in bias, with the RE% reduced to a mere -0.81%, signifying a highly accurate representation of the total flow volume. These results collectively classify the model's performance at Awash Awash as Satisfactory to good, demonstrating its reliability for this specific location.

Similarly, the Mojo gauging station (ID:292) demonstrated consistently good performance across both assessment periods. During calibration, the model achieved an NSE of 0.65 and a very strong CC of 0.82, accompanied by a remarkably low relative volume error of -6.01%. This indicated a close alignment between simulated and observed flows with minimal bias. This high level of accuracy was maintained during validation, with an NSE of 0.67, a CC of 0.83 and a nearly identical RE% of -5.85%. The consistently good performance at Mojo underscores the model's strong predictive capability and reliable representation of the hydrological processes within this sub-basin.

In contrast, while the model exhibited strong statistical indicators for efficiency and correlation at the Hombole gauging station (ID:233), a significant concern emerged regarding its water balance representation. During the calibration period, a Nash-Sutcliffe Efficiency (NSE) of 0.71 and a Correlation Coefficient (CC) of 0.86 were achieved, indicating a good-to-very-good model performance. However, a substantial relative volume error of -22.64% indicated a notable underestimation of the total flow volume. This systematic negative bias became even more pronounced during the independent validation period, where the RE% deteriorated to -29.41%. Despite maintaining good NSE (0.69) and very good CC (0.85) in validation, the result shows a persistent and considerable underestimation (approaching 30%) of flow volume. While the model accurately reproduces the hydrograph's shape and timing (the temporal pattern of flow), it exhibits a systematic underestimation of the total inflow volume from Hombole station to the Koka reservoir. This suggests a significant, consistent discrepancy in capturing the total water balance either by missing a major component of the water input or by inadequately accounting for actual losses within the sub-basin.

In conclusion, the model demonstrates high reliability for streamflow simulation at the Awash Awash and Mojo gauging stations, with particularly strong performance at Mojo.

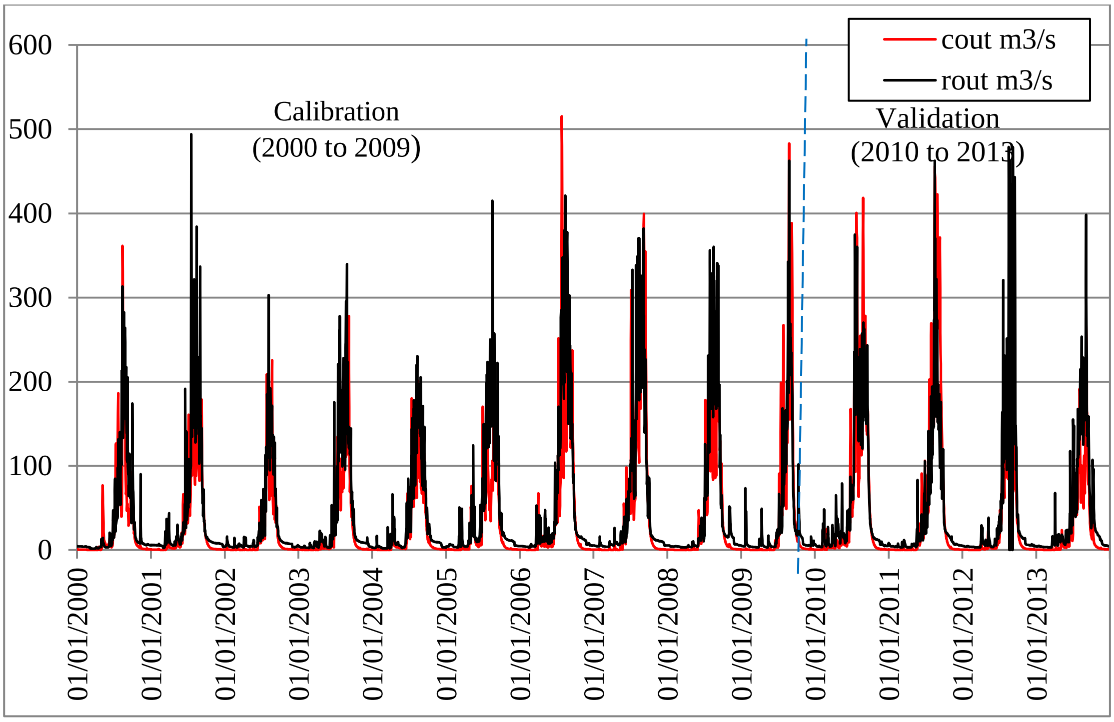

Figure 16: Hombole Station river flow calibration and validation

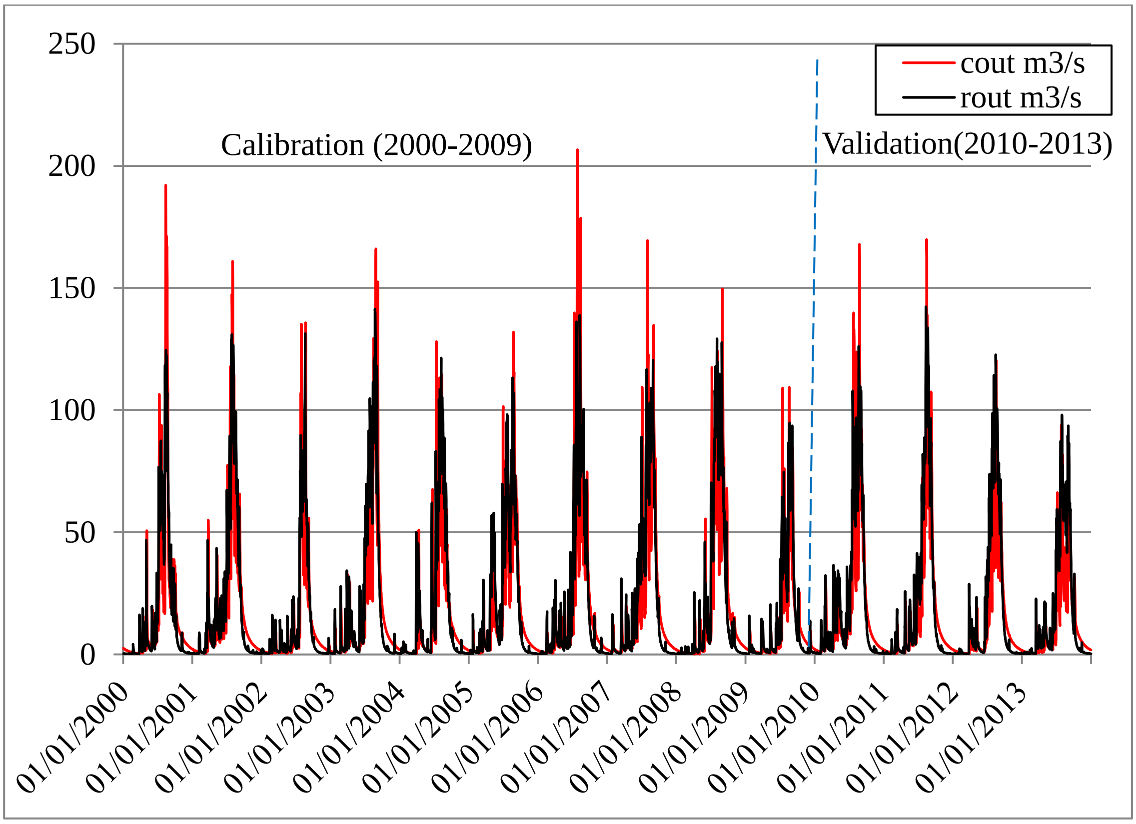

Figure 17: Mojo Station river flow calibration and validation

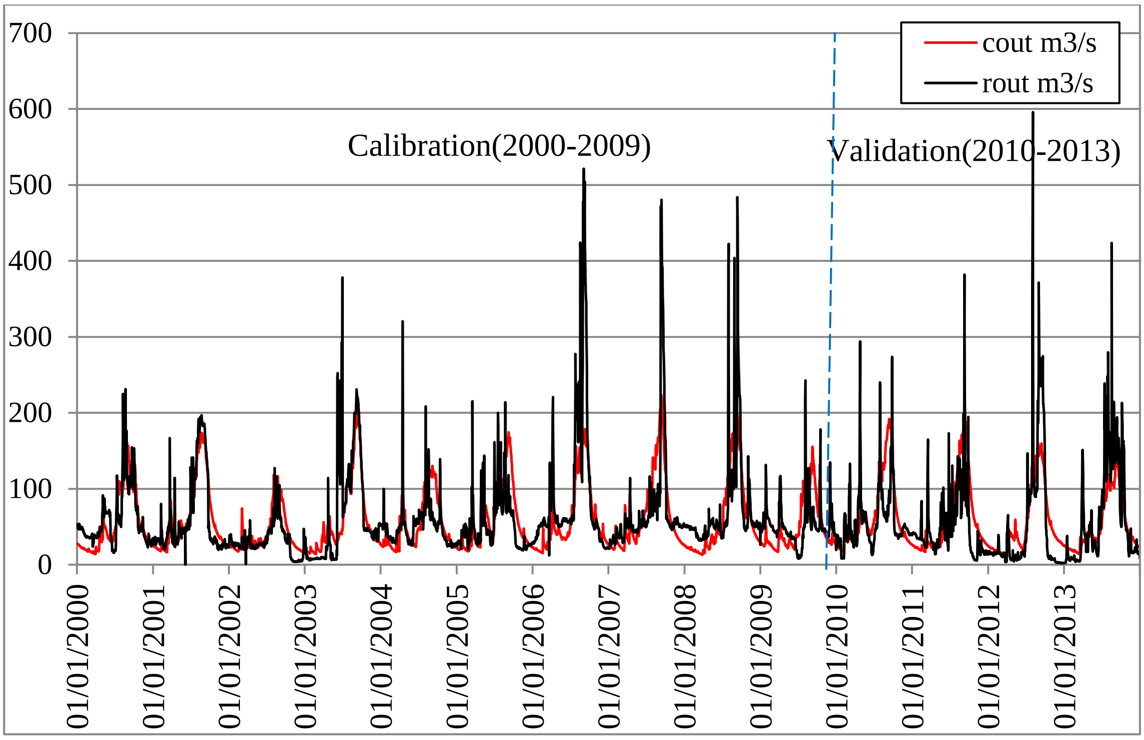

Figure 18: Awash Awash Station river flow calibration

Table 8: Model performance result during calibration and validation

Gauging Station	SUBID	calibration			Validation		
		NSE	CC	RE(%)	NSE	CC	RE(%)
Awash Awash	223	0.53	0.74	-11.43	0.65	0.80	-0.81
Hombole	233	0.71	0.86	-22.64	0.69	0.85	-29.41
Mojo	292	0.65	0.82	-6.01	0.67	0.83	-5.85

The mean annual runoff volumes of the simulated flow at the Hombole, Mojo, and Awash sub-basin gauging stations were determined to be 1035.62 MCM, 530.32 MCM, and 1840.523 MCM, respectively. While these simulated volumes were underestimated compared to observed flows, this finding is consistent with Amin & Nuru (2020) assessment of water resource availability in the Mojo watershed. Similarly, Al-Weshah et al.(2019) estimated the mean annual runoff volume for the Hombole watershed at 1035 MCM, a figure closely aligning with the current study's estimate, despite differences in methodology, spatial data, model selection, and study duration.

4.2. Trend of the Reservoir Release

Building a model like Et-HYPEv2.0 using historical data from 1990-1999 is crucial for understanding the Koka Reservoir's past. This information helps us to identify long-term patterns and trends, which are vital for predicting future conditions and ensuring effective reservoir management.

The monthly average outflow of the Koka Reservoir shows a clear seasonal trend. The flow rate is relatively low and stable during the first half of the year, from January to July, with average flows ranging from approximately 29.85 to 35.46 cubic meters per second (m^3/s). This period represents a dry season, where the reservoir receives minimal inflow, and releases are likely controlled to maintain a steady, but lower level of hydropower generation.

A significant increase in the flow rate begins in August, and the peak is reached in September, where the flow rises to 111.41m^3/s. This spike is a strong indicator of the primary rainy season, where high inflows into the reservoir lead to increased water availability. This period allows for a substantial boost in hydropower production.

After the peak in September, the flow gradually declines through October and November, and then stabilizes again in December at a low level, marking the transition back to the dry season. The seasonal pattern indicates that hydropower generation from the Koka reservoir is highly dependent on the rainy season, with peak production occurring in the months following the heaviest rainfall.

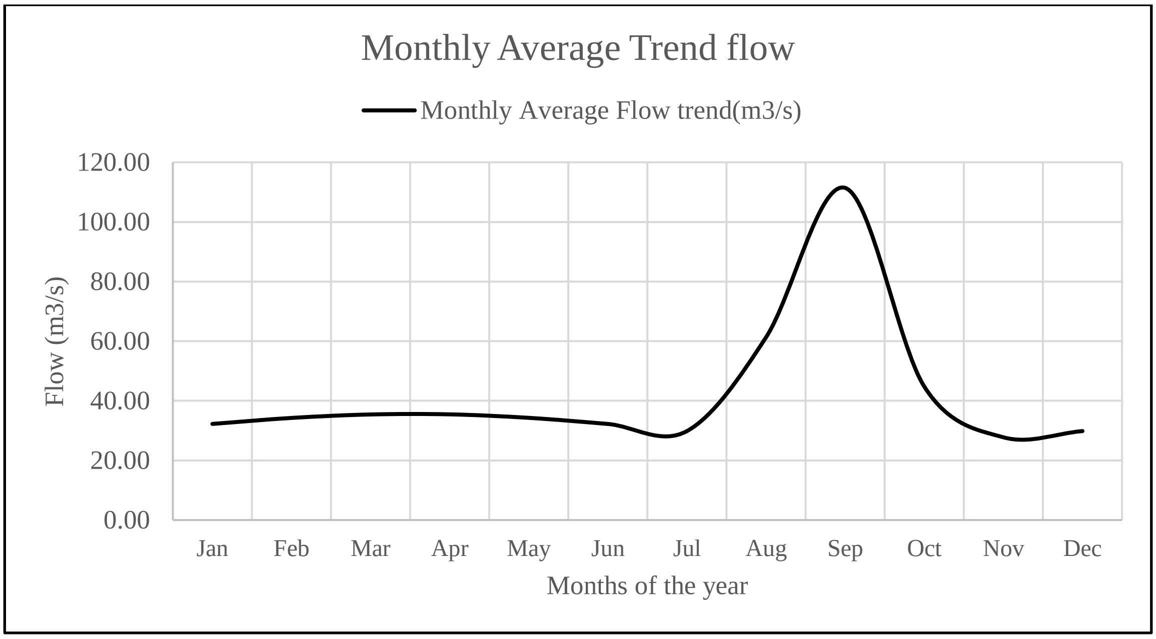

Figure 19: Average Monthly Flow Trend of Koka Reservoir(1990-1999)

4.3. Reservoir Operation and Optimization Model in HYPE.

The Et-HYPEv2.0 model for Koka Reservoir operation optimization is a valuable tool. It was built using historical data on monthly dry and wet season flow, which allows it to identify optimal operational trends and provide key insights for future reservoir management.

While the Koka Dam was initially constructed for hydropower generation, its management has evolved to accommodate and prioritize irrigation demands. To assess this operational shift, this research employs the Et-HYPEv2.0 reservoir operation optimization model, which has demonstrated a strong capacity for providing reliable and accurate hydrological simulations. The successful calibration ensured the model's parameters were optimally tuned to reflect observed hydrological processes within the contributing basin. Consequently, this validated Et-HYPEv2.0 model serves as a critical tool for informing optimized reservoir release strategies, enabling the determination of efficient outflow management plans that effectively balance complex, often competing, objectives such as hydropower generation, irrigation water supply, and flood mitigation of the study area.

Table 9: Monthly average Inflow and reservoirs optimized operation release

Month	Ave. Inflow (m3/s)	Ave. Optimized release(m3/s)
Jan	1.92	45.40
Feb	1.56	45.40
Mar	3.74	45.37
Apr	7.39	45.21
May	13.21	44.62
Jun	27.45	44.82
Jul	134.14	45.40
Aug	205.67	46.92
Sep	148.63	76.71
Oct	21.44	47.10
Nov	6.72	45.40
Dec	3.39	45.40

The provided table 9 above illustrates the Ave. Optimized release demonstrates a relatively consistent release strategy for much of the year, maintaining around 45 m3/s from January through July, and again in November and December. Notably, there's a significant surge in optimized release during September (76.71 m3/s) and a lesser increase in August (46.92 m3/s) and October (47.10 m3/s), coinciding with or immediately following the peak inflow months. In contrast, seasonal variability of inflow into the reservoir are significantly low during the early months of the year (January-May), ranging from 1.56 m3/s to 13.21 m3/s. A dramatic increase in inflow occurs during the mid-year, peaking in August at a substantial 205.67 m3/s, followed by high inflows in July (134.14 m3/s) and September (148.63 m3/s).

This pattern of optimized release strongly suggests a strategy designed to balance flood control during the wet season with maintaining a consistent water supply during drier periods. The relatively stable baseline release of approximately 45 m^3/s during months of low inflow indicates an effort to meet continuous downstream demands or maintain environmental flows. The marked increase in optimized release during August, September, and October directly corresponds to the period of maximum inflows. This elevated release is crucial for managing the large volumes of incoming water, preventing the reservoir from overfilling and potentially causing downstream flooding, and creating storage capacity for future inflows. The fact that the release volume in September (76.71 m^3/s) is significantly higher than in August (46.92 m^3/s) despite August having the highest inflow suggests a strategic decision to make larger controlled releases after the absolute peak inflow. This optimized operation demonstrates a proactive approach to reservoir management, aiming to mitigate flood risks while ensuring water security throughout the year.

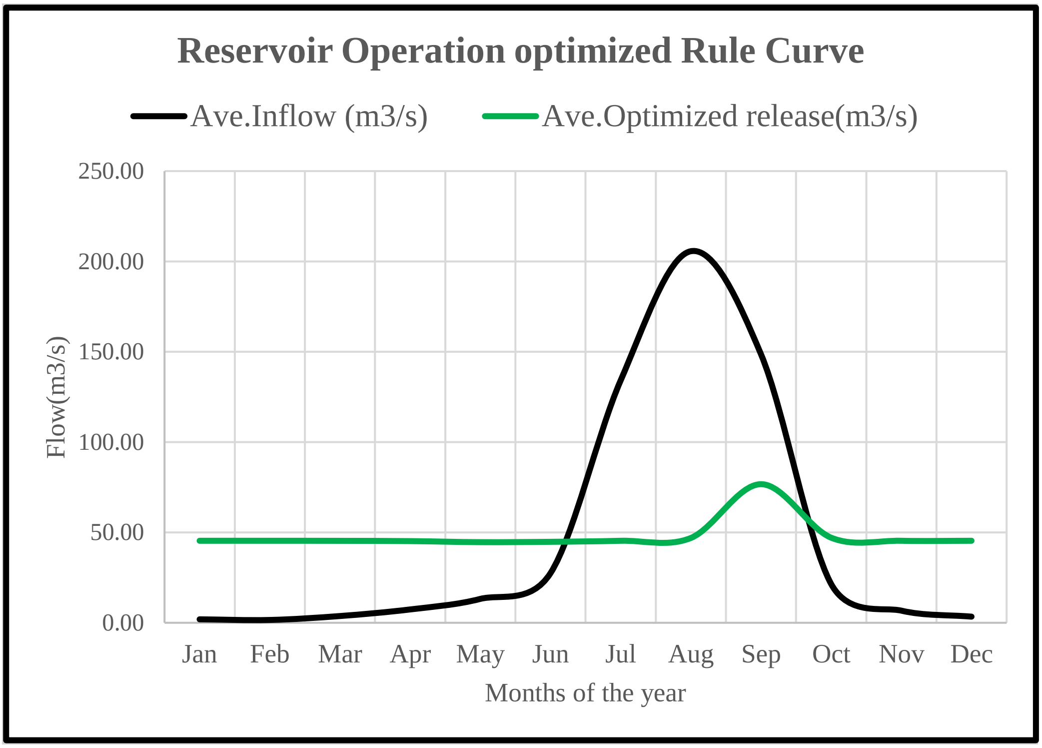

Figure 20: Reservoir Operation Optimized Release Rule Curve (m^3/s)

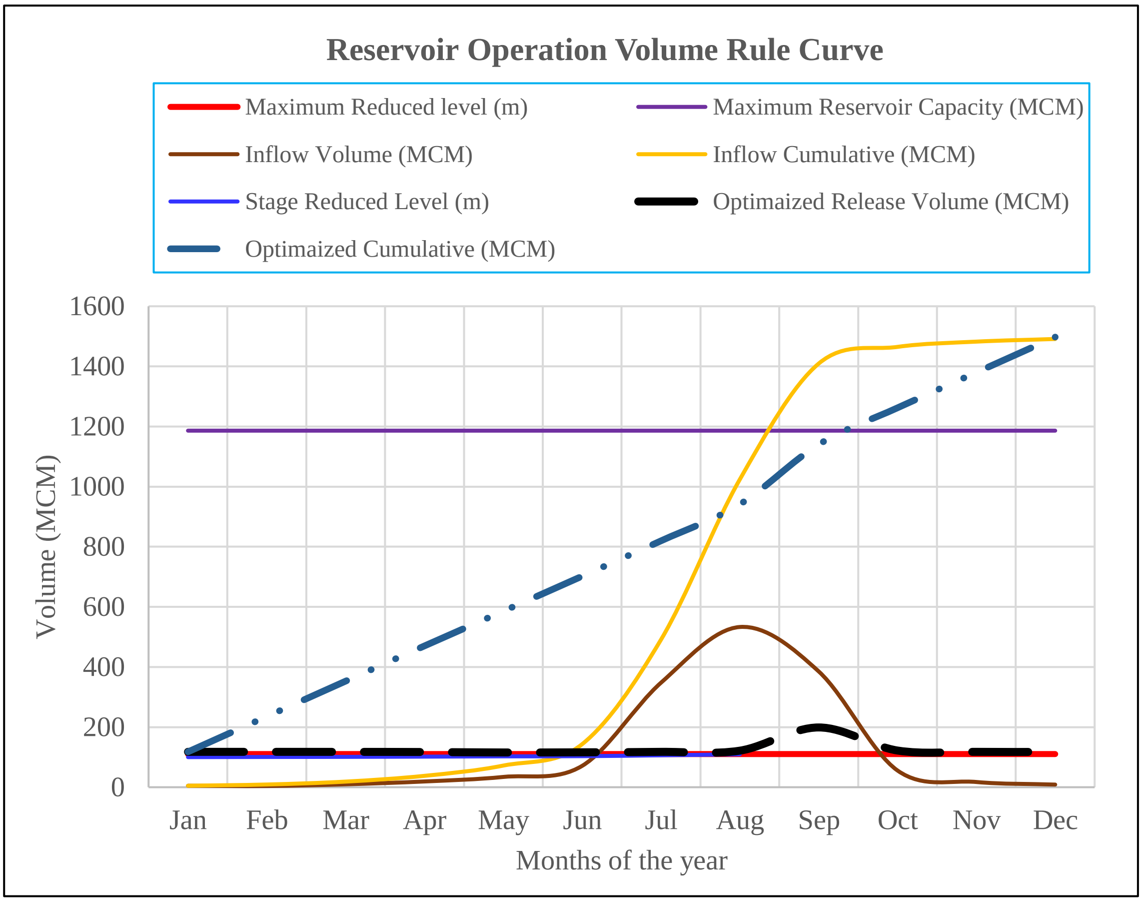

Figure 21: Reservoir Operation Volume Rule Curve (MCM)

The Reservoir Operation Volume Rule Curve figure 20 clearly illustrates a planned strategy for managing water levels and releases from a reservoir over a 12-month cycle. A key observation is the distinct annual hydrological pattern of Inflow Volume (brown line) shows a significant peak around month 8, reaching over 500 MCM, which corresponds with a rapid increase in Inflow Cumulative (yellow line) during months 6-9, indicating a pronounced wet season. Despite these substantial inflows, the Optimized Release Volume (black dash-dot line) demonstrates a carefully controlled release strategy, with a notable increase around month 8-9 that then declines, aiming to manage the reservoir's volume. The Optimized Cumulative (dark blue dash-dot line) shows a steady, managed release over the year, while the reservoir's actual volume (implied by the optimized curves) consistently stays above the Maximum Reduced Level (red line) and Stage Reduced Level (blue line), both around 120 MCM, ensuring a minimum operational level is maintained. The reservoir's Maximum Capacity (purple line) is clearly defined at 1200 MCM, serving as an upper bound for storage.

This rule curve's design highlights a robust approach to balancing water availability with demand and flood control. The sharp rise in Inflow Volume necessitates careful management to prevent overtopping or excessive spillage, which the Optimized Release Volume addresses by increasing releases during the peak inflow period. This proactive release strategy helps to maintain the reservoir's volume below its Maximum Reservoir Capacity, thereby safeguarding against potential flood risks downstream. Concurrently, by ensuring the Optimized Volume remains consistently above the critical Maximum Reduced Level, the strategy prioritizes sustained water availability for various uses during drier periods, demonstrating an effective allocation of resources throughout the year. The overall pattern suggests an optimized operation designed to mitigate the impacts of highly variable seasonal inflows, ensuring both system safety and supply reliability.

4.4. Crop Scenarios development and Reservoir operation

The scenario development and analyzing reservoir operation consider both monoculture and multi-crop systems water requirements within the study area. This method allows for the exploration of improvements in reservoir management, aiming to optimize irrigation water supply while simultaneously maximizing hydropower generation.

A rule curve in water resource management is essentially a predefined set of operational guidelines for a reservoir, dictating how much water should be released or stored over time, typically on a monthly or seasonal basis. It acts as a blueprint for managing water levels and flows to meet the three scenario based objectives.

This study applied for the reservoir operation simulation based on the CLIMWAT v2.0 for CROPWAT8.0 model to improve the current reservoir operation practice and storing the highest capacity at the end of rainy season. The Rule Curve aims to meet the required releases during these scarcer months.

This research uses Wonji station CLIMWAT v2.0 data as the primary climate input to generate a dynamic irrigation calendar. While this enables responsive water management, the data's representativeness is limited. Wonji is not suitable for the Upper Awash headwaters due to their cooler, wetter climate. Furthermore, the station is significantly milder than the hot, arid Middle Awash Valley (e.g., Metehara). Therefore, while Wonji serves as the case study's main input, critical verification must be performed using data from extreme points like the high-altitude Upper Awash and the hot, arid Middle Awash to ensure the CROPWAT model accurately captures the entire basin's climatic variability.

Table 10: Cropping Pattern of Multi Crop Scenario

Cropping pattern name : Multi Crop				
No.	Crop name	Planting date	Harvesting date	Area(%)
1	Sugarcane (Ratoon)	03-Nov	02-Nov	7
2	Barley	03-Nov	01-Apr	2
3	Dry beans	03-Nov	31-Jan	8
4	Sorghum	03-Nov	30-Apr	3
5	Cotton	03-Nov	16-May	5
6	Teff	03-Nov	02-May	2
7	Maize (Grain)	03-Nov	07-Mar	10
8	Mango	03-Nov	02-Nov	27
9	Spring Wheat	03-Nov	12-Mar	10
10	Small Vegetables	03-Nov	18-Apr	26

The table 10 provides the Cropping Pattern Data which is the fundamental input for calculating the overall Scheme Water Requirement using CROPWAT 8.0. Essentially, this data defines the specific demands placed on the irrigation system in terms of when and how much water is needed across the command area. The Table 10 lists ten distinct crops, including Cereals (Maize, Spring Wheat), Vegetables (Tomato, Potato), Cash crops (Cotton, Sugarcane), and other uses (Turf grass, Mango). For each crop, the table specifies its planting and harvest dates which establish the exact duration and timing of the growing season. Crucially, the Area % column indicates the percentage of the total irrigated land dedicated to each crop (e.g., Spring Wheat accounts for 27% of the area). By combining the unique water needs of each crop derived from its specific CROPWAT file with its designated area and growth timing, the model can accurately aggregate these individual demands to determine the necessary gross scheme water supply required for the entire multi-crop operation throughout the year.

The cropping pattern illustrated in table 10 serves as the primary input for modelling the scheme water supply, as it defines the precise spatial distribution and seasonal timing of water use. The gross scheme demand is calculated by aggregating the monthly net irrigation requirements, which are a direct function of the crop-specific evapotranspiration (ETc) and the percentage of the total area cultivated by each crop. This process allows for the determination of the required continuous flow rate, expressed as the Irrigation Requirement for the Actual Area (in l/s/ha)

The optimized release curve is well designed to meet the varying and time sensitive water requirements of all three agricultural systems scenario, ensuring crop establishment and growth even when natural water sources are scarce.

The reservoir acts as a crucial buffer, bridging the significant gap between the seasonal availability of water and the year round demands of agriculture. By using a rule curve to dictate consistent releases, the system provides a reliable and predictable water supply, mitigating the risks of drought induced crop failure and ensuring agricultural productivity. This approach not only maximizes the use of available water but also provides a stable foundation for agricultural planning and food security.

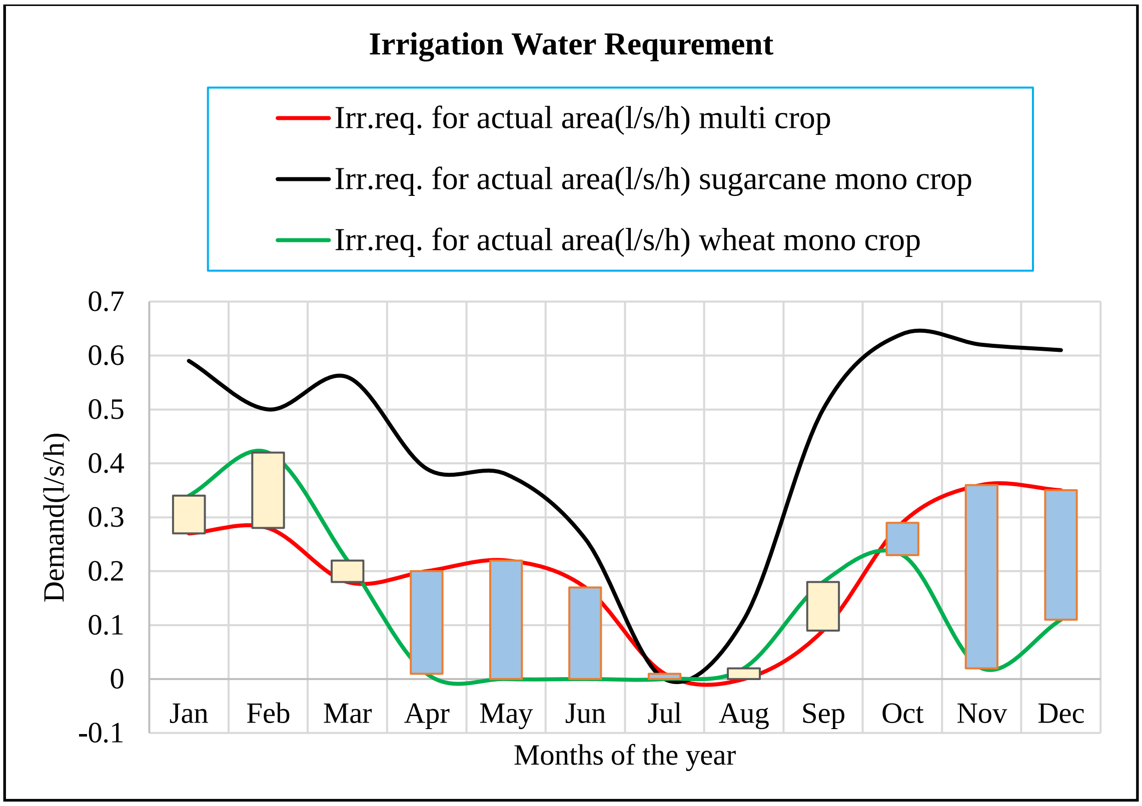

Figure 22: Multi and mono crop actual irrigation water requirement(l/s/ha)

As indicated in figure 21 above, for the sugarcane monoculture scenario, the irrigation water requirement at the head of the system (the dam release point) is higher than multi crop scenario for all months of the year except Juley and in the case of monoculture wheat scenario even if based on dual production (two times in the year) the requirement of water is higher than the multi crop scenario from January to mid of April and August to mid of October. Therefore, mono crop culture of sugarcane scenario indicates significantly higher water requirement than the multi-crop scenario and mono crop culture crop scenario of wheat.

Table 11: Optimized irrigation water demand in the case of multi crop scenario

Month	Irr.req. for actual Area(MCM) multi crop	Cumulative Irr.req. for actual Area(MCM) multi crop	Inflow Cumulative (MCM)
Jan	50.10	50.10	4.98
Feb	51.96	102.06	9.02
Mar	33.40	135.46	18.71
Apr	37.11	172.57	37.87

May	40.82	213.39	72.12
Jun	31.55	244.94	143.26
Jul	1.86	246.79	490.95
Aug	0.00	246.79	1024.05
Sep	16.70	263.49	1409.31
Oct	53.81	317.31	1464.89
Nov	66.80	384.11	1482.31
Dec	64.95	449.05	1491.09

As shown in the table 11, the irrigation water demand for the multi-crop scenario shows significant monthly variation, with to a total annual requirement of 449.05 MCM. The demand is highest in November (66.80 MCM), followed by December (64.95 MCM) and October (53.81 MCM), indicating a peak in irrigation needs during the late autumn and early winter months. Conversely, the demand is minimal or non-existent in July (1.86 MCM) and August (0.00 MCM), suggesting a period of reduced or no irrigation due to natural rainfall or crop dormancy.

When comparing the cumulative irrigation requirements with the cumulative inflow, it becomes evident that the natural inflow significantly exceeds the irrigation demand for a considerable portion of the year. For example, by July, the cumulative irrigation requirement is 246.79 MCM, while the cumulative inflow reaches 490.95 MCM, indicating a substantial surplus of water during the wet season. This trend continues, with the total annual cumulative inflow reaching 1491.09 MCM, which is more than three times the total cumulative irrigation requirement of 449.05 MCM. This suggests that while there are specific months with high irrigation demands, the overall water availability from inflow appears to be sufficient to meet the multi-crop irrigation needs, with potential for water storage or other uses during periods of high inflow.

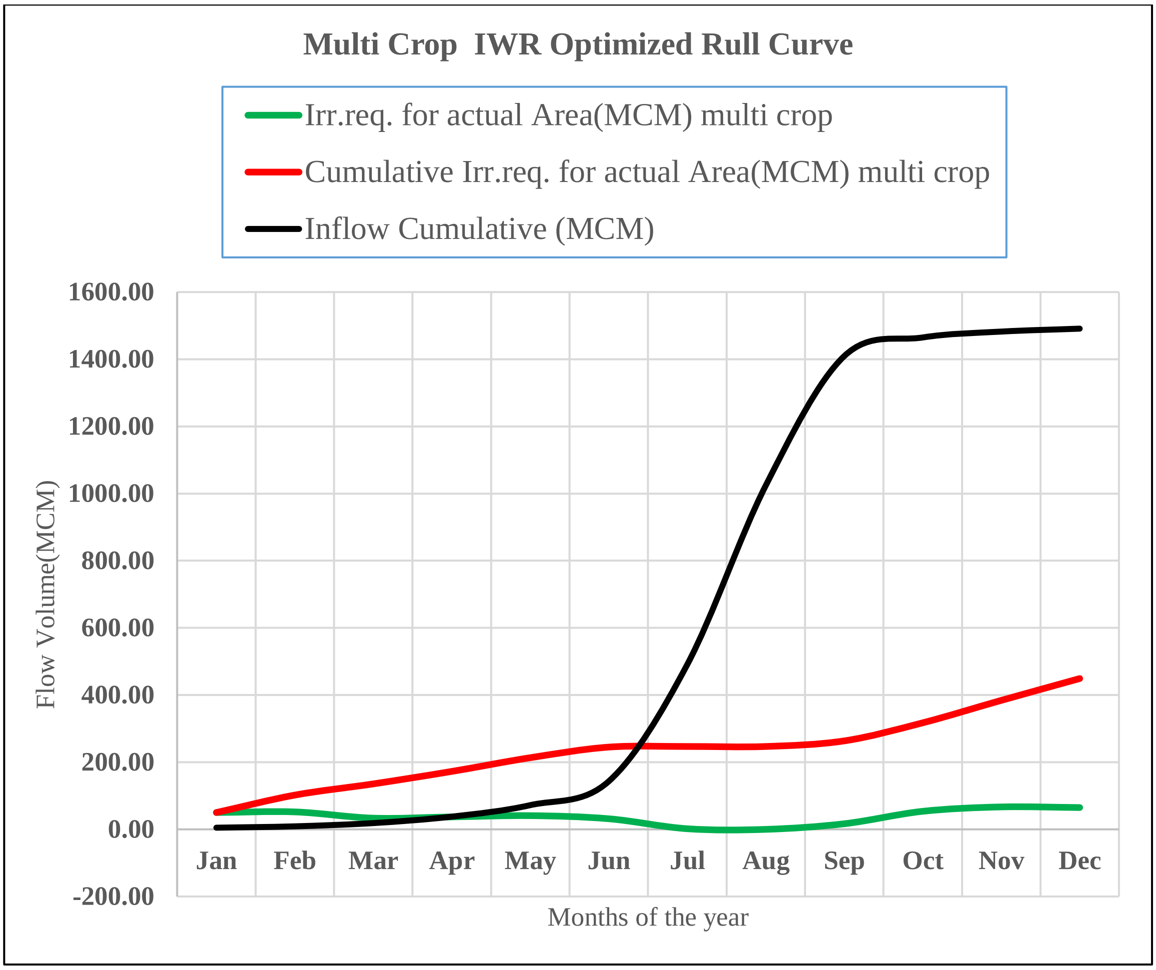

Figure 23: Multi Crop IWR Reservoir Operation Volume Rule Curve (MCM)

Figure 22 visually represents the interplay between irrigation water demand and natural inflow over a year for a multi-crop cultivation area. The green line, indicating the monthly irrigation requirement, shows a fluctuating pattern: higher demands are observed in the early and late parts of the year (e.g., January-May and October-December), while demand significantly drops, even to zero, during the mid-year months (July-August). This corresponds to the monsoon or rainy season when natural precipitation fulfils crop water needs, reducing the necessity for supplemental irrigation. The red line, representing the cumulative irrigation requirement, illustrates continuous increase throughout the year, accumulating to approximately 450 MCM by December, which signifies the total annual water volume required for the multi-crop system.

In stark contrast, the black solid line, depicting the cumulative inflow, demonstrates a dramatic surge, particularly between June and September, where it rises steeply from a relatively low level to over 1400 MCM. This rapid increase in cumulative inflow during the summer months clearly signifies a period of abundant water availability, due to heavy rainfall or river flows. By the end of the year, the total cumulative inflow reaches nearly 1500 MCM, which is significantly higher than the total annual cumulative irrigation requirement of about 450 MCM. This substantial surplus of water during the peak inflow season, combined with lower irrigation demands during those very months, underscores the Koka reservoir for effective water storage and management strategies to capture and hold this excess water to meet the irrigation requirements during the drier periods when the natural inflow is considerably less than the demand.

Table 12: Optimized irrigation water demand in the case of monoculture sugarcane crop scenario

Month	Irr.req. for actual area(MCM) sugarcane mono crop	Cumulative Irr.req. for actual Area(MCM) Sugarcane mono crop	Inflow Cumulative (MCM)
Jan	109.48	109.48	4.98
Feb	92.78	202.26	9.02
Mar	103.91	306.17	18.71
Apr	72.37	378.54	37.87
May	70.51	449.05	72.12
Jun	48.25	497.30	143.26
Jul	0.00	497.30	490.95
Aug	20.41	517.71	1024.05
Sep	92.78	610.49	1409.31
Oct	118.76	729.25	1464.89
Nov	115.05	844.30	1482.31
Dec	113.19	957.49	1491.09

Table 12 outlines the optimized irrigation water demand for a monoculture sugarcane crop scenario. The monthly irrigation requirements (Irr.req. for actual area(MCM) sugarcane mono crop) show a consistently high demand for sugarcane throughout most of the year, particularly in the drier months. Demands are highest in October (118.76 MCM), November (115.05 MCM), December (113.19 MCM), and January (109.48 MCM), indicating substantial water needs during the late autumn and winter seasons. While there is a dip in demand in July (0.00 MCM), due to a rainy season or specific crop growth stage where natural precipitation suffices, and a relatively lower demand in June (48.25 MCM) and May (70.51 MCM), the overall monthly figures are considerably higher than those observed in a multi-crop scenario, reflecting sugarcane's high water consumption. The cumulative irrigation requirement steadily builds up, reaching a substantial total of 957.49 MCM by the end of December.

When comparing this cumulative irrigation demand with the cumulative inflow (Inflow Cumulative MCM), a clear trend emerges. While the inflow also accumulates significantly, especially from July to September (reaching over 1400 MCM), the initial months (January to June) present a substantial deficit where the cumulative irrigation requirement far outstrips the available cumulative inflow. It shows that, by May, the cumulative irrigation demand is 449.05 MCM, whereas the cumulative inflow is only 72.12 MCM, highlighting a severe water deficit in the first half of the year. Although the annual cumulative inflow (1491.09 MCM) is ultimately greater than the total annual sugarcane irrigation demand (957.49 MCM), effective water management, including significant reservoir storage, is critical to bridge the gap during the early and late dry seasons. The high demand from sugarcane, particularly outside the peak rainy season, is effectively accommodated by the substantial stored water in the reservoir, which ensures consistent supply and mitigates crop stress.

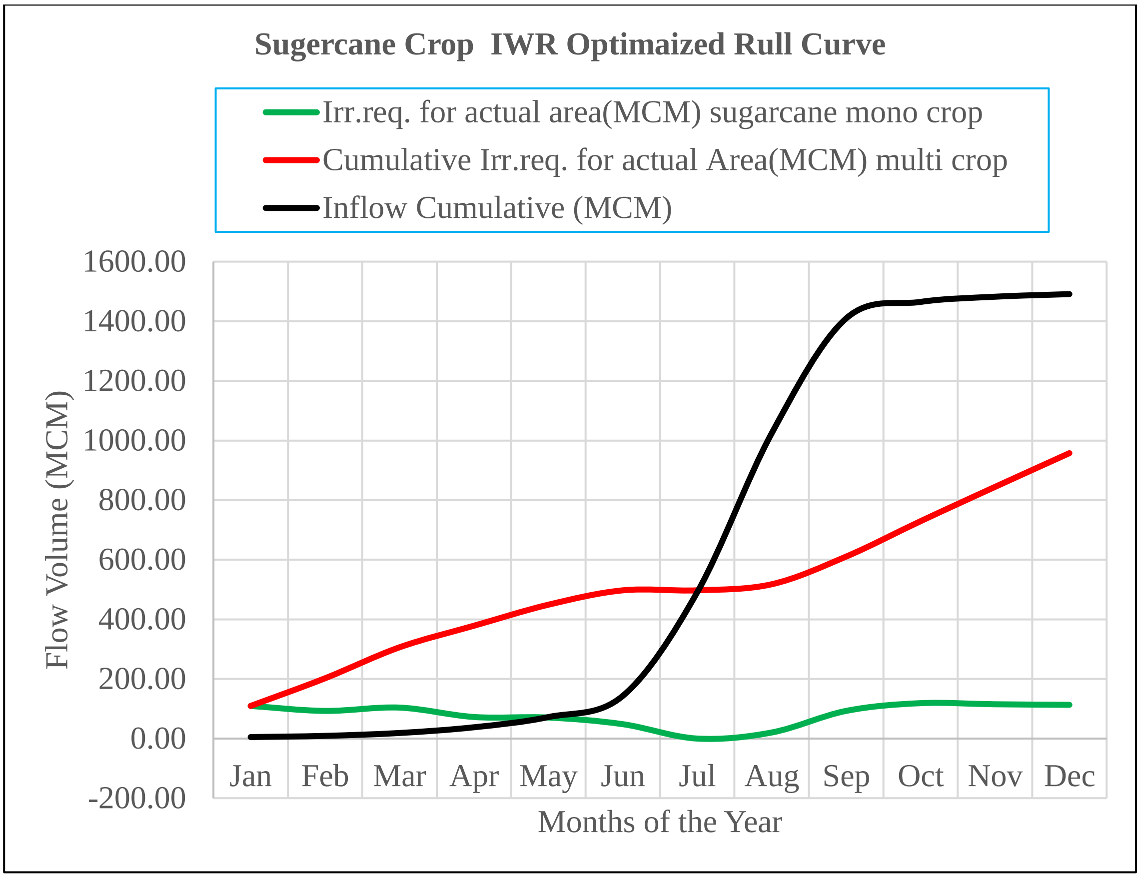

Figure 24: Sugar cane IWR Reservoir Operation Volume Rule Curve (MCM)

The provided figure 23 illustrates the monthly and cumulative irrigation water requirements for a monoculture sugarcane crop alongside the cumulative water inflow over a year. The green line, representing monthly sugarcane irrigation demand, exhibits significant fluctuations: it starts high in early months, decreases towards mid-year with a notable dip to zero in July (due to a rainy season), and then increases again through late autumn and winter. The red line, which depicts the cumulative irrigation requirement shows a consistent and substantial upward trend, indicating a high annual water consumption for sugarcane, reaching approximately 950 MCM by the end of the year.

A critical observation from the graph is the stark contrast between the cumulative irrigation demand and the cumulative inflow (black line). During the initial part of the year, from January to June, the cumulative irrigation demand for sugarcane significantly outstrips the cumulative inflow, highlighting a period of severe water deficit if relying solely on immediate natural inflow. However, from July to September, the cumulative inflow experiences a dramatic surge, far exceeding the cumulative irrigation requirements during these months. Although the total annual inflow of approximately 1,490 MCM exceeds the annual sugarcane demand of roughly 950 MCM. The temporal mismatch between water availability and crop demand highlights the reservoir, is vital. This infrastructure would capture the immense surplus water during the wet season, allowing for a consistent supply during drier periods to ensure crop viability and optimize yields.

Table 13: Optimized irrigation water demand in the case of mono culture wheat crop scenario

Month	Irr.req. for actual area(MCM) wheat mono crop	Cumulative Irr.req. for actual Area(MCM) wheat mono crop	Inflow Cumulative (MCM)
Jan	63.09	63.09	4.98
Feb	77.94	141.03	9.02
Mar	40.82	181.85	18.71
Apr	1.86	183.70	37.87
May	0.00	183.70	72.12
Jun	0.00	183.70	143.26
Jul	0.00	183.70	490.95
Aug	3.71	187.42	1024.05
Sep	33.40	220.82	1409.31
Oct	42.68	263.49	1464.89
Nov	3.71	267.21	1482.31
Dec	20.41	287.62	1491.09

The provided data in table 10 illustrates the optimized irrigation water demand for a monoculture wheat crop scenario. The monthly irrigation requirements (Irr.req. for actual area(MCM) wheat mono crop) exhibit a distinct seasonal pattern. Demands are highest in February (77.94 MCM) and January (63.09 MCM), indicating significant water needs during the cooler and drier months. The demand then drastically decreases, reaching zero during May, June, and July, and remains very low through August. This period of minimal or no irrigation coincides with the typical rainy season and the dormancy or harvesting phase of wheat. The demand picks up again in September, October, and December as the next growing cycle begins. The cumulative irrigation requirement for the monoculture wheat crop steadily increases throughout the year, culminating in a total annual demand of 287.62 MCM by December.

When comparing the cumulative irrigation requirement for wheat with the cumulative inflow (Inflow Cumulative MCM), it becomes apparent that the natural water availability largely surpasses the demand. In the initial months (January to April), the cumulative irrigation demand exceeds the cumulative inflow, indicating a need for stored water during the early part of the year. However, from May onwards, the cumulative inflow rapidly accelerates, significantly outstripping the cumulative irrigation requirement. By July, the cumulative inflow (490.95 MCM) is already more than double the total annual cumulative irrigation demand for wheat (183.70 MCM at that point). The total annual cumulative inflow reaches a substantial 1491.09 MCM, which is vastly greater than the total annual wheat irrigation demand of 287.62 MCM. This significant surplus of water, particularly during the mid-year high-inflow months, suggests that while careful management for the initial deficit period is needed, the overall water resources are abundant for monoculture wheat, potentially allowing for reservoir filling and meeting other demands.

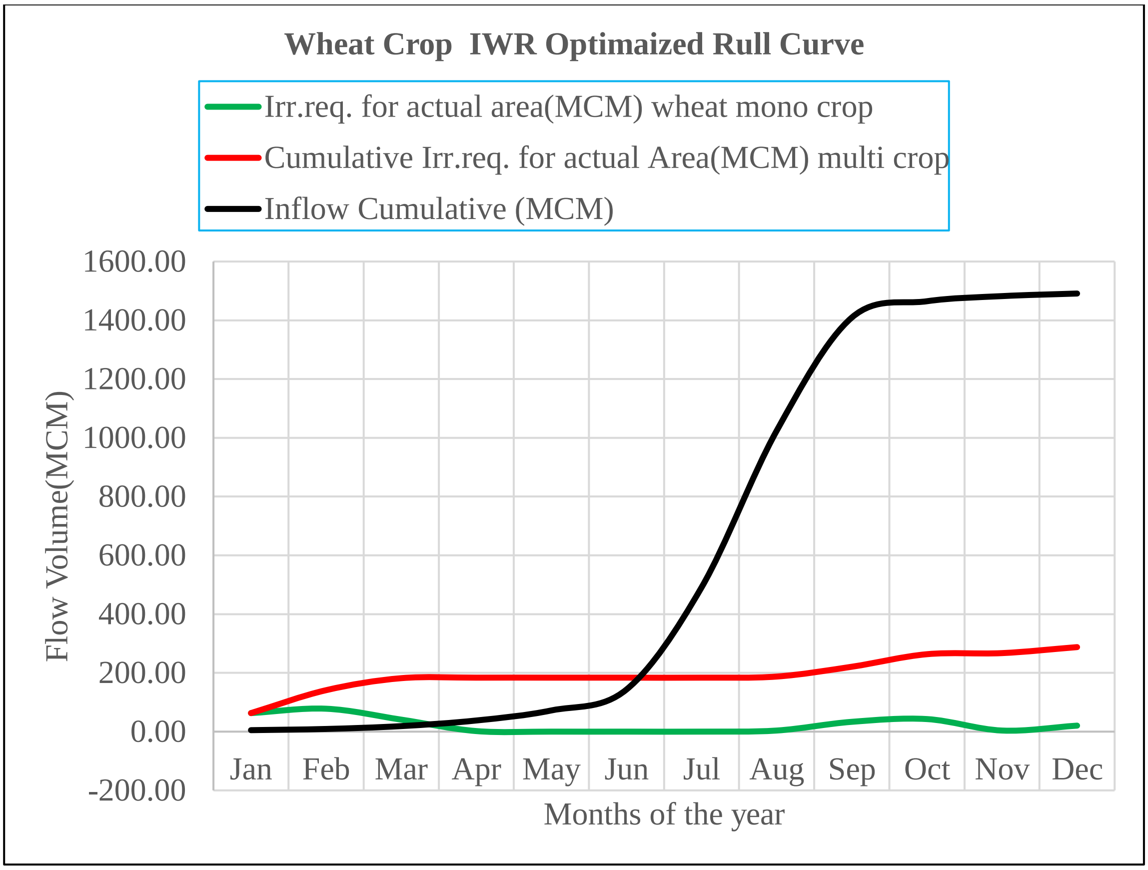

Figure 25: Wheat IWR Reservoir Operation Volume Rule Curve (MCM)

The provided Wheat Crop - IWR Optimized Rule Curve in Figure 24 illustrates the monthly irrigation requirements for monoculture wheat and its cumulative demand, juxtaposed against the cumulative water inflow over a year. The green line, representing the monthly irrigation requirement for wheat, shows distinct peaks in the early months (January and February), indicating the need for irrigation during these drier, cooler periods of wheat growth. This demand then sharply declines, reaching zero from May to July, and remaining minimal in August, which typically aligns with the natural rainy season and potentially the harvesting or dormant period for wheat. The demand subsequently rises again in September and October as new planting cycles or later growth stages commence. The red line, depicting the cumulative irrigation requirement for the wheat monocrop, demonstrates a relatively modest and steady increase, accumulating to approximately 280-300 MCM by the end of the year, signifying wheat's overall lower water consumption compared to crops like sugarcane.

In contrast, the black line, representing the cumulative inflow, reveals a dramatic surge starting around June and peaking rapidly by September, reaching over 1400 MCM. This substantial influx of water during the mid-year months signifies a strong wet season, providing an overwhelming amount of natural water. While the initial months (January to April) show the cumulative irrigation demand for wheat slightly exceeding the limited cumulative inflow, this deficit is relatively small and quickly overshadowed by the massive subsequent inflow. The total annual cumulative inflow (approximately 1490 MCM) vastly exceeds the total annual cumulative irrigation requirement for wheat (around 280-300 MCM). This significant surplus implies that sufficient water resources are available to meet the demands of a monoculture wheat crop, with the primary water management challenge shifting from scarcity to effective storage and distribution to cover the initial dry period and manage the large surplus during the wet season by storing in the reservoir.

5. Conclusion and Recommendations

5.1. Conclusion

The analysis of distinct cropping scenarios reveals that the primary challenge in operating the Koka Reservoir system is not a lack of total water, but a profound temporal misalignment between the consistent annual cumulative inflow (1491 MCM) and the highly variable seasonal agricultural demands. This finding underscores the necessity of a sophisticated storage and release strategy to unlock the region's full irrigation potential.

A) The Dynamics of Demand and Deficit

The three scenarios demonstrated sharply different profiles:

- Monoculture Sugarcane: With the highest annual water requirement (957.49 MCM), this scenario imposes the greatest regulatory burden. Its consistently high monthly demand creates a severe and prolonged dry-season deficit when natural river flow is at its annual minimum. Successful management here requires maximum storage capacity utilization.
- Monoculture Wheat: While having the lowest annual demand (287.62 MCM), its water needs are critically concentrated in the pre-inflow period (early months of the year). This creates a sharp initial deficit that, if unmet, would jeopardize the entire harvest, emphasizing the need for timely, precise early-season releases.
- Multi-crop Strategy: This pattern, demanding an intermediate volume (449.05 MCM), shows the best synchronization with the natural hydrograph, minimizing demand during the peak wet season. However, it still requires the reservoir to bridge substantial deficits during the initial dry months to sustain crops like cotton, barley, and early vegetables.

B) The Impact of Optimized Reservoir Policy

The derived operating policy effectively addresses this temporal mismatch, demonstrating the transformative power of regulating the flow regime. The strategy deliberately shifts water from periods of surplus to periods of scarcity, resulting in a successful stabilization of the downstream flow:

- Flood Attenuation (Wet Season): The policy reduced the average wet-season flow by 27% (from 62.25 m3/s to 45.4 m3/s), mitigating potential flood risks and conserving water.
- Flow Augmentation (Dry Season): Crucially, it increased the average dry-season flow by 46% (from 31m3/s to 45.4 m3/s). This augmentation ensures the reliable delivery of the required annual cumulative volume to the actual irrigated command area.

C) Strategic Implications for Agricultural Expansion

The findings hold significant implications for future planning, quantifying the specific capacity for agricultural growth based on crop selection:

- The **Wheat Monoculture scenario** presents the optimal opportunity for expansion, enabling a remarkable **5.0-fold increase** of the actual irrigated command area.
- The **Multi-crop strategy** offers a balanced approach, supporting a **3.2-fold expansion** of the actual irrigated command area, promoting crop diversity and reduced market risk.
- Even the most demanding **Sugarcane Monoculture** allows for a significant 50% expansion of the actual irrigated command area, illustrating the fundamental value of the reservoir infrastructure.

This research confirms that the systematic search for the optimal release parameter vector (R) is paramount. The resulting robust operating rules ensure that the reservoir fulfills its role as a buffer against hydrological uncertainty, providing the necessary balance of performance and risk management to support sustainable and intensified agriculture.

5.2. Recommendation

In light of the demonstrated challenges of temporal water mismatch and the potential for agricultural expansion, the following recommendations are crucial for maximizing the utility and resilience of the regulated reservoir system.

A) Maximizing Existing Reservoir Utilization and Operational Strategy

The primary recommendation is the implementation of optimized dynamic rule curves for the existing reservoir infrastructure. This strategy must focus on mitigating the significant dry-season deficits identified across all scenarios.

- **Wet-Season Capture:** Operational rules must be designed to effectively capture the 27% flow surplus observed during the peak inflow months (July-September). This requires accurate forecasting and the establishment of dedicated **conservation storage zones** within the existing capacity.
- **Targeted Dry-Season Release:** The release schedule must be precisely calibrated to meet the distinct periods of critical demand:

  - **Sugarcane:** Ensure sustained, reliable releases throughout the long growing season, particularly outside the main rainy period, where demand is highest.
  - **Wheat:** Guarantee sufficient early-season releases during the critical **January–March period** to support crop establishment, as this initial requirement is essential for the crop's success despite its lower total annual need.

- **Water Use Efficiency:** Concurrently, the **universal promotion of efficient irrigation** is paramount to maximize water productivity and ensure the maximum actual irrigated command area benefits from the strategically stored water.

B) Strategic Policy Alignment for Agricultural Expansion

To mitigate the inherent risks of rain-fed cultivation and better utilize conserved reservoir flows, a key policy objective should be the expansion of irrigated cultivation. The expansion strategy should be guided by the quantified potential of each cropping pattern:

- Diversification for Flexibility: The Multi-crop scenario should be favoured where feasible, as it offers significant flexibility in water management and supports a 3.2-fold expansion. Strategies should continue to align lower-demand crops with natural inflow periods to ease pressure on reservoir storage.
- High-Value Growth: Recognize that the 5.0-fold expansion potential under Monoculture Wheat offers the highest leverage for increased irrigated land area, justifying the precise, high-stakes early-season water management required.

C) Future Research and Modelling Accuracy

To ensure the long-term reliability of the optimized operating policies and the continued utility of the introduced Et-HYPEv2.0 model, immediate research investment is required in three core areas:

- Integrated Uncertainty Analysis: Future studies must move beyond stochastic hydrology by integrating the quantified effects of projected climate change and anticipated land-use evolution (e.g., changes in upstream agricultural practices) to produce truly robust, climate-resilient operational forecasts.
- Data Validation and Input Quality: Rigorous performance evaluation and validation of high-resolution satellite-based meteorological forcing datasets, such as CHIRPSv2.0, are necessary to eliminate input uncertainty and guarantee the reliability of model outcomes.
- Physical Modelling Accuracy: Immediate integration of an up-to-date reservoir bathymetry survey is non-negotiable. This is essential to ensure the physical integrity of the (storage-area-depth) relationships within the HYPE model, guaranteeing that simulated storage volumes accurately reflect the reservoir's actual physical capacity.

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ANNEX 1

Hombole sub catchment Parameters script

```
!!      Land use dependent evapotranspiration parameters

!!------------------------------------------------------------------------

!! LUSE         Agriculture (Rainfed) Agriculture (Irrigated)Bare/Desert    Urban
        Grassland       Shrubland       Closed forest   Open forest     Olake   Ilake
        Mainriver
kc2     1.3606 1.21     1.13    0.73    1.05    1.21    0.73    0.73    1.13    1.13    1.13
kc3     1.34    1.34    1.02    0.9     1.02    1.27    1.33    1.33    0.58    0.58    0.58
kc4     1.57    1.57    1.04    0.2     1.12    1.26    1.09    1.09    0.89    0.89    0.89
alb     0.4     0.4     0.45    0.2     0.5     0.67    0.45    0.45    0.4     0.4     0.4
ttrig   0       0       0       0       0       0       0       0       0       0       0
treda   0.9     0.9     0.8     0.8     0.95    0.95    0.84    0.84    0.8     0.8     0.8
tredb   0.4     0.4     0.4     0.4     0.4     0.4     0.4     0.4     0.4     0.4     0.4
cevp    0.21    0.21    0.07    0.07    0.07    0.17    1.6     1.6     0.17    0.17    0.17
fepotsnow       0.21    0.21    0.2     0.44    0.16    0.46    0.53    0.53    0.44    0.44
        0.44
!!

!!      Soil type parameters
!!------------------------------------------------------------------------

!! SOIL         Fine    Moderately Fine         Medium          Moderately Coarse       Coarse
wcwp    0.1     0.15    0.09    0.07    0.05
wcfc    0.45    0.4     0.35    0.25    0.15
wcep3   0.0299 0.015    0.03    0.05    0.08
wcep2   0.0299 0.015    0.025   0.06    0.1
wcep1   0.0999 0.08     0.1     0.15    0.2
trrcs   0.15    0.15    0.15    0.15    0.15
srrate  0.07    0.065   0.06    0.06    0.045
sfrost  0       0       0       0       0
rrcs2   0.09996         0.02    0.01    0.009   0.008
rrcs1   0.09999         0.12    0.1     0.08    0.05
mperc210.097 12         15      18      20
mperc111.218 12         15      18      20
mactrsm         0.9     0.6     0.6     0.6     0.6
mactrinf        10      10      10      10      10
macrate         0.1     0.3     0.3     0.3     0.3
!!------------------------------------------------------------------------
```

ANNEX 2

Mojo sub catchment Parameters script

```
!!      Land use dependent evapotranspiration parameters


!!-------------------------------------------------------------------------

!! LUSE         Agriculture (Rainfed)   Agriculture (Irrigated)Bare/Desert     Urban
        Grassland       Shrubland       Closed forest   Open forest     Olake   Ilake
        Mainriver
kc2     4.77    0.34    0.13    0.13    0.03    0.03    0.03    0.03    0.05    0.003   0.005
kc3     1.34    1.34    1.02    0.9     1.02    1.27    1.33    1.33    0.58    0.58    0.58
kc4     1.57    1.57    1.04    0.2     1.12    1.26    1.09    1.09    0.89    0.89    0.89
alb     0.45    0.54    0.45    0.32    0.5     0.47    0.45    0.45    0.4     0.4     0.4
ttrig   0       0       0       0       0       0       0       0       0       0       0
treda   0.9     0.8     0.8     0.8     0.95    0.95    0.84    0.84    0.8     0.8     0.8
tredb   0.1     0.4     0.4     0.4     0.4     0.4     0.4     0.4     0.4     0.4     0.4
cevp    0.21    0.21    0.07    0.07    0.07    0.17    1.6     1.6     0.17    0.17    0.17
fepotsnow       0.21    0.21    0.2     0.44    0.16    0.46    0.53    0.53    0.44    0.44
        0.44
!!

!!      Soil type parameters
!!-------------------------------------------------------------------------

!! SOIL         Fine    Moderately Fine         Medium          Moderately Coarse       Coarse
wcwp    0.5     0.015   0.05    0.05    0.45
wcfc    0.578   0.5     0.5     0.5     0.5
wcep3   0.0175  0.033   0.0235  0.05    0.08
wcep2   0.0428  0.0003  0.025   0.07    0.05
wcep1   0.0999  0.039   0.03    0.0015  0.12
trrcs   0.15    0.15    0.15    0.15    0.15
srrate  0.056   0.065   0.06    0.06    0.045
sfrost  0       0       0       0       0
rrcs2   0.0997  0.06    0.01    0.009   0.008
rrcs1   0.0225  0.07    0.07    0.18    0.05
mperc25         12      15      18      20
mperc15         13.3    15      18      0
mactrsm         0.89    0.5     0.6     0.6     0.6
mactrinf        8       0       10      10      10
macrate         0.29    0.3     0.3     0.3     0.3
```

ANNEX 3

Awash Awash sub catchment parameters script

```
!!        Land use dependent evapotranspiration parameters

!!--------------------------------------------------------------------------

!! LUSE          Agriculture (Rain fed)Agriculture (Irrigated)Bare/Desert     Urban
          Grassland        Shrub land        Closed forest    Open forest       Olake   Ilake    Main
river
kc2       2.0111 0.88555           0.5555 0.0001 0.000111          3.0001 1.0000115         0.0005
          0.00001          7.11111           0.0005
kc3       0.5555 1.5       1.5      1        1.3      1.5      1        0.001    1.5      0.5      0.9
kc4       0.5      1.5      1.2      1.3      1.2      1.4      1.2      1.2      0.89     0.89     0.89
alb       0.5      0.4      0.45     0.4      0.5      0.67     0.45     0.45     0.45     0.4      0.4
ttrig     0.01     0        0        0        0        0        0        0        0        0        0
treda     0.5      0.9      0.5      0.5      0.55     0.95     0.84     0.84     0.84     0.84     0.84
tredb     1        0.41     0.4      0.4      0.4      0.4      0.4      0.4      0.4      0.4      0.4
cevp      0.21     0.21     0.07     0.07     0.07     0.17     1.6      1.6      0.17     0.17     0.17
fepotsnow          0.00021           0.00021           0.002    0.44     0.16     0.46     0.53     0.53
          0.44     0.44     0.44
!!

!!        Soil type parameters
!!--------------------------------------------------------------------------

!! SOIL            Fine     Moderately Fine           Medium           Moderately Coarse         Coarse
wcwp      0.31     0.001555          0.12     0.001    0.001
wcfc      0.44444           0.3335 0.996455          0.4111 0.0001115
wcep3     0.2333 1.00015           0.555    0.05555           1.08555
wcep2     0.2223 0.111    0.005    0.188    0.00222
wcep1     0.3099 2.17     0.001    0.15     0.2
trrcs     0.15     0.15     0.15     0.15     1.15
srrate    0.07     0.065    0.06     0.06     0.045
sfrost    0        0        0        0        0
rrcs2     0.0999999        0.01     0.01     0.559    0.008
rrcs1     0.001    0.12     0.1      0.09     0.95
mperc212.196 12         11       18       18
mperc165.88  50.55    5        18       18       18
mactrsm            0.5      0.6      0.6      0.6      0.6
mactrinf           150      150      100      100.1    50
macrate            0.5      0.3      0.3      0.3      0.3
!!--------------------------------------------------------------------------
```

ANNEX 4

Multi crop irrigation water requirement of the study area

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation deficit												
1. Sugarcane (Ratoon)	125.6	114.6	118.9	89.8	62.6	27.7	0	0	54.3	124.9	123.8	123.4
2. Barley	8.9	54.5	104.4	86.2	9.2	0	0	0	0	0	0	0
3. Dry beans	0	6.2	34.6	91.8	80.6	2.1	0	0	0	0	0	0
4. Sorghum	105.1	92.4	6.1	0	0	0	0	0	9.6	62.3	76.7	97
5. Cotton	0	0	0	0	0	1.5	0	0	54	118.5	106.1	72.8
6. Teff	83.1	72.8	71.3	61.7	55.8	42	0	0	14.9	74.4	77.5	82.4
7. Maize (Grain)	42.3	0	0	0	0	0	0	0	1.2	37.4	106.4	110.5
8. Mamgo	108.1	97.3	99.7	81.7	67	48.5	0	0	25.2	92.8	100.1	106.2
9. Spring Wheat	0	0	1.3	4.8	72.3	79	0	0	0	0	0	0
10. Small Vegetables	0	0	0	16.7	48.7	67.5	1.8	0	0	0	0	0
Net scheme irr.req.												
in mm/day	1.2	1.2	1.1	1.2	1.3	1	0	0	0.4	1.3	1.6	1.6
in mm/month	37.3	34.6	34.2	36.5	40.4	30.9	0.2	0	11.6	41	49.2	49.4
in l/s/h	0.14	0.14	0.13	0.14	0.15	0.12	0	0	0.04	0.15	0.19	0.18
Irrigated area(% of total area)	52	52	70	70	70	70	10	10	52	52	52	52
Irr.req. for actual area(l/s/h)	0.27	0.28	0.18	0.2	0.22	0.17	0.01	0	0.09	0.29	0.36	0.35

ANNEX 5

Mono crop Sugarcane irrigation water requirement of the study area

Menthes	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1. Sugarcane (Ratoon)	158.9	120	148.8	100.3	102.5	67.6	0	30.4	129.3	170.6	161.3	162.3
Net scheme irr.req. in mm/day	5.1	4.3	4.8	3.3	3.3	2.3	0	1	4.3	5.5	5.4	5.2
in mm/month	158.9	120	148.8	100.3	102.5	67.6	0	30.4	129.3	170.6	161.3	162.3
in l/s/h	0.59	0.5	0.56	0.39	0.38	0.26	0	0.11	0.5	0.64	0.62	0.61
Irrigated area(% of total area)	100	100	100	100	100	100	0	100	100	100	100	100
Irr.req. for actual area(l/s/h)	0.59	0.5	0.56	0.39	0.38	0.26	0	0.11	0.5	0.64	0.62	0.61

ANNEX 6

Mono crop Wheat irrigation water requirement of the study area

Menthes	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation deficit												
1. Spring Wheat	0	0	0	0	0	0	0	5.1	47	61.8	0	0
2. Spring Wheat	90.1	101	58.9	2.7	0	0	0	0	0	0	6	29.9
Net scheme irr.req.												
in mm/day	2.9	3.6	1.9	0.1	0	0	0	0.2	1.6	2	0.2	1
in mm/month	90.1	101	58.9	2.7	0	0	0	5.1	47	61.8	6	29.9
in l/s/h	0.34	0.42	0.22	0.01	0	0	0	0.02	0.18	0.23	0.02	0.11
Irrigated area(% of total area)	100	100	100	100	0	0	0	100	100	100	100	100
Irr.req. for actual area(l/s/h)	0.34	0.42	0.22	0.01	0	0	0	0.02	0.18	0.23	0.02	0.11