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Ethiopian Institute of Technology-Mekelle

(EiT-M)

Evaluation of irrigation water allocation for improving water use efficiency and conflict resolution in Hatset irrigation scheme, Eastern Tigray, North Ethiopia

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A Thesis submitted to the School of Civil Engineering in partial fulfillment of the Requirements for the Degree of Master of Science

In

Irrigation & Drainage Engineering

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March 2025

Mekelle, Ethiopia

Ethiopian Institute of Technology-Mekelle (EiT-M)

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Declaration

I declare that all information in this thesis entitled "Evaluation of irrigation water allocation for improving water use efficiency and conflict resolution in Hatset Irrigation scheme, North Ethiopia" is my work and has been obtained and presented according to the academic rule and ethical conduct of Mekelle University legislation under the guidance I am also the principal author of this research work.

Dedication

This thesis manuscript is dedicated to my family: Father Kinjeta Kiros Lema and Mother Mulu Wbie for their endless and generous support!

Acknowledgment

I begin by expressing my sincere gratitude to Almighty God for His guidance throughout this journey, which led to its successful completion. I am deeply thankful to my advisor, Dr. Ing. Haddush Goitom, and co-advisor, Dr. Gebremedhin Gebremeskel, for their invaluable support and direction in my thesis work. Their encouragement was instrumental in the success of this research. I also appreciate the staff of the Tigray Water Resource Bureau for their assistance and provision of materials for my thesis. Special thanks to the staff of the Tigray Agricultural Research Institute, particularly Mr. Esaias Gebrekidan, for their support. My sincere gratitude goes to Mr. Yemane Adane, the soil lab technician, for his help during the laboratory work. Lastly, I extend my heartfelt appreciation to my family, especially my wife, Bethel Mebrahtu, for their unwavering support throughout this journey.

Abstract

Efficient water allocation is crucial for enhancing irrigation water use efficiency and mitigating conflicts among users, especially regions where water is limited. This study tried to evaluate the irrigation water allocation system to optimize water allocation and improve conflict resolution mechanisms in the Hatset irrigation scheme, Eastern Tigray, North Ethiopia. The primary data was collected through soil sampling, flow measurements, household surveys, key informant interviews, and focus group discussions, and the secondary data was collected through meteorological, hydrological and spatial data. WEAP model used to assess current water allocation scenarios and propose improved strategies. Additionally, CROPWAT model was used to estimate crop water demand and HEC-HMS also used to estimate reservoir inflows. The findings reveal, unmet demand 0 m^3, 0 m^3, 895,360 m^3 and water losses 155,721 m^3, 309,160 m^3, and 430,479 m^3, head, middle and tail-end users respectively. Three scenarios were analyzed: a reference scenario, an improved water use efficiency scenario, and an irrigation expansion scenario. The reference scenario was business-as-usual approach and the enhanced water uses efficiency scenario demonstrated a 37.5% reduction in water demand by incorporating canal lining, efficient scheduling, and efficient irrigation techniques and the irrigation expansion scenario, which increased the irrigated area but resulted in a 23% increase in water demand with no unmet demand. Moreover, the study investigated the effect of efficient water allocation in resolving conflicts within the Hatset irrigation scheme, where infrastructure issues and governance gaps created significant disparities. It conducted how inadequate access for tail-end users caused conflict, while traditional and formal mechanisms proved ineffective due to poor coordination. The proposed hybrid approach, which integrated community-driven and IWUAs, addressed systemic challenges and promoted sustainable conflict resolution.

Keywords: Water allocation, irrigation efficiency, WEAP model, conflict resolution, IWUAs, Hatset irrigation scheme.

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1 Introduction

1.1 Background

Globally, irrigation development is becoming more and more important since freshwater is scarce; only 2.8% of Earth's water is freshwater, and only 2.2% of that is surface water **(1)**. While most of the world's freshwater is found in places like America and Asia, which have developed irrigation systems, Africa faces several obstacles in spite of its wealth of surface water resources. According to **(2)**, just 12 million hectares of Africa's 185 million hectares of arable land are irrigated, making up only 7% of the continent's total irrigable land. Investment in irrigation systems is necessary to optimize agricultural production and food security due to the continent's untapped irrigation potential, infrastructure constraints, and water management issues **(3, 4)**.

Ethiopia is endowed with water resource potential in Africa and the volume of water resource for annual surface runoff potential is estimated to be 124.5 km^3 **(5)** The groundwater potential is also estimated at 6.5 km^3. The development of irrigation potential for surface runoff water resources and groundwater resources is estimated at 5.3 million and 1.1 million hectares, respectively. Nonetheless, the established irrigation from these water resource potentials is so far, less than 0.7 million hectares **(3)**. In the Tigray region, the surface runoff water resource is estimated at 9 billion m^3 and the irrigation potential is 325000 ha of which about 15000 ha is irrigable traditionally **(6)**.

However, the development of irrigation in the Tigray region is not adequate due to different reasons such as disproportionate allocation of water, poor water management, and so on. More of the inequity water distribution of limited irrigation water resources is a problematic issue due to a mismatched allocation of irrigation water between the supply and demand of irrigation water among water users. **(7)**. Additionally, irrigation water resources are also often hit by temporal water shortage, climate change, and losses due to poor design, operation, and maintenance of conveyance canals. This could lead to unfair distribution of irrigation water over the irrigation schemes. And likewise, that happened in the Hatset irrigation scheme in the Tigray region **(8, 9)**. In recent years, the unequal supply of allocation of irrigation water resources seriously increased **(8, 9)** in line with this the disproportionate irrigation water allocation was a dispute among the farmers **(8)**.

Similarly, **(10)** pointed out the disparities in farmers' capabilities to utilize irrigation water resources were possible to cause distributional conflicts and factionalism. This led to inadequate irrigation water supply downstream users mostly, and/or lesser crop yields compared to the farms located on upstream users. In other word, the downstream users in some irrigation systems cannot plant high water consumptive crops hence, they as a replacement for cultivating crops with lower water requirements Several studies have assessed that upstream users had irrigation water accessibility than middle and tail end users because they were found near the water source [**(11)**, **(12)**]. Additionally, a study has shown that tail end users suffered from water scarcity. **(13)** And likewise, that happened in the Hatset irrigation scheme in the Tigray region.

Therefore, the main objective of this study is to address inadequate water use efficiency, and social conflict by evaluating the existing irrigation water allocation, optimizing the future irrigation water resources, and developing improvement options for better irrigation water efficiency to reconcile the social disputes between competing water users in Hatset irrigation scheme, Tigray region.

1.2 Statement of the problem

Irrigated agriculture is the cornerstone of industrialization in developed countries. It is also the backbone of developing countries. However, the growth of agricultural irrigation in developing countries is still inadequate. Although traditional and modern irrigation activities have been practiced in Ethiopia, their distribution and allocation among users are insufficient. This is much pronounced in the Tigray region due to its dependence on seasonal rainfall, insufficient irrigation structures, weak water management, disproportionate allocation of irrigation water, and inefficient use of water **(8, 14, 15)**.

The Hatset Kebele in the Hawzen district is one of the most critical locations dealing with issues related to water distribution. Here, water allocation is still extremely unequal despite the existence of both traditional and modern irrigation systems. This inequality is made worse by inefficient irrigation water use, and persistent social tensions between various user groups. In particular, inefficient water usage practices and water loss along the conveyance process have resulted in a situation where the available water resources are not being fully exploited. The problem has been made more difficult by ongoing social tensions between upper, middle, and lower irrigation users, which have resulted in unequal access to water.

A thorough and integrated strategy is needed to address this problem, one that takes into account the social dynamics at work in addition to the hydrological aspects of water distribution and availability. To ensure a just and equitable distribution of water, social tensions must be reduced while the effective use of water resources is maximized through improved management techniques. It is feasible to improve water use efficiency, settle current disputes, and raise the irrigation system's total production by tackling these interconnected problems. Therefore, this research aims to assess the current state of irrigation water resources in the Hatset Kebele and propose strategies to optimize water use, improve efficiency, and mitigate social conflicts. By focusing on both the technical and social dimensions of irrigation water management, the goal is to ensure a more equitable distribution of water, thereby fostering sustainable agricultural development and contributing to the economic advancement of the region.

1.3 Objectives

1.3.1 General objective

The general objective is to evaluate the hydrological and social aspects of the Hatset irrigation scheme, optimize future irrigation water resources for improved irrigation water use efficiency, and resolve social conflict.

1.3.2 Specific objectives

- ✓ To evaluate the irrigation water allocation systems and the water loss at the head, middle, and tail-end users of the irrigation scheme
- ✓ To optimize the future irrigation water allocation and improve the water use efficiency of the irrigation scheme
- ✓ To investigate the effect of efficient irrigation water allocation for resolving social conflicts between the head, middle and tail-end users of the dam

1.4 Research questions

- ✓ What is the existing situation of irrigation water allocation and water loss at the head, middle, and tail-end users of the irrigation scheme?
- ✓ How to optimize future irrigation water allocation and improve water use efficiency in the irrigation scheme?
- ✓ How to evaluate social conflicts between the head, middle and tail-end users of the dam through irrigation water allocation?

1.5 Scope and Limitation of the Study

This study is limited to the hydrological and social problems that emerged from disproportionate irrigation water allocation and inefficient use of irrigation water in the Tigray region, eastern zone, at the Hangoda catchment and Hatset irrigation scheme.

1.6 Significance of the Study

This study provides valuable insights into the water allocation strategies implemented by water user associations in the community-managed Hatset irrigation scheme. It can serve as a useful resource for policymakers, stakeholders, and beneficiaries, offering baseline information for future research on water allocation. In general, the research will be helped improve knowledge of water distribution strategies in irrigation scheme and provide detailed information on the particular methods adopted in the Hatset irrigation scheme.

2 Literature review

2.1 General

Research on water allocation from reservoirs is crucial, particularly in areas with water scarcity and conflicting needs from industry, domestic use, and agriculture. Maintaining an appropriate water balance, which takes into account inflows (precipitation, river flows) and outputs (evaporation, seepage, and water usage), is essential for effective distribution. In order to optimize water distribution while addressing climate unpredictability and stakeholder conflict, integrated water resource management and dynamic reservoir operating models, such as Water Evaluation and Planning (WEAP), are vital **(16)**. Efficiency and equity in allocation are further improved by modernizing irrigation systems, strengthening governance and incorporating stakeholders. In addition to reducing conflicts and promoting long-term water security, a well-managed water balance enables the sustainable use of reservoir resources **(17)**.

2.2 Water allocation System and its mechanisms

Water allocation is defined as the rules and processes through which access to water is decided for single or collective as stated by **(18)**, the shared use and availability. According to **(19)** The water allocation is defined by two sets of rules. The first set of rules determines the principles by which water will be shared between individuals and forms the basis of water rights. The second is the degree of conditionality of the right, normally based on a determination of actual water availability at the head of the system. It is the combination of these two sets of rules that determines the overall right to water in each system, at any given moment in time, and the rules have to be known before any assessment can be made of performance related to water distribution.

In addition to this water allocation refers to the procedure of sharing a limited water resource among different regions and competing uses and consumers. It is a process made essential when the natural delivery and availability of water fails to meet the demands of all water users in terms of quantity, quality, timing of availability, or reliability. In clear terms, it is the mechanism for estimating who can take water, how much they can take, from which places, when, and for what purpose. Access to water has to be controlled to meet a wide range of social purposes, which include agricultural production, economic development, public health, and more currently environmental protection. **(20)**.

The efficient water allocation mechanism can be defined as the precise and effective delivery policies of water resources to enhance agricultural productivity and increase crop production in applied irrigation applications. Precise water allocation mechanisms can diminish water losses, overcome topographic constraints, avoid uncontrolled water abstractions, and be used to precisely measure the exact quantity of water consumed and facilitate the soil/water equilibrium, determining the optimal irrigation schedule and cropping arrangement in cultivated agriculture **(21)**. The most common mechanisms of water allocation worldwide are marginal cost pricing, administrative allocation, water markets, and user-based allocation **(22)**.

In order to solve water constraint and ensure sustained agricultural productivity, irrigation water allocation and management need to be done effectively. To be able to manage conflicting needs from industry, domestic usage, and agriculture, water allocation mechanisms such as administrative allocation, water markets, marginal cost pricing, and user-based approaches are crucial (FAO, 2020).

Accurate estimates of runoff and peak flows are provided by hydrological models like HEC-HMS, which help inform the WEAP model and other tools **(23)**. According to, the WEAP model also optimizes water supply in the face of changing population pressures and climate.

2.3 Applications of HEC-HMS Model

As a hydrological model for modeling rainfall-runoff processes, the U.S. Army Corps of Engineers developed HEC-HMS **(24)**. It has developed throughout time to incorporate sophisticated computational techniques for baseflow, channel routing, direct runoff, and precipitation loss, making it an essential tool in hydrological study. Across a range of watersheds, HEC-HMS has demonstrated efficacy in modeling rainfall-runoff connections. Its accuracy in peak flow estimation and runoff production simulation was validated by studies conducted in the Meki River, Dabus Sub-Basin, and Tikur Wuha watersheds (**(23); (25), ;(26))**. The model well represented peak discharge fluctuations and runoff dynamics in the May Gabat watershed, assisting in the evaluation of flood risk **(27)**. Studies conducted in semi-arid areas further emphasized its application in comprehending rainfall-runoff interactions and water storage planning was further emphasized by research conducted in semi-arid regions **(28)**.

The results of these investigations show that HEC-HMS provides precise predictions for extreme rainfall events and seasonal changes by efficiently estimating runoff volume, peak flow, and hydrograph characteristics. Finding flood-prone locations, evaluating how watersheds react to changes in land use, and enhancing water resource planning have all benefited greatly from the model. It is now a dependable instrument for hydrological assessments under various topographic and climatic situations because to its connection with GIS tools, which has further improved spatial analysis.

2.4 Assessment of irrigation water allocation

Different investments in hydraulic structures such as dams and diversion structures have been constructed in need of rain-fed irrigation. Even though, the performance of water delivery structures was inadequate due to improper design, mismanagement, weak operation, and maintenance. **(29)**. Therefore, the health of the irrigation system could be evaluated using performance indicators and water allocation model.

2.4.1 Performance indicators

In most literature, the water allocation performance of a given irrigation scheme was estimated using a quantitative approach by calculating the ratio of the water delivered to the water released at various levels in other means by using the basic four performance indicators such as equity, adequacy, dependability, and efficiency. **(30)**.

1. **Equity:** according to **(30)** Equity in a water system can be defined as the delivery of fair shares of water to users throughout the system. However, equity does not mean exactly equal but equity is the succeeding of a fair distribution of water hence, equitable distribution of water is achieved when the ratio of water supplied at the main end to water supplied at the terminal outlets is one. In addition to this equity is an extent of variability in relative water delivery from reach to reach over the command area **(31)**.
2. **Adequacy:** adequacy is a measure that reveals if the required amount of water is adequately supplied to crops under an irrigation system. It is a measure of the degree to which water deliveries meet soil-plant-water requirements. **(30)**. According to **(32)** also, the two most important aspects in irrigation planning, design, and operation are the available water supply and the water demands.

3. **Dependability:** dependability is defined as the system's capability to provide water at the right time and in the right location. The forecasting of water deliveries is concerned with the time of water delivery compared to the planned time. **(33)**. It refers to the temporal uniformity of the ratio of the amount of water delivered to the water required or scheduled. If a system performs constantly, then it can be considered dependable. **(34)**.
4. **Efficiency :** according to **(35)** efficiency expresses the amount of water misused by proving the amount of water delivered and the amount of irrigation water requisite per block in other words the capacity to preserve irrigation water by relating water delivery with water requirement.

Several studies have utilized performance evaluation tools based on four key indicators adequacy, efficiency, equity, and dependability to assess irrigation water conveyance systems. In Uganda, the hydraulic performance evaluation of the Doho Rice Irrigation Scheme revealed poor water distribution, particularly at the tail reaches, due to high conveyance losses and inadequate diversion control **(36)**. In Burundi, a similar tool was applied to evaluate irrigation systems using technical indicators and farmers' knowledge, showing good adequacy but poor efficiency, with moderate performance in equity and dependability **(37)**. In Ethiopia, the assessment of the Koftu irrigation system indicated inadequate, unreliable, and unequal water supply to irrigators, with poor canal maintenance and operation cited as the main constraints **(14)**.In Shanxi, China, the Jiamakou Irrigation Scheme was evaluated using the same four performance indicators. The study revealed poor water allocation, where crop water requirements calculated through the FAO56 Penman-Monteith method were not met in a timely manner, despite good water delivery performance **(38)**.

While existing studies have demonstrated the usefulness of performance evaluation tools in assessing irrigation systems, there is a clear research gap in integrating all four indicators adequacy, efficiency, equity, and dependability to simultaneously evaluate both water delivery and water allocation. Most studies prioritize water delivery performance, with limited emphasis on how allocation affects overall system efficiency and fairness. The Jiamakou study is one of the few that incorporates both delivery and allocation metrics, highlighting the need for a more holistic approach. Further research is required to leverage performance evaluation tools that comprehensively address these four indicators, ensuring sustainable and equitable water resource management in irrigation systems.

2.4.2 Water Allocation Model

The Stockholm Environment Institute developed WEAP (Water Evaluation and Planning) as a comprehensive instrument for evaluating and improving water allocation **(39)**. The model has been widely recognized as a powerful tool for evaluating and optimizing irrigation water allocation. It provides a comprehensive framework for simulating water demand, supply, and distribution under various management scenarios. By integrating hydrological data, water availability, and demand patterns, WEAP helps decision-makers optimize water allocation to meet agricultural, domestic, and industrial needs. Studies conducted in the Awash Basin demonstrated how improved irrigation efficiency through WEAP significantly reduced water stress, even under climate change and population growth scenarios **(40)**. Similarly, research in the Upper Blue Nile Basin showcased the model's ability to balance competing demands between hydropower and agriculture by optimizing reservoir operations **(41)**.

Despite its versatility, many studies using WEAP primarily focus on technical optimization, with limited attention to its application in improving equitable water allocation. However, research from the Mekabo small-scale irrigation project in Tigray illustrated how WEAP can enhance allocation efficiency by ensuring a fair distribution of water among users **(8)**. Moreover, its ability to evaluate water supply dependability and optimize distribution in semi-arid regions has demonstrated its relevance across diverse climatic conditions **(42)**. Future research should further explore how WEAP can address both efficiency and equity in irrigation water allocation to ensure sustainable water resource management.

Results from these applications demonstrate how well WEAP works to assess the risks of water scarcity, improve allocation strategies, and assist adaptive water management. Prioritizing irrigation water use, manipulating conflicting demands, and governing policy decisions for sustainable resource use have all benefited from the approach.

2.5 Irrigation water use efficiency

Irrigation water use efficiency (IWUE) is vital for optimizing water use in agriculture, especially in water-scarce regions. Recent studies highlight significant water losses during conveyance and application, which impede IWUE. For example, inefficiencies in canal systems, such as seepage and overtopping, result in substantial water loss before reaching the fields **(43)**. Maintaining and upgrading canal infrastructure, including regular cleaning and repairs, is essential to minimize these losses. Inefficient irrigation scheduling further exacerbates water wastage, with over-irrigation or under-irrigation leading to significant losses. Advanced irrigation techniques, such as drip or sprinkler systems, are crucial for enhancing water distribution and reducing evaporation and runoff **(17)**.

Additionally, traditional irrigation methods, such as flood irrigation, often lead to water loss through deep percolation and leakage, further reducing IWUE. Modern techniques that precisely apply water to the root zone are critical for improving water efficiency. The integration of real-time monitoring tools, like soil moisture sensors, allows for more precise irrigation scheduling, ensuring crops receive the appropriate amount of water. While many studies have explored these solutions in isolation, there is an opportunity to explore the interaction between different irrigation components, including canal systems, scheduling, and technologies, to create more integrated, efficient systems **(44)**. Furthermore, while much of the focus has been on large-scale irrigation systems, smaller-scale systems, particularly those used by smallholders or local communities, often face unique challenges that require tailored approaches. Lastly, more empirical data is needed to assess the long-term impacts of integrating technologies on water savings and crop yields, especially under varying climatic conditions **(45)**. Therefore, the irrigation water use efficiency and irrigation water management in Ethiopia is still a concerned issue. Hence, the irrigation water use efficiency is insufficient due to inappropriate irrigation scheduling and losses at the file level, conveyance, and distribution channel. **(46)**.

2.5.1 Irrigation scheduling

Irrigation scheduling is the procedure of determining how much irrigation water to apply and when to irrigate, and thus has a direct influence on irrigation water use efficiency. **(46)**. Correspondingly **(47)** Irrigation scheduling conceptualizes the question that has to be answered through irrigation scheduling firstly when to irrigate the crops and secondly how much water should be applied. The optimization of irrigation-scheduling is a useful approach for conserving irrigation water, improving the productivity of water, and enhancing the benefits to farmers Irrigation-scheduling optimization is very important to accomplish a fair distribution of irrigation water among users at the basin level, and it can also improve water-use efficiency. Additionally, helps to increase crop growth, yields, and efficient use of water. Irrigation scheduling facilities make available peasants with commendations on the timing and quantity of irrigation water, thus participating in enhancing on-farm water administration **(48)**.

However, according to **(49)** weak irrigation scheduling practices have been considered the main obstacle to the sustainability of irrigation schemes due to the lack of simple and applied scheduling techniques, inaccessibility of soil water monitoring tools, cost, lack of local climate data, and soil-water parameters in Ethiopia, especially in Tigray region, the irrigation scheduling is practiced and decided by a local water committee and based on the farmer’s perception, without considering for soil, plant, and climate condition **(6)**. Therefore, the main priority to improve scheduling irrigation efficiency is required to have knowledge of the crop water requirement, root zone depth, and soil water holding capability **(50)**.

2.5.2 Irrigation water management on-farm level

Among the most critical factors affecting the uneven distribution of water in a farmer's field is deep percolation loss along the watercourse, which results in lower water availability to farmers at the tail end compared to farmers at the headwaters. The rate of deep percolation loss increases from head to tail along the length of the watercourse. Inequality has a direct effect on productivity, as parts of the system receiving less water than their potential demand, and another area receiving more water than they need, do not optimize yields, in both cases resulting in decreased yields **(51)**. Similarly, **(52)** conducted a research study on the evaluation of canal water conveyance and on-farm water application for a small-scale irrigation scheme in Ethiopia and he found that the application efficiency on-farm level was improved from head end to tail end. Hence, the farmers at the head and middle end were receiving more water and practicing the water less efficiently as compared to the farmers at the tail end. The deep percolation losses at the head and middle end were higher as compared to the tail end. The farmers at the tail end were receiving less water and thus most of the applied irrigation water was stored in the crop root zone. The other factor of low application efficiency at the head and the middle end was high soil moisture contents in the soil as compared to the tailwater users.

However, **(53)** pointed out the main factors contributing to poor on-farm water management are poor irrigation scheduling, non-uniform on-field level water distribution, and wrong duration of irrigation. Hereafter, tail irrigators typically suffer from water scarcity. So, the water use efficiency level of irrigation can be improved by saving water in agriculture, while trying to minimize the impact on yield through crop selection and potential alternatives, such as water price assessment and consumption-based water charges should be considered in efforts to discourage over-irrigation and increase equitable water management by smallholder farmers. Since water productivity is different due to unavoidable water losses. It can be estimated based on water delivery in different compartments within the irrigation system. Not only these but also the efficiency of irrigation water can be improved by knowing the character of soil texture on-farm level to recognize the soil infiltration rate. **(14)**.

2.5.3 Irrigation water management on conveyance system

Irrigation water is generally inadequate or improperly managed in canal conduits and is the main challenge limiting agricultural production in Ethiopia as well as in the Tigray region **(53)**. This is because poor organization of canals that break maintenance, illegal water intake, and damage from animals have been recognized as the main causes of damage and a threat to the safety of the irrigation system **(54)**.

The main causes accountable for water losses are lack of maintenance, higher density of vegetation, siltation problems, sediment deposition, sharp curves, seepage loss, and leakage loss. Water losses comprise both evaporation and seepage loss. The evaporation loss is the function of temperature, humidity, and wind velocity. In practice the evaporation loss cannot be controlled however in most researchers it was negligible. **(51)** and the seepage loss could be controlled by providing impermeable media such as concrete, brick, asphalt, and geosynthetic material between porous soil and water flowing in the system. Seepage loss in a canal is the main reason for water loss from the canal as compared to the other forms of water loss **(55)**.

In addition to this **(56)** pointed down that most open and unlined canals, and structures require minor maintenance, and status quo ante, water losses are inevitable. Therefore, analyzing their causes and estimating conveyance losses is essential to provide measures to enhance system efficiency and support improved water management. Lessening of these irrigation system losses will consequently improve water use efficiency by this means increasing the cultivated area and crop production. The participation of farmers in water use associations (WUAs) is critical in improving irrigation water management and crop productivity efficiently and equitably under the canal-irrigated area **(57)**.

Effective irrigation water management also relies on strong governance frameworks to ensure equitable water distribution. In many irrigation schemes, poor governance leads to water scarcity for tail-end farmers due to non-uniform allocation **(53)**. Water User Associations (WUAs) have been recognized as essential for improving irrigation efficiency and equitable distribution **(57)**. However, current governance structures often lack the capacity to enforce fair water allocation or involve farmers in decision-making processes. Strengthening WUAs and incorporating local governance frameworks could improve irrigation management by promoting equitable resource distribution. Despite this, research on how to effectively enhance governance structures remains limited.

2.6 Causes of conflict on water allocation and its reconciliation

From a water resource perspective conflict is defined as disputes between the exploiting communities, groups, and individual users. The water conflict is categorized into four types, these being international, national, regional, and local, and happens between two or more regions or groups competing with each other to access and exploit water resources **(58)**. The conflict is considered as an inevitable part of life. Nevertheless, it is aware of the causes of conflict and it leads to opportunities and provides interfaces among people **(59)**.

According to **(60)** the causes of conflict on water resource utilization are theft, water scarcity, lack of good governance, high poverty level and largely subsistence-based agriculture, and failure to share data and information. Similarly, as **(61)** pointed down increasing water demand between agriculture and hydropower, domestic and agricultural uses, agriculture and fisheries, agriculture and industry, highland and lowland, upstream and downstream, and rural and urban areas. In a water shortage environment, competition for accessible water resources between many different water users is possible to become concentrated. If sufficient measures to improve water use efficiency and to preserve this scarce resource are not taken, water security will be a critical challenge and has already become a challenge in many places.

The agricultural sector competes with municipal and urban water users, and local water resources are under growing pressure due to increased agricultural productivity this tension has led also to a conflict among competing users **(62)**. Hence, **(63)** the causes of conflict on agricultural water were divided into two groups of uncontrolled and controlled factors. The uncontrolled factors such as the physical structure of the irrigation network, water scarcity, drought, and mismatched size of the irrigation network with irrigation structure water capacity while the controlled factors were mentioned as a lake for local management of water resources by farmers, weakness of governmental water management, government's reluctance about farmers' participation and farmers' unwillingness to participate in water management.

After well understanding of the causes of water resource conflict the water conflict reconciliation procedure has been approached by many disciplines such as engineering, law, economics, political economy, anthropology, geography, and systems theory **(64)**. Additionally, the cause's conflict emerged from ineffective and inequity of water allocation resolving through decision support system/modeling tools **(65)**.

Conflict reconciliation in irrigation water allocation requires a multi-dimensional approach that integrates socio-economic analysis, institutional engagement, and technical tools. Water conflicts often arise due to socio-economic disparities, governance weaknesses, and inequitable distribution. Participatory decision-making, as seen in Serbia’s Nadela catchment, strengthens local governance and fosters consensus-based allocation **(66)**. Establishment Irrigation Water User Associations (IWUAs) also enhances cooperation and reduces disputes **(67)**.

Investigating socio-economic data can help uncover the root causes of conflict by highlighting patterns of inequity and governance failures. While institutional engagement and stakeholder participation have been identified as essential for conflict reconciliation **(68)**, there is a need for studies that integrate socio-economic analysis to inform policy decisions. Exploring how socio-economic dynamics affect water allocation could improve the fairness and sustainability of water governance. Future research should prioritize using socio-economic data to design more inclusive and equitable water management frameworks that address both resource scarcity and social conflict.

3 Materials and Methodology

3.1 Description of the study area

The Hatset Irrigation Scheme, located in the Hawzen district, while the Hangoda watershed is located in Edagahamus district, Eastern Zone of Tigray Region, Ethiopia. approximately 80 km northwest of Mekelle. Geographically, Hatset is located between 14.06°N and 39.49°E, and Hangoda watershed is located between 14.04°N and 39.49°E, with elevations ranging from 2314 to 3155 meters above sea level. The area is accessible via the Mekelle-Adigrat road to Sinkata, followed by the Sinkata-Hawzen road.

The topographic map of the project area starting from the reservoir area up to the tail end of the command area is prepared at a scale of 1:1000. Furthermore, a topographic map of 1:500 at the reservoir area and dam axis which is around 1000m upstream and downstream is prepared. The river cross-section at the dam axis and spillway is also surveyed in addition to the river longitudinal profile collected & prepared for the site. Finally, topographic map of the dam axis location, spillway, outlet position and command area.

The region experiences low and erratic rainfall, making irrigation essential for sustaining agricultural activities. Historically, farmers relied on traditional water management methods, such as temporary dykes and small pumps, which were inefficient, leading to high costs, frequent maintenance issues, and underutilization of available water resources. To address these challenges, the Hangoda Dam was constructed on the Hangoda River, a tributary of the Suluh River Valley in the Tekeze Basin. The dam has a maximum storage capacity of 4.06 million cubic meters, a live storage of 3.05 million cubic meters, and a height of 20.49 meters.

The dam supplies water to the Hatset Irrigation Scheme, which was designed to irrigate 350 hectares of farmland. The irrigation infrastructure includes a main canal, five secondary canals, and over 35 tertiary canals. The system operates with a design flow rate of 1.6 liters per second per hectare and a total discharge capacity of 0.56 m^3/s. However, due to water shortages, siltation, infrastructure failures, and weak water management, only 202 hectares are currently under irrigation.

The Hatset Irrigation Scheme serves 625 farmers, organized into 25 Irrigation Water User Associations (IWUAs) and categorized as head, middle, and tail-end users based on their location within the irrigation user network. Water distribution system, supplied through a structured canal network. The system begins with a main canal, which delivers water to five secondary canals (SC-1 to SC-5) hence, the head users receive water from SC-1 and SC-2, the middle users are supplied through SC-3 and SC-4, and the tail-end users delivered by SC-5. Finally, irrigation water is distributed to farmlands through over 35 tertiary canals.

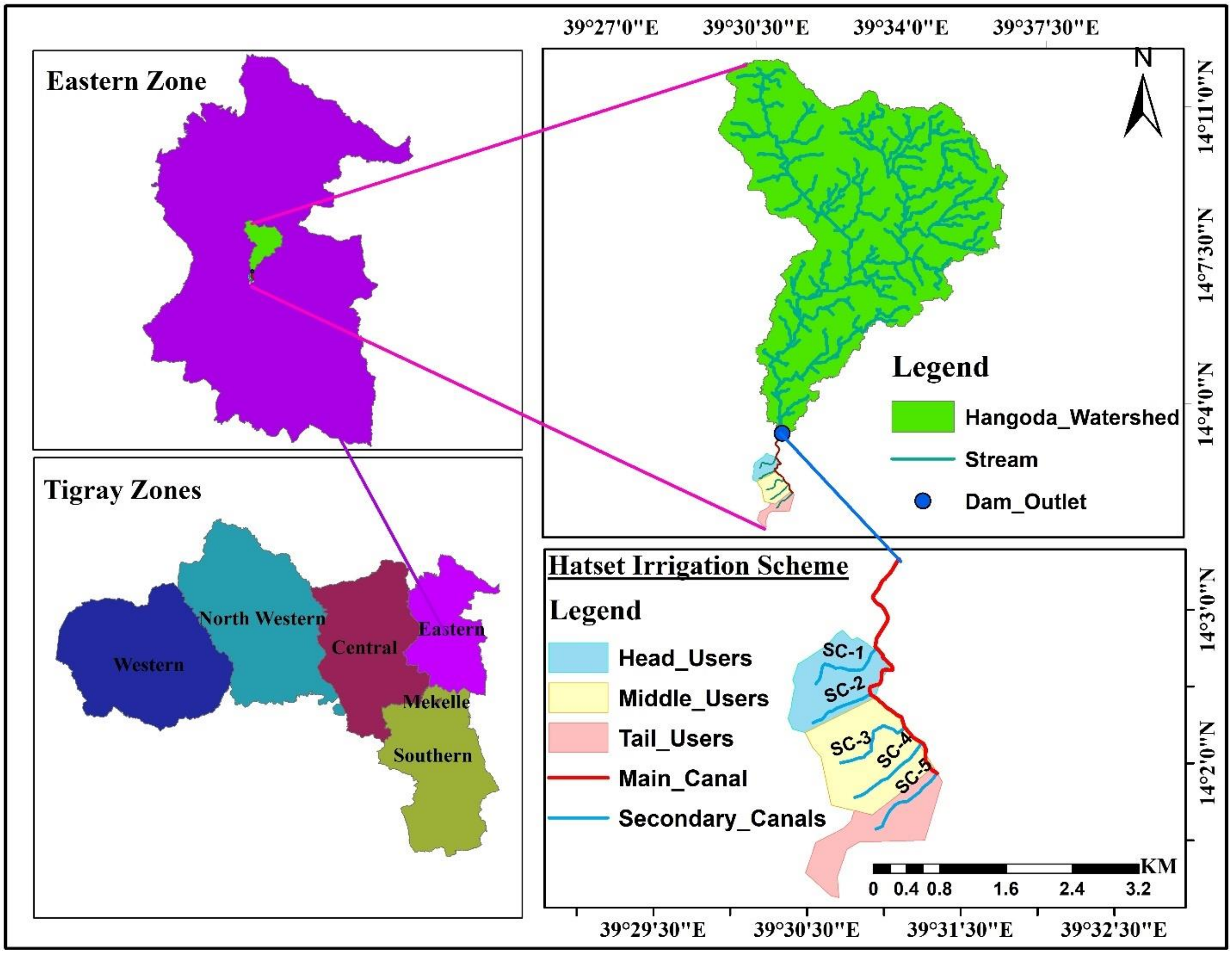


Figure 3-1: Location of study area

3.2 Data collection

3.2.1 Primary data source

The primary data were collected through questionnaire (household surveying), key informant interview, focus group discussion, and direct field data and/or field works, through observation and transit walk, laboratory, and flow measurements.

3.2.2 Secondary data source

Secondary data for this study included spatial data (DEM, land use/cover, soil types), meteorological data (rainfall, temperature, streamflow) from the Tigray Meteorological Service and Water Resource Bureau, reservoir data from design documents, and agronomic data from the Hatset agricultural office.

3.3 Soil sampling and determination of parameters

This study used stratified random sampling **(69)** based on time and cost efficiency. The irrigable area was divided into three user groups: head, middle, and tail, based on proximity to irrigation water sources. Nine soil samples were taken from each group at various depths (up to 60 cm) in the Hatset irrigation scheme, totaling 18 samples. Particle size distribution was analyzed using the hydrometer method, bulk density with the core technique, and field capacity and permanent wilting point (PWP) with pressure plate equipment. Wet and dry weights were measured after oven-drying at 105°C for 24 hours, and lab analysis determined moisture content, bulk density, field capacity, PWP, and total accessible water (TAW).

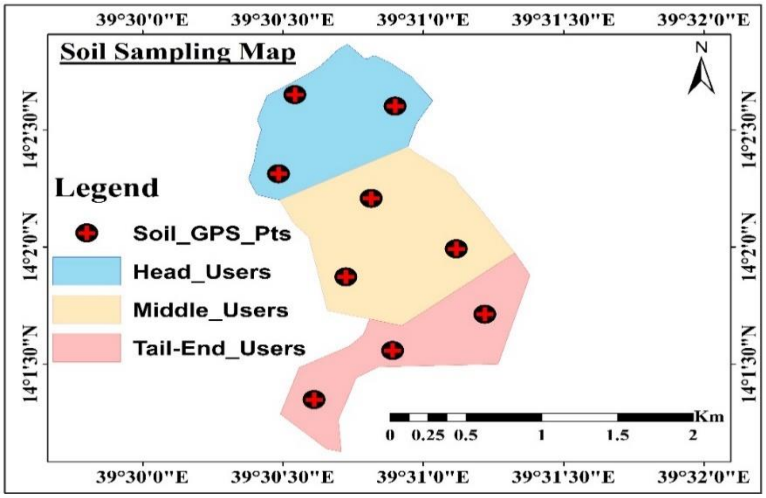


Figure 3-2: Location points where soil samples collected

Using pressure plate equipment, the moisture content at field capacity (FC) and wilting point (WP) were determined at 1/3 bar and 15 bar, respectively **(70)**. The volumetric total accessible water (TAW) was determined using equation (3.1).

$$TAW = 1000 \times (\sum_{i=0}^{n} (\theta_{FCi} - \theta_{PWi}) \times Z_{di}) \text{.................................} (3.1)$$

Where: TAW : total available water in the soil (mm) θ_{FCi} : Volumetric moisture content at field capacity (m^3/m^3) θ_{PWi} : Volumetric moisture content at wilting point (m^3/m^3) Z_{di} : Root depth (m) in i^{th} soil layer and n: number of observations

3.4 Flow measurement and analysis

3.4.1 Flow measurement

Flow discharge across the main and secondary canals was measured using a current meter (Figure 3-3), and wetted width and depth were recorded with a tape meter/staff gauge at selected points. Measurements were taken at fourteen points for the main canal and five or more for the secondary canals.

Figure 3-3: Flow measurement using current meter

3.4.2 Determination of flow discharge

Discharge measurements have been made to assess canal water conveyance's effectiveness and calculate water loss.

a) **Average flow Velocity**

The current meter is operating by recording the number of revolutions per ten seconds (10 seconds). The velocity of flow calculated using equation (3.2).

$$V = 0.11n + 0.0403 ------------------------ (3.2)$$

Where; V = flow velocity (m/s), n = number of revolutions per 10 sec.

b) **Wetted cross-sectional area**

The wetted cross-sectional area was determined for uniformly straight and well-chosen segments of the canal using equation (3.3). $A = w \times h ---------------------------$ 3.3

Where: A: area of wetted cross-section (m), w: wetted width of the canal (m), and h: wetted depth of the canal (m).

After estimating the average velocity and the wetted cross-sectional area the discharge was then determined using continuity as given in equation (3.4).

$$Q = V_a \times A ---------------------------- 3.4$$

I. Conveyance efficiency and water loss

The conveyance efficiency of the lined main and secondary canals was estimated using the ratio of inflow-outflow discharges as shown in equation (3.5), with flow measurements taken at control points along varying canal lengths (see Figure 3-4).

$$E_C = \frac{Q_i}{Q_o} * 100\% ------------------------- (3.5)$$

Where: E_C : Conveyance efficiency (%), Q_i : Inflow and Q_o : Outflow discharges in (m^3/s)

The water loss L (m^3/s) can be determined by the inflow-outflow method and it is a water balance approach that comprises the direct measurement of flow discharge flowing into and out of the reaches of the sub canal.

$$L = Q_i - Q_o ------------------------------------ (3.6)$$

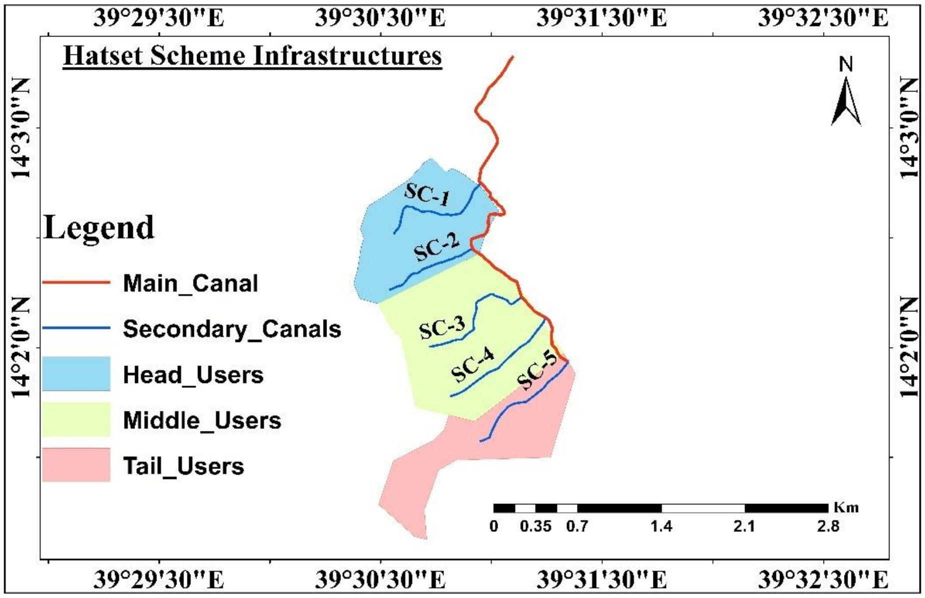


Figure 3-4: Location of infrastructures in the Hatset irrigation scheme

3.5 Data Used For HEC-HMS

3.5.1 Soil Types

After obtaining the FAO soil classification shapefile from MoWEI, it was clipped and processed using ArcGIS's DEM. There are three classes of soil texture and two types of soil in the study region (Figure 3.5, Table 3-1).

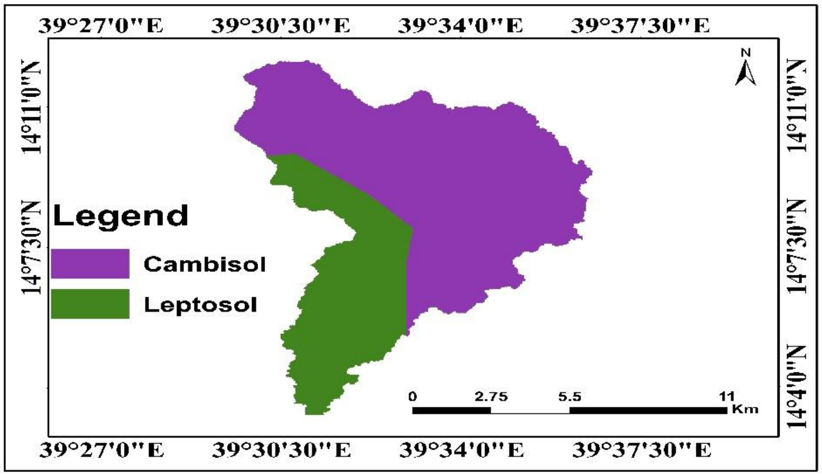


Figure 3-5: Soil map of the study area

Table 3-1: The dominant soil classes in the study area

Soil Type	USDA textural classification	Hydrologic soil group	Area (Km2)	%Area
Cambisol	Sandy Loam	B	72.00	69.07
Leptosol	Clay Loam	D	32.24	30.93
Total			104.24	100

3.5.2 Land Use/Cover

The Landsat data used was downloaded from the official website https://www.usgs.gov/ study area for the year 2024 G.C was selected and used (Figure 3.6).

Table 3-2: Hangoda watershed coverage area of LULC type

Class Name	Agriculture	Grazing Land	Forest Land	Shrub Land	Bare Land	Built-Up	Water Body	Total
Area (Km2)	58.09	4.54	3.95	20.4	13.98	2.72	0.58	104.24
% Area	55.73	4.35	3.79	19.57	13.41	2.6	0.56	100

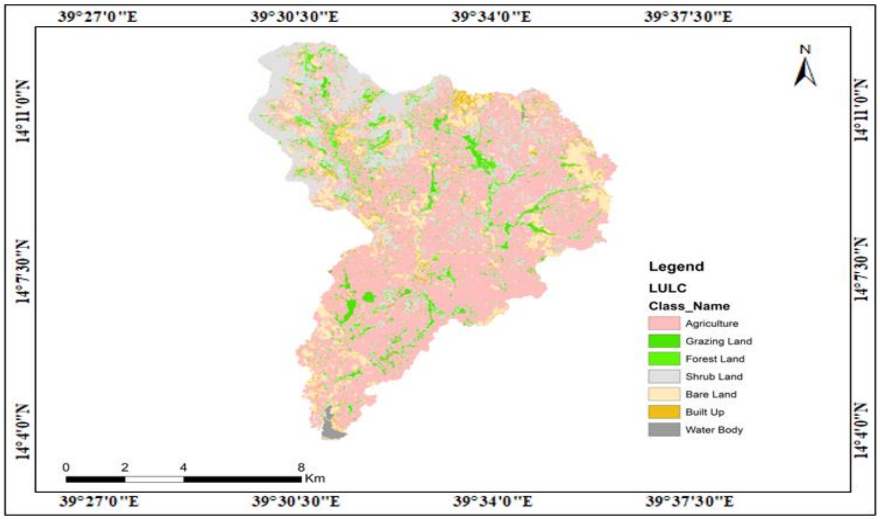


Figure 3.6: Hangoda watershed LU by supervised classification

3.5.3 Meteorological Data Analysis

There are number of meteorological stations in the river basin, however, due to limitation of data only three stations were considered.

a) **Filling missing rainfall data:** missing rainfall data for 2001-2019 (Edagahamus, Hawzen, and Snkata stations) were filled using the arithmetic mean method, among other techniques like inverse distance weighting and multiple regression, as shown in equation (3.7).

$$P_x = \frac{1}{N}(P_1 + P_2 + P_3 --\_\_\_ + P_n)--(3.7)$$

Where, Px = Daily missing value of precipitation at station x to be computed and P1, P2, P3, and Pn are daily precipitation depths at the adjacent stations 1, 2, 3, and up to n adjacent stations and N number of stations.

b) **Data consistency:** the double-mass curve technique checks record inconsistencies by plotting a single station's cumulative rainfall on the ordinate and nearby stations' cumulative rainfall on the abscissa, resulting in a straight-line graph (Figure 3-9).

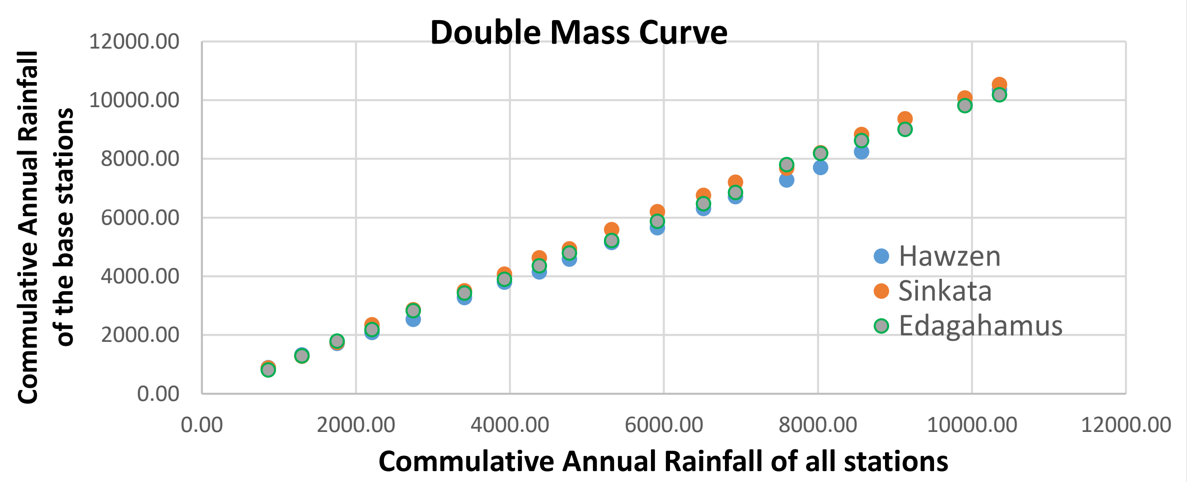


Figure 3-7: DMC test for Edagahamus, Snkata, and Hawzen stations

3.5.3.1 Areal rainfall determination

The rainfall for the Hangoda watershed was computed using the Thiessen polygon method based on nearby rainfall gauging stations, namely, Hawzen, Snkata, and Edagahamus as shown in Figure 3-8.

$$AP = \frac{P_1A_1 + P_2A_2 + --- + P_nA_n}{A} ------------------(3.8)$$

Where: - AP = areal precipitation over the sub-basin (mm); P1, 2…n = precipitation depth in each station (mm); A1, 2 …n = area of each polygon (km2); A = total watershed area of sub-basin (km2).

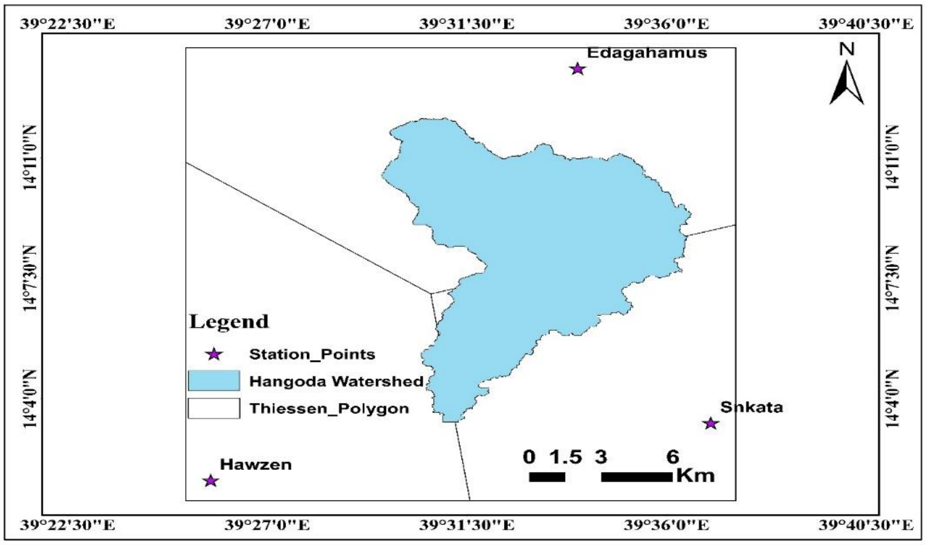


Figure 3-8: Rainfall gauging stations for Hangoda catchment

3.5.4 Hydrological Data Analysis

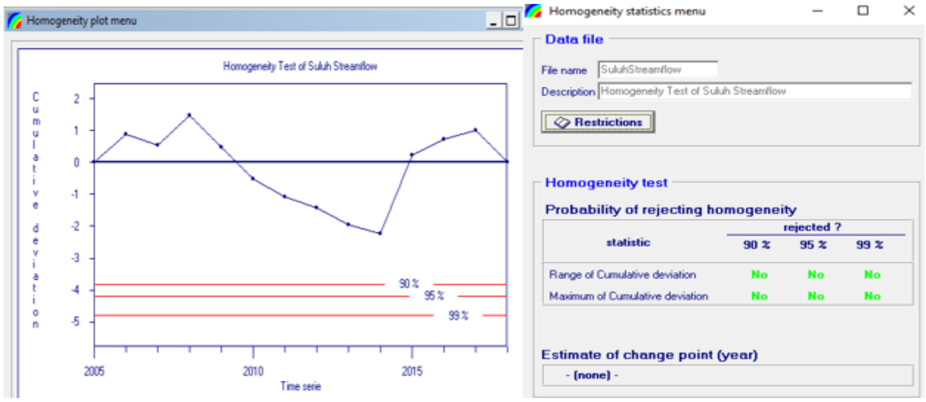
Simulating streamflow is crucial in hydrological studies as it impacts water resource availability. To compare observed data with simulated flows, discharge data from a nearby gauging station was adjusted for the catchment area difference, since the dam site lacks historical flow data for the Hangoda River.

Rainbow software was used to assess streamflow data homogeneity, crucial for ensuring observations come from the same population in hydro-meteorological analysis. Developed by Raes et al. **(71)**, RAINBOW conducts frequency analysis and homogeneity testing, with the latter based on the cumulative deviation from the mean, as proposed by **(72)** and referenced by Raes et al. **(73)**.

$$S_K = \sum_i^K (X_i - \bar{X}) \text{---(3.9)}$$

Xi (i = 1, 2,..., n) is the representation of the series, where X is the mean. The values of SK are zero at both the beginning (SK=0) and final (SK=n) points. A residual mass curve that displays mean changes is formed using the SK values. SK rises when Xi exceeds the mean, and falls when

Xi falls. Since Xi deviations from X do not exhibit a regular pattern, SK for a homogeneous series oscillates about zero.



File name: SuluhStreamflow

Description: Homogeneity Test of Suluh Streamflow

Probability of rejecting homogeneity

statistic	rejected ? 90 %	rejected ? 95 %	rejected ? 99 %
Range of Cumulative deviation	No	No	No
Maximum of Cumulative deviation	No	No	No

Estimate of change point (year): - (none) -

Figure 3-9: Stream flow data Homogeneity test of Suluh River

Figure 3-9 shows the homogeneity test for the Suluh station, which revealed that the data were homogeneous. The cumulative deviation range and maximum cumulative deviation could not be rejected at the 90%, 95%, and 99% probability levels, confirming the homogeneity of the annual data series and indicating that the observations are nearly from the same population.

3.5.4.1 Estimation of missing observed streamflow data

To fill missing streamflow data at Suluh station, the Normal Ratio (NR) method (Equation 3.10) was used, as reported by Gebreyohannes et al. and Shabalala et al. (74, 75). The Hangoda catchment, located upstream of Suluh River, is a tributary of the river, with adjacent stations at Genfel and Agula. Gebreyohannes et al. (75) also found the NR method to be the best for estimating missing data at Suluh station.

$$P_t = \frac{1}{n}\sum_{i=1}^{n}\frac{N_t}{N_i}x_i \text{-------------------------------} (3.10)$$

Where Nt is the annual rainfall and stream flow amount at the target station and Ni is the annual rainfall and stream flow amount at the ith nearby station.

3.5.4.2 Flow data Transfer to the Dam site

To transfer data from an ungauged to a gauged catchment, the watersheds must have similar characteristics, such as land use/land cover (LULC) and soil type. Additionally, the gauged and ungauged catchments should be within 50 km of each other, and the gauged sites must have at least 10 years of mean monthly river flow data (76, 77). Typically, the stream gage closest to the site of interest is selected to transmit streamflow statistics from the gauged location to the ungauged one. Hence, the transfer of streamflow data was carried out according to [William H. Asquith, 2006] as outlined in equation (3.11). This formula is based on the area ratio method within the recommended value between 0.3 to 1.5 that pointed out by [Ries, 2000]. Therefore, according to Hailay et. al. 2023 (78) the predicated dominant land use/land cover and dominant soil of Suluh catchment (gauged) were given by Table 3-3.

Table 3-3: The characteristics of watersheds above the gaged and ungagged site

	Gaged catchment	Ungagged catchment
Dominant Land use/cover	Agriculture, Grazing Land, Forest Land, Shrub Land, Bare Land, Built-Up, and Water Body.	Agriculture, Grazing Land, Forest Land, Shrub Land, Bare Land, Built-Up, and Water Body.
Dominant Soil	Cambisol, and Leptosol	Cambisol, and Leptosol

$$Q_{ung} = Q_g \left(\frac{A_{ung}}{A_g} \right) ------------------(3.11)$$

Where: Q_{ung} Is discharge at an ungauged location (m3 /s), Aung is the drainage area of an ungauged location (km2), Q_g Is discharge at the gauged location (m3/s) Ag is the drainage area at the gauged location (km2).

3.6 CROPWAT For Crop Water Demand

3.6.1 Input Data For CROPWAT

To estimate crop water requirements using CROPWAT 8.0 (70), the following data are needed:

1) **Climate Data:** includes air temperature, humidity, solar radiation, wind speed, and rainfall for calculating reference evapotranspiration (ETo).
2) **Effective rainfall:** refers to the rainfall available for plant use, considering losses due to runoff and percolation. Factors like soil type and storm intensity affect infiltration (79).

Cropping Pattern Data: includes planting date, crop coefficient (Kc), growth stage, root depth, and area planted. Cropping patterns were determined through surveys and field observations, with key crops being potato, tomato, cabbage, and maize. Data from Hatset Kebele and a household survey are shown in Table 3.4.

Table 3.4: Cropping pattern of Hatset irrigation scheme for all users of irrigable area

Crop Type	Head (70ha)	Middle (70ha)	Tail (62ha)	%-of-area coverage	Planting date
Potato	17.5	17.5	15.5	25	3-Jan
Tomato	15.4	15.4	13.64	22	6-Jan
Cabbage	7	7	6.2	10	3-Nov
Maize	17.5	17.5	15.5	25	25-Dec
Vegetables	9.1	9.1	8.06	13	20-Jan
Wheat	3.5	3.5	3.1	5	18-Nov
Total	70	70	62	100	

Assumption: The cropping area % remains proportionally the same for all the three users.

3) **Soil and infiltration data:** includes soil moisture, rooting depth, initial moisture depletion, and infiltration rate. Soil data was collected from field observations.

Therefore, CWR was estimate using the following mathematical equations, according to (70) the crop evapotranspiration expresses as:

$$ET_c = K_c \times ET_o -------------------(3.12)$$

Where: ET_c Is the crop evapotranspiration in mm/day

K_c Is a crop coefficient (dimensionless) and

ET_o Is the reference crop evapotranspiration in mm/day

Similarly, FAO express the net irrigation requirement as:

$$IR_n = ET_c - RF_{eff} --(3.13)$$

Where: IR_n is a crop water requirement (mm/period), RF_{eff} Is effective rainfall and N is the total number of crops.

Net scheme irrigation requirement for a given irrigation scheme is thus the product of crop water requirement and irrigation area as given by equation (3.14).

$$\mathrm{NSIR} = \mathrm{IR}_n * \mathrm{A_S}\ (\mathrm{m}^3/\mathrm{s})\text{--}(3.14)$$

Where: NSIR Is net scheme irrigation requirement and $\mathrm{A_s}$ Is irrigation area for a specific scheme.

The gross irrigation water requirements (GIWR) also expressed by equation (3.15), for this study, a 50% overall irrigation efficiency ($\mathrm{I_{Ef}}$) was used to calculate the gross irrigation requirement, as per the Hangoda earthen dam design document.

$$\mathrm{GIWR} = \frac{\mathrm{NSIR}}{\mathrm{I_{Ef}}}\text{---}(3.15)$$

CROPWAT also used to estimate potential evapotranspiration (input for HEC-HMS) **(44)** and evaporation from the reservoir **(80-82)**.

3.7 Rainfall-runoff modeling Using HEC-HMS

3.7.1 Implementation of HEC-HMS

HEC-HMS 4.12 was used to simulate watershed hydrology, converting precipitation to streamflow at the outlet. It effectively estimated inflow into the dam reservoir. The modeling process included three steps: (1) creating a basin model, (2) preparing hydrologic parameters, and (3) developing the HEC-HMS model.

1. Basin Model Development

The basin model was developed using HEC-GeoHMS (ArcGIS 10.4) with a DEM to define watershed characteristics, project in WGS84, UTM Zone-37N, generate datasets for basin and stream network delineation, and calculate key hydrological parameters, including river length, slope, longest flow path, centroid, and centroidal elevation (see Figure 3-10).

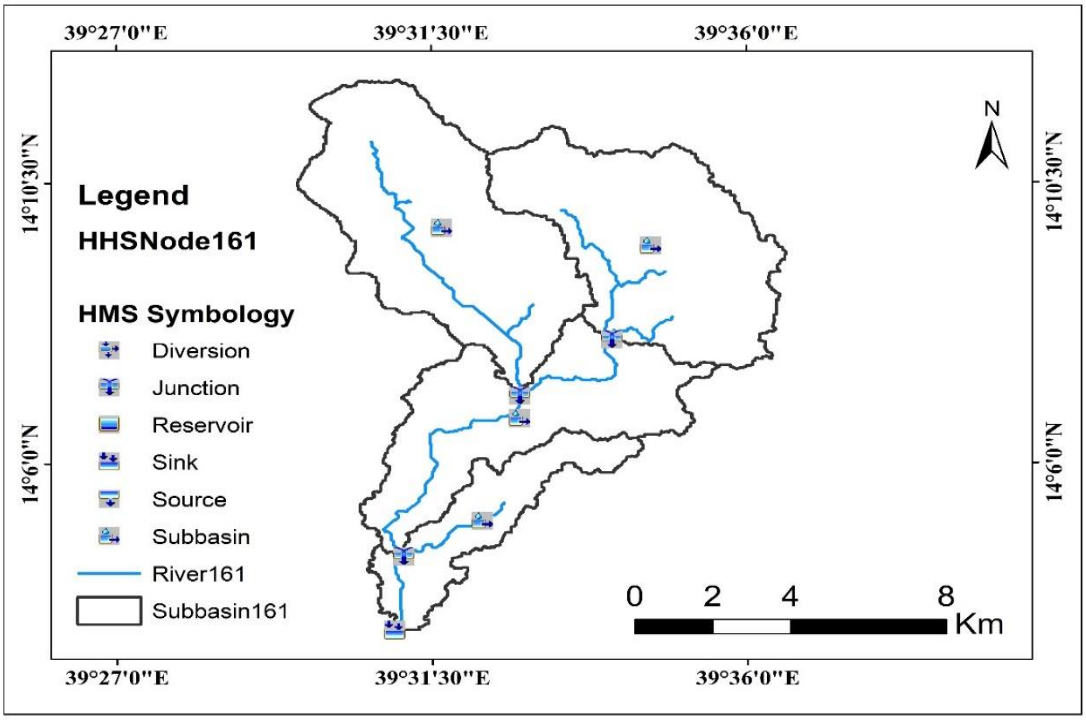


Figure 3-3-10: Output of HEC-GeoHMS for Hangoda basin

2. Preparation of Model Parameters

HEC-GeoHMS generated input files for HEC-HMS, including a background map with sub-basins, stream networks, and meteorological data. The output also produced a schematic of the primary hydrologic flow, with input nodes and junctions (Figure 3-10), simplifying HEC-HMS model configuration.

3. HEC-HMS Model Development

The HEC-HMS model, configured with the Basin Model, Meteorological Model, and Control Specifications (simulation period: January 1, 2006, to December 31, 2018), underwent calibration from 2006 to 2014 and validation from 2015 to 2018 using daily time steps, with HEC-GeoHMS integration in ArcGIS enabling hydrological simulations for the Hangoda River Basin to support these phases (Figure 3-11).

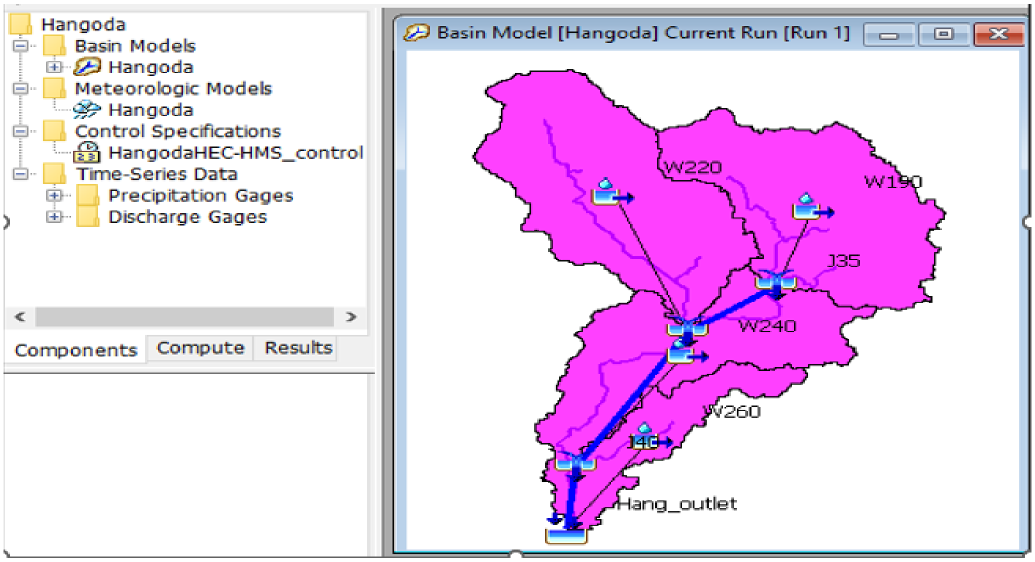


Figure 3-11: Hangoda watershed hydrologic model components

3.7.2 Hydrological Method Selection in HEC-HMS

The HEC-HMS model selected methods for each runoff process based on suitability and reliability, using the SCS-CN method for infiltration losses, the SCS-UH method for transforming rainfall into runoff, and the lag time method for channel routing, all aligned with prior research recommendations.

The CN-grid used for determination of SCS-CN, was generated by superimposing the land use and soil maps in HEC-GeoHMS, which is given in Figure 3-12.

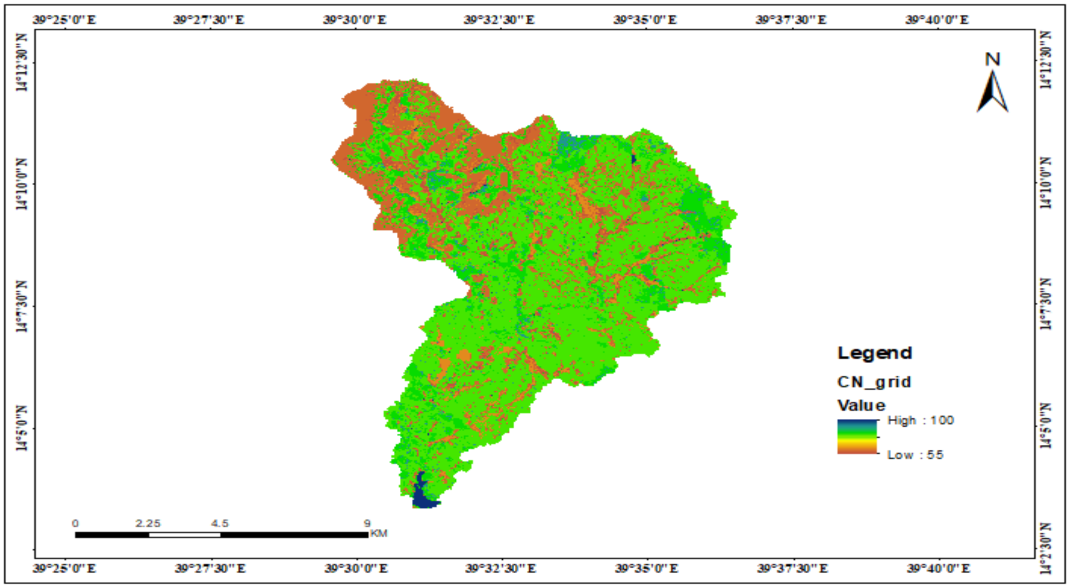


Figure 3-12: Curve number grid map

3.7.3 Model calibration and validation performance criteria

The HEC-HMS model's performance was evaluated using four statistical indicators: Nash-Sutcliffe Efficiency (NSE), percentage relative bias error (PBAIS), coefficient of determination (R²), and root mean square error (RMSE). After manual parameter adjustments, the best fit between observed and simulated hydrographs was achieved. Higher values of R², NSE, and lower RMSE indicate better model performance, with acceptable NSE values above 0 and RMSE below 50% of the observed standard deviation **(83)**.

$$R^2 = \frac{\sum_{i=1}^{n}(Q_{oi}-\bar{Q}_o)^2 - \sum_{i=1}^{n}(Q_{si}-\bar{Q}_s)^2}{\sum_{i=1}^{n}(Q_{oi}-\bar{Q}_o)^2} -------------------(3.16)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{oi}-Q_{si})^2}{\sum_{i=1}^{n}(Q_{oi}-\bar{Q}_o)^2} -------------------(3.17)$$

$$PBIAS = 100 * \left(\frac{\sum_{i=1}^{n}(Q_{si}-Q_{oi})}{\sum_{i=1}^{n}(Q_{oi})} \right) ----------------------(3.18)$$

$$RMSE = \frac{\left[\sqrt{\sum_{i=1}^{n}(Q_{oi}-Q_{si})^2} \right]}{\left[\sqrt{\sum_{i=1}^{n}(Q_{oi}-\bar{Q}_o)^2} \right]} -------------------(3.19)$$

Where: Q_{oi} is observed values, Q_{si} Is simulated values. $\bar{Q}_o$ is the mean of observed data and n is the total number of observations

Table 3.5: Performance evaluation criteria for calibration and validation

No	Rating	R²	NSE	PAIAS
1	Very Good	> 0.8	> 0.8	≤ ± 5
2	Good	0.7 ≤ R2 ≤ 0.8	0.6 ≤ NSE ≤ 0.8	≤ ± 5 < PBAIS < ± 10
3	Satisfactory	0.5 < R2 < 0.7	0.5 < NSE < 0.6	≤ ± 10 < PBAIS < ±25
4	Unsatisfactory	≤ 0.5	≤ 0.5	≥ ± 25

Source: (Moriasi et al. **(84)**)

3.8 WEAP for Water Allocation

The Water Evaluation and Planning (WEAP) model simulates water allocation in dam reservoirs by integrating hydrological processes and management strategies, using a water balance approach. It accounts for inflows from precipitation, river discharge, and groundwater recharge, while considering losses due to evaporation, seepage, and withdrawals. WEAP prioritizes water allocation, incorporates reservoir operation rules, and serves as a decision-support tool for optimizing reservoir management and equitable water distribution Yates et al., **(85)**.

3.8.1 Modeling Procedures

Before data entry into WEAP, a GIS-based shapefile map was uploaded, representing rivers and reservoirs (Figure 3-14). Demand sites were added, and reservoirs were positioned along rivers with transmission links connecting water sources to demand sites. Figure 3-13 shows the schematic layout, with the Hangoda River (blue) as the primary water source and the reservoir (triangle symbol), while transmission links (green) represent water flow.

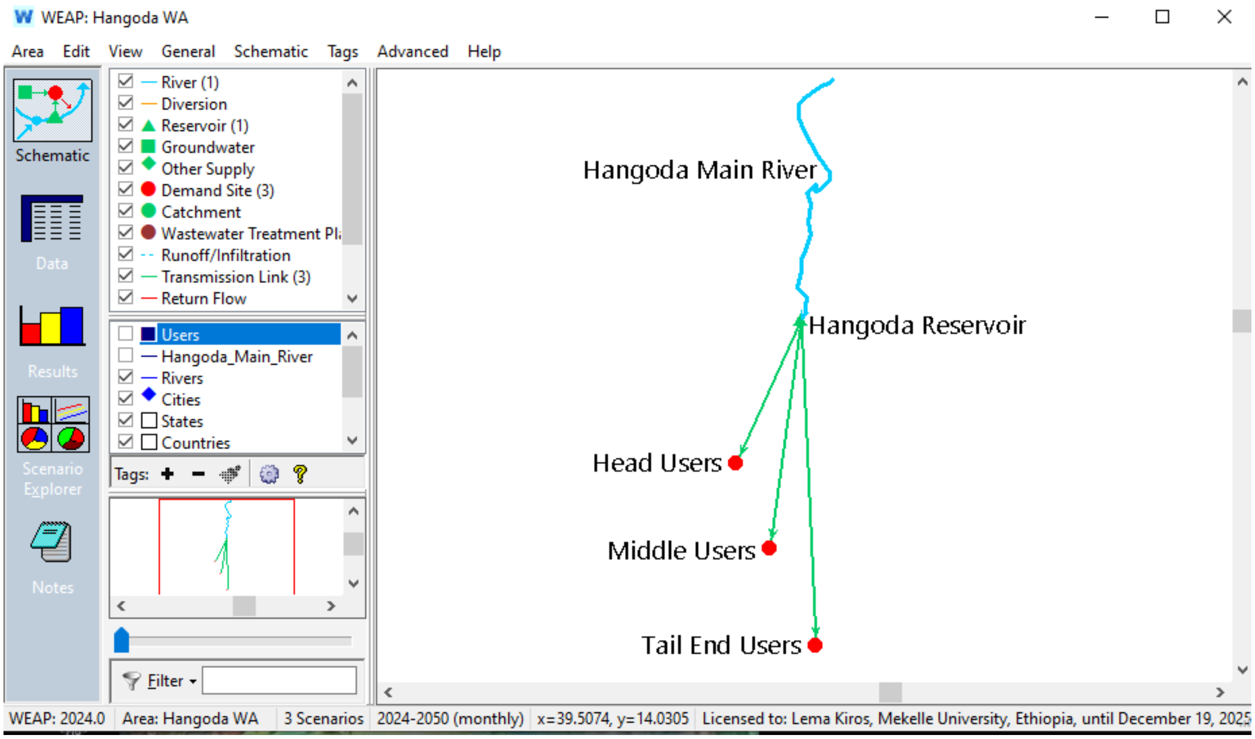


Figure 3-13: WEAP screen view, schematic diagram of the demand side of Hangoda Dam

3.8.2 Priority Setting in Water Allocation

Demand priority, as defined by **(39)**, is the level of priority for allocating the available water supply. As a result, until all demands are satisfied, the highest priority demand sites would be supplied first, followed by lower priority sites. Irrigation water is extracted at the head users of the Hatset irrigation scheme without taking middle users demands into account. This indicates a "first come, first served" situation. The priority was set such that the execution of the prior was guaranteed the success of a later re-allocation plan so that, the WEAP model was employed for computer-based simulation and optimization, enabling the estimation of optimal allocation priorities and schedules under competing water demands hence the irrigation water was not supplied all users at once **(86)**, this was illustrated in Figure 3-14.

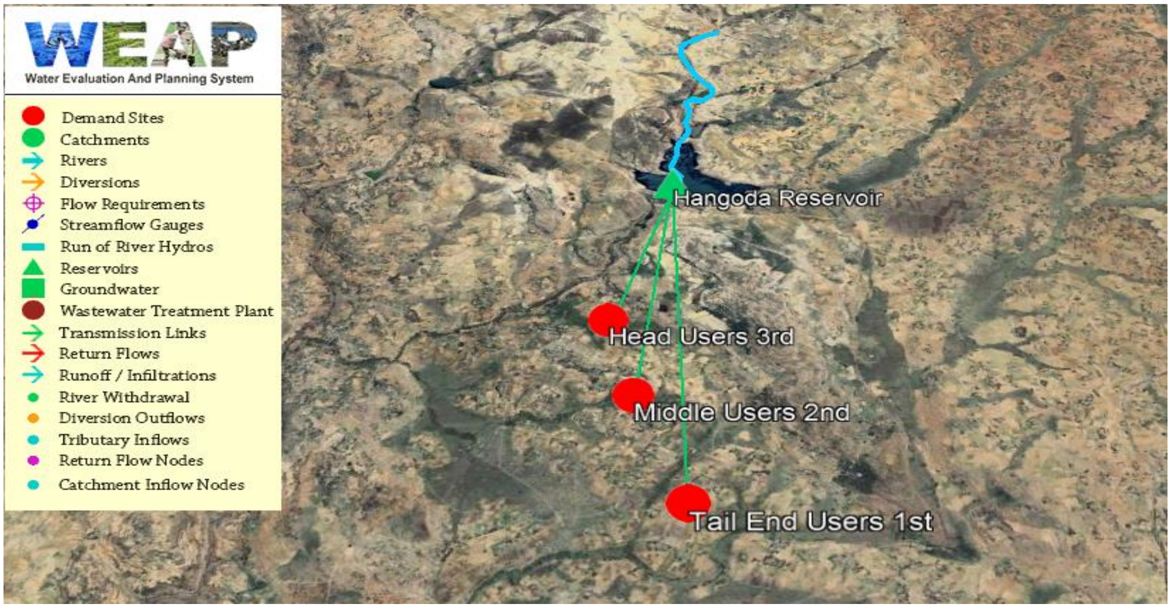


Figure 3-14: Priorities Setting of demand sites using Google Earth Pro

3.8.3 Reservoir water balance

The reservoir system consists of inflow, storage, evaporation, and outflow, all impacting its efficiency. Storm runoff is stored, though some water evaporates, and the remaining water is released as needed, requiring optimization for effective management.

Change in the storage = Inflow – Outflow

$$\Delta S = I - O \text{ –} (3.20)$$

Where: ΔS = Change in the storage, I = Inflow, and O = Outflow (reservoir release and evaporation loss).

I. **Reservoir operational assumptions:** to simplify the complexity of actual reservoir operations, several assumptions were made:
   - There is no reduction due to sedimentation which means constant reservoir effective Storage
   - Seepage through the body of the dam is assumed zero and the reservoir is assumed a constant.
   - The Tail water level is considered constant due to data constraints.

II. **Reservoir operational rules:** reservoir operation in WEAP uses predefined rules, dividing storage into zones: flood-control, conservation, buffer, and inactive as shown in Figure 3-15. The conservation and buffer zones are active, with the flood-control zone kept empty. Water is released from the conservation pool to meet downstream demand, but releases are limited by a buffer coefficient to protect residual supply. Water can't be distributed in the inactive zone, but evaporation may cause water to enter it in extreme cases.

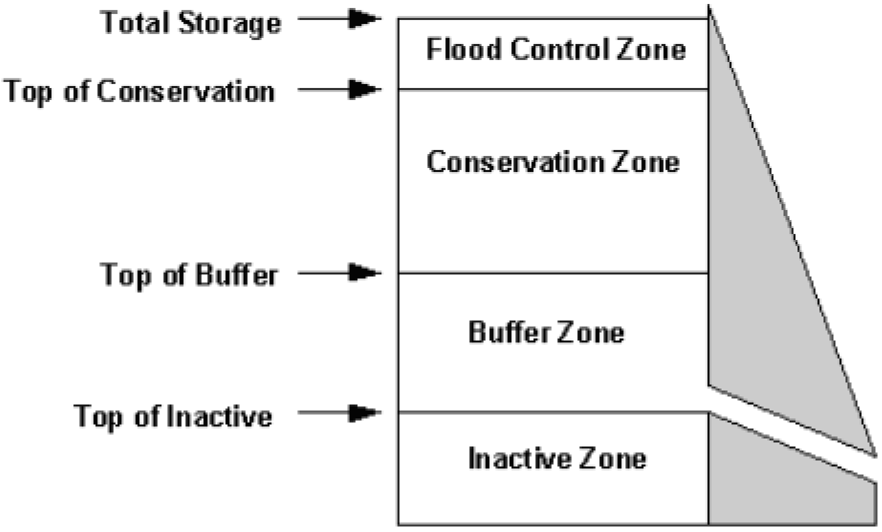


Figure 3-15: Reservoir storage zones (source: WEAP User Guide)

The formula for total available water is:

$$S_r = S_f + S_c + (b_c * S_b) \text{------------------------}(3.21)$$

Where: Sr is the total available water for release, Sf is the flood-control zone storage, Sc is the conservation zone storage, bc is the buffer coefficient and Sb is the buffer zone storage.

III. **Water demand calculation:** water demand is calculated as the sum of the demands for all the demand site bottom-level branches (Br). A bottom-level branch has no branches below it. Annual water demand was then calculated as follows:

$$Annual\ Demand = Total\ activity\ level\ \ {*}Water\ Use\ Rate --------------- (3.22)$$

Loss Rate Calculation per Demand site: to evaluate water transmission efficiency and distribution equity across an irrigation system hence, equation (3.23) provides a quantitative measure of inefficiencies, highlighting critical points of water loss that require intervention to improve irrigation system performance and equity.

$$Loss\ Rate\ \left(\%\right) = \frac{Water\ Lost\ in\ Transmission\ \left(m^3\right)}{Water\ Released\ to\ the\ \text{Demand Site}\ \left(m^3\right)} {*}100 --------------- (3.23)$$

Where: Water Lost in Transmission includes seepage, and overflow specific to each group of users and Water Released to the demand site is the total flow diverted or allocated to that site.

3.8.4 Development of Scenarios

According to (39), the effective water evaluation and planning require water modeling and scenario analysis. Scenarios represent various assumptions that help predict future water demand in a specific area, affected by factors like irrigation water use efficiency and irrigation expansion. This study used scenario analysis to evaluate irrigation water allocation in Hatset, aiming to assist the irrigation scheme fair share of water allocation. The analyses explored "IF" conditions, such as the effects of changes in irrigation water use efficiency and irrigation expansion.

To meet its objectives, three scenarios were developed.

1) **Reference scenario:** assuming that present irrigation techniques and water consumption don't change, this scenario serves as the baseline. It acts as a benchmark for assessing the effects of expansion or modifications in water efficiency. It offers a status quo perspective on water distribution, assuming neither major changes in water availability nor improvements in irrigation efficiency.

2) **Improved water use efficiency scenario:** enhancing irrigation water use efficiency by improved irrigation efficiency at field level and improving infrastructures were the main goals in this scenario. It assesses how these improvements might lower water demand, assisting in determining how saving water might be accomplished without reducing crop yields or irrigation requirements.
3) **Irrigation expansion scenario:** In order to cover additional land, this scenario investigates the effects to develop the irrigation system, either by increasing the irrigated area or by enhancing infrastructure. It takes into account how extending irrigation may impact the system's water allocation due to the increased demand for water. The viability and sustainability of increasing irrigation areas while preserving a balanced water distribution are evaluated in this scenario.

3.9 Socio-Economic Data Analysis

1) Sampling Procedure and Techniques

Using a stratified random sampling technique, the effect of the efficient irrigation water allocation for conflict resolution procedures will be investigated. Farmers are categorized based on their location within the command area head, middle, and tail-end users. To examine the equity of water distribution between the locations, respondents from all areas of the irrigation scheme were included (as head, middle, and tail-end users). From each site, a basic random sample was taken (head, middle, and tail-end users). Equation (3.24) was utilized to determine the sample size and conduct a household survey with a total of 73 respondents. The Sample size determination is computed as:

$$n = \frac{Z^2 * P * Q * N}{P^2(N-1)} + Z^2 * P * Q \text{------------------------------} \quad 3.24$$

Where: n: Sample size, N: Number of households=73, P: Level of precision =5%

Q: Expressed as 1-P for P= 0.05; Q=1-0.05=0.95 and

Z = 1.96 for Confident interval 95% (Using Excell Sheet)

2) Data Collection Methods

The required data for investigating the effect of efficient water allocation for resolving social conflict between upper and lower PAs of the Dam will be collected through household surveys, key informant interviews, and focus group discussions (FGDs). The survey covered topics such as water allocation and distribution systems, canal cleaning, and maintenance, irrigation water management systems, conflict and causes conflict, and conflict resolution mechanisms.

A. Household survey

A semi-structured questionnaire was utilized to gather information from 73 respondents of the Hangoda irrigation scheme. Before the main survey, the questionnaire is pre-tested, and adjustment is done in response to the findings. Respondents included both male and female irrigators and represented all water user locations (head, middle, and tail-end).

B. Key informant interview (KII)

Key informant interviews were conducting to gain insights into the irrigation system and managerial challenges affecting water distribution. Informants included the Irrigation Water User Associations (IWUAs) leaders, Kebele irrigation experts and model farmers.

C. Focus Group Discussions (FGDs)

To supplement the survey data, FGDs were held with 5 selected irrigators (both male and female) and WUA committee members. Participants were purposively selected based on their farm locations (head, middle, and tail-end users) to record a range of viewpoints regarding irrigation management and challenges.

3) Data Analysis Techniques

The SPSS Version 27.0 was used to analyze the data collected from the household questionnaire survey after being coded, the gathered data was entered into an excel spreadsheet on a computer for examination. Descriptive statistical techniques consisting percentage, frequency, and Pearson's chi-square (χ^2) test comparisons was applied. Qualitative analysis was used to evaluate the information gathered from key informant interviews and focus group discussions.

4 Results and Discussion

4.1 Soil Characterization

4.1.1 Soil texture

The average percentage values of sand were higher than the percentage of silt and clay and the soil textural class as per the USDA textural triangle was sandy loam at the head, middle, and tail users of the scheme as shown in Table 4-1. The sandy loam soil texture was the dominant one in most of the command areas. of the scheme. Therefore, the sandy soil texture was used for CROPWAT software as input for analysis of crop water requirements. The laboratory result of soil texture was almost similar with the finding reported by GG Haile et. at. **(87)**.

Table: 4-1: Soil particle distribution & textural class in the Hangonda scheme

Soil depth (cm)	Clay (%)	Silt (%)	Sand (%)	Textural Class
(0-30)	18.64	24.16	57.20	Sandy Loam
(30-60)	18.42	23.18	58.40	Sandy Loam
Average	18.53	23.67	57.8	Sandy Loam

The laboratory results of the soil moisture characteristics values of field capacity (FC), permanent wilting point (PWP), and total available water content (TAW) are given in Table 4-2. The estimated average value of total available moisture water contents was 106.39 mm/m. The average values of the soil moisture content in volume percentage, FC of 23.69%, PWP of 12.58% and the average estimated value of TAW contents equal to 111.23 mm/m, this was within the acceptable range that recommended by FAO **(44)**.

Table 4-2: Soil parameters of the Hangoda irrigation scheme

	Parameters			
Soil depth (cm)	FC (%)	PW (%)	Bd (g/cm3)	TAW (mm/m)
0-30	24.06	12.72	1.48	113.52
30-60	23.32	12.43	1.48	108.93
Average	23.69	12.58	1.48	111.23

The water-holding capacity of soil is greatly influenced by its texture and structure, which can have an effect on irrigation systems' agricultural water output.

4.1.2 Soil Infiltration Rate

According to **(44)**, the recommended basic infiltration rate for sandy loam soil ranges from 25 to 40 mm/hr. Therefore, for this study, the value of the infiltration rate for sandy loam soil, 25.4 mm/hr, was taken.

4.2 Crop water Requirements in the Hatset irrigation scheme

The CROPWAT 8.0 model was computed the irrigation demand as shown in Table 4-3.

Table 4-3: Monthly irrigation water requirements on Hatset irrigation scheme (mm)

No	Crop Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Potato	54.1	107	160	135	44.4	0	0	0	0	0	0	0
2	Tomato	58.5	86.8	151	148	132	0	0	0	0	0	0	0
3	CABBAGE	108	124	143	66.5	0	0	0	0	0	0	62	76
4	MAIZE	51.1	130	169	70	0	0	0	0	0	0	0	6.9
5	Vegetables	32.7	91.6	141	98.5	0	0	0	0	0	0	0	0
6	Wheat	126	138	67.3	0	0	0	0	0	0	0	11	39

Therefore, the net scheme irrigation requirement was computed, and the gross irrigation requirement was also estimated (see Table 4-4).

Table 4-4: Monthly net and gross irrigation water demand in ((m3/ha)

Month	Jan	Feb	Mar	API	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Net demand	4307	6770	8308	5177	1759	0	0	0	0	0	729	1214
Gross demand	8614	13540	16616	10354	3518	0	0	0	0	0	1458	2428

4.3 Conveyance efficiency and water loss

The average main canal and secondary canal conveyance efficiency and water losses of the irrigation scheme were presented in Tables 4-5 and 4-6.

4.3.1 Main canal conveyance efficiency and water loss

Water conveyance efficiency ranged from 86.21% to 95.72%, with each canal segment having distinct efficiency. P-14 (3250-3500 m) had the highest efficiency at 95.72%, while P-2 (250-500 m) had the lowest at 88.62%. The total mean efficiency of 88.38% for the lined main canal fell below the required 95%, with water losses of 12.59%, 12.43%, and 9.82% for head, middle, and tail users, respectively. Section P-2, particularly at the head end, had the highest water loss and requires maintenance. Major causes of conveyance losses include illegal water abstractions, nonfunctional flow control gates, and unauthorized water turnouts, as well as household use of canal water. These issues impacted equitable water distribution, especially for tail consumers. Table 4-5 summarizes the canal water transport efficiency and losses.

Table 4-5: Estimated conveyance efficiency and water loss through the main canal

Reach	Measured Points	Canal section(m)	Q inflow(m3/s)	Q outflow(m3/s)	Ec (%)	Loss (%)	L(m3/s)
Head	P-1	0-250	0.2105	0.1897	90.14	9.86	0.021
	P-2	250-500	0.1897	0.1636	86.21	13.79	0.026
	P-3	500-750	0.1636	0.1427	87.23	12.77	0.021
	P-4	750-1000	0.1427	0.1234	86.49	13.51	0.019
	P-5	1000-1250	0.1234	0.1073	86.96	13.04	0.016
Average					87.41	12.59	0.02
Middle	P-6	1250-1500	0.1073	0.0932	86.89	13.11	0.014
	P-7	1500-1750	0.0932	0.0815	87.36	12.64	0.012
	P-8	1750-2000	0.0815	0.0720	88.45	11.55	0.009
	P-9	2000-2250	0.0720	0.0631	87.57	12.43	0.009
	P-10	2250-2500	0.0631	0.0552	87.57	12.43	0.008
Average					87.57	12.43	0.01
Tail	P-11	2500-2750	0.0552	0.0483	87.41	12.59	0.007
	P-12	2750-3000	0.0483	0.0420	86.90	13.10	0.006
	P-13	3000-3250	0.0420	0.0381	90.68	9.32	0.004
	P-14	3250-3500	0.0381	0.0364	95.72	4.28	0.002
Average					90.18	9.82	0.00
Overall	Average				88.38	11.62	0.01

4.3.2 Secondary canal conveyance efficiency and water loss

The conveyance efficiencies of three secondary canals (Sc1, Sc3, and Sc5) that were chosen based on the observation of canal damage are shown in Table 4-6 and Figure 4-2. Sc1-Head, Sc3-Middle, and Sc5-Tail had maximum efficiencies of 80.00%, 94.91%, and 89.84%, respectively, and minimum efficiencies of 78.13%, 80.85%, and 84.09%. The efficiencies were below the recommended 95% for lined canals, with averages of 79.00%, 87.80%, and 87.76%, in line with these the average water losses were 21.0%, 12.2% and 11.93% respectively. A disproportionate loss at the start of the system may impact equitable irrigation distribution, especially for tail-end users, as indicated by the increased water loss at the head in comparison to the middle and tail-end sites. Leakage, seepage losses, canal degradation, siltation, weeds, overflow, and inadequate gate management are some of the factors that lower efficiency. The findings point to the necessity of improvement in conveyance efficiency to minimize water loss and ensure equitable water distribution.

Figure 4-1: Current status of physical infrastructures in the Hangoda irrigation scheme

Table 4-6: Conveyance efficiency and water loss through secondary canals

Reach canal	Measured Points	Canal section(m)	Q inflow(m3/s)	Q outflow(m3/s)	Ec (%)	L (%)	L (l/s)
Sc1-Head	Sc1-1	0-200	0.0339	0.0267	78.79	21.21	7.19
	Sc1-2	200-400	0.0267	0.021	78.84	21.16	5.65
	Sc1-3	400-600	0.021	0.0164	78.13	21.87	4.6
	Sc1-4	600-800	0.0164	0.0132	80	20	3.29
	Sc1-5	800-1000	0.0132	0.0103	78.47	21.53	2.83
	Sc1-6	1000-1200	0.0103	0.0082	79.77	20.23	2.09
Average					79	21	4.27
Sc3-Middle	Sc3-1	0-200	0.0264	0.0222	84.17	15.83	4.17
	Sc3-2	200-400	0.0222	0.0205	92.59	7.41	1.64
	Sc3-3	400-600	0.0205	0.0195	94.91	5.09	1.05
	Sc3-4	600-800	0.0195	0.0169	86.51	13.49	2.63
	Sc3-5	800-1000	0.0169	0.0136	80.85	19.15	3.23
Average					87.8	12.2	2.55
Sc5-Tail	Sc5-1	0-200	0.0357	0.032	89.84	10.16	3.62
	Sc5-2	200-400	0.032	0.0287	89.74	10.26	3.29
	Sc5-3	400-600	0.0287	0.0242	84.09	15.91	4.57
	Sc5-4	600-800	0.0242	0.021	87.06	12.94	3.13
	Sc5-5	800-1000	0.021	0.0185	88.07	11.93	2.51
Average					87.76	12.24	3.42

Sc1-Secondary canal one, Sc3-Secondary canal three, and Sc5-Secondary canal five

4.4 HEC-HMS Inflow Result

The reservoir inflow was estimated after calibrating and validating of flow at Hangoda watershed.

4.4.1 Flow Calibration and Validation at Hangoda Catchment

For calibration and validation, the model was simulated for daily streamflow from 2006–2014 and 2015–2018, respectively, using default parameters, and since the differences between simulated and observed streamflow at the sub-basin W260 outlet were within the acceptable range, calibration was performed for the seven-year period from January 1, 2006, to December 31, 2014 (see Table 4-7).

Table 4-7: Model peak values of calibration and validation results

Simulation Type	Simulated			Observed		
	Time of Peak	Qs (m3/s)	Vs (Mm3)	Time of Peak	Qob (m3/s)	Vob (Mm3)
Calibration	30Jul2011, 00:00	4.8	312.96	30Jul2011, 00:00	5.8	296.80
Validation	16Aug2017, 00:00	3.5	115.73	16Aug2017, 00:00	2.9	100.54

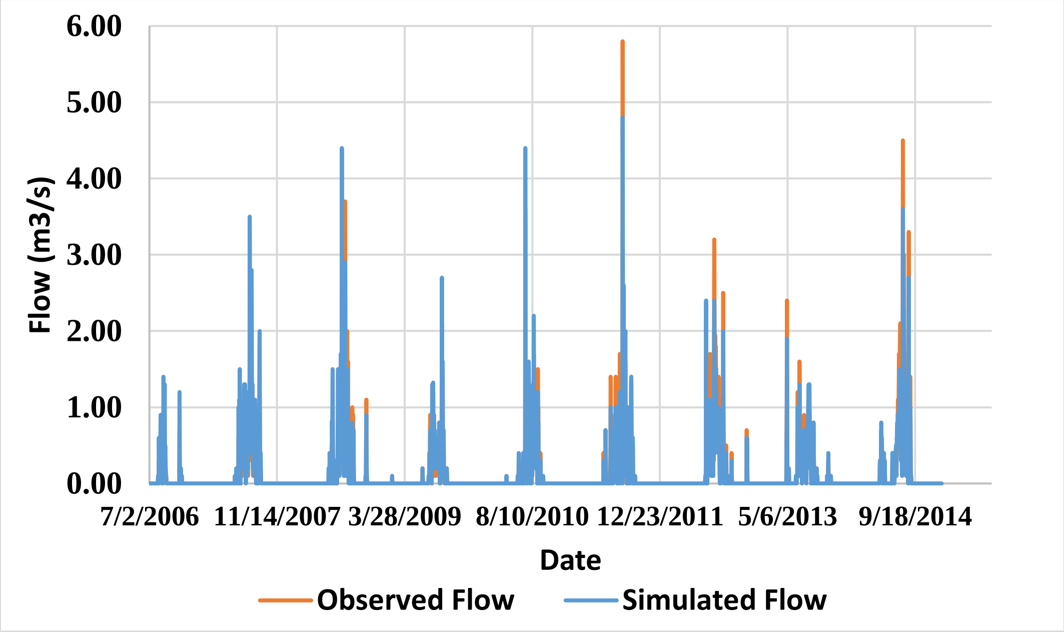


Figure 4-2: Hydrograph of daily flow calibration

The daily calibration results for NSE, R², and PBIAS were 0.793, 0.878, and 4.47%, respectively, after adjusting sensitive parameters, meeting acceptable ranges (Table 3-4). Figure 4-2 shows strong correlation between measured and simulated results. The model was validated from January 1, 2015, to December 31, 2018, with constant parameters. Validation results for NSE, R², and PBIAS were 0.870, 0.969, and 13.81%, respectively, all meeting statistical criteria ($R^2 > 0.7$, NSE > 0.6, PBIAS < ±15). Figure 4-3 shows good agreement between measured and simulated results.

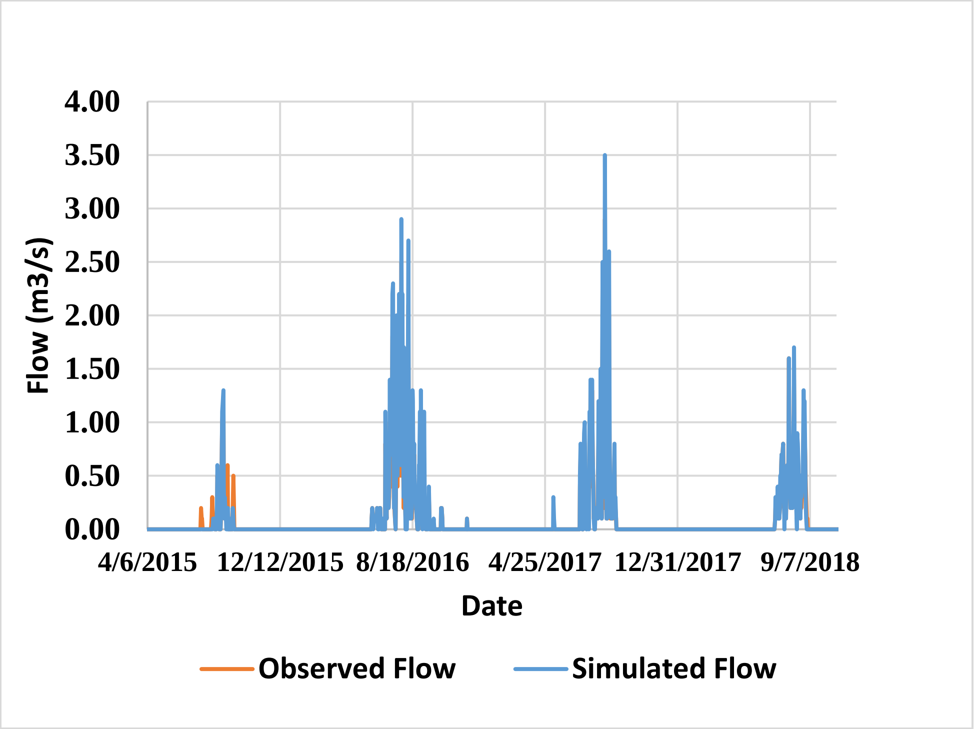


Figure 4-3: Hydrograph of daily flow validation

Table 4-8: Model performance evaluation results

Simulation Type	Evaluation criteria			
	NSE	R^2	RMSE	PBIAS (%)
Calibration	0.793	0.878	0.5	4.47
Validation	0.870	0.969	0.4	13.81

Therefore, using HEC-HMS, the average monthly inflow to Hangoda reservoir was estimated and entered into the WEAP model through the Hangoda main river, as seen in Figure 4-4 below.

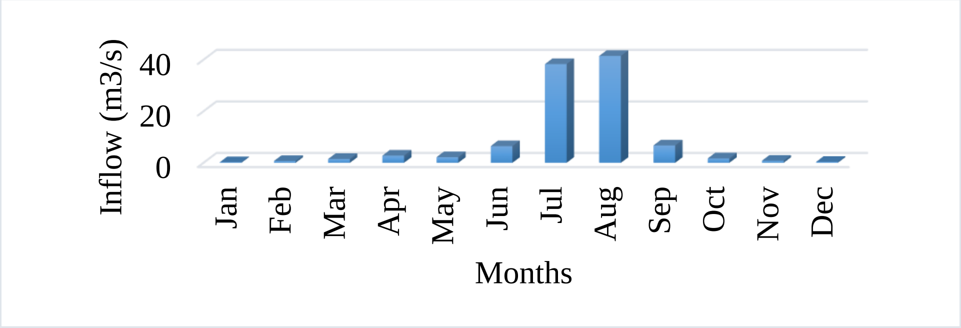
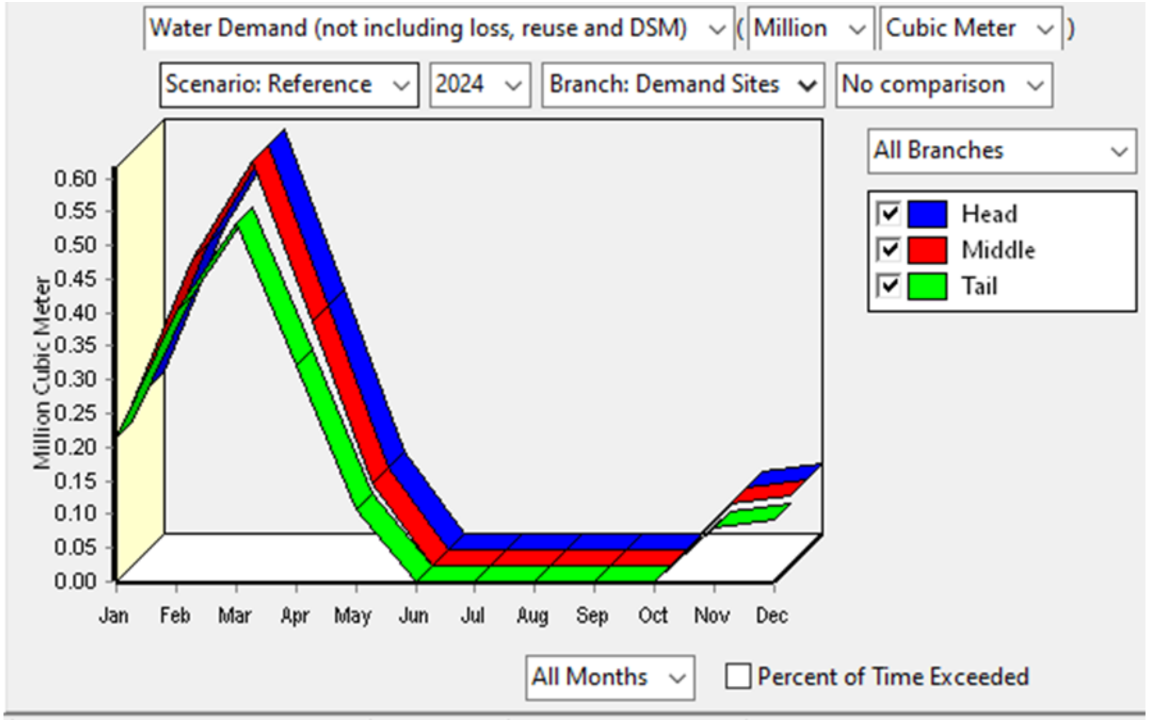


Figure 4-4: Monthly average inflow for Hangoda dam reservoir

4.5 Evaluation of existing water allocation and estimation of water loss

WEAP determined the annual water demand for head, medium, and tail-end users; hence, the cultivated areas in the current year 2024 were 70, 70, and 62 hectares, respectively. According to the model result as shown in Figures 4-5, the annual total water demand was 5,709,328 m³, the demand peaks in March 1,735,636 m³ and then progressively decreases starting in April from June to October, no demand was observed. The tail zone has the lowest total water demand at 1,752,368 m³, while the head and middle users each provide 1,978,480 m³ yearly. The head and middle users have similar water demand, while the tail-end users have somewhat lower needs because of less intense agricultural practices or smaller irrigated area (62 ha).



Water Demand (not including loss, reuse and DSM) (Million Cubic Meter)

Scenario: Reference

2024

Branch: Demand Sites

No comparison

All Branches

All Months

☐ Percent of Time Exceeded

Figure 4-5: Monthly water demand Hatset irrigation scheme

The Hatset irrigation scheme's water distribution and balance are examined in Table 4-9, which also emphasizes the effect of canal losses on supply and unmet demand. There is no unmet demand, and the head and middle users meet all of their supply requirements, demonstrating sufficient upstream delivery. However, as water flows downstream, cumulative canal losses from overflow and seepage result in an 895,360 m³ shortage for the tail-end users. The head, middle, and tail users contribute 155,721 m³, 309,160 m³, and 430,479 m³ to the 895,360 m³ of water losses that occur annually. Seepage and canal damage are the primary causes of these losses. In order to satisfy downstream unmet demand and provide equitable distribution, the analysis emphasizes the necessity of improved infrastructure.

Table 4-9: Annual water balance in current Hatset irrigation system (2024)

Users	Supply Requirement (m^3)	Supply Delivered (m^3)	Unmet Demand (m^3)	Water Loss (m^3)
Head	3325176	3325176	0	155,721
Middle	3964890	3964890	0	309,160
Tail	4978318	4082958	895360	430,479

As per the current account year estimates, the monthly unmet demand at the head and middle sites remains at zero. Even though, as Figure 4-6 illustrates, unmet demand at the tail-end site is 619,136 m^3 in March and 276,225 m^3 in April, for a total of 895,360 m^3 for the year.

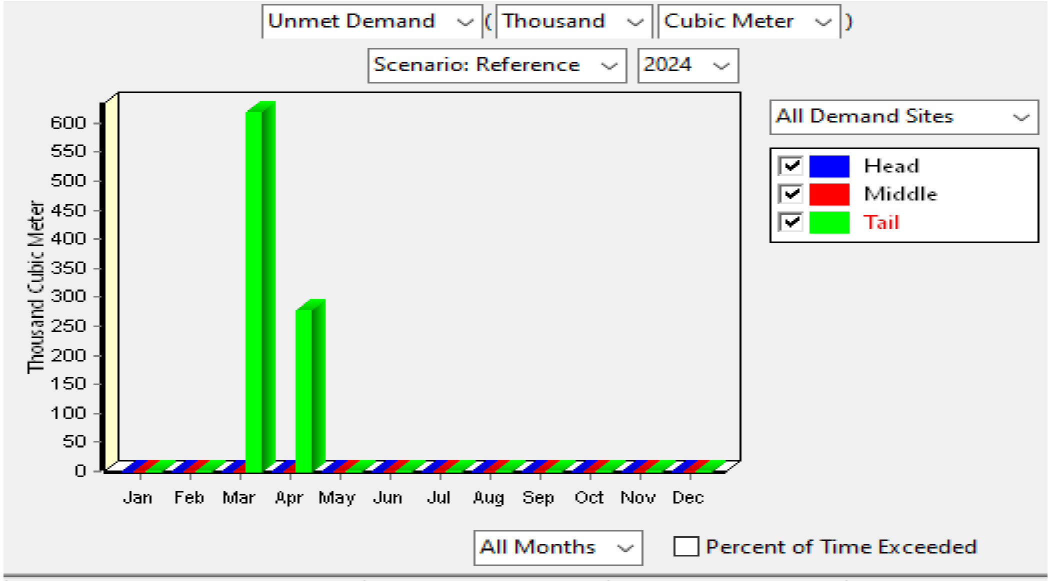


Figure 4-6: Monthly unmet demand for all demand sites

4.6 Optimization of Future water allocation

The reservoir, serving as the primary water source for three irrigation sites, required careful management to balance future demand sustainably. Three scenarios were considered: the reference, improved water use efficiency, and irrigation expansion scenarios. The analysis compared water allocation, irrigation demand satisfaction, reservoir sustainability, and the impact of inflow variability. Improved efficiency was expected to reduce demand and enhance resilience, while expansion added pressure, especially with reduced inflows. These scenarios offered insights for informed decision-making in sustainable water management.

4.6.1 Evaporation from the reservoir

This section describes the baseline net evaporation loss from the reservoir, which is 5.62 MCM per year with significant seasonal variation (Table 4-10). Losses are highest during the dry season, particularly in March, April, and May, and lowest in the wet season, especially in July and August. Evaporation significantly impacts water availability, particularly during dry months with high irrigation demand. Optimizing storage during the rainy season and reducing losses in dry months are key for effective water management and reservoir sustainability.

Table 4-10: Net monthly evaporation of Hangoda reservoir (Mm3)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Net-evapo	0.29	0.64	0.67	0.63	0.63	0.56	0.04	0.10	0.53	0.52	0.52	0.49

4.6.2 Reservoir inflows and outflows

The main source of water entering the Hangoda reservoir is the Hangoda catchment. As shown in Figure 4-7, the reservoir's yearly inflow volume from upstream and outflow volume downstream were both variable, with the inflow peaking in August and the outflow volume falling in January. Because there was no rainfall in January, February, March, April, May, October, November, and December, inflows were lower than outflows, resulting in a decline in reservoir volume. However, in June, July, August, and September, inflows exceeded outflows, increasing reservoir volume. The monthly inflows and outflows of the Hangoda reservoir for the baseline year are displayed in Table 4-11 below from WEAP model.

Table 4-11: Monthly Inflow and outflow of Hangoda reservoir (MCM/month)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Inflow	0.62	1.81	3.82	7.19	5.65	16.79	99.30	107.49	17.46	4.42	2.06	0.94
Outflow	6.28	7.90	14.92	12.90	7.80	14.84	82.35	83.85	15.61	4.07	4.60	4.79

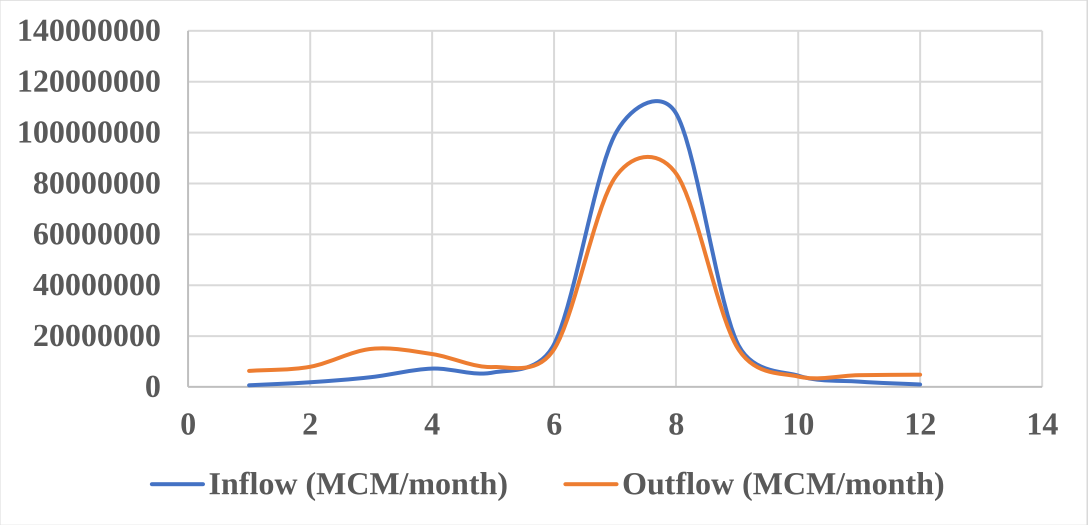


Figure 4-7: Monthly Inflow and outflow of Hangoda reservoir

4.6.3 Reservoir Storage Capacity

Modeling results show that improved water use efficiency and irrigation expansion scenarios lead to notable changes in average annual reservoir storage compared to the reference scenario. Water use efficiency scenario increases storage by 0.24 MCM (from 2.73 MCM to 2.97 MCM), while irrigation expansion scenario increases it by 0.22 MCM (from 2.73 MCM to 2.95 MCM). These increases are most noticeable during the rainy season, with both scenarios reaching a peak storage of 3.05 MCM in August. While both scenarios maintain higher storage in dry months, water use efficiency consistently performs better, especially in dry periods. This highlights the importance of efficient water management for improving reservoir storage and water security year-round.

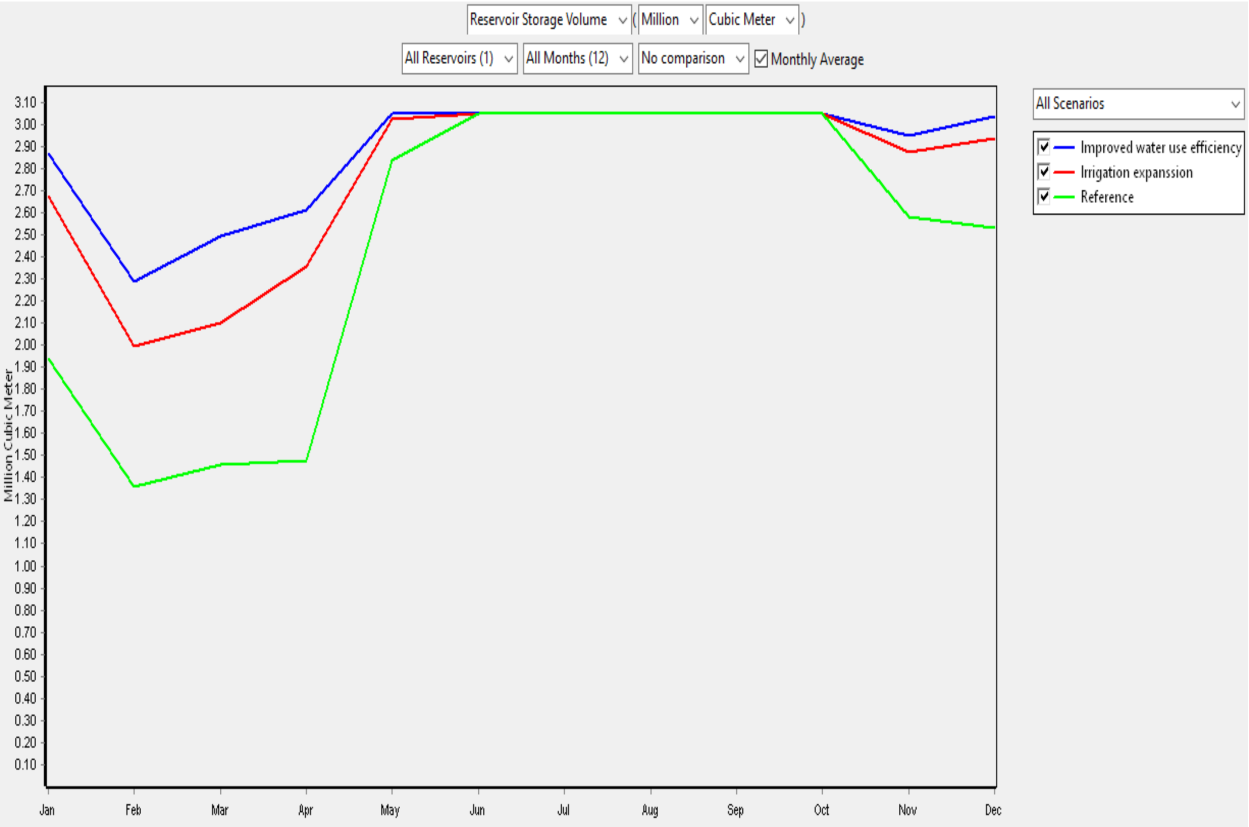


Figure 4-8: The Storage capacity of Hangoda reservoir

4.6.4 Reference scenario

Table 4-12 shows that in refence scenario (2025-2050), the tail users annual average water demand was less than that of the head and middle users. However, this reflected the smaller area of the tail-end users in comparison to the head and middle users. The head and middle users annually water demands of 51,440,480 m³ were the same, indicating comparable command area or irrigation needs. However, due to its relatively smaller size, the tail-end users annual average water demand was 45,561,568 m³.

Table 4-12: Annual average water demand of Reference scenario

Water Demand (Cubic-Meter)	
Scenario: Reference (2025-2050)	**Annual Total**
Head	51440480
Middle	51440480
Tail	45561568

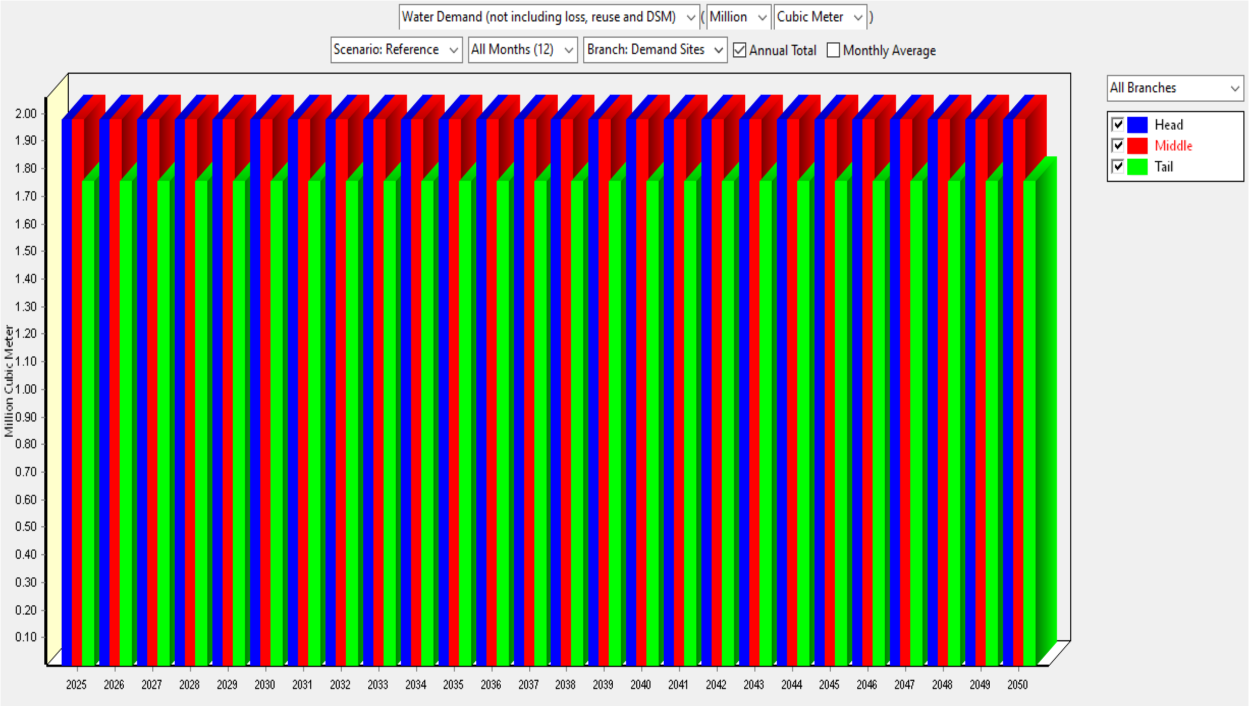


Figure 4-9: Annual water demand of Reference scenario

Analysis of the WEAP model results for the future allocation of irrigation water showed that the head and middle users received their entire needed supply; the tail users suffered from a significant shortage of water. In particular, Table 4-13 demonstrates that only 92.1 million cubic meters of the needed 134.4 million cubic meters were delivered to the tail users, leaving 42.3 million cubic meters of demand unsatisfied. This showed that the water allocation was obviously out of balance, with the tail users getting far less water than they required.

Despite an adequate water supply, inefficiencies at the head users nearest to the reservoir resulted in substantial waterlogging, canal overflow, and seepage losses. These problems limited the supply that reached downstream users and wasted water in addition to decreasing system efficiency overall.

On the other hand, medium users were able to use water more efficiently since they had fewer issues with seepage and overflow. Tail-end users benefited from fewer losses compare to head and middle users, which made their water consumption more efficient, even though they received a smaller supply. This draws attention to a typical problem in irrigation systems. Upstream inefficiencies make water distribution less effective, which eventually causes downstream water scarcity this led to unmet water demand as shown in Figure 4-10.

The analysis in this study emphasizes how crucial it is to solve operational inefficiencies at the head users, where seepage losses and canal overflow were most noticeable. Enhancing the control of these losses and ensuring more efficient water delivery, especially to the tail-end users, might make the system more sustainable, equitable, and balanced. The findings recommend that optimizing water management practices and reducing these inefficiencies at the head users could resolve the imbalance in supply and help achieve long-term water use efficiency across the entire system.

Table 4-13: Reference scenario water balance

Users	Supply Requirement (m^3)	Supply Delivered (m^3)	Unmet Demand (m^3)
Head	89779765	89779765	0
Middle	107052026	107052026	0
Tail	134414591	92104512	42310078

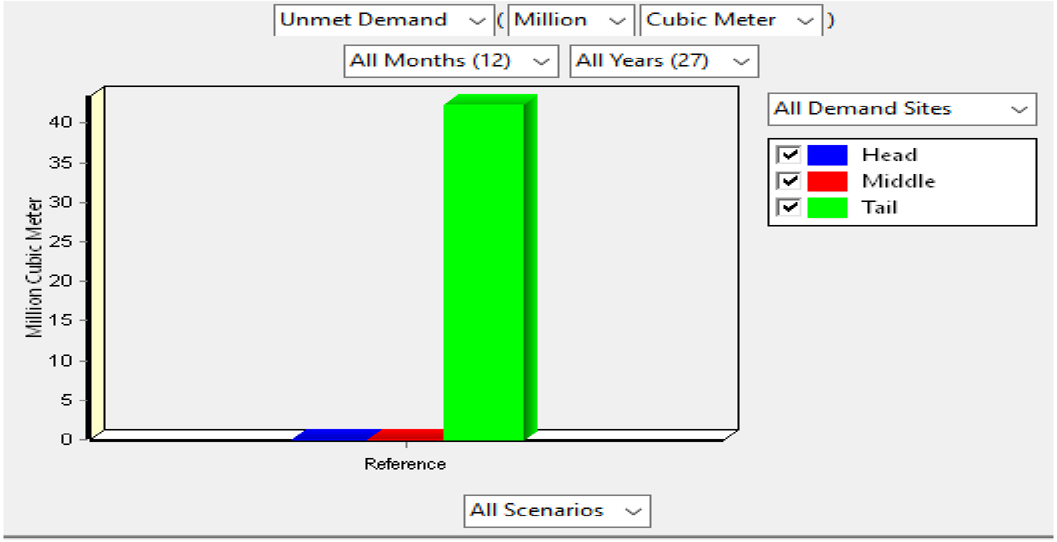


Figure 4-10: Annual unmet demand of Reference scenario

4.6.5 Improved Water Uses Efficiency Scenario

The Hatset irrigation system's water allocation was significantly optimized as a result of the enhanced water use efficiency scenario (2025–2050), which included canal repair, cleaning and maintenance, and an irrigation application efficiency of 80%. Implementation of these improved water use efficiency scenarios the irrigation water demand significantly dropped by 37.5% in all users as compared to the baseline, with decreases of 19,290,180 m^3 in the head and middle users and 17,085,588 m^3 in the tail-end users. This result demonstrated the significant contribution canal lining made to lowering conveyance losses. In the end, lined canals helped to lower total water demand by ensuring more effective water delivery to fields by reducing seepage.

Additionally, irregular canal dimensions such as uneven depth, excessive flow diversion, and insufficient flow due to poor canal design caused canal overflow at head users, which was a major problem for the system. Water waste was a result of these problems, particularly when demand was at its highest. As a corrective action, canal reshaping was done to resolve these irregularities. To produce a more steady and effective flow, the canal's depth, width, and slope had to be changed throughout the reshaping process. This procedure decreased the possibility of overflow and waste in addition to stabilizing water flow. These upgrades successfully reduced water losses and increased system efficiency when paired with canal lining.

For improved canal water regulation, sluice gate installation was crucial in addition to lining and reshaping. By enabling precise flow control, these gates made sure that the irrigation water was distributed uniformly throughout the system. Inefficiencies resulting from irregular canal dimensions were addressed by the gates, which enabled timely changes to avoid excessive water diversion and further optimize water allocation.

Improved water use efficiency was also supported by on-farm management techniques. Adoption of an efficient technology, like mulching, this technique allowed farmers to apply water more effectively, which further decreased overall demand, when combined with better irrigation scheduling based on the current climate information and crop water requirements. On-farm management supplemented the structural improvements in the canal system by optimizing water use at the farm level.

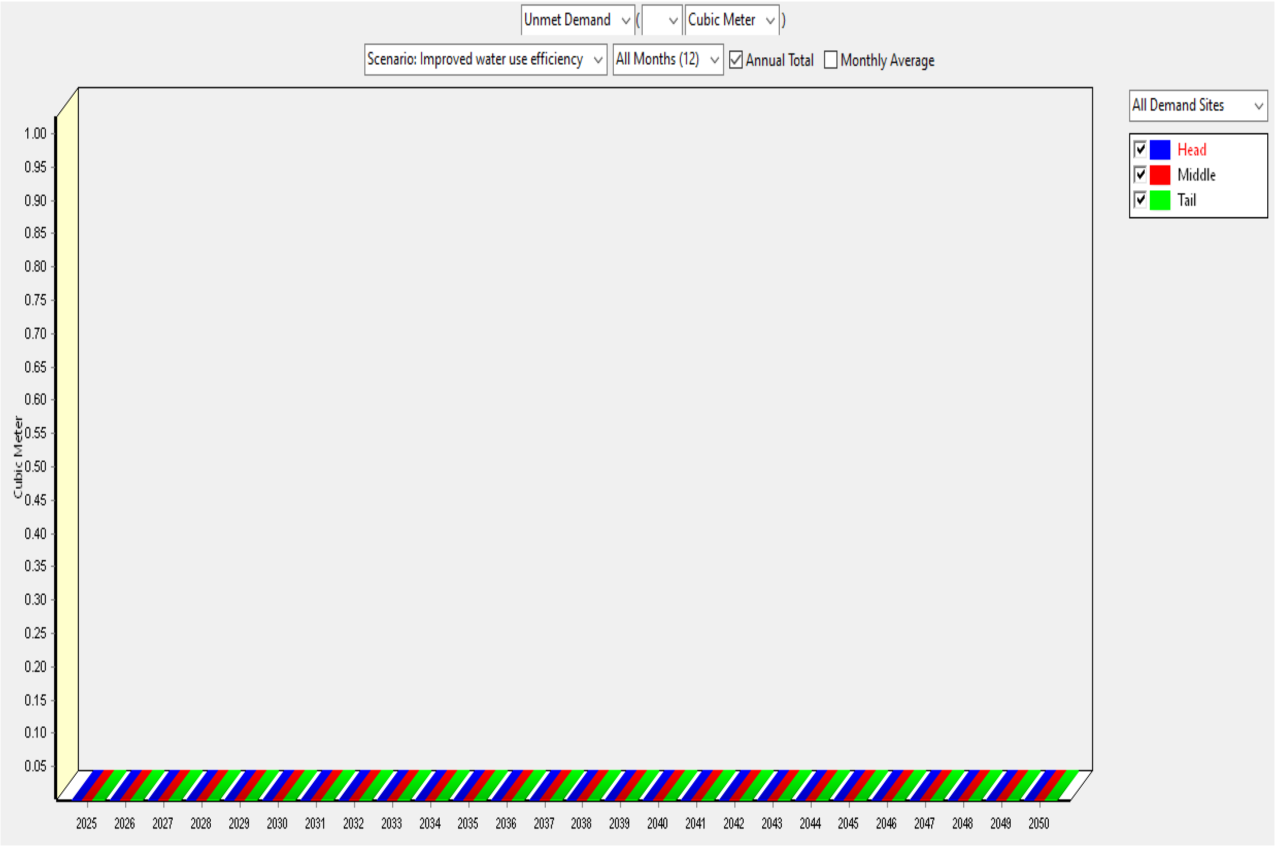
Figure 4-11 shows the ideal water distribution across the Hatset irrigation system, which reflects the enhanced water usage efficiency scenario backed by canal reshaping, lining, cleaning, sluice gate regulation, and on-farm management approaches. Table 4-14 shows that there was no unmet demand and that the supply requirements for the head, middle, and tail users were all satisfied. In particular, the head and middle users were fully supplied with 32,150,300 m³ each, while the tail-end users received 28,475,980 m³.

By performing this, the measures put in place become effective. The water redirected from the reservoir reached the designated places with minimal loss because of canal lining, and cleaning, which reduced water losses. This achievement was facilitated by the installation of sluice gates and the redesigning of the canal's proportions, which kept the flow steady and controlled, avoided overflow, and made sure that water was divided fairly among all users. The lack of unmet demand also showed that on-farm water management techniques, like effective scheduling and precision irrigation, enhanced the enhanced canal system by minimizing over-irrigation and ensuring water was utilized only as required.

When combined with complete demand coverage, the alignment of supply provided with supply requirements for all users demonstrated how operational adjustments and infrastructure upgrades can work together. In addition to improving water delivery reliability, this integration showed that the system was sustainable, provided that water resources were used effectively to satisfy agricultural demands while preserving fair distribution.

Table 4-14: Improved water uses efficiency scenario water balance

Users	Supply Requirement (m³)	Supply Delivered (m³)	Unmet Demand (m³)
Head	32150300	32150300	0
Middle	32150300	32150300	0
Tail	28475980	28475980	0


Unmet Demand (Cubic Meter)

Scenario: Improved water use efficiency All Months (12) ☑ Annual Total ☐ Monthly Average

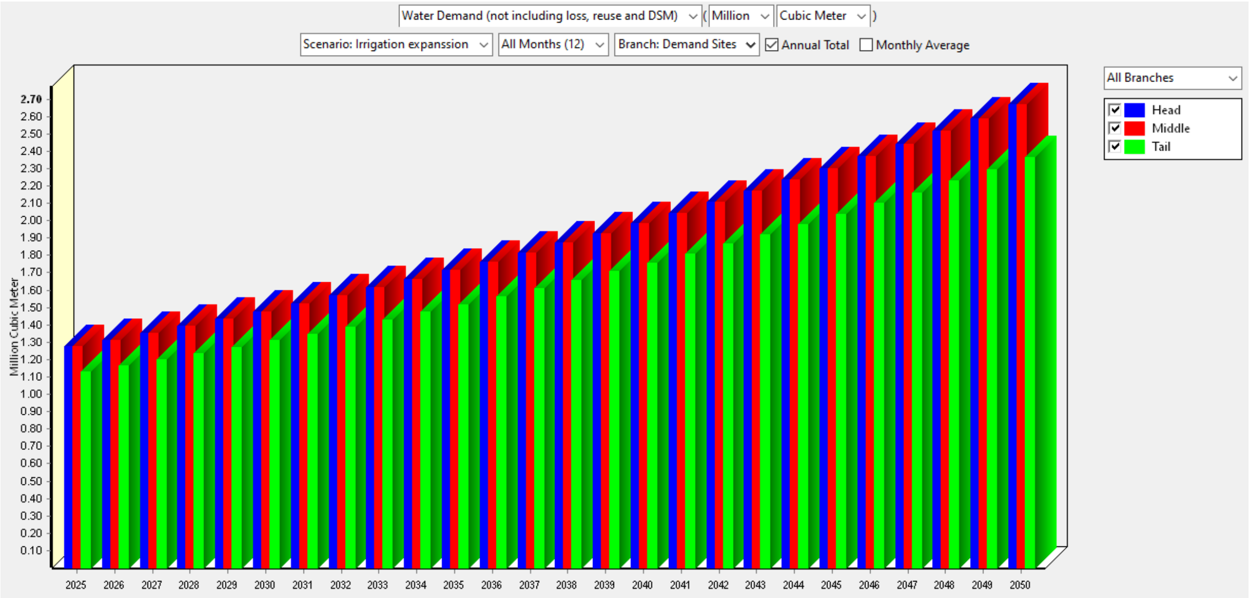
All Demand Sites

Figure 4-11: Unmet demands of improved water use efficiency scenario

4.6.6 Irrigation Expansion Scenario

The reservoir's ability to meet the increasing irrigation demands was assessed by a major analysis in the framework of the irrigation extension scenario (2025–2050) for the Hatset scheme, as seen in Figure 4-11. Since maximizing irrigation growth is thought to be the main policy goal, the Hangoda reservoir dam. The findings showed that, despite the cropped area gradually increasing from 202 hectares to 360 hectares, growing at a 3% annual pace until 2050, the reservoir could continue to provide water to irrigation projects downstream.

Additionally, as Table 4-15 demonstrates, the simulation indicated that the optimal water allocation procedures assured that the unmet demand across all users (head, middle, and tail-end) remained at zero during the period. This demonstrates the reservoir's capacity. to sustainably support agricultural growth, ensure equitable water distribution throughout the irrigation scheme, and continually fulfill the growing irrigation demands until 2050.



Fugue 4-12: Annual water demands of irrigation expansion scenario

Table 4-15: Water balance in Irrigation expansion scenario

Users	Supply Requirement (m³)	Supply delivered (m³)	Unmet Demand (m³)
Head	49102947	49102947	0
Middle	49102947	49102947	0
Tail	43491182	43491182	0

The targeted area for the development is visualized in detail in Figure 4-13, which clearly shows the projected irrigated area for the irrigation expansion scenario.

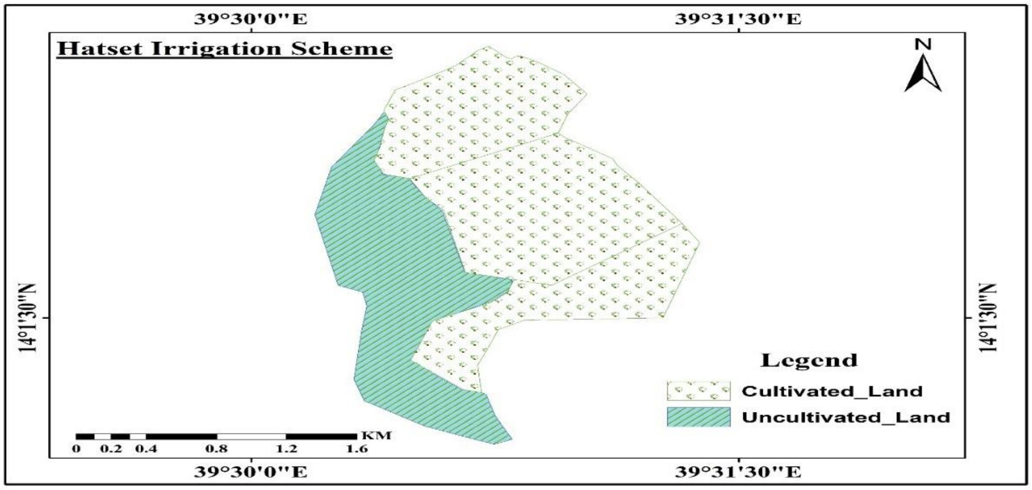
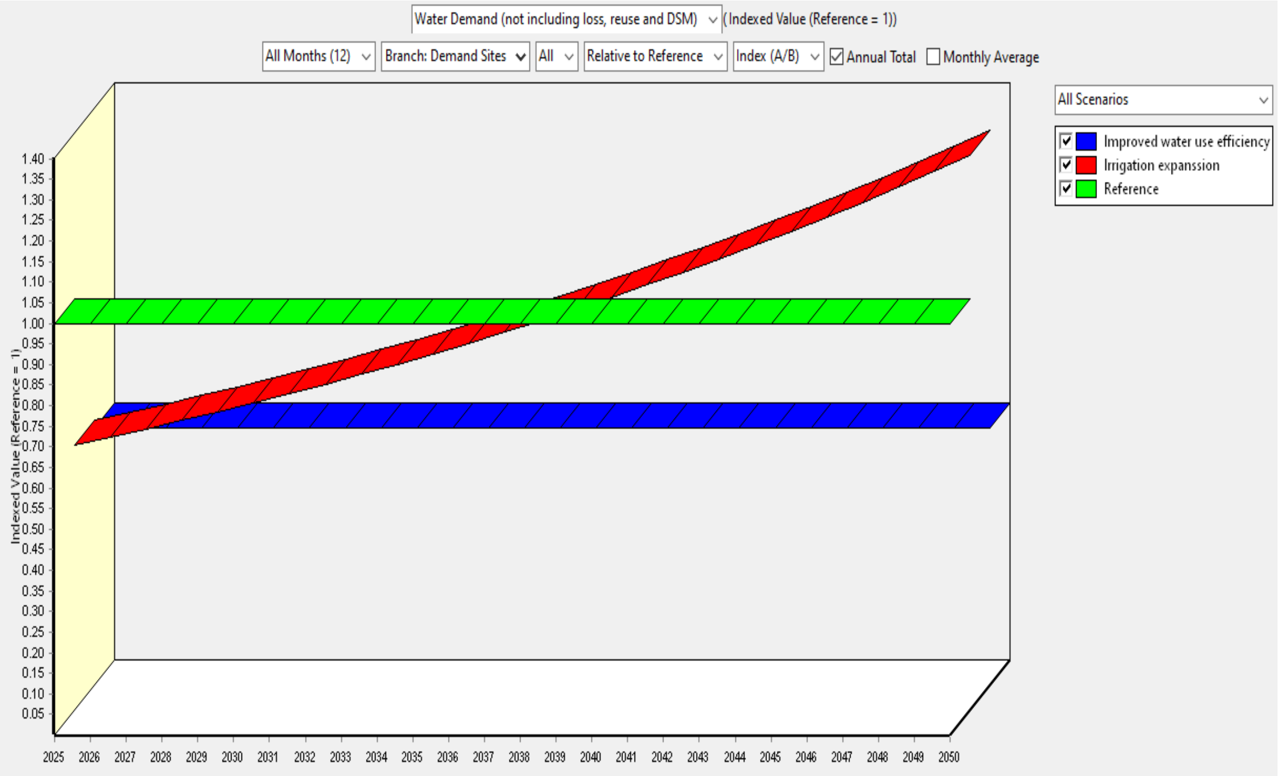


Figure 4-13: Cultivated and uncultivated areas of Hatset irrigation scheme

4.6.7 Comparison of Scenarios

Figure 4-14 illustrates the importance of water management strategies by comparing several scenarios based on a monthly average. When the water demand for the 2025–2050 scenarios was compared, clear patterns emerged. In the Reference Scenario, which reflected baseline conditions with negligible adjustments in water use, demand remained constant. The impact of improved irrigation techniques, on the other hand, was evident in the Improved Water Use Efficiency Scenario, which showed a significant decrease in water demand by 2050, reaching about 37.5% less demand than the Reference Scenario.

However, the intended development of cultivated area in the Irrigation Expansion Scenario resulted in a steady rise in water demand over time. The Irrigation Expansion Scenario's cultivated area by 2050 was almost 78% greater than that of the Reference Scenario with increasing water demand about 23%, highlighting the increasing strain that agricultural development is placing on water supplies. This analysis emphasizes how crucial it is to strike a balance between expanding irrigation and using sustainable water management techniques in order to meet the growing demand for water between 2025 and 2050.



Water Demand (not including loss, reuse and DSM) (Indexed Value (Reference = 1))

All Months (12) | Branch: Demand Sites | All | Relative to Reference | Index (A/B) | ☑ Annual Total | ☐ Monthly Average

All Scenarios

☑ 🟦 Improved water use efficiency
☑ 🟥 Irrigation expanssion
☑ 🟩 Reference

Figure 4-14: Comparison of annual total water demand in all scenarios

4.6.8 Reliability

The demand site reliability for the Hatset irrigation scheme's head, middle, and tail users is shown in Figure 4-15 under the following three scenarios: Reference, Irrigation Expansion, and Improved Water Use Efficiency.

Reliability is maximized for all users in the Improved Water Use Efficiency Scenario, demonstrating the substantial advantages of eliminating water losses and improving irrigation techniques. This situation provides fair water distribution, successfully satisfying the needs of every irrigation water user. In addition to maintaining high reliability for all users, the Irrigation Expansion Scenario shows that the system can handle growing demand brought on by expanding crops while maintaining fair water distribution. Reliability is noticeably lower in the Reference Scenario, though, suggesting that it will be difficult to meet water demand in the present without increasing system capacity or improving efficiency.

Finally, Figure 4-15 emphasizes the significance of implementing efficiency measures or system extensions to provide reliable and fair water distribution. While the improved Water Use Efficiency and Irrigation Expansion scenarios achieve satisfaction across all users, the Reference Scenario underlines the limitations of the current system in addressing future water demand sustainably. With the exception of tail-end users, who had 81% satisfaction in the reference scenario, it is clear from this result that every user was completely satisfied in every month and year across all situations.

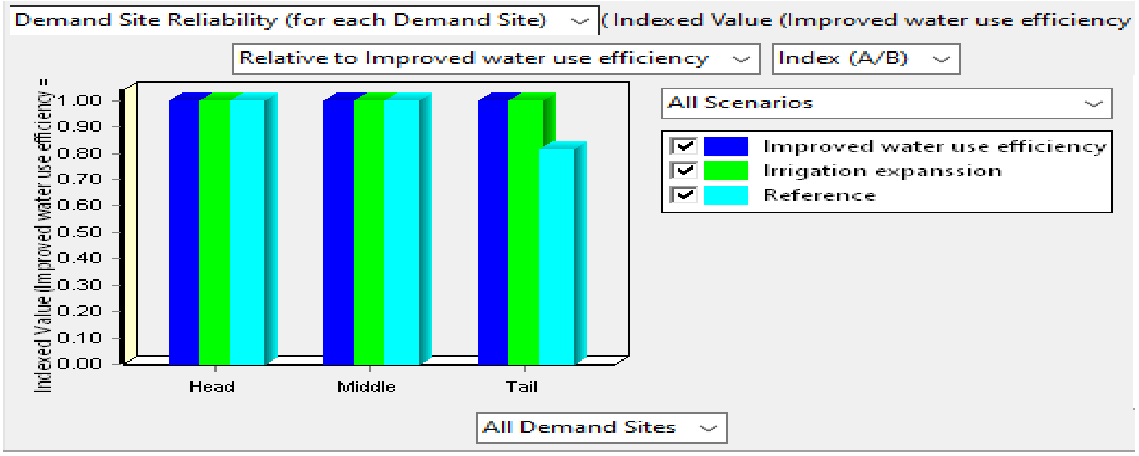


Figure 4-15: Demand Site's Reliability in all Scenarios

4.7 Effect of efficient water allocation for conflict resolution

In irrigation schemes, water allocation efficiency is essential for maintaining fair distribution. encouraging sustainable water management and reducing conflict. Water equity and conflict resolution are greatly impacted by issues with water distribution and governance processes in the Hatset irrigation scheme. The results of the household survey, key informant interviews, and focus group discussions reveal light on important problems such as gate manipulation, inadequate infrastructure, and weak governance, all of which cause disputes over water allocation and conflict resolution mechanisms.

4.7.1 Water allocation and distribution system

I. Accessibility of irrigation water

The three system users' availability to adequate irrigation water varies significantly, according to the household survey. 92.3% of responders said they had enough water for the head users. which shows extremely great accessibility. Similarly, 88.5% of respondents who were medium users attested to having sufficient access to irrigation water. The tail-end users, on the other hand, show a sharp contrast, with 81% reporting severe shortages and only 19% reporting adequate access. Inequities in water distribution and the urgent difficulties experienced by farmers in the tail users to meet their irrigation needs are shown by these percentages, which clearly show a pattern of declining water accessibility from the head to the tail users.

II. Importance of Fair Water Distribution

In irrigation schemes, the water distribution system is essential to the fair distribution of water. While tail-end users in Hatset show a great deal of dissatisfaction, head users typically believe that the distribution is fair. Table 4-16, the survey data, shows that while none of the tail users perceive the water distribution as very fair, 57.1% of head users think it is unfair. The fundamental flaws in the allocation process are highlighted by this significant discrepancy, which reflects the growing hostility and perceived unfairness among downstream users.

Table 4-16: Farmer's response to water distribution fairness status

Users	Fairness of Water Distribution	Frequency(N=73)	Percent (%)
Head	Unfair	3/26	11.5
	Fair	15/26	57.7
	Very Fair	8/26	30.8
Middle	Unfair	14/26	53.8
	Fair	9/26	34.6
	Very Fair	3/26	11.5
Tail	Unfair	12/21	57.1
	Fair	9/21	42.9
	Very Fair	0/21	0

III. Causes of Inequity in Water Distribution

The Household survey in Table 4-17, highlights the factors affecting unfair water distribution across the head, middle, and tail users of the irrigation system. The results of this study reveal that poor irrigation infrastructure is the most significant factor affecting unfair water distribution, with the head users experiencing the highest impact at 65.4%, followed by the middle at 53.8% and tail at 47.6% users. Issues with implementing rotational schedules are more pronounced in the middle users 23.1% compared to the head 11.5% and tail 9.5% users. Illegal water abstraction affects the head 19.2% and middle 19.2% users but is absent in the tail users. However, a major issue facing the tail-end users 42.9%, who greatly exceed the head and middle users 3.8% each, is the water user committee inadequate coordination. At a 1% significance level, a chi-square test (x2 = 22.46, df = 6, p < 0.001) verifies that these changes are statistically significant.

The main causes of Hatset water distribution disparities include inadequate infrastructure and poor implementation of rotating schedules and water gate manipulation. According to KIIs, those in charge of gate operations frequently miss or postpone water delivery, which results in an unstable water supply, particularly for users at the tail end.

This is consistent with research by **(14)** on irrigation water allocation in Koftu, Ethiopia, where they highlight how inadequate irrigation infrastructure and inadequate implementation of rotational schedules have a major impact on equitable water allocation. especially disadvantageously affecting downstream users. This is also consistent with research by Ghazouani et al. and Yohannes et al. **(67, 88)** which emphasizes the importance of institutional frameworks and governance. They demonstrate that inadequate coordination by water user committees exacerbates water distribution disparities, particularly in downstream regions. These recurring results highlight the necessity of addressing institutional and infrastructure issues in order to enhance irrigation water management and allocation.

Table 4-17: Farmers response to causes of unfair water distribution system

Users	Factors Affecting Unfair Water Distribution (%)			
	Poor irrigation infrastructure	Rotations are not strictly implemented	Illegal water abstraction	Poor coordination of water distribution by the water users committee
Head	65.4	11.5	19.3	3.8
Middle	53.8	23.2	19.2	3.8
Tail	47.6	9.5	0	42.9

4.7.2 Infrastructures and Irrigation Water Management

Canal cleaning and maintenance performance indicators in irrigation schemes were used as measures to assess future improvements in scheme structures. These indicators required significant time and labor but proved valuable in enabling the efficient use of irrigation water. In the present study, the status of breached and damaged structures, sedimentation, and weed growth in canals was taken into account to evaluate the cleaning and maintenance performance of the irrigation scheme’s canals. These indicators played a significant role in preventing obstacles to water deliveries and maximizing the lifespan of the system’s facilities **(89, 90)**.

The infrastructure and governance of the Hatset irrigation scheme were severely challenged. There was a structural failure happened with 96.2% of head users, 80.8% of middle users, 61.90% of tail users. Table 4-18 below demonstrates that structural failures were typical, especially in canals, division boxes and gates.

Table 4-18: Type of structural failure in Hatset scheme

Users	Type of Structural Failure (% believe)			
	Gate	The Canals	Division box	All
Head	7.7	19.3	11.5	61.5
Middle	19.2	38.5	23.1	19.2
Tail	0	61.9	38.1	0

The poor canal cleaning and maintenance was observed in Tables 4-19, with 84.6% of head users evaluating it as inadequate. A proper cleaning routine did not exist in Hatset. Users faced obstacles from external, institutional, and structural causes. Canal breaching was less important in the head-users, with siltation 30.8% and poor coordination 50% predominating. The main problems among middle users were animal damage 42.3% and canal breaching 38.5%, with inadequate coordination 19.2% coming in second. Canal breaching 47.6% and inadequate coordination 23.8% were problems for the tail users. KIIs emphasized IWUAs inability to fix issues, and FGDs revealed that users prioritized canals close to their plots over common infrastructure.

According to similar findings from **(90-92)**, the irrigation schemes of Serenta, Tahtay-Tsalit, and May-Nigus (Northern Ethiopia) have considerable seepage losses and inadequate canal maintenance. For Hatset to overcome these obstacles, community-driven maintenance plans that are supervised by fortified IWUAs must be established in order to make sure of fair involvement and thorough infrastructure repair.

Table 4-19: Performance of canal cleaning, maintenance, and causes of poor performance

Users	Performance of Canal Cleaning and Maintenance (%)			Poor Performance of Canal Cleaning and Maintenance (%)			
	Very Good	Good	Poor	Poor coordination of water user committees	Breaching of the canal by water users	Animal damage	Siltation
Head	0	15.4	84.6	50	19.2	0	30.8
Middle	0	23.1	76.9	19.2	38.5	42.3	0
Tail	14.3	47.6	38.1	23.8	47.6	19	9.5

Additionally, IWUAs' management function was severely lacking. As seen in Table 4-20, 95.2% of tail-end users expressed unhappiness with IWUAs, which were perceived as ineffectual by all users. According to FGDs, middle and tail users feel left out of IWUAs decision-making, which erodes their confidence in the company even more. These results align with those of Yohannes et al. **(67)**, who emphasized the Gumselassa irrigation scheme's IWUAs symbolic significance. Improving Hatset irrigation management requires reinforcing IWUA governance through leadership development and capacity-building initiatives.

Moreover, expanding women's participation in IWUA decision-making may improve equity and governance. While 71.2% of respondents in Hatset believe that female participation is vital, efforts should be made to actively include women in leadership positions in order to put this recognition into practice. Women's inclusion in irrigation governance is crucial, according to research by **(93)** and **(94)** which highlights better accountability and resource allocation results. In Hatset, encouraging female leadership via focused training and mentoring initiatives can improve inclusivity, strengthen governance, and guarantee more fair water management techniques.

Table 4-20: Assessment of the Effectiveness of IWUAs Across Different Reaches

Users	Role of IWUAs	Frequency(N=73)	Percent (%)
Head	Ineffective	22/26	84.6
	Effective	3/26	11.6
	Very Effective	1/26	3.8
Middle	Ineffective	23/26	88.5
	Effective	3/26	11.5
	Very Effective	0/26	0
Tail	Ineffective	20/21	95.2
	Effective	1/21	4.8
	Very Effective	0/21	0

4.7.3 Conflicts and causes of conflict

Conflicts over the distribution and receipt of shares of water were common, both generally at the scheme level and specifically among various locales. At the scheme level, 71.2% of participants said they had encountered conflicts both inside and among the water users. All locations saw a high level of conflict intensity, with tail-end users seeing the most severe incidents. According to Table 4-21, the household survey indicated that the head had the highest conflict presence at 42.3%, followed by the center at 80.8% and the tail at 90.5%. Consequently, the water users reported having to deal with disputes between themselves and other organizations; this was also noted by (95).

There were notable differences. throughout the plan when the sources of conflicts over irrigation water use were examined. The chi-square test ($x^2 = 15.08$, DF = 2, $p = 0.001$) verified that there was a significant correlation between conflicts and the water source's closeness. The main causes at the scheme level were water scarcity 14%, water theft 24.9%, and uneven water distribution 35.5%. 30.8% of the head users reported water theft, and 42.3% cited unequal distribution. Here, there was no shortage of water. Theft 23.1% and unequal distribution 46.2% were the most common issues among middle users, while 3.8% noted water scarcity. Water scarcity was the top worry for tail-users 38.1%, followed by theft 23.8% and unequal distribution 33.3%. These results show how geographic location and particular user challenges influence conflicts, highlighting the necessity of addressing behavioral and structural concerns in order to lessen conflicts.

The KIIs and FGDs give significant perspectives into the institutional and social dynamics that drive water conflicts within the irrigation scheme. Informants in the head users emphasize the difficulty of managing rising water demand, which intensifies competition and exposes gaps in user registration and allocation systems; in the middle users, systemic inefficiencies, like poor maintenance and delayed water delivery, result in unequal water distribution, which drives conflict and frustration; and in the tail-end users, upstream over-extraction and weak enforcement of water-sharing agreements exacerbate water scarcity, causing tensions among downstream users. Farmers in all reaches stress the significance of community-driven solutions, like rotating water schedules and local enforcement mechanisms, which are seen as essential for lowering conflicts and maintaining a more equitable distribution of water.

Table 4-21: Farmers’ response to the presence of conflict and causes for conflict

Users	Conflict presence (%)		Causes of Conflict (%)			
	Yes	No	Water scarcity	Water theft	Uneven water distribution	Increasing number of water users
Head	42.3	57.7	0	30.8	26.9	42.3
Middle	80.8	19.2	3.8	23.1	46.2	26.9
Tail	90.5	9.5	38.1	23.8	33.3	4.8
Scheme level	71.2	28.8	14.0	25.9	35.5	24.7

4.7.4 Conflict Resolution in Hatset Irrigation Scheme

1. Traditional Conflict Resolution Methods

The findings showed that traditional techniques were widely used, with the tail users having the highest acceptance. rate 95.2%, followed by the middle users 80.8% and the head users 61.5%. Their perceived efficacy, however, differed. substantial. 80.8% of respondents said that the process was "not effective," and only 15.4% said it was "highly effective." Just 6.8% of tail users said it was "highly effective," while 64.4% thought it was "not effective." The intermediate reach showed a marginally improved perception, with 42.3% evaluating the mechanism as "not effective" and 53.8% evaluating it as "moderately effective" (Table 4-22).

These findings suggested that although traditional methods were still commonly used, there was considerable doubt about their efficacy, particularly with regard to the head and tail reaches. This result was in line with recent research, such as **(96)**, which discovered that traditional methods frequently lacked consistency and did not address systemic issues, especially in regions with complicated irrigation schemes.

Table 4-22: Farmer's response to traditional mechanisms and their effectiveness

	Traditional Mechanism (%)		Effectiveness of Traditional Mechanism (%)		
Users	Yes	No	Highly effective	Moderately effective	Not effective
Head	61.5	38.5	15.4	3.8	80.8
Middle	80.8	19.2	3.8	53.8	42.3
Tail	95.2	4.8	6.8	28.8	64.4

Across the irrigation users, different traditional systems presented different challenges. Although bias against particular people or groups was less noticeable in the middle 26.9% and head 11.5% users, it was a considerable problem in the tail-end users 47.6%. On the other hand, the most significant challenge in the middle 57.7% and head 50% users was the neglect of addressing the underlying reasons. According to Table 4-23, the absence of enforceable rulings was a significant issue in the middle 15.4% but less so in the tail 42.9% and head 38.5% users.

At the 1% significance level, the chi-square test result ($x^2 = 16.26$, df = 4, $p < 0.003$) verified that these changes were statistically significant. This finding was in line with Getahun et al. **(88)**, who noted that traditional methods frequently had trouble enforcing equality, especially in downstream irrigation areas where power disparities and social dynamics made conflicts worse.

Table 4-23: Farmer's response to challenges to traditional mechanism

	Challenges of Traditional Mechanism (%)		
Users	Bias towards certain individuals/groups	Failure to address root causes	Lack of enforceable decisions
Head	11.5	50	38.5
Middle	26.9	57.7	15.4
Tail	47.6	9.5	42.9

2. Formal Conflict Resolution Methods

Formal methods were the least used. dispute resolution technique; just 7.7% of middle users and 23.1% of head users reported using them, while none at all. The main issues were the low farmer engagement rate of 33.3% among tail-end users and the inactive IWUAs 57.1%. Inactive IWUAs 50% and ignorance of IWUA mechanisms 38.5% were major problems for head users, and low farmer participation 61.5% was the main problem for middle users (see Table 4-24).

There was a statistically significant correlation between the challenges and the users at the 1% significance level, according to the Pearson chi-square test result ($x^2 = 19.01$, df = 4, $p < 0.001$). Studies by **(96, 97)**, have observed similar difficulties, highlighting the organizational and institutional constraints of IWUAs, especially with regard to successfully resolving conflicts and involving farmers (see Table 4-25).

Table 4-24: Farmers response for formal mechanism and its challenges

	Formal Mechanisms (%)		Challenges of Formal Mechanisms (%)		
Users	Yes	No	IWUAs are not active or well-organized	Lack of awareness about IWUA-led conflict resolution mechanisms	Limited participation of farmers in IWUA activities
Head	23.1	76.9	50	38.5	11.5
Middle	7.7	92.3	30.8	7.7	61.5
Tail	0	100	57.1	9.5	33.3

3. Combating Systemic Issues with a Hybrid Approach

As seen in Table 4-25, combined methods were hardly used, with little adoption in the middle 11.5% and head 19.2% users and no usage observed in the tail-end users. The biggest challenge was the lack of cooperation between IWUAs and traditional leaders, especially when it came to the 90.5% tail users. As indicated in Table 4-26, among the head users, inadequate teamwork (46.2%) and a lack of belief in IWUAs 23.1% were significant obstacles, whereas among the middle users, the limited ability of IWUAs to integrate conventional methods (53.8%) was a major difficulty. At the 1% significance level, the Pearson chi-square test result ($x^2 = 21.53$, df = 4, $p < 0.001$) verified that these changes were statistically significant.

Conflicts in irrigation systems may be resolved more thoroughly with a hybrid approach that blends formal institutional frameworks with community-driven solutions. According to **(97)**, this approach handles the systemic problems of unequal water distribution and governance shortcomings in addition to the severe symptoms of conflicts. A more open and equitable system could be produced by strengthening the institutional framework for water management and encouraging community-based solutions, which would ultimately ease tensions and enhance the sustainability of water distribution.

Table 4-25: Farmer's response for combined mechanism and its challenges

	Combined Mechanism (%)		Challenges of Combined Mechanism (%)			
Users	Yes	No	Poor collaboration between IWUAs and traditional leaders	The limited capacity of IWUAs to incorporate traditional practices	Resistance from IWUA members to adopt combined approaches	Lack of trust in IWUAs by farmers
Head	19.2	80.8	46.2	26.9	3.8	23.1
Middle	11.5	88.5	34.6	53.8	0	11.5
Tail	0	100	90.5	9.5	0	0

5 Conclusion and Recommendations

5.1 Conclusion

In the Hatset irrigation scheme, this study assessed the effectiveness of irrigation water allocation and its effects on water use efficiency and conflict resolution. The severe water shortages happened, especially in tail-end users, were caused by poor irrigation techniques, unbalanced water distribution, and inadequate infrastructure. About 30% of all water redirected was lost due to seepage, overflow, and ineffective gate operation, resulting in the tail users having 45% less water available than the head users.

The inflows to the reservoir were estimated, and the hydrological response of the Hangoda watershed was simulated using the HEC-HMS. Strong model performance was shown in the calibration and validation findings, with NSE values of 0.79 and 0.87 and R^2 values of 0.88 and 0.97, respectively. By integrating with WEAP, the model supported sustainable irrigation planning by precisely modeling rainfall-runoff processes. In a similar manner, CROPWAT estimated the potential evapotranspiration for HEC-HMS and the water demand for WEAP.

Three scenarios were analyzed using the WEAP model. The first scenario represented current water management practices, serving as a baseline. The second scenario emphasized improved irrigation efficiency through measures such as canal lining and optimized water scheduling, leading to a significant reduction in water demand by 37.5%. The third scenario involved expanding the irrigated area, which improved demand satisfaction. Among these, the scenario focusing on irrigation efficiency proved most effective, enhancing water availability for tail-end users while reducing overall demand.

There were significant challenges in the areas of management, infrastructure, and conflict resolution for the Hatset irrigation scheme. Water distribution was hampered by weak management of IWUAs, frequent structural failures, and poor canal maintenance, which the tail-end users highly suffered. Water theft and unequal distribution are the main causes of conflicts, which were made worse by inadequate institutional frameworks and poor farmer participation. In addition to the underutilization and inefficiency of formal and traditional conflict resolution techniques, women in particular, from decision-making. Enhancing water management, lowering conflict, and strengthening the sustainability of the scheme all depend on enforcing IWUAs through capacity-building, increasing women's engagement, and putting in place a hybrid conflict resolution approach.

5.2 Recommendations

- Improve Irrigation Infrastructure
    - Line main and secondary canals to minimize water losses.
    - Regularly maintain gate valves and control structures to ensure proper water regulation.
- Enhance Water Use Efficiency
    - Improved water use efficiency and irrigation expansion scenarios should be implemented.
- Strengthen IWUAs
    - Empower IWUAs to oversee water distribution and conflict resolution mechanisms.
    - Develop clear regulations for fair water allocation and enforce penalties for illegal abstraction.
- Future Research
    - Conduct further studies on climate change impacts on water availability in the Hatset irrigation scheme.
    - Integrate remote sensing and GIS technologies for real-time water monitoring and allocation.

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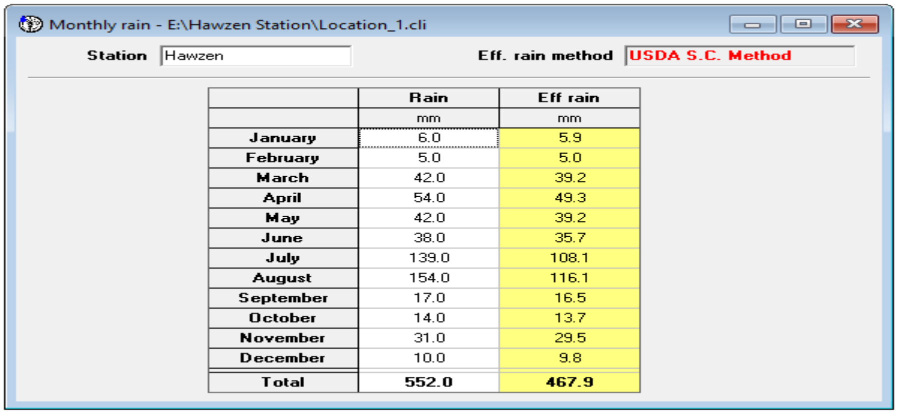
Appendices

Appendix A-1: Hydrometer test for soil texture analysis

Appendix A-3: Potential evapotranspiration results by FAO Penman-Monteith method

Month	Min Temp °C	Max Temp °C	Humidity %	Wind km/day	Sun hours	Rad MJ/m^2/day	ETo mm/day	ETo mm/month	Pan coefficient
Jan	4.9	24.1	59	130	9.6	20.3	3.66	109.8	0.7
Feb	6.5	24.6	60	138	8.9	21	3.99	119.7	0.7
Mar	7.3	26	55	147	9.5	23.4	4.67	140.1	0.7
Apr	10.6	27	53	147	9.8	24.6	5.14	154.2	0.7
May	9.3	25.7	63	173	11	26.3	5.17	155.1	0.7
Jun	9.1	26.8	40	156	9.8	24.1	5.32	159.6	0.7
Jul	10.6	23.2	58	147	7.3	20.4	4.25	127.5	0.7
Aug	9.8	22.7	80	147	7.2	20.4	3.76	112.8	0.7
Sep	8.1	23.6	74	147	9.1	22.9	4.19	125.7	0.7
Oct	7.3	22.2	78	173	9.9	22.7	3.87	116.1	0.7
Nov	5.6	22.1	81	112	9.3	20.2	3.28	98.4	0.7
Dec	3.5	22	82	104	9.6	19.7	3.04	91.2	0.7

Appendix A-4: Total annually Rainfall and Effective Rainfall



Monthly rain - E:\Hawzen Station\Location_1.cli

Station: Hawzen

Eff. rain method: USDA S.C. Method

	Rain	Eff rain
	mm	mm
January	6.0	5.9
February	5.0	5.0
March	42.0	39.2
April	54.0	49.3
May	42.0	39.2
June	38.0	35.7
July	139.0	108.1
August	154.0	116.1
September	17.0	16.5
October	14.0	13.7
November	31.0	29.5
December	10.0	9.8
Total	**552.0**	**467.9**

Appendix A-9: Questionnaire, KII & FGDs Prepared for investigating the effect of efficient water allocation for conflict resolution

A. Household Questionnaire

This questionnaire is formulated to collect factual and relevant data that will help to investigate effect of efficient water allocation for conflict resolution of Hatset irrigation scheme on procedures and principles to distribute fair water through all irrigation water users. Therefore, the information you offer will be kept confidential. Therefore, you are kindly requested to answer the questions below carefully and responsibly.

Section 1: General Information

1) Name of Respondent: ____________

2) Gender of Household Head: {1} Male {2} Female

3) Age of Household Head: {1} Below 30 {2} 30–40 {3} 41–50 {3}51-60

4) Educational Level of Household Head:

{1} No formal education {2} Primary education {3} Secondary education {4} Higher education

5) Location of Irrigation Users: {1} Head Users {2} Middle Users {3} Tail End Users

Section 2: Water Allocation System and Conflict Resolution

1) What is the current availability of irrigation water in your reach?

{1} Sufficient (Water meets crop needs throughout the season) {2} Moderate (Water is sometimes insufficient) {3} Insufficient (Severe water shortages are frequent)

2) Do you think the distribution of irrigation water is fair? {1} Unfair {2} Fair {3} Very Fair

3) If water distribution is unfair, what are the main reasons?

{1} Poor irrigation infrastructure {2} Rotations are not strictly implemented {3} Illegal water abstraction {4} Poor coordination of water distribution by the water users committee

4) Do you see any structural failure? {1} Yes {1} No

5) If yes, what structural failure have you seen? {1} Gate {2} The canals {3} Division box {1} All

6) How frequently is the canal cleaned or maintained in your reach?

{1} Monthly {2} Seasonally {3} Yearly {4} More than a year

7) How would you rate the performance of canal cleaning and maintenance in your irrigation system? {1} Very Good {2} Good {3} Poor

8) What do you think are the causes of poor performance of canal cleaning and maintenance?

{1} Poor coordination of water user committees {2} Breaching of the canal by water users

{3} Animal damage {4} Siltation

9) How do you rate the role of IWUAs in water allocation and management?

{1} Ineffective {2} Effective {3} Very Effective

10) How important is the involvement of females in decision-making?

{1} Not important {2} Important {3} Very important

11). Have you experienced conflicts over water allocation?{1} Yes {2} No

12) What are the main causes of conflicts over irrigation water?

{1} Water scarcity {2} Water theft {3} uneven water distribution {4} Increasing No of water users

13) Are traditional conflict resolution methods currently being used in your reach?{1} Yes {2} No

14) If yes, how effective are these methods in resolving conflicts within your reach?

{1} Highly effective {2} Moderately effective {3} Not effective

15. What challenges do traditional conflict resolution methods currently face in your reach?

{1} Bias towards certain individuals/groups {2} Failure to address root causes {3} Lack of enforceable decisions

16) Has your reach accessed formal conflict resolution mechanisms? {1} Yes {1} No

If the response to question 16 is No, you could ask:

16.a. What are the reasons your reach has not accessed formal conflict resolution mechanisms?

{1} IWUAs are not active or well-organized {2} Lack of awareness about IWUA-led conflict resolution mechanisms {3} Limited participation of farmers in IWUA activities

17) Has your reach accessed combining traditional and formal approaches? {1} Yes {2} No

If the response to question 17 is No, you could ask:

17. a. What are the challenges to combining traditional and formal approaches in conflict resolution?

{1} Poor collaboration between IWUAs and traditional leaders

{2} The limited capacity of IWUAs to incorporate traditional practices

{3} Resistance from IWUA members to adopt combined approaches

{4} Lack of trust in IWUAs by farmers

Participants: Irrigation Water User Associations (IWUAs) leaders**,** Kebele irrigation experts, and model farmers.

B. Key Informant Interview (KII)

1. How would you assess the current fairness and efficiency of water distribution in the irrigation scheme?

2. What are the main challenges affecting efficient water distribution (e.g., infrastructure issues, illegal use, or poor coordination)?

3. How do IWUAs monitor and enforce water allocation fairness across the head, middle, and tail users?

4. What are the primary causes of water-related conflicts in the scheme?

5. What mechanisms are currently used to resolve conflicts, and how effective are they?

6. What role do community-led initiatives and IWUAs play in addressing water allocation conflicts?

7. What specific interventions or policies would you recommend to improve water allocation fairness and reduce conflicts?

C. Focus Group Discussion (FGD)

Participants: Representatives from head, middle, and tail reaches and water user committees.

1. How do you perceive the fairness of water allocation in your irrigation reach?

Are some reaches (head, middle, or tail) more disadvantaged? Why?

2. What are the key challenges you face in accessing sufficient irrigation water (e.g., seepage, overflow, illegal use)?

3. What are the most common causes of water-related conflicts in your community?

4. How effective are the existing conflict resolution mechanisms (e.g., elders' mediation, IWUA intervention)?

5. How important is community participation (e.g., training, capacity-building efforts) in improving water management and resolving conflicts?