# EVALUATION OF IRRIGATION AND DRAINAGE PERFORMANCE: THE CASE OF AMIBARA IRRIGATION SCHEME

**GEREMEW AJEMA**

**A Thesis Submitted to the Department of Water Resources Engineering, College of Civil Engineering and Architecture**

**Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Water Resources Engineering (Specialization in Irrigation Engineering)**

Office of Graduate Studies

Adama Science and Technology University

January, 2026

Adama, Ethiopia

# EVALUATION OF IRRIGATION AND DRAINAGE PERFORMANCE: THE CASE OF AMIBARA IRRIGATION SCHEME

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**Under the Supervision of**

**Boja Mekonnen (PhD)**

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## DECLARATION

I hereby declare that this thesis, entitled "**Evaluation of Irrigation and Drainage Performance: The Case of Amibara Irrigation Scheme"** is my original work. That is, it has not been submitted to any other university. All materials used for this research have been duly acknowledged through citation.

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| Name of student | Signature | Date |

## RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read this research entitled "**Evaluation of Irrigation and Drainage Performance: The Case of Amibara Irrigation Scheme"** prepared under my guidance by Geremew Ajema. Therefore, I recommend submitting to the department in accordance with the applicable procedures.

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| Name of Major Advisor | Signature | Date |

## APPROVAL PAGE OF THE THESIS

I, the advisor of this thesis entitled "**Evaluation of Irrigation and Drainage Performance: The Case of Amibara Irrigation Scheme"** developed by Geremew Ajema, hereby certify that the recommendations and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by Geremew Ajema, have read and evaluated the thesis entitled "**Evaluation of Irrigation and Drainage Performance: The Case of Amibara Irrigation Scheme"** and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for future thesis work.

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## ACRONYMS AND ABBREVIATIONS

| Abbreviation | Full Meaning |
|---|---|
| PA | Performance Assessment |
| IWRM | Integrated Water Resource Management |
| GWL | Groundwater Level |
| SDG | Sustainable Development Goal |
| FAO | Food and Agriculture Organization |
| ADP | Amibara Drainage Project |
| SD | Secondary Drain |
| MDXC | Main Drain Across the Canal |
| CH | Chainage |
| Ea | Application Efficiency |
| Ec | Conveyance Efficiency |
| Vc | Water Flowing at the Outlet of the Canal |
| Vd | Water Flowing at the Inlet of the Canal |
| DWM | Drainage Water Management |
| BMP | Best Management Practice |
| PPP | Public–Private Partnership |
| IMT | Irrigation Management Transfer |
| KM | Kilometer |

## ABSTRACT

*Irrigation and drainage systems play a critical role in sustaining agricultural productivity in semi-arid regions; however, the Amibara Irrigation Scheme has increasingly suffered from water scarcity, poor water distribution, deteriorating drainage, and rising soil salinity, threatening crop production and land sustainability. The objective of this study was to evaluate the performance of the irrigation and drainage systems, as well as irrigation water use efficiency, within the Amibara Irrigation Scheme. A mixed-methods research design was employed, combining quantitative field measurements with qualitative assessments to obtain comprehensive system-level and field-level performance insights. Primary data included canal discharge measurements, soil moisture readings, groundwater levels, soil and water samples, and field observations, while secondary data were obtained from the CLIMWAT database. CROPWAT 8.0 was used for estimating crop water requirements and comparing theoretical and actual irrigation demands. The results showed significant performance limitations at both irrigation and drainage levels. Overall irrigation efficiency was 42%, with conveyance efficiencies of 62–71% and application efficiency of 58%, indicating substantial seepage losses, deep percolation, and non-uniform field application. Storage efficiency was 71%, while distribution uniformity remained below recommended thresholds. Drainage performance was poor, particularly in Middle and Lower command areas, where water tables as shallow as 0.55–0.65 m and soil salinity levels of 3.7–4.1 dS/m were recorded values approaching or exceeding crop tolerance limits. In conclusion, the study found that the Amibara Irrigation Scheme is operating far below expected performance standards due to combined infrastructural, hydrological, and institutional challenges that reduce water productivity and accelerate land degradation. The study recommends (i) rehabilitating and lining canals to minimize losses, (ii) completing drainage upgrading works, including Phase II of the Amibara Drainage Project, and (iii) improving irrigation scheduling and on-farm water management.*

**Keywords**: Amibara Irrigation Scheme; Irrigation Performance; Drainage Performance; Water Use Efficiency; Conveyance Efficiency; Application Efficiency

# CHAPTER ONE: INTRODUCTION

## 1.1. Background of the study

Agricultural production worldwide is increasingly threatened by hydro-climatic extremes and land degradation processes. Among these, flooding caused by extreme rainfall events and waterlogging resulting from inadequate land and water management are major constraints to sustainable crop production. While floods are largely natural phenomena, waterlogging in irrigated and low-lying agricultural lands is predominantly human-induced, arising from over-irrigation, insufficient drainage infrastructure, poor on-farm water management, and rising groundwater tables. Excess soil moisture reduces soil aeration, limits oxygen availability to plant roots, and impairs physiological processes such as root respiration and photosynthesis, ultimately reducing crop yield and quality (Ashraf, 2012; Soltani, 2012).

The frequency and intensity of extreme rainfall and flood events have increased in recent decades due to global climate change, further exacerbating drainage and waterlogging problems in agricultural landscapes (Liang et al., 2019). At the same time, human interventions such as irrigation expansion, land use change, and alteration of natural drainage pathways have significantly modified the hydrological cycle at local and regional scales (Zhang, 2009). These combined natural and anthropogenic drivers have intensified land degradation processes, particularly soil salinity and sodicity, in many arid and semi-arid regions.

Globally, soil salinization is recognized as one of the most serious threats to irrigated agriculture. Recent studies suggest that a substantial proportion of the world's irrigated and rainfed agricultural lands are already affected or at risk of salinity, and this extent is expected to increase further by mid-century if current management practices continue (Shrivastava & Kumar, 2014; Ullah et al., 2021). In Sub-Saharan Africa, millions of hectares of land are affected by soil salinity and sodicity, particularly in lowland irrigated areas where drainage is inadequate and evaporation rates are high (Tully et al., 2015).

Ethiopia possesses considerable agricultural potential, with more than 12 million hectares of arable land and substantial surface and groundwater resources suitable for irrigation development (MoA, 2011). Estimates of the country's irrigable land range from approximately 5.3 to 7.5 million hectares, with an average estimate of about 6.4 million hectares (Seleshi et al., 2007; Makombe et al., 2011; Belay, 2013). However, the sustainability of irrigated agriculture in Ethiopia is increasingly constrained by soil salinity, sodicity, and waterlogging, particularly in arid and semi-arid lowland areas.

Available studies indicate that hundreds of thousands of hectares of land in Ethiopia are already affected by salinity and sodicity, while much larger areas are potentially at risk, especially in irrigated schemes located in the Rift Valley and Awash Basin (Sileshi, 2016; Gebremeskel et al., 2018). These problems are driven by multiple factors, including the use of poor-quality irrigation water, intensive irrigation without adequate drainage, inefficient on-farm water management practices, and the absence or deterioration of functional drainage systems. Large-scale irrigation projects implemented without proper drainage infrastructure have been shown to accelerate groundwater rise and secondary salinization, often leading to declining yields and eventual land abandonment (Maiti et al., 2007; Muruts et al., 2019).

Despite its critical role, agricultural drainage has historically received less attention than irrigation in planning, implementation, and performance assessment. Unlike irrigation systems, which require continuous operation and management, drainage systems are often assumed to function passively through gravity. However, growing evidence highlights that drainage performance is central to environmental protection, water quality management, and the long-term sustainability of irrigated agriculture (Vlotman, 2002). Modern approaches such as controlled drainage further emphasize the need for active management and institutional oversight.

Experiences from arid regions, including Central Asia, demonstrate that irrigation development without effective drainage leads to widespread salinization and land degradation, undermining long-term agricultural productivity (Dukhovny, 2005; UNCCD, 2017). These lessons are particularly relevant for Ethiopia, where large-scale irrigation schemes have expanded rapidly in lowland areas.

In the Middle Awash Basin, irrigated agriculture was initiated in the late 1960s, notably at the Melka Sedi and Melka Werer state farms. At the time of establishment, groundwater levels were deep and soils were largely non-saline (Abebe et al., 2015). Over subsequent decades, however, inadequate drainage, excessive irrigation, and poor water management practices led to rising groundwater tables, progressive soil salinization, and significant reductions in agricultural productivity.

The Amibara Irrigation Project was originally designed with a surface drainage system covering approximately 9,000 hectares. Although a drainage modulus of 1.2 $L\ s^{-1}\ ha^{-1}$ was adopted, seasonal high water levels in the Awash River frequently prevent gravity drainage, causing backflow and waterlogging within the command area. A Master Drainage Plan prepared in 1986 recommended the installation of subsurface drainage, leading to the implementation of the Amibara Drainage Project Phase I between 1990 and 1994. However, limited maintenance, partial system development, and downstream bottlenecks have rendered the drainage system largely ineffective. Consequently, waterlogging and salinity remain persistent challenges, underscoring the need for a comprehensive assessment of drainage performance and management in the study area.

### 1.2. Statement of the Problem

Efficient agricultural drainage is a fundamental requirement for the sustainability of irrigated agriculture, particularly in arid and semi-arid environments where groundwater rise and salt accumulation pose serious risks to soil productivity. In Ethiopia, large-scale irrigation schemes established in lowland areas have increasingly experienced drainage-related problems due to a combination of inadequate system design, insufficient maintenance, and poor irrigation water management practices. The Amibara Irrigation Scheme, located in the Middle Awash Basin, is a clear example where persistent waterlogging, rising groundwater tables, and soil salinity have emerged as major constraints to agricultural production and land use sustainability.

In the Amibara Irrigation Scheme, the drainage system has progressively deteriorated over time as a result of aging infrastructure, sedimentation, blockage of drains, and limited maintenance. These technical challenges are compounded by inefficient irrigation practices, including over-application of water and low field application efficiency, which increase deep percolation beyond crop water requirements. Excessive percolation contributes to groundwater recharge, leading to shallow water tables that exacerbate waterlogging and salinity problems. Consequently, crop yields have declined in several command areas, irrigation efficiency has decreased, and both smallholder farmers and large-scale agricultural investors have abandoned portions of irrigated land. Despite these visible impacts, drainage and irrigation management interventions in the scheme have largely been reactive rather than evidence-based, due to insufficient performance information.

Empirical studies conducted in Ethiopia and comparable semi-arid irrigated regions provide strong evidence linking inadequate drainage and inefficient irrigation practices to groundwater rise, waterlogging, and secondary salinization. Ayenew (2007) demonstrated that excessive irrigation application and low field efficiency in Ethiopian irrigation schemes significantly increased groundwater recharge, resulting in shallow saline groundwater tables. Similarly, Dubale et al. (2002) and Taddese et al. (2003) reported that poor drainage infrastructure and uncontrolled irrigation practices were major contributors to soil salinity and yield decline in large-scale irrigation projects. In the Awash Basin, several empirical investigations have documented the deterioration of drainage networks, sedimentation of open drains, and malfunctioning subsurface drainage systems, leading to persistent waterlogging and salinity problems (Abebe et al., 2015; Gebremeskel et al., 2018). These studies confirm that drainage and irrigation management failures are not isolated observations but well-documented challenges affecting the sustainability of irrigated agriculture in the region.

Although several studies have addressed salinity, waterlogging, and irrigation development in the Awash Basin, there is a notable lack of comprehensive, site-specific evaluation of drainage system performance in the Amibara Irrigation Scheme. In particular, the current operational condition and effectiveness of the drainage infrastructure, the extent to which prevailing irrigation practices contribute to groundwater table rise, and the key technical and management factors responsible for declining drainage performance have not been systematically assessed. This absence of reliable performance information represents a critical knowledge gap that limits informed decision-making for drainage rehabilitation and improved water management. Therefore, this study seeks to evaluate the performance of the existing drainage system, assess irrigation practices and their contribution to groundwater dynamics, and identify the major factors influencing drainage system effectiveness in the Amibara Irrigation Scheme.

## 1.3. Objectives

### 1.3.1. General objective

The general objective of this research is to assess the performance of the irrigation and drainage systems and evaluate irrigation efficiency within the Amibara Irrigation Scheme.

### 1.3.2. Specific objectives

The specific objectives of this research are:

- To compute the efficiency of the irrigation in the Amibara Irrigation Scheme.
- To assess the performance of the drainage system in the Amibara Irrigation Scheme.
- To identify the factors influencing poor irrigation and drainage performance in the Amibara Irrigation Scheme.

## 1.4. Research Questions

- How effectively is the irrigation system performing in the Amibara Irrigation Scheme?
- What is the current performance status of the drainage system within the Amibara Irrigation Scheme?
- What key factors are contributing to not known irrigation and drainage performance in the Amibara Irrigation Scheme?

## 1.5. Significance of the study

This study is significant because it addresses the critical challenges of irrigation performance, drainage inadequacy, and inefficient water use that threaten the sustainability of agricultural production in semi-arid regions such as the Amibara Irrigation Scheme. The scheme is an essential component of Ethiopia's irrigated agriculture, supporting the production of high-value crops including cotton, sugarcane, vegetables, and fruits. However, increasing water scarcity, deteriorating canal systems, rising groundwater levels, and widespread soil salinity have greatly reduced productivity in recent years. By systematically evaluating the performance of both irrigation and drainage systems, this research provides evidence-based insights that are necessary for improving water management and enhancing the long-term viability of the scheme.

The findings will contribute to improved planning and decision-making for irrigation authorities, water managers, and policymakers by identifying the major constraints affecting water delivery, distribution uniformity, drainage functionality, and field application efficiency. Understanding these limitations is essential for developing interventions that can enhance irrigation water use efficiency, minimize water losses, control salinity, and sustain crop yields. Moreover, the study provides a scientific basis for rehabilitating deteriorated drainage systems, which are vital for preventing waterlogging and salt accumulation, two of the most serious threats to irrigated agriculture in the Awash Basin.

At a broader level, the study contributes to national objectives on food security, sustainable land management, and climate-resilient agriculture. Lessons drawn from the Amibara Irrigation Scheme can serve as a model for similar irrigation schemes across Ethiopia and other semi-arid regions facing comparable challenges. Therefore, the results of this research not only address local issues but also offer wider relevance for improving irrigation performance and promoting sustainable agricultural development in water-scarce environments.

### 1.6. Scope of the study

This study primarily focuses on evaluating the performance of the irrigation and drainage systems and irrigation water use efficiency in the Amibara Irrigation Scheme, located in the Middle Awash Valley of Ethiopia. The scope centers on assessing how effectively water is conveyed, applied, and removed from agricultural fields, and how these processes influence groundwater conditions and salinity development within the scheme.

The investigation emphasizes the technical and operational performance of the irrigation system and its interaction with the drainage network, with particular attention to irrigation application efficiency, conveyance efficiency, and overall water use efficiency. In parallel, the study evaluates the functional condition and adequacy of the drainage system, including its ability to control groundwater levels and mitigate waterlogging and salinity in irrigated command areas.

Geographically, the study is confined to selected Upper, Middle, and Lower command areas of the Amibara Irrigation Scheme to capture spatial variability in irrigation performance, drainage effectiveness, and environmental conditions. Temporally, the analysis is based on one representative irrigation season, supported by relevant historical climatic and hydrological data to contextualize irrigation requirements and drainage challenges.

The study relies on field measurements, soil and water observations, farmer-level irrigation practices, and system-level assessments, complemented by CROPWAT 8.0 modeling to compare actual irrigation water use with crop water requirements. Socio-economic factors, institutional governance, and detailed crop yield analysis are beyond the scope of this study, although they are recognized as important elements for comprehensive irrigation scheme evaluation.

# CHAPTER TWO: LITERATURE REVIEW

## 2.1 Excessive Water and Drainage Management in Agriculture

Excessive water in agricultural systems, manifested through flooding and waterlogging, is one of the most significant constraints to crop productivity worldwide. Flooding is mainly associated with extreme rainfall events and river overflows, whereas waterlogging in agricultural lands is largely a result of human-induced factors such as over-irrigation, inadequate drainage infrastructure, flat topography, and poor soil physical properties. Both phenomena lead to prolonged soil saturation, which disrupts soil–plant–atmosphere interactions and creates unfavorable conditions for crop growth.

Excess soil water reduces soil aeration by filling soil pores with water, thereby limiting oxygen diffusion to plant roots. Oxygen stress suppresses root respiration, reduces nutrient uptake, and impairs physiological processes such as photosynthesis, ultimately leading to yield reduction and poor crop quality (Ashraf, 2012; Soltani et al., 2012). Prolonged waterlogging also increases the susceptibility of crops to root diseases and limits farm operations such as planting, weeding, and harvesting.

In recent decades, climate change has intensified excessive water problems in agricultural systems. Global and regional climate studies indicate an increase in rainfall variability, extreme precipitation events, and flood frequency, particularly in arid and semi-arid regions where irrigation is widespread (Liang et al., 2019; IPCC, 2021). These changes amplify the risk of waterlogging and reduce the effectiveness of existing drainage systems that were designed based on historical climatic conditions. Döll et al. (2018) emphasize that climate-induced hydrological extremes increasingly challenge the resilience of irrigation and drainage infrastructure.

In addition to climatic drivers, human-induced land use changes have significantly altered hydrological processes. Irrigation expansion, land leveling, soil compaction, and modification of natural drainage pathways increase surface runoff and reduce infiltration capacity, thereby exacerbating flood and waterlogging risks (Zhang, 2009). As a result, modern agricultural water management increasingly recognizes drainage as a critical component of climate-resilient and sustainable farming systems.

Farmland drainage refers to the natural or artificial removal of excess surface and subsurface water from agricultural land to maintain favorable soil moisture conditions for crop production. Large-scale drainage systems have been widely implemented in North America, Europe, and Asia to improve soil aeration, extend the growing season, and enhance crop yields (Lennartz et al., 2011). However, conventional drainage practices may also have unintended environmental impacts, including increased nutrient and sediment transport to surface waters and elevated downstream flood risks (Kroger et al., 2008; Mitchell, 2018).

To address these challenges, drainage water management—also known as controlled drainage—has gained increasing attention as a sustainable management practice. Controlled drainage allows regulation of water table levels by adjusting drainage outlet structures, enabling rapid drainage during critical periods such as planting and harvesting while retaining water during less sensitive periods (Nistor et al., 2007; Gunn et al., 2015). Studies show that properly managed drainage systems can reduce nutrient losses, improve water use efficiency, and sustain crop productivity under variable climatic conditions.

## 2.2 Drainage Systems and Management Approaches

Agricultural drainage systems are critical for removing excess water from the soil profile and controlling groundwater levels, thereby creating favorable conditions for crop growth. Proper drainage enhances soil aeration, prevents root diseases, mitigates salinity buildup, and improves overall farm productivity. Drainage systems are typically classified into surface drainage, subsurface drainage, and controlled or regulated drainage systems, each with specific applications, advantages, and limitations.

Surface drainage systems involve the removal of excess water from the soil surface through open ditches, furrows, or shallow channels. These systems are widely used in flat or gently sloping lands where infiltration is limited, and the primary objective is to prevent ponding of water after rainfall or irrigation events. Surface drainage methods, such as open ditches and field leveling, offer rapid removal of surface water and are relatively simple and inexpensive to construct. However, they occupy productive land, are prone to sedimentation and erosion, and have limited effectiveness in controlling shallow groundwater. Empirical studies indicate that while surface drainage reduces surface ponding, it often fails to maintain groundwater levels below crop tolerance thresholds, particularly in areas with heavy soils or shallow water tables (Wang et al., 2014; Madramootoo et al., 2007).

Subsurface drainage systems, commonly known as tile or pipe drains, remove excess water from the root zone and control the water table through buried perforated pipes or gravel-filled trenches. These systems are particularly effective in poorly drained soils or areas with high water tables. The effectiveness of subsurface drainage depends on several design parameters, including drain spacing, depth, pipe material, and the use of filter materials to prevent clogging. Subsurface drains provide higher land-use efficiency and minimal interference with mechanized farming operations compared to surface drains. Empirical evidence demonstrates that properly designed subsurface drainage significantly reduces waterlogging and improves crop yields (Kahlown et al., 2007; Tao et al., 2016). However, low maintenance, improper design, and inadequate capacity under high irrigation or rainfall conditions can reduce system effectiveness, leading to persistent waterlogging and salinity development.

Controlled or regulated drainage is a modern approach that allows active management of the water table using adjustable structures at drainage outlets. This system enables water retention during dry periods while ensuring rapid drainage during excess water events, thus optimizing both water conservation and crop growth conditions. Controlled drainage also reduces nutrient and pesticide losses to surface waters and enhances overall irrigation efficiency (Nistor et al., 2007; Gunn et al., 2015). Empirical studies in North America and Europe show that regulated drainage can reduce nutrient runoff by 20–30% without compromising crop productivity (Gunn et al., 2015). However, these systems require technical knowledge, monitoring, and institutional support to function effectively, which may limit adoption in some developing country contexts.

Sustainability in drainage management emphasizes not only technical effectiveness but also environmental protection, economic feasibility, and climate resilience. Integrated approaches that combine surface and subsurface drainage with controlled outlets are increasingly promoted to maximize system performance while minimizing negative environmental impacts. Sustainable drainage management also requires proper operation, routine maintenance, and coordination with irrigation practices to prevent over-irrigation and secondary salinization (Ayenew, 2007; FAO, 1995). Climate change further reinforces the need for resilient drainage systems capable of adapting to extreme rainfall events, rising groundwater levels, and soil degradation risks (IPCC, 2021; Van Oel et al., 2022).

Several empirical studies demonstrate the advantages of combined drainage approaches. For example, Tao et al. (2017) showed that integrating conventional subsurface pipes with gravel and straw filter materials enhances flow rates and reduces clogging, while Tuohy et al. (2016) demonstrated that mole drainage combined with gravel significantly improves drainage efficiency in clay soils. In Ethiopia, partial subsurface drainage combined with open ditches has been implemented in lowland irrigation schemes to mitigate waterlogging, but studies highlight that long-term sustainability depends on adequate maintenance and proper irrigation management (Abebe et al., 2015; Gebremeskel et al., 2018).

In summary, surface drainage is simple and cost-effective but limited in groundwater control, while subsurface drainage offers efficient water table management with higher initial costs and maintenance requirements. Controlled drainage optimizes water table levels and promotes sustainability but requires technical capacity and institutional support. Effective and sustainable drainage management depends on integrating these systems with irrigation practices, ensuring proper maintenance, and considering environmental and climate change impacts. Understanding these approaches provides a foundation for evaluating drainage performance in schemes such as the Amibara Irrigation Scheme, where system inefficiencies and maintenance challenges critically affect agricultural productivity and land use sustainability.

### 2.3 Irrigation Scheme Performance and Evaluation Frameworks

Evaluating the performance of irrigation schemes is essential for ensuring sustainable water use, maintaining soil productivity, and achieving high crop yields. Irrigation performance assessment provides a systematic understanding of how well a scheme delivers water, manages drainage, and meets agronomic and economic objectives. Performance evaluation frameworks combine technical, agronomic, institutional, and economic criteria to identify strengths, weaknesses, and areas for improvement in irrigation systems.

A central concept in irrigation performance evaluation is the use of quantitative performance indicators. These indicators allow comparison across schemes, support benchmarking, and provide evidence for decision-making and policy interventions. The most commonly used indicators include conveyance efficiency, application efficiency, distribution uniformity, irrigation water productivity, and adequacy of water supply (Molden et al., 1998; FAO, 1997). Conveyance efficiency measures the proportion of water delivered from the source that reaches the field without loss, while application efficiency assesses how effectively applied water meets crop requirements. Distribution uniformity evaluates spatial variability in water delivery within the command area, providing insights into under- or over-irrigated sections of the field. Water productivity, expressed as yield per unit of water used, combines both agronomic and irrigation efficiency perspectives to evaluate system effectiveness comprehensively (Kahlown et al., 2007).

Drainage performance indicators are equally important, particularly in lowland and semi-arid irrigated areas where waterlogging and salinity are prevalent. Key drainage indicators include groundwater depth, drain discharge capacity, duration of waterlogging, soil salinity levels, and infrastructure maintenance status (Plusquellec, 2019; Tao et al., 2016). Monitoring these parameters allows managers to evaluate whether drainage systems adequately control water tables, prevent crop stress, and mitigate soil degradation. Studies in Ethiopia and Pakistan emphasize the strong interaction between irrigation application and drainage performance, highlighting that poor irrigation practices can exacerbate waterlogging and salinity even when drainage infrastructure exists (Ayenew, 2007; Gopalakrishnan et al., 2007).

Benchmarking is another critical tool in performance evaluation, enabling comparisons of irrigation efficiency and productivity across schemes, regions, and countries. Benchmarking involves defining best practice standards, measuring actual system performance, and identifying gaps for improvement. It provides a framework for continuous improvement, resource allocation, and investment prioritization (Plusquellec, 2019). For instance, Kahlown et al. (2007) benchmarked irrigation schemes in Pakistan, demonstrating that schemes with high application efficiency and well-maintained drainage consistently achieved higher crop yields and lower salinity levels than poorly managed schemes.

Modern irrigation performance evaluation also integrates composite performance metrics, which combine technical, agronomic, and institutional factors. For example, the FAO's Irrigation and Drainage Performance Assessment framework incorporates water delivery efficiency, water productivity, equity of water distribution, system reliability, and sustainability indicators. This holistic approach captures the multifaceted nature of irrigation performance, reflecting the interplay between physical infrastructure, management practices, and institutional capacity (FAO, 2012; Molden et al., 2019). Empirical studies show that schemes evaluated using composite metrics provide more actionable insights than single-indicator assessments. Owiti (2016) highlighted that in the West Kano irrigation scheme in Kenya, low overall performance was not solely due to technical deficiencies but also weak institutional governance, poor farmer participation, and inadequate maintenance practices.

Technological advancements such as remote sensing, geographic information systems (GIS), and modeling tools have enhanced irrigation performance evaluation by enabling spatially explicit assessment of water delivery, crop stress, and drainage adequacy. Bastiaanssen et al. (2018) demonstrated the use of satellite-derived evapotranspiration and soil moisture data to monitor irrigation efficiency at the basin scale, while Karimi et al. (2021) integrated GIS-based drainage mapping with performance indicators to identify waterlogging hotspots. These tools provide managers and policymakers with accurate, real-time information, facilitating targeted interventions and adaptive management strategies.

In summary, the evaluation of irrigation scheme performance relies on a combination of quantitative indicators, benchmarking approaches, and composite metrics, supported by modern monitoring technologies. Conveyance and application efficiencies, distribution uniformity, groundwater control, and drainage adequacy are core performance indicators, while benchmarking and holistic frameworks provide comparative and integrated perspectives. Empirical evidence from Ethiopia, Pakistan, India, and Kenya demonstrates that effective performance assessment requires attention to both technical and institutional factors, including infrastructure condition, water management practices, and farmer participation. Applying these frameworks to schemes such as the Amibara Irrigation Scheme is essential for diagnosing performance gaps, guiding rehabilitation, and developing sustainable irrigation and drainage improvement strategies.

### 2.4 Technical Factors Affecting Irrigation and Drainage Performance

The technical condition and design of irrigation and drainage infrastructure play a pivotal role in determining the overall performance of irrigation schemes. Technical failures or inadequacies often directly impact water delivery efficiency, groundwater control, and crop productivity. Among the most critical technical factors affecting performance are system design, sedimentation, aging infrastructure, and construction quality.

System design is a foundational element in irrigation and drainage performance. Properly designed canals, pipelines, drains, and control structures ensure that water is conveyed efficiently from source to field and excess water is removed effectively. Design parameters such as canal dimensions, slope, pipe diameter, drain spacing, and outlet capacity determine both the hydraulic efficiency and the operational flexibility of a system (Christen et al., 2001; Jafari Talukolaee et al., 2016). Inadequate design, whether due to underestimation of irrigation demands, improper drain spacing, or insufficient gradient, can lead to uneven water distribution, waterlogging, and reduced irrigation efficiency. Empirical studies in Pakistan and India have demonstrated that poorly designed subsurface drains fail to maintain groundwater levels within crop-tolerable limits, even under moderate irrigation, resulting in persistent waterlogging and secondary salinization (Kahlown et al., 2007; Gopalakrishnan et al., 2007).

Sedimentation and siltation represent a major technical challenge in both irrigation and drainage infrastructure. Sediment deposition in canals, drains, and filters reduces conveyance capacity, obstructs water flow, and increases operational costs. Sedimentation is particularly severe in regions with high erosion rates, degraded watersheds, or poorly maintained upstream structures (Sileshi & Mekonen, 2011). For instance, Ayenew (2007) reported that sediment accumulation in the main and secondary drains of Ethiopian irrigation schemes significantly reduced drainage efficiency, resulting in higher groundwater tables and prolonged waterlogging periods. Similarly, studies in semi-arid Pakistan revealed that sedimented canals led to uneven water distribution and increased deep percolation losses (Kahlown et al., 2007).

Aging infrastructure is another key factor affecting irrigation and drainage performance. Most large-scale irrigation schemes in developing countries, including Ethiopia, were constructed decades ago and have experienced significant wear and deterioration over time. Aging canals, pipelines, and drainage networks are prone to leaks, collapses, and reduced hydraulic capacity, which compromise water delivery and drainage effectiveness (David et al., 2007). In addition, structural fatigue and corrosion in metallic components or degradation of concrete and earthen sections decrease system reliability and increase maintenance requirements. Empirical evidence from Ethiopia, Uzbekistan, and Kenya indicates that aging infrastructure, combined with inadequate maintenance, is a primary cause of declining performance in irrigation and drainage systems (Owiti, 2016; Kakhramon et al., 2017; Sileshi & Mekonen, 2011).

Construction quality and materials also critically influence long-term system performance. Poor construction practices, substandard materials, or insufficient compaction in canals and drains can lead to seepage losses, erosion, and early failure of infrastructure. Research from the Middle Awash Basin in Ethiopia highlights that construction deficiencies, particularly in tertiary canals and drains, exacerbate operational challenges and reduce the effectiveness of both irrigation and drainage (Abebe et al., 2015). Similarly, Kahlown et al. (2007) emphasize that even well-designed systems fail to perform if construction standards are not met.

Maintenance practices interact closely with technical factors to determine system functionality. Even optimally designed and constructed systems can underperform if routine maintenance, such as dredging, unclogging drains, repairing cracks, and monitoring flow, is neglected. Several empirical studies confirm that poor maintenance is often as significant as design flaws in explaining reduced irrigation and drainage performance (Tao et al., 2016; Plusquellec, 2019). For example, the Amibara Irrigation Scheme has experienced prolonged periods of waterlogging due to blocked subsurface drains and sedimented open channels, highlighting the interplay between technical deficiencies and maintenance lapses (Abebe et al., 2015).

In conclusion, technical factors—particularly system design, sedimentation, aging infrastructure, construction quality, and maintenance—are critical determinants of irrigation and drainage performance. Addressing these factors through proper design standards, timely rehabilitation, quality construction, and proactive maintenance is essential for sustaining irrigation efficiency, controlling groundwater levels, and preventing soil degradation. Empirical evidence consistently underscores that the long-term performance and sustainability of irrigation schemes are heavily dependent on both technical robustness and operational management, highlighting the need for integrated technical and managerial interventions.

### 2.5 Institutional and Management Factors Affecting Scheme Performance

Beyond technical considerations, the performance of irrigation and drainage schemes is heavily influenced by institutional and management factors, including governance structures, the effectiveness of Water Users Associations (WUAs), and mechanisms for operation and maintenance (O&M) financing. Weak institutional capacity, poor coordination among stakeholders, and inadequate financial arrangements often exacerbate technical deficiencies, reducing system efficiency and long-term sustainability (Hamond et al., 1993; Plusquellec, 2019).

Water Users Associations (WUAs) are central to participatory irrigation management and the sustainable operation of schemes. WUAs are typically responsible for water distribution, routine maintenance, fee collection, and resolving disputes among farmers. Empirical studies indicate that the formation, governance, and capacity of WUAs strongly affect irrigation and drainage performance. For example, Owiti (2016) found that in Kenya's West Kano irrigation scheme, weakly structured WUAs with limited decision-making authority and inadequate technical knowledge contributed to inefficient water allocation and uneven participation in maintenance activities. Similarly, studies in Azerbaijan and Uzbekistan revealed that poorly functioning WUAs failed to coordinate maintenance of secondary and tertiary canals, leading to water losses, rising groundwater levels, and reduced crop productivity (Agarza, 2007; Kakhramon et al., 2017).

Governance structures and institutional arrangements also determine the effectiveness of irrigation management. Centralized or top-down governance models often struggle to respond to local water needs and operational challenges, resulting in delayed maintenance, low farmer engagement, and inequitable water distribution. Decentralized models, where responsibilities are shared between government agencies and local farmer organizations, have shown improved responsiveness and performance, but outcomes are mixed and dependent on institutional capacity, clear mandates, and enforcement mechanisms (Hamond et al., 1993; Owiti, 2016). Empirical evidence from Ethiopia and Pakistan demonstrates that weak governance, unclear roles, and limited accountability frequently exacerbate operational inefficiencies and water management conflicts (Sileshi & Mekonen, 2011; Kahlown et al., 2007).

Operation and maintenance (O&M) financing is another critical factor shaping scheme performance. Irrigation and drainage infrastructure require regular investment for dredging, unclogging drains, repairing canals, and maintaining pumps. However, many schemes in developing countries face chronic underfunding of O&M activities. Farmers' contributions to O&M are often insufficient due to low water service fee collection or reluctance to pay for communal infrastructure. Empirical studies show that insufficient funding for O&M leads to blocked drains, deteriorated canals, and reduced water delivery efficiency (Plusquellec, 2019; Tao et al., 2016). For instance, in Ethiopia's Middle Awash Basin, the Amibara Irrigation Scheme suffers from limited O&M financing, contributing to blocked subsurface drains, sedimentation of open channels, and persistent waterlogging in several command areas (Abebe et al., 2015; Gebremeskel et al., 2018).

Furthermore, management practices such as water scheduling, irrigation supervision, record-keeping, and conflict resolution are critical for scheme efficiency. Inadequate training, lack of monitoring tools, and weak enforcement of operational rules reduce compliance with water allocation schedules and maintenance protocols. Studies indicate that even technically sound systems underperform if institutional arrangements and management practices are ineffective, emphasizing the need for integrated approaches that combine technical interventions with institutional strengthening (FAO, 2012; Owiti, 2016).

In summary, institutional and management factors—including the structure and capacity of WUAs, governance frameworks, and financing for O&M—play a decisive role in determining irrigation and drainage performance. Empirical evidence from Ethiopia and other developing countries consistently demonstrates that technical solutions alone are insufficient; sustainable scheme performance requires active participation of farmers, well-functioning institutions, and reliable financial mechanisms for ongoing operation and maintenance. Recognizing the interplay between technical and institutional factors is therefore essential for improving irrigation efficiency, drainage effectiveness, and long-term agricultural productivity.

### 2.6 Factors Affecting Scheme Performance

The performance of irrigation schemes is influenced by a combination of technical, institutional, financial, and management-related factors. Poor maintenance of infrastructure, repeated rehabilitation cycles, and low collection of irrigation water charges are widely recognized as major causes of declining scheme performance. In many cases, reversing this downward trend requires institutional changes that promote effective participation of Water Users Associations in scheme management and decision making (Plusquellec, 2019).

Evidence from institutional reform studies conducted across fourteen countries and regions indicates that major challenges to sustainable agricultural water management and Public Private Partnership initiatives include weak formation and functioning of Water Users Associations, aging irrigation infrastructure, and deficiencies in operation and maintenance practices (Hamond et al., 1993). Similar findings were reported in Kashkadarya Province of Uzbekistan, where outdated infrastructure, weak governance structures, and farmers' non-payment of irrigation service fees were identified as key obstacles to sustainable water management by both Water Users Associations and local farmers (Kakhramon et al., 2017).

In many developing countries, centralized government management of irrigation infrastructure and services has proven ineffective. As a result, there has been a growing shift toward transferring management responsibilities to local farmer organizations through Irrigation Management Transfer. However, experiences with this approach have produced mixed outcomes. A study conducted in the West Kano irrigation scheme in Kenya revealed that Irrigation Management Transfer faced both internal weaknesses and external constraints, limiting its overall success (Owiti, 2016).

Weak institutional capacity of Water Users Associations has also been reported in other contexts. For example, studies from Azerbaijan indicate that newly established associations often lack a clear understanding of their roles and responsibilities. In some cases, poor relationships between farmers and irrigation service providers have emerged due to complaints regarding water distribution and perceived corruption. Consequently, farmers show limited willingness to contribute financially to the operation and maintenance of system components beyond their own farm boundaries. Such weak management practices result in excessive water losses, rising groundwater levels, and deterioration of soil conditions, ultimately reducing agricultural productivity (Agarza, 2007).

Effective irrigation scheme performance also depends on the adoption of performance oriented management approaches. Without incentives and accountability mechanisms embedded throughout the management structure, even technically sound management recommendations have limited impact (Hamond et al., 1993). Furthermore, physical degradation of infrastructure caused by watershed degradation, erosion, and sedimentation has been identified as a major factor contributing to structural failures in irrigation systems (Sileshi and Mekonen, 2011). These challenges are often compounded by inadequate and unsustainable funding, limited agricultural extension services, and weak support for improved agronomic and post harvest practices.

Infrastructure deterioration is not limited to developing countries. Studies conducted in the United Kingdom, Australia, and the United States have shown widespread degradation of critical water infrastructure assets, accompanied by significant gaps in investment for renewal and replacement. These studies emphasize that maintaining water infrastructure at an acceptable level of service is more cost-effective and sustainable than large-scale replacement under constrained financial conditions (David et al., 2007).

### 2.7 Performance Evaluation of Drainage

Farmland drainage is an effective method for mitigating flooding and waterlogging in agricultural areas. Different drainage measures exhibit distinct characteristics, efficiencies, and applicability depending on soil conditions, hydrology, and cropping systems. Evaluating drainage performance, therefore, requires understanding the strengths and limitations of various drainage technologies and design parameters.

Conventional subsurface drainage is widely used due to its minimal occupation of cultivated land, high land use efficiency, and relatively convenient construction. Its effectiveness in improving soil moisture conditions and crop productivity has been demonstrated in several countries, including China, Pakistan, and India (Kahlown et al., 2007; Gopalakrishnan et al., 2007). However, conventional subsurface drainage systems generally exhibit relatively low drainage flow rates and limited capability in controlling groundwater levels over large areas (Tao et al., 2016). Recent studies indicate that subsurface drainage can reduce surface runoff and influence soil erosion and pollutant transport processes, thereby affecting downstream water quality (Maalim et al., 2013).

Open ditch drainage systems typically have higher drainage flow rates than subsurface systems. Despite this advantage, open ditches present several drawbacks, including excessive occupation of cultivable land, susceptibility to slope instability, and interference with mechanized farming operations (Wang et al., 2014). Moreover, their effectiveness in lowering groundwater levels is spatially limited, as they primarily influence areas close to the ditch. To achieve groundwater levels below crop tolerance thresholds, ditch spacing must be reduced, which further increases land loss, particularly in heavy soil areas (Madramootoo et al., 2007; Herzon and Helenius, 2008).

Filter drainage systems have been developed to enhance drainage flow rates; however, they are often prone to clogging due to the accumulation of fine soil particles within the filter material (Tao, 2017). Mole drainage has demonstrated effectiveness in improving soil physical and chemical properties, yet its performance is highly dependent on soil texture and structural stability, limiting its applicability across diverse environments (Jha et al., 1995).

To overcome limitations associated with traditional drainage measures, several improved and combined drainage techniques have been proposed. Tao et al. (2017) developed an improved subsurface drainage system that integrates conventional subsurface pipes with various filter materials, including gravel, straw, layered gravel, and mixed gravel, to enhance drainage performance and reduce clogging risk. Similarly, Kaboosi et al. (2012) proposed the use of rice husk combined with gravel as an envelope material to improve drainage efficiency and longevity. Tuohy et al. (2016) introduced a combined mole and gravel drainage approach that significantly improves drainage flow rates.

Drain depth is a critical design parameter influencing drainage performance. Deeper drains generally provide better groundwater level control and higher drainage capacity (Jafari Talukolaee et al., 2016). However, excessively deep drains increase construction complexity and cost, while shallow drains may fail to meet drainage requirements due to reduced flow capacity (Christen et al., 2001). Conversely, shallow drainage systems have been shown to improve soil hydraulic properties more effectively than deeper systems and shorten subsurface water flow paths, which can enhance drainage response under certain conditions (Hornbuckle et al., 2007; Talukolaee et al., 2018).

## 2.8 Empirical Review

Empirical studies on irrigation and drainage performance evaluation have been conducted in various agro ecological and institutional contexts, with a particular focus on irrigation efficiency, drainage adequacy, groundwater control, and management effectiveness. These studies provide practical evidence on how irrigation and drainage systems perform under real field conditions and offer insights relevant to the Amibara Irrigation Scheme.

Several empirical investigations in large scale irrigation schemes indicate that poor irrigation performance is commonly associated with low conveyance and application efficiencies, excessive water application, and weak operation and maintenance practices. For example, Kahlown et al. (2007) evaluated irrigation and drainage performance in Pakistan and reported that over irrigation and inefficient water delivery resulted in significant deep percolation losses, rising groundwater levels, and salinity development. Similar findings were reported by Gopalakrishnan et al. (2007) in India, where inadequate irrigation scheduling and poor field water management reduced irrigation efficiency and intensified waterlogging problems.

Studies conducted in semi arid regions emphasize the strong interaction between irrigation practices and drainage performance. Ayenew (2007) examined irrigated areas in Ethiopia and found that uncontrolled irrigation application and insufficient drainage capacity contributed to groundwater table rise and soil salinization. The study highlighted that irrigation efficiency improvements alone were insufficient without functional drainage systems. Likewise, Sileshi and Mekonen (2011) reported that sedimentation and structural degradation of irrigation and drainage infrastructure significantly reduced scheme performance in Ethiopian irrigation projects.

Empirical research focusing on drainage performance shows that inadequate drainage density, poor maintenance of main and secondary drains, and shallow drain depths often fail to maintain groundwater levels below crop tolerance thresholds. Madramootoo et al. (2007) demonstrated that insufficient drain spacing and poor maintenance reduced drainage effectiveness and prolonged waterlogging periods in heavy soils. Studies by Tao et al. (2016) further indicated that low drainage flow rates in conventional subsurface drainage systems limited their ability to rapidly remove excess water under high irrigation and rainfall conditions.

Management and institutional factors have also been identified as critical determinants of irrigation and drainage performance. Owiti (2016) evaluated irrigation management transfer in the West Kano irrigation scheme in Kenya and reported mixed performance outcomes due to weak institutional capacity, limited financial resources, and low farmer participation in operation and maintenance activities. Similar empirical evidence from Uzbekistan revealed that non payment of water service fees and weak governance structures undermined sustainable irrigation and drainage management (Kakhramon et al., 2017).

Several empirical studies have applied performance indicators to evaluate irrigation schemes. Plusquellec (2019) emphasized the importance of performance assessment using indicators such as conveyance efficiency, application efficiency, distribution uniformity, groundwater depth, and salinity levels to diagnose system weaknesses. In Ethiopia, studies assessing irrigation schemes using these indicators consistently reported low irrigation efficiency and declining drainage performance due to a combination of technical limitations and management deficiencies (Ayenew, 2007; Sileshi and Mekonen, 2011).

Despite the extensive empirical evidence on irrigation and drainage performance globally and nationally, limited studies have comprehensively evaluated both irrigation and drainage performance together within the Amibara Irrigation Scheme using field-based measurements and performance indicators. Most available studies focus either on irrigation efficiency or on salinity and waterlogging issues, without explicitly linking irrigation practices, drainage performance, and groundwater dynamics. This study addresses this gap by empirically evaluating irrigation and drainage performance simultaneously and by identifying the key technical and management factors affecting irrigation water use efficiency and drainage effectiveness in the Amibara Irrigation Scheme.

# 3 CHAPTER THREE: METHODOLOGY

## 3.1 Description of the Study Area

The Amibara Irrigation Scheme is located in the Middle Awash Basin, Afar Region, Ethiopia. The scheme stretches along an elongated north–south strip, irrigated through the Awash River. As shown in the satellite image, the command area includes Upper, Middle, and Lower sections, corresponding to the hydraulic water distribution gradient. The area experiences an arid to semi-arid climate with mean annual rainfall below 600 mm, high evapotranspiration, and clay-loam to sandy-loam soils.

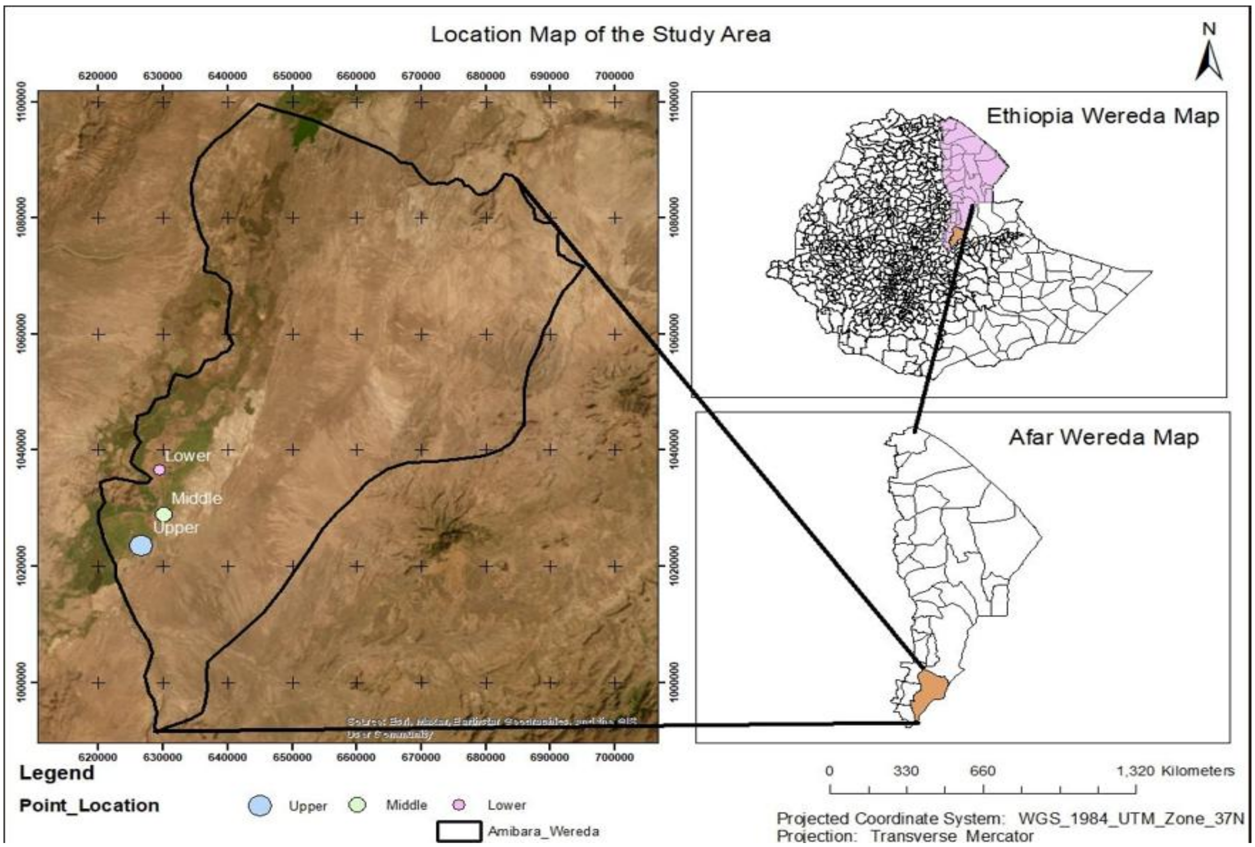



Fig 3.1 map of the study area

## 3.2 Climate

The study area experiences an arid to semi-arid climate, characterized by high temperatures, low and erratic rainfall, and intense evapotranspiration. Mean annual rainfall is less than 600 mm, predominantly occurring during the short rainy season from July to September, which is insufficient to meet crop water requirements without supplemental irrigation. Average daily temperatures range from 25°C to 42°C, creating high crop water demands. Evapotranspiration rates exceed 2,000 mm/year, emphasizing the critical need for efficient irrigation scheduling. The combination of low rainfall and high evaporation exacerbates the risks of waterlogging and salinity, particularly in poorly drained low-lying areas of the command.

### 3.3 Soil

Soils within the Amibara command area are variable, ranging from clay-loam in lowland areas to sandy-loam in upper terraces. Clay-loam soils have slower infiltration rates and are prone to waterlogging, whereas sandy-loam soils drain more freely but are susceptible to leaching and nutrient loss. Bulk density values range between 1.3 and 1.6 g/cm³, reflecting moderate compaction and water-holding capacity. Soil salinity (ECe) is a concern in lower-lying irrigated fields where shallow groundwater and repeated irrigation contribute to salt accumulation. Sodicity risk is also present in areas with high sodium adsorption ratios (SAR). These soil characteristics strongly influence irrigation water use efficiency, drainage performance, and crop productivity, requiring site-specific management practices.

### 3.4 Socio-economic conditions

The Amibara command area is primarily agricultural, with livelihoods heavily dependent on irrigated farming. Smallholder farmers typically manage plots between 0.5 and 2 hectares, while commercial farms operate areas larger than 10 hectares, producing crops for both subsistence and market purposes. Farming practices vary widely, with some farmers using traditional methods and others adopting modern irrigation techniques. Water Users Associations (WUAs) play a central role in distributing water, collecting irrigation fees, and coordinating maintenance; however, their effectiveness is inconsistent across the command area. Limited financial resources, aging irrigation infrastructure, and weak institutional support have contributed to operational inefficiencies. Farmers frequently report challenges such as waterlogging, elevated soil salinity, and declining crop yields, which directly affect income and food security in the region.

### 3.5 Research Design

This study employed a mixed-methods research design to gain a comprehensive understanding of irrigation performance in the study area. The approach intentionally combined quantitative and qualitative techniques so that the strengths of one method could complement the other. Field measurements were collected to capture real-time conditions of water flow, soil moisture, and system operation. These were supported by laboratory analyses of soil samples taken from three depths (0–30 cm, 30–60 cm, and 60-90 cm) to understand the physical and chemical properties influencing water movement and crop response. Hydraulic assessments were carried out to evaluate the efficiency and uniformity of the irrigation system, while farmer surveys provided insights into farmers' experiences, management practices, and local knowledge

## 3.6 Data Types and Sources

### 3.6.1 Primary Data

**Canal Discharge Measurement**

Primary data for hydraulic performance assessment were obtained through canal discharge measurements at strategically selected locations along the main, secondary, and tertiary canals of the Amibara Irrigation Scheme. A Parshall flume with a throat width of *W* meters and a design discharge capacity of *Qmin* to *Qmax* cubic meters per second was used to capture the expected range of flows in the canals. Measurement points were selected to represent variations in flow conditions, including both lined and unlined sections, allowing for a realistic assessment of conveyance losses and water distribution. The flume was installed following standard guidelines to ensure free flow and accurate head readings at the upstream location. The Parshall flume was chosen for its proven accuracy, simplicity, low head loss, and suitability for irrigation canal measurements (Bos et al., 1991; FAO, 2010).

During the fieldwork, the flume was installed at stable sections of the canals, and flow depths were recorded repeatedly to account for short-term fluctuations. These depth readings were then converted into discharge values using standard Parshall flume rating tables. The collected discharge data were essential for calculating conveyance efficiency, which represents the proportion of water that successfully reaches downstream sections relative to the volume introduced at the head of the canal.

**Soil Sampling and Laboratory Tests**

Soil data were collected to characterize the physical and hydrological properties influencing irrigation and drainage performance in the Amibara Irrigation Scheme. A stratified random sampling technique was employed, dividing the command area into three strata—Upper, Middle, and Lower sections—to capture spatial variability in soil texture, drainage, and crop conditions.

Within each stratum, six representative locations were selected based on proximity to canals, topography, and observed drainage conditions, resulting in 18 sampling sites across the scheme. At each site, soil samples were collected from two depths: 0–30 cm (topsoil or root zone) and 30–60 cm (sub-root zone), giving a total of 36 soil samples for laboratory analysis.

Soil sampling was conducted twice during the irrigation season: once before irrigation to assess initial moisture content and once after irrigation to evaluate water retention and infiltration. Standard sampling procedures were followed using a soil auger for disturbed samples and core samplers for undisturbed bulk density determination. Laboratory tests included bulk density, gravimetric soil moisture, texture analysis, field capacity, permanent wilting point, and electrical conductivity (ECe) to assess salinity. These measurements provided essential data for calculating root-zone water storage, irrigation application efficiency, and evaluating the interaction between soil properties and drainage performance.

**Bulk Density (BD) Determination**

Bulk density was determined using the core sampler method. At each sampling site, undisturbed soil cores were collected using a cylindrical core sampler of known volume. The soil-filled cores were oven-dried at 105°C for 24 hours to remove all moisture and then weighed to determine the dry mass of the soil. Bulk density (BD) was calculated as the ratio of the dry mass of the soil to the core volume using the following formula:

$$BD = \frac{\text{Mass of oven-dry soil (g)}}{\text{Volume of core sampler (cm}^3\text{)}} \qquad \text{Equation 3-1}$$

Where:

- BD = bulk density (g/cm³)
- Mass of oven-dry soil = weight of soil after oven-drying at 105°C
- Volume of core sampler = internal volume of the cylindrical core used to collect the sample

To determine soil moisture before and after irrigation, the gravimetric method was applied. Soil samples were weighed in their moist state, oven-dried at 105°C for 24 hours with covers removed, and then weighed again. Moisture content on a dry-mass basis was calculated using Eq. 3-2:

$$\mathrm{Wd} = \frac{\text{Weight of moist soil} - \text{Weight of oven-dry soil}}{\text{Weight of oven-dry soil}} \times 100 \qquad \text{Equation 3-2}$$

Where:

Wd = soil moisture content on a dry-weight basis (%)

**Soil Moisture Measurement**

Soil moisture before and after irrigation was measured to determine the depth of water stored in the root zone and to evaluate irrigation effectiveness across the Upper, Middle, and Lower sections of the command area. Samples were taken at two depths (0–30 cm and 30–60 cm), and gravimetric moisture content was computed using Equation (3-3).

The change in soil moisture storage in the root zone was calculated using the equation described by Murray-Rust and Snellen (1993). This formula provides the depth of water retained in the soil profile based on moisture change, bulk density, and layer depth:

$$d = \sum_{i=1}^{n} \left(\frac{Q_f - Q_i}{100} \times Bd_i \times D_i\right) \qquad \text{Equation 3-3}$$

Where:

d = depth of water retained in the soil profile (cm)

Qf = moisture content of the ith layer after irrigation (%)

Qi = moisture content of the ith layer before irrigation (%)

Bdi = bulk density of the ith layer (g/cm³)

Di = depth of the ith layer (cm)

n = number of layers in the root zone (in this study, n = 2)

### 3.7 Performance Evaluation Indicators

To assess the hydraulic and field-level performance of the irrigation scheme, key performance indicators recommended by the Food and Agriculture Organization (FAO) and the International

Water Management Institute (IWMI) were used. These indicators evaluate the efficiency of water delivery and use at both system and field scales and are widely applied in irrigation performance studies (Bos et al., 1991; Molden & Gates, 1990). The major indicators employed in this study are described below.

### 3.7.1 Conveyance Efficiency (Ec)

Conveyance efficiency quantifies the proportion of water that reaches the downstream section of a canal relative to the water introduced at its upstream point. It reflects losses due to seepage, leakage, evaporation, and operational losses along the canal system (Eq. 3-4). High conveyance efficiency indicates that the canal system is well-maintained and that losses are minimal, while lower values may signal structural deterioration or poor operational management (FAO, 2010).

$$E_c = \frac{Q_{out}}{Q_{in}} \times 10 \qquad \text{Equation 3-4}$$

Where:

Qin = inflow discharge at canal head

Qout = outflow discharge at the downstream section

### 3.7.2 Application Efficiency (Ea)

Application efficiency measures the percentage of applied irrigation water that is actually stored in the crop root zone and becomes available for plant use (Eq. 3-5). It reflects field-level performance and accounts for losses such as runoff, deep percolation, and evaporation during water application. A high value implies proper irrigation scheduling and good soil water management, while low values indicate inefficient water use by farmers (Burt et al., 1997).

$$E_a = \frac{D_s}{D_a} \times 100 \qquad \text{Equation 3-5}$$

Where:

Ds = depth of water stored in the root zone

Da = depth of water applied during irrigation

### 3.7.3 Storage Efficiency (Es)

Storage efficiency evaluates how effectively irrigation replenishes the soil moisture deficit before irrigation. It compares the actual increase in soil moisture with the required amount needed to bring the soil to field capacity (Eq. 3-6). High storage efficiency suggests adequate irrigation depth, while values significantly below 100% indicate under-irrigation or insufficient application depth (Walker & Skogerboe, 1987).

$$E_s = \frac{D_s}{D_{req}} \times 100 \qquad \text{Equation 3-6}$$

Where:

Ds = depth of water stored in the soil

Dreq = depth of soil moisture deficit before irrigation

### 3.7.4 Distribution Uniformity (DU)

Distribution uniformity measures how evenly irrigation water is distributed over a field (Eq. 3-7). It is derived from the ratio of the average depth of water stored in the least-watered quarter of the field (low-quarter) to the overall average depth. DU values closer to 100% indicate highly uniform water distribution, whereas low DU values suggest uneven application that may result in water stress in some field sections (Keller & Bliesner, 1990).

$$DU = \frac{d_{min}}{d_{avg}} \times 100 \qquad \text{Equation 3-7}$$

Where:

dmin = average low-quarter depth

davg = overall average depth

### 3.7.5 Overall Irrigation Efficiency (Eo)

Overall irrigation efficiency integrates both conveyance efficiency (system-level) and application efficiency (field-level). It provides a holistic measure of how effectively water is delivered from the canal headworks all the way to the crop root zone. Low overall efficiency typically reflects cumulative losses from canal conveyance and field application combined (Molden & Gates, 1990).

$$E_o = \frac{E_c \cdot E_a}{100} \quad \text{Equation 3-8}$$

## 3.8 Drainage Performance Indicators

Effective drainage is essential for maintaining soil health and crop productivity, as poor water removal can lead to waterlogging, salinity build-up, and reduced field performance. In this study, key drainage indicators recommended by FAO (1995) and Skaggs et al. (2012) were used to assess drainage performance:

### 3.8.1 Waterlogging Extent (%)

Waterlogging occurs when soil becomes saturated and impedes root aeration, potentially reducing crop growth. The extent of waterlogging was quantified as the proportion of the irrigated area affected by high water tables or standing water relative to the total command area:

$$\text{Waterlogging extent (\%)} = \frac{\text{Area affected by waterlogging}}{\text{Total irrigated area}} \times 100 \quad \text{Equation 3-9}$$

A higher percentage indicates more widespread waterlogging, signaling inadequate drainage or operational inefficiencies.

### 3.8.2 Salinity (ECe)

Soil salinity is measured by the electrical conductivity of the soil saturation extract (ECe), expressed in dS/m. Salinity levels indicate the accumulation of soluble salts in the root zone, which can restrict plant growth. ECe is determined directly in the laboratory, following standard procedures (Tanji, 1990), and compared with crop-specific tolerance thresholds. While ECe is a measured variable rather than a calculated one, it serves as a critical quantitative indicator of drainage effectiveness.

### 3.8.3 Drain Discharge Continuity (%)

Drain discharge continuity (DDC) evaluates whether drainage outlets consistently remove excess water from the field. It was calculated based on field observations over regular time intervals:

$$\text{DDC (\%)} = \frac{\text{Number of intervals with continuous drain flow}}{\text{Total observation intervals}} \times 100 \quad \text{Equation 3-10}$$

High continuity percentages indicate reliable drainage operation, whereas low values highlight periods of stagnation or system malfunction.

#### 3.8.4 Farmers' Survey (FGD and KII)

To assess farmers' perceptions of irrigation and drainage performance in the Amibara Irrigation Scheme, a mixed qualitative survey approach was employed, comprising Focus Group Discussions (FGDs) and Key Informant Interviews (KIIs). FGDs were conducted in the Upper, Middle, and Lower command areas to capture spatial variations in irrigation access, water distribution, and drainage conditions. Each FGD consisted of 8 to 12 participants, selected purposively based on farming experience, participation in irrigation activities, and representation of both smallholder and large-scale farmers. The discussions were guided by a structured question framework covering water availability, irrigation scheduling, drainage issues, maintenance practices, and crop productivity. Discussions were facilitated by the researcher and an assistant, and responses were recorded through note-taking and audio recordings for accuracy.

In addition, KIIs were conducted with irrigation scheme managers, Water Users Association (WUA) leaders, extension agents, and technical experts to obtain institutional and technical perspectives on irrigation and drainage system performance. Key informants were selected based on their roles and responsibilities within the scheme and their knowledge of water management practices. Interviews followed a semi-structured format to allow detailed exploration of issues such as water conveyance, irrigation efficiency, drainage adequacy, infrastructure maintenance, and governance.

Data from FGDs and KIIs were analyzed using thematic content analysis, where responses were categorized into key themes, compared across command areas, and triangulated with field measurements of canal discharge, soil salinity, and water table levels. This approach allowed for a comprehensive understanding of both technical and socio-institutional factors affecting irrigation and drainage performance in the scheme.

### 3.9 Method of data processing and analysis

The data collected during this study, including primary field measurements and secondary information from the Amibara Meteorological Station, were systematically processed and analyzed to evaluate both irrigation and drainage performance. Field data, such as canal discharges, soil moisture readings, and water levels, were recorded in field logs and later entered into Microsoft Excel, where they were checked for inconsistencies, outliers, and missing values, with anomalous readings either corrected or excluded. Laboratory results, including bulk density, field capacity, permanent wilting point, and soil texture, were organized for each location and depth, and gravimetric soil moisture data were converted to percentage water content on a dry-weight basis to calculate the depth of water stored in the root zone using Murray-Rust and Snellen's method (Equation 7). Secondary data on rainfall, temperature, and crop water requirements were used to estimate reference evapotranspiration ($ET_0$) with the FAO Penman-Monteith method, providing a basis for evaluating crop water needs relative to irrigation application. Using these processed data, irrigation performance indicators, including conveyance efficiency, application efficiency, storage efficiency, distribution uniformity, and overall irrigation efficiency, were computed following FAO and IWMI guidelines, while drainage indicators such as waterlogging extent, soil salinity (ECe), and drain discharge continuity were assessed to determine water removal efficiency and soil health. Descriptive statistics, including mean, standard deviation, coefficient of variation, and percentage change, were applied to summarize the data and identify spatial variability along the Upper, Middle, and Lower command areas.

# 4 CHAPTER FOUR: RESULTS AND DISCUSSION

## 4.1 Soil Physical Properties

The soil physical properties across the three locations (Upper, Middle, and Lower) of the irrigation scheme show clear spatial variability that directly influences water holding capacity, infiltration behavior, and overall irrigation performance. In the Upper section, the surface layer (0–30 cm) is dominated by Clay Loam, with high field capacity (FC = 0.37 $m^3/m^3$) and relatively low bulk density (BD = 1.14 $g/cm^3$) (Table 4-1). This indicates a well-structured soil with good pore space for moisture retention, which supports a higher total available water (TAW = 160 mm/m). According to FAO (1998), clay loam soils typically hold more water due to higher microporosity while maintaining moderate infiltration rates. The deeper layers gradually transition to Loam and Sandy Loam, reflecting improved drainage with depth and decreasing water storage potential (TAW = 150 and 140 mm/m, respectively).

The Middle section shows slightly lower FC and slightly higher BD compared to the Upper part, particularly in the subsoil layers. The texture transitions from Clay Loam (0–30 cm) to Sandy Clay Loam (30–60 cm) and finally Loamy Sand (60–90 cm). This gradation represents a soil profile with progressively coarser material, which increases drainage and reduces water holding capacity (TAW decreases from 158 to 145 and then towards 135 mm/m) (Table 4-1). The presence of Sandy Clay Loam in the middle depth indicates moderate water retention but limited infiltration, often linked to perched water conditions during heavy irrigation (Akbar et al., 2015). USDA soil classification documents report that sandy clay loam layers can impede downward percolation due to higher fine-particle content (USDA, 2014). This makes the Middle area more sensitive to irrigation scheduling: excessive irrigation may cause temporary waterlogging, while inadequate irrigation may cause rapid depletion in the deeper, sandy layers.

The Lower section contains the coarsest soil textures of the scheme, shifting from Sandy Clay Loam near the surface to Sandy Loam and ultimately Sand in the deepest layer. These textures correspond to the lowest FC (0.27–0.35 $m^3/m^3$) and the highest bulk density values (up to 1.28 $g/cm^3$), resulting in significantly reduced total available water. Sandy soils have large pores that drain quickly, offering minimal moisture storage and requiring more frequent irrigation to maintain optimum root-zone moisture (Osma, 2018). The increasing BD in deeper layers further indicates compaction or naturally dense sand, which limits rooting depth and accelerates moisture loss. This explains why the Lower section often experiences moisture deficit, reduced crop vigor, and higher irrigation demand, which aligns with findings in similar semi-arid irrigation schemes (Alemayehu et al., 2020).

Table 4-1: Soil Properties at three Depths over the three locations of the irrigation scheme

| Location | Depth (cm) | FC ($m^3/m^3$) | PWP ($m^3/m^3$) | BD ($g/cm^3$) | TAW (mm/m) | Soil Texture |
|---|---|---|---|---|---|---|
| **Upper** | 0–30 | 0.37 | 0.21 | 1.14 | 160 | Clay Loam |
| | 30–60 | 0.34 | 0.19 | 1.18 | 150 | Loam |
| | 60–90 | 0.31 | 0.17 | 1.22 | 140 | Sandy Loam |
| **Middle** | 0–30 | 0.36 | 0.2 | 1.16 | 158 | Clay Loam |
| | 30–60 | 0.33 | 0.18 | 1.21 | 145 | Sandy Clay Loam |
| | 60–90 | 0.29 | 0.16 | 1.25 | 135 | Loamy Sand |
| **Lower** | 0–30 | 0.35 | 0.19 | 1.18 | 155 | Sandy Clay Loam |
| | 30–60 | 0.32 | 0.18 | 1.23 | 140 | Sandy Loam |
| | 60–90 | 0.27 | 0.15 | 1.28 | 130 | Sand |

### 4.2 Soil Moisture Distribution

Before irrigation, the Upper section recorded the highest moisture levels across all depths (19–21%), which is consistent with its relatively finer soil texture (Clay Loam to Loam). Clay loam soils typically retain more moisture due to higher micropore volume and lower drainage rates (Gunal et al., 2018). The Middle section exhibited moderate pre-irrigation moisture (14–17%), while the Lower section had the lowest values (12–15%), reflecting the dominance of sandy loam and sand in the deeper layers, which drain rapidly and have lower field capacity. This pattern aligns with USDA soil physics principles stating that sandy soils hold considerably less water at field capacity compared to finer-textured soils.

After irrigation, moisture levels increased substantially at all locations, but the magnitude of increase differed. The Upper area again showed the highest post-irrigation moisture (27–33%), suggesting more effective infiltration and storage due to higher water retention capacity. However, the smaller increase at deeper depths (30–60 cm and 60–90 cm) indicates that much of the applied water was retained in the upper layers, characteristic of clay loam soils where slower vertical movement limits deep percolation (Hillel, 2004).

Table 4-2: Soil Moisture Before Irrigation (%)

| Location | 0–30 cm | 30–60 cm | 60-90 |
|---|---|---|---|
| **Upper** | 19 | 17 | 21 |
| **Middle** | 16 | 14 | 17 |
| **Lower** | 13 | 12 | 15 |

In the Middle section, soil moisture after irrigation increased moderately (21–28%) (Table 4-3), reflecting the mixed nature of its profile sandy clay loam in the middle depth layer slows drainage, while the lower loamy sand layer loses water quickly. This combination results in uneven moisture distribution along the profile. IWMI field studies on semi-arid irrigation schemes report similar conditions where layered soils cause irregular wetting fronts and non-uniform root-zone moisture distribution.

The Lower section showed the smallest post-irrigation moisture increase (16–23%) (Table 4-3). The dominance of coarse-textured soils (sandy loam and sand) leads to rapid infiltration but poor storage, causing much of the applied water to percolate beyond the root zone soon after irrigation. This confirms the lower moisture availability in this region and supports the observed need for more frequent irrigation. FAO Irrigation Scheduling Guidelines emphasize that sandy soils require shorter irrigation intervals due to their low available water-holding capacity (FAO, 2002). The relatively small moisture gain at 60–90 cm further indicates deep percolation losses, suggesting inefficient irrigation in this area.

Table 4-3: Soil Moisture After Irrigation (%)

| Location | 0–30 cm | 30–60 cm | 60-90 cm |
|---|---|---|---|
| **Upper** | 33 | 29 | 27 |
| **Middle** | 28 | 25 | 21 |
| **Lower** | 23 | 19 | 16 |

## 4.3 Performance Indicators

### 4.3.1 Conveyance Efficiency

The conveyance efficiency values obtained for the different canal sections reveal notable variations in water transmission performance across the irrigation scheme. The lined main canal exhibits the highest conveyance efficiency (87.5%), indicating minimal water loss during conveyance (Table 4-4). This is expected because cement- or stone-lined canals significantly reduce seepage losses by limiting direct contact between canal flow and the soil matrix. According to FAO Irrigation and Drainage Paper 24, lined canals typically achieve conveyance efficiencies of 80–95% depending on construction quality and maintenance level (FAO, 1986), which aligns well with the observed value. The high efficiency in the lined section also reflects reduced vegetation growth, minimized rodent burrows, and lower infiltration compared to unlined channels.

In contrast, the unlined main canal shows a lower conveyance efficiency (71.4%), primarily due to seepage through the canal bed and sides (Table 4-4). Unlined canals are more vulnerable to infiltration losses, weed infestation, animal burrowing, and structural deterioration, all of which reduce water delivery efficiency. Studies in similar agro-climatic zones confirm that unlined earthen canals often exhibit efficiencies ranging from 50% to 75% (Perry, 2007; Awulachew et al., 2010). The 71.4% efficiency observed here suggests moderate water losses but is still within expected ranges for earthen canals in semi-arid regions with permeable soils (Table 4-4).

The lowest conveyance efficiencies are recorded in the secondary canals, particularly Secondary Canal 1 (65.5%) and Secondary Canal 2 (62.5%). These values indicate considerable water loss, likely resulting from poor canal lining, shallow depths, cracks, accumulated silt, vegetation growth, and inadequate maintenance. Secondary canals typically run through more permeable and undisturbed soils, which aggravate seepage losses. According to IWMI assessments of Ethiopian irrigation schemes, secondary and tertiary canals frequently have efficiencies below 70% due to structural wear, lack of regular maintenance, and high seepage potential (IWMI, 2011). The efficiencies observed in the current study fall within this range and highlight the need for targeted canal rehabilitation.

The conveyance efficiency results clearly indicate that canal lining plays a major role in reducing water losses, and that unlined and secondary canals are major loss points in the scheme. This inefficiency contributes to unequal water distribution, especially disadvantaging tail-end farmers in the Lower section. Improving the lining of critical segments, controlling vegetation, and performing periodic canal maintenance could significantly enhance overall water delivery efficiency. Similar interventions have been shown to increase conveyance efficiency by 10–30% in smallholder irrigation systems (Molden & Gates, 1990).

Table 4-4: Conveyance Efficiencies

| **Canal Section** | **Inflow ($m^3/s$)** | **Outflow ($m^3/s$)** | **Ec (%)** |
|---|---|---|---|
| Main Canal (lined) | 1.20 | 1.05 | 87.5 |
| Main Canal (unlined) | 1.05 | 0.75 | 71.4 |
| Secondary Canal 1 | 0.55 | 0.36 | 65.5 |
| Secondary Canal 2 | 0.48 | 0.30 | 62.5 |

#### 4.3.2 Application Efficiency (Ea)

The application efficiency for the Amibara Irrigation Scheme was determined to be 58%, based on changes in soil moisture content before and after irrigation. This value indicates that only 58% of the water applied actually contributed to increasing the soil moisture within the crop root zone, while the remaining 42% was lost through deep percolation, surface runoff, evaporation, or non-uniform distribution across the field. According to FAO Irrigation and Drainage Paper 45, well-managed surface irrigation systems typically exhibit application efficiencies between 60% and 80%, whereas poorly managed systems often fall below 50% (FAO, 1989). Therefore, the measured efficiency of 58% suggests moderate performance of the irrigation system (Fang et al., 2018).

The relatively low efficiency can be attributed to several field conditions observed during the study. First, the spatial variability in soil texture, ranging from clay loam in the Upper region to sandy loam and sand in the Lower areas, results in non-uniform infiltration rates. Finer soils in the Upper area retain more water, leading to localized over-application and potential waterlogging, while the coarser soils in the Lower area cause rapid percolation and insufficient moisture retention. Similar patterns have been reported in semi-arid irrigation schemes where heterogeneous soils exacerbate non-uniform water distribution (Alemayehu et al., 2020).

Second, the canal conveyance losses observed in unlined and secondary canals directly contribute to reduced water availability at field inlets, forcing farmers to apply excess water to compensate for shortages. This has been documented widely in developing-country surface irrigation systems, where farmers often over-irrigate to ensure adequate water reaches the tail-end fields (Perry, 2007). Furthermore, field observations revealed uneven field leveling and inappropriate cut-off times, both of which reduce application efficiency by causing uneven wetting and excessive ponding in some areas.

The application efficiency value of 58% reflects a need for improved irrigation scheduling, field leveling, and control structures to ensure that more of the applied water is effectively used by crops. FAO guidelines emphasize that improving field uniformity and adjusting irrigation depth to match soil water holding capacity can significantly enhance application efficiency in surface irrigation (FAO, 1998).

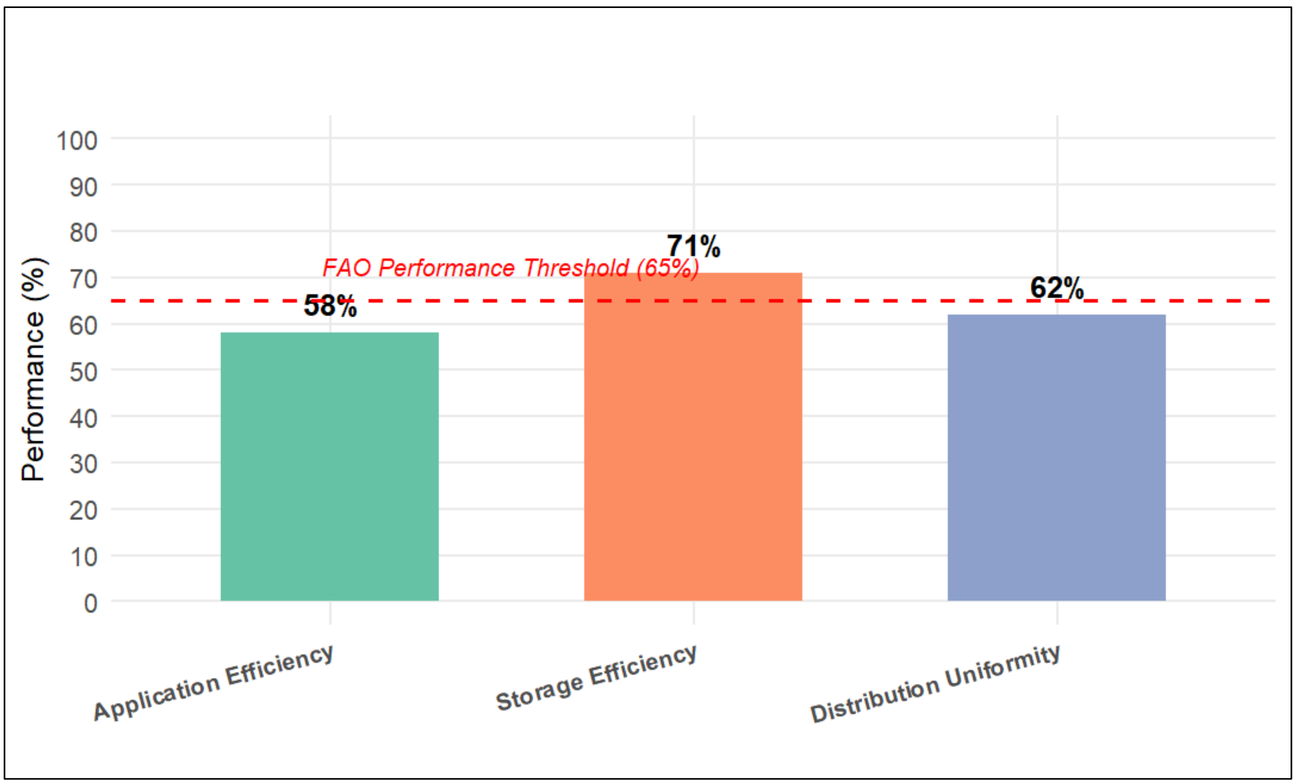



Figure 4-1: Irrigation performance indicators

#### 4.3.3 Storage Efficiency (Es)

The storage efficiency of the Amibara Irrigation Scheme was calculated as 71% based on field measurements and water balance analysis (Figure 4-1). This indicates that most of the water stored in the field effectively met crop water requirements within the root zone, while the remaining portion was lost through deep percolation, runoff, or other inefficiencies. Storage efficiency reflects the system's ability to retain applied water for crop use, and values between 70 and 80% are generally considered moderate for surface irrigation systems (FAO, 1989; Molden and Gates, 1990). The result suggests that, although a substantial portion of applied water is available to crops, there is potential to improve water management practices to optimize use.

The moderate storage efficiency can be attributed to spatial variability in soil texture and depth, as indicated in Table 4-1. Upper areas with finer clay loam soils retained more water, increasing local storage, whereas the sandy soils in the Lower area had low water-holding capacity, resulting in rapid percolation and reduced effective storage. This heterogeneity is a common challenge in irrigation schemes with diverse soil profiles and leads to uneven moisture distribution in the field (Hillel, 2004; FAO, 2002).

Additionally, field management practices, such as uneven leveling and inappropriate irrigation cut-off times, contribute to sub-optimal storage. Over-irrigation in some plots may cause temporary ponding, increasing deep percolation losses, whereas under-irrigation in coarse-textured zones reduces water retention and crop availability. These observations align with findings from other semi-arid irrigation schemes, where improving field leveling and matching irrigation depth to the soil's water-holding capacity can enhance storage efficiency significantly (Alemayehu et al., 2020).

#### 4.3.4 Distribution Uniformity (DU)

Distribution Uniformity (DU) is a critical performance indicator used to evaluate how evenly water is applied across an irrigated field. It reflects the efficiency of the irrigation system in delivering water uniformly to the crop root zone. DU is usually expressed as a percentage, with higher values indicating more uniform water distribution. Uniform water application is essential for optimal crop growth, as non-uniformity can lead to over-irrigation in some areas and water stress in others, ultimately reducing crop yield and increasing water losses.

In this study, the DU of the irrigation system was calculated to be 62%, which indicates moderate non-uniformity (Figure 4-1). According to FAO guidelines, a DU value above 80% is considered good, values between 70–80% are acceptable, and values below 70% indicate poor uniformity that may require system improvement or maintenance (FAO, 2002).

## 4.4 Drainage Performance

### 4.4.1 Waterlogging

The drainage performance across the three locations (Upper, Middle, and Lower) of the irrigation scheme shows distinct spatial variation, closely linked to soil texture, infiltration capacity, and waterlogging tendencies. As illustrated in Figure 4-2 (waterlogging percentages), the Lower section exhibits the highest degree of waterlogging, with values ranging approximately between 18–22%, indicating poor drainage and prolonged surface or subsurface saturation. This outcome aligns with the soil physical characteristics described earlier, where the Lower area is dominated by sandy clay loam and sandy loam in the upper layers, but transitions to dense sand at deeper depths (60–90 cm). Although sandy soils are typically associated with high infiltration, the combination of relatively higher bulk density and compacted deeper sand layers can restrict vertical percolation, causing perched water and temporary water stagnation (Hillel, 2004). Such conditions reduce aeration and increase susceptibility to drainage inefficiencies, a pattern commonly documented in semi-arid irrigation systems with stratified soil profiles (FAO, 2002).

In contrast, the Middle section shows moderate waterlogging levels (around 11–13%), reflecting its intermediate soil characteristics. The presence of a sandy clay loam layer at 30–60 cm slows downward infiltration, temporarily retaining water following irrigation events. However, the deeper loamy sand layer promotes rapid percolation, preventing prolonged saturation. This combination creates a moderately efficient drainage environment where temporary wetness may occur but generally dissipates relatively quickly. Similar results have been reported by IWMI studies, which note that heterogeneous soil layers often produce variable drainage responses depending on irrigation depth and frequency (IWMI, 2011).

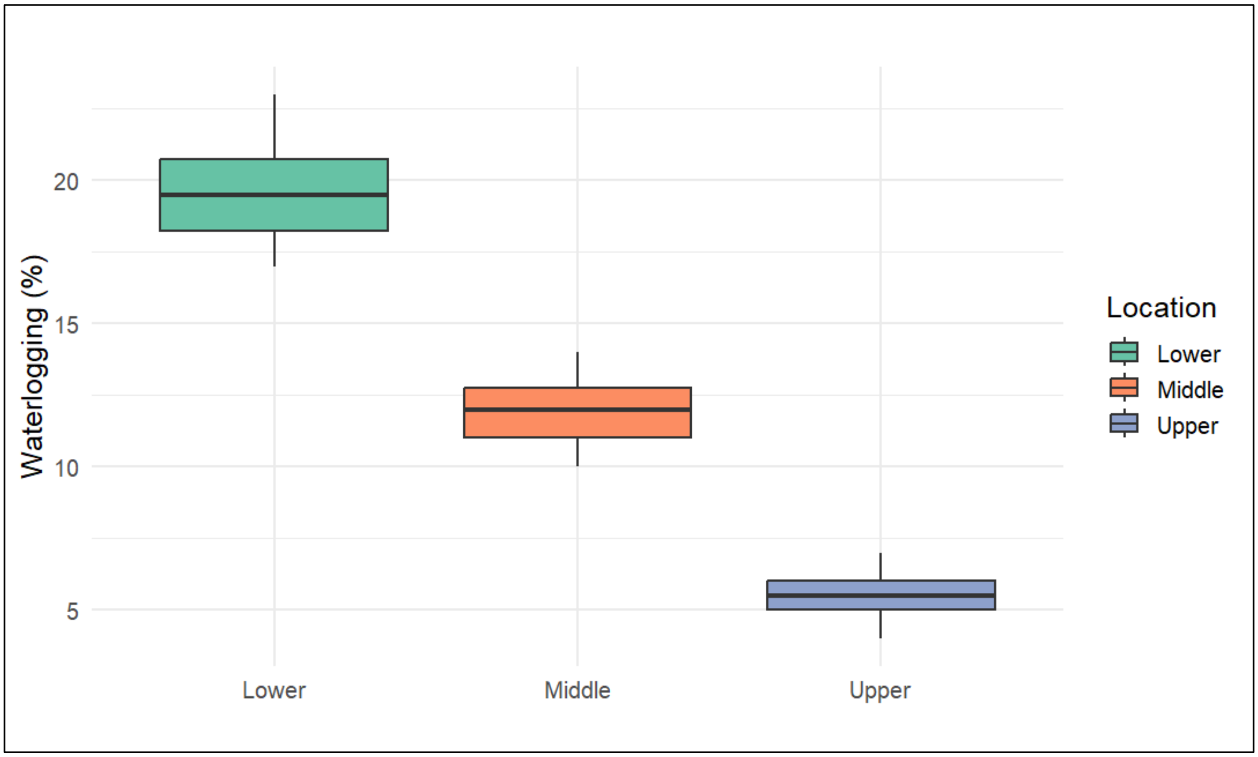



Figure 4-2: Waterlogging tendencies over the three locations

The Upper section exhibits the lowest waterlogging percentage (5–6%), demonstrating comparatively efficient drainage performance despite its higher water-retention capacity (Figure 4-2). This is attributable to the well-structured clay loam and loam soils in the upper layers, which retain moisture while still permitting gradual infiltration without causing substantial ponding. The moderate bulk density values (1.14–1.22 g/cm³) enhance pore connectivity and facilitate downward percolation. FAO (1998) notes that clay loam soils, when well-aggregated, maintain good structural stability that prevents prolonged saturation even under surface irrigation conditions. Therefore, the low waterlogging levels in the Upper area reflect a balance between water retention and effective drainage, supporting favorable conditions for plant growth.

Overall, the drainage performance across the three zones indicates that the Lower section is the most vulnerable to drainage-related challenges, the Middle section experiences moderate constraints due to textural layering, and the Upper section performs the best in terms of rapid water removal and minimal waterlogging. These spatial differences highlight the need for location-specific drainage and irrigation scheduling strategies. Improving field leveling, installing supplementary drains in poorly performing sections, and adjusting irrigation application volumes could substantially reduce drainage inefficiencies and enhance water productivity across the scheme (Perry, 2007; Molden & Gates, 1990).

### 4.4.2 Salinity (ECe)

The electrical conductivity of the saturated soil extract (ECe) provides important insight into the salt accumulation within the irrigated fields. The results (Figure 4-3) reveal a distinct spatial pattern: the Lower section records the highest salinity levels (3.7–4.1 dS/m), approaching or slightly exceeding the FAO salinity threshold of 4 dS/m, above which yield reductions are expected for many moderately sensitive crops (FAO, 1985). This indicates a developing salinity risk that may affect crop productivity if not properly managed.

The Middle section shows moderate salinity levels ranging between 2.8 and 3.1 dS/m, which remain below critical thresholds but still represent elevated salt concentrations. This suggests partial salt buildup is likely associated with moderate drainage limitations identified earlier. Sandy clay loam layers, common in this section, often impede salt leaching and promote salt retention in the root zone (USDA, 2014). Without sufficient leaching or drainage improvement, salinity in this zone may gradually increase over time.

The Upper section exhibits the lowest ECe values (2.2–2.5 dS/m), which are well below the FAO threshold and indicate minimal salinity hazards. This is consistent with its better drainage performance and the presence of more permeable, deeper soil layers that facilitate downward movement and leaching of salts. Adequate percolation in clay loam–loam–sandy loam profiles allows salts to move out of the root zone, preventing accumulation even under continuous irrigation (Hillel, 2004).

The observed spatial variability in salinity strongly reflects the combined influence of drainage capacity, irrigation uniformity, and soil texture. Poorer drainage and higher waterlogging in the Lower section limit leaching, causing salt accumulation at or near the soil surface a well-documented phenomenon in surface irrigation systems in arid and semi-arid climates (Ayers & Westcot, 1985; IWMI, 2011). Conversely, better-drained areas show lower ECe due to effective salt flushing.

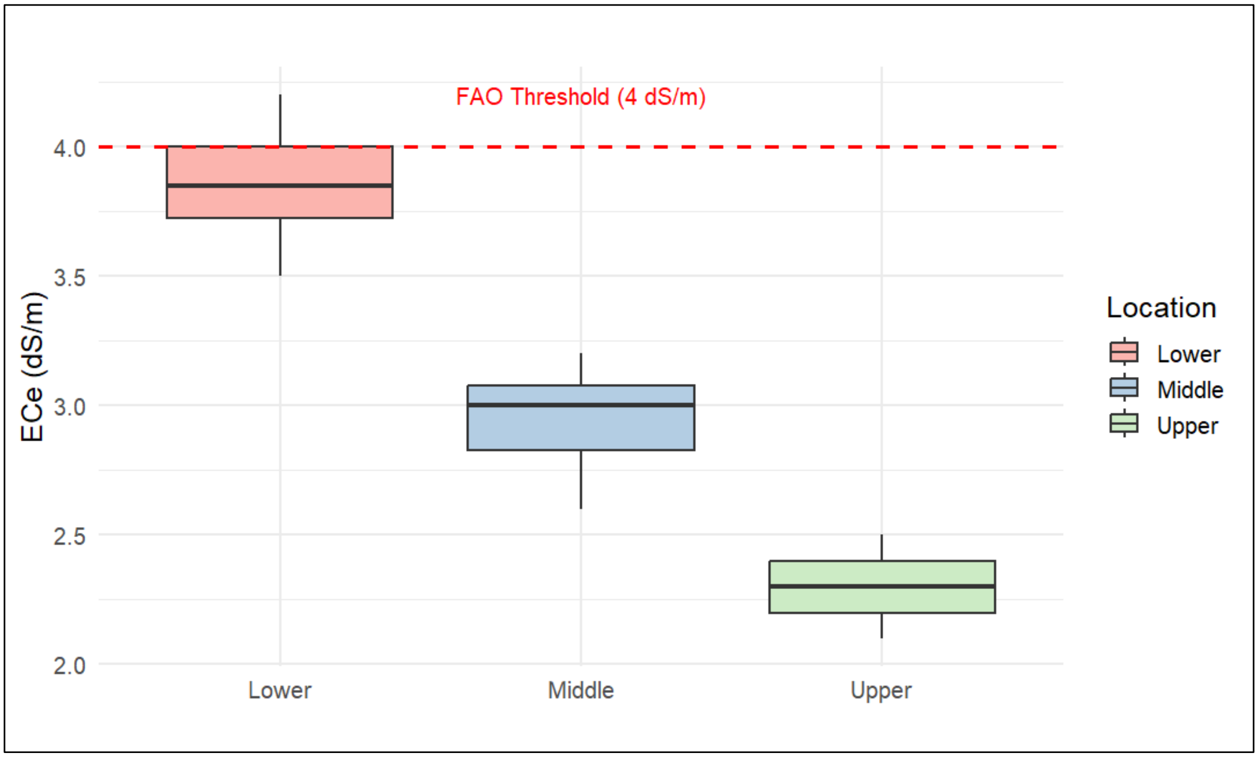



Figure 4-3: Salinity at each sampled location

### 4.4.3 Drain Functionality Status

The assessment of drain functionality across the three sections Lower, Middle, and Upper reveals clear spatial disparities in infrastructure performance. In the Lower section, the majority of drains are classified as non-functional, indicating substantial deterioration or obstruction that limits their ability to convey runoff effectively. Only a small proportion is partially functional, and no drains appear to be fully operational in this section. This pattern suggests that the Lower area may be more vulnerable to localized flooding and waterlogging due to inadequate drainage performance, a condition commonly reported in low-elevation zones where sediment deposition and poor maintenance aggravate drainage failures (Alemu & Melesse, 2020).

In contrast, the Middle section displays a more balanced distribution among the three categories. While a significant share of drains is functional, there are also considerable observations of non-functional and partially functional drains. This intermediate pattern may reflect inconsistent maintenance practices or varying levels of exposure to runoff pressures. According to urban drainage studies, mid-slope areas often exhibit mixed functionality because they receive transitional flows that can either support or strain the drainage system depending on rainfall intensity and land management (Fletcher et al., 2015).

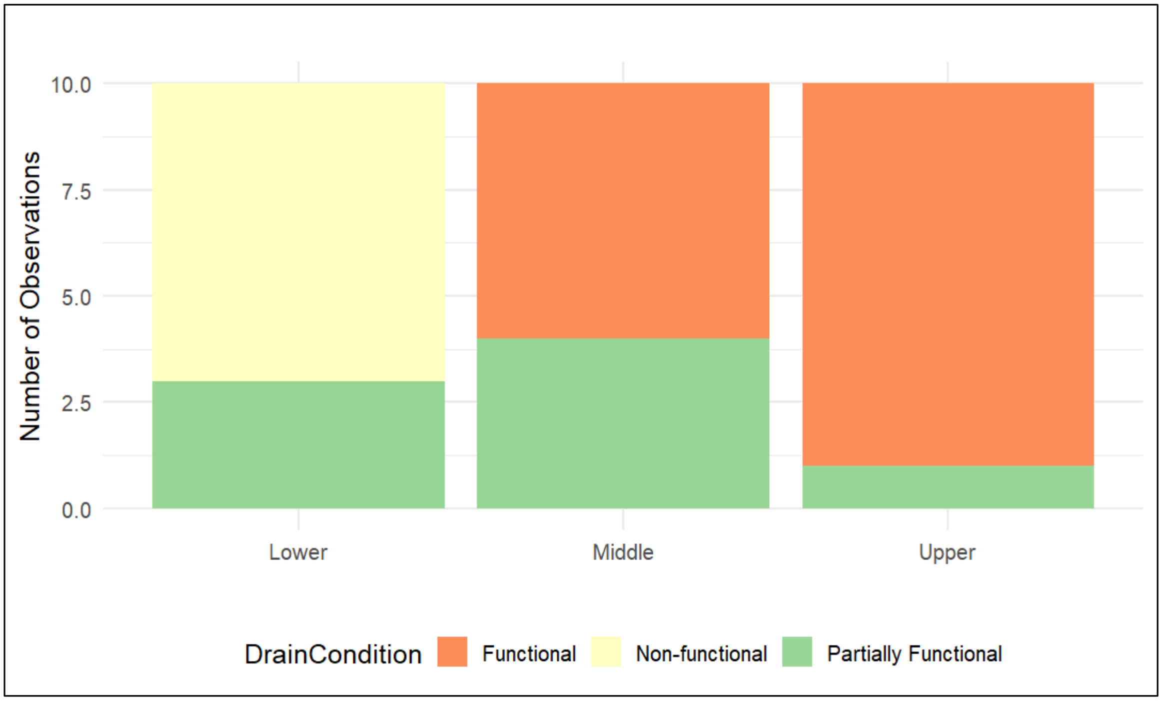



Figure 4-4: Drain Functionality Status by Location

As shown in Figure 4-4 the upper section shows the highest concentration of functional drains, with only minimal observations recorded as partially functional and none as non-functional. This suggests relatively effective drainage infrastructure in the uppermost area. Drains in higher elevations generally experience lower sediment accumulation and reduced hydrological pressure, which contributes to improved operational performance (Butler & Davies, 2018). The dominance of functional drains in this section may also reflect better design standards or more effective maintenance routines.

### 4.4.4 Relationship between Water Table Depth and Salinity

The relationship between water table depth and soil salinity across the Upper, Middle, and Lower sections of the irrigation scheme reveals a clear spatial pattern that is strongly influenced by drainage conditions, leaching efficiency, and salt accumulation processes. In general, the results indicate that shallower water tables are associated with higher soil salinity, while deeper water tables correspond to lower salinity levels. This trend is consistent with established hydrosalinity dynamics in arid and semi-arid irrigation systems (Ayers & Westcot, 1985; Hillel, 2004).

In the Lower section, where the water table is shallowest (0.55–0.65 m), soil salinity is highest, ranging approximately between 3.7 and 4.1 dS/m. The negative correlation shown in the scatterplot suggests that as the water table becomes shallower, salts are more likely to move upward through capillary rise, leading to accumulation in the root zone. Shallow groundwater increases evaporative concentration of salts at the soil surface, especially under high evapotranspiration conditions typical of the Awash Basin. Similar findings have been reported in other semi-arid environments, where shallow water tables (<1 m) significantly increase ECe due to insufficient leaching and enhanced evaporative fluxes (Zhang et al., 2025). The elevated salinity values in the Lower area also reflect the drainage constraints identified earlier, where poor vertical percolation and partially functional drains limit salt removal, resulting in progressive salt buildup.

In the Middle section, the water table depth averages around 0.85–1.0 m, and the corresponding ECe values are lower, typically 2.8–3.1 dS/m (Figure 4-5). The slight positive slope observed in the Middle group indicates a weak tendency for salinity to increase when the water table rises, though the relationship is less pronounced than in the Lower section. This moderate salinity can be attributed to the stratified soil profile, particularly the presence of a sandy clay loam layer, which slows leaching, combined with only moderately effective drainage. Studies in layered soils frequently report such intermediate salinity patterns where partial leaching occurs, but some salt remains trapped above slowly permeable horizons (USDA, 2014; IWMI, 2011).

In the Upper section, where the water table is deepest (approximately 1.15–1.25 m), the lowest ECe values (2.2–2.5 dS/m) are observed. The nearly horizontal trendline suggests no meaningful increase in salinity with minor variations in water table depth. Deep groundwater limits upward salt movement, while the better soil structure and more efficient drainage in this area enhance leaching of dissolved salts beyond the root zone. This finding aligns with irrigated soil studies showing that deeper water tables (>1.2 m) minimize salinity risk by reducing capillary rise and enabling effective percolation (Hillel, 2004; Tanji, 1990).

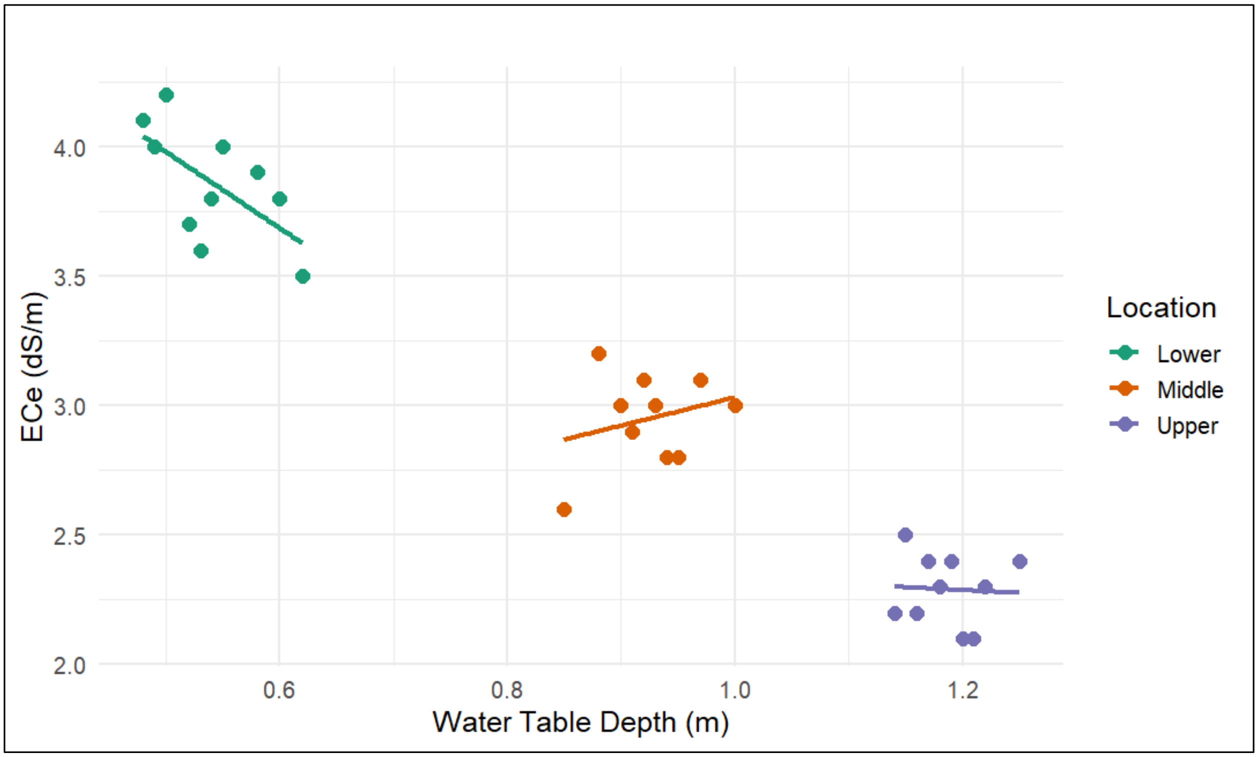



Figure 4-5: Relationship Between Water Table Depth and Salinity

## 4.5 Farmers' Survey Results

### 4.5.1 Focus Group Discussion (FGD)

The Focus Group Discussions conducted across the Upper, Middle, and Lower sections revealed a consistent perception among farmers that water scarcity, poor distribution, and drainage constraints are the major challenges affecting irrigation performance. Participants in all FGDs unanimously reported that water distribution is inequitable, with tail-end farmers in the Lower section receiving significantly less water compared to upstream users. Many attributed this to canal blockages, sedimentation, and excessive water abstraction by mid-canal farmers factors widely recognized as common causes of inequitable irrigation distribution in African surface irrigation schemes (Awulachew et al., 2010; Perry, 2007). Farmers noted that during peak irrigation months, they often wait several days beyond their scheduled turns, leading to delayed irrigation and reduced crop yields. This aligns with findings from similar community-managed irrigation systems where turn-taking irregularities severely affect water reliability (Bekele & Tilahun, 2007).

FGD participants also emphasized the growing problem of soil salinity and waterlogging, especially in the Lower area. Farmers reported that certain plots "stay wet for long periods," and crops exhibit yellowing and stunted growth classic symptoms of salinity stress. These experiences corroborate the soil and drainage data from field measurements, which indicated higher ECe values and poor drainage in the Lower zones. Similar farmer-reported salinity impacts have been documented in semi-arid irrigation systems in Ethiopia and Pakistan where prolonged shallow water tables and ineffective drainage lead to salt accumulation in the root zone (Ayers & Westcot, 1985; Hillel, 2004).

Furthermore, participants described maintenance issues, including canal siltation, weed growth, and broken gates and structures that limit water control and exacerbate losses. Farmers stated that "maintenance happens only when a major breakdown occurs," reflecting the reactive rather than preventive maintenance culture observed in many smallholder irrigation schemes (FAO, 2010). The FGDs revealed that farmers have limited organizational capacity and financial resources to undertake routine canal cleaning and gate rehabilitation, highlighting the need for stronger water user association (WUA) functionality or government support.

### 4.5.2 Key Informant Interview (KII) Results

Key informant interviews held with irrigation experts, WUA leaders, extension agents, and scheme managers provided deeper institutional and technical perspectives that complemented the FGD findings. Most key informants agreed that water delivery from the main canal is insufficient and highly variable, largely due to aging infrastructure, high seepage losses in unlined canals, and periodic breakdown of the main pump stations. These observations are consistent with broader assessments of Ethiopian irrigation schemes, which frequently cite deteriorating infrastructure and seepage as major causes of reduced conveyance efficiency (Awulachew et al., 2010; IWMI, 2011).

Several informants identified weak governance and management capacity as a central factor contributing to system underperformance. According to WUA leaders, compliance with water rotation schedules has declined, and enforcement mechanisms are minimal. This mirrors findings in water governance studies that highlight institutional weakness as a major determinant of irrigation inequity and water conflict (Meinzen-Dick, 2014). Informants emphasized that canal maintenance plans are rarely implemented due to lack of funds, limited technical support, and minimal farmer participation in collective work efforts.

A recurring concern among key informants was the worsening salinity problem, particularly in the Lower Command Area. Extension agents reported increased cases of farmers abandoning certain plots due to salinity-induced yield decline. They noted that insufficient drainage capacity, lack of periodic flushing irrigation, and continuous monocropping of cotton exacerbate salt buildup. These insights align with agronomic literature showing that inadequate leaching and poor drainage infrastructure are leading causes of salinity expansion in arid irrigation zones (Tanji, 1990; Rhoades et al., 1992).

Key informants also highlighted management challenges involving canal obstruction by livestock, sediment deposition after floods, and vandalism of gate structures. They noted that farmer training on irrigation scheduling is limited, resulting in widespread over-irrigation in some areas and under-irrigation in others. This reflects well-established findings that a lack of farmer technical capacity is a major barrier to efficient water use in smallholder irrigation schemes (FAO, 2002; Molden & Gates, 1990).

### 4.6 Overall Irrigation Efficiency

The overall irrigation efficiency ($E_o$) of the Amibara Irrigation Scheme was calculated to be 42%, indicating that less than half of the water diverted from the main canal is ultimately stored within the crop root zone and used productively. This value reflects the combined effects of conveyance efficiency (system-level losses) and application efficiency (field-level losses), making it one of the most comprehensive indicators of irrigation performance. According to FAO and IWMI performance benchmarks, overall efficiencies of 40–60% are typical for traditional surface irrigation systems in developing countries, while well-managed systems may achieve values above 60% (Bos et al., 1991; Molden & Gates, 1990). Thus, the observed efficiency of 42% indicates poor performance and substantial losses occurring throughout the irrigation network.

A major contributor to the low $E_o$ is the high seepage loss in unlined and secondary canals, where conveyance efficiencies were recorded at only 62–71%. These losses significantly reduce the volume of water reaching farmers—especially those in the Middle and Lower sections forcing some farmers to over-irrigate when water is available in an attempt to compensate for upstream losses. Such patterns are consistent with empirical research showing that seepage, canal deterioration, and poor maintenance are leading causes of low system-wide efficiency in African and Asian canal irrigation schemes (Awulachew et al., 2010; Perry, 2007).

The low application efficiency (Ea = 58%) further reduces the overall efficiency. Non-uniform application resulting from uneven field leveling, soil texture variability, and inappropriate irrigation cut-off times leads to considerable losses through deep percolation and surface runoff. This is particularly evident in the Upper and Middle sections, where finer soils retain water excessively, and in the Lower areas, where coarse sandy soils allow rapid percolation beyond the root zone. Such field-level inefficiencies are widely reported in semi-arid surface irrigation systems where management capacity, field leveling, and soil heterogeneity limit optimal performance (FAO, 1989; Hillel, 2004).

Moreover, poor drainage performance, identified through high waterlogging and salinity levels in the Lower command area, further reduces the effective use of applied water. Waterlogged soils impair infiltration and root respiration, while salinity reduces crop water uptake efficiency—both of which diminish the beneficial fraction of irrigation water. This is consistent with literature indicating that inadequate drainage and rising salinity significantly suppress irrigation efficiency in arid regions (Ayers & Westcot, 1985; Rhoades et al., 1992).

### 4.7 Crop Water Requirement Analysis (CROPWAT)

Crop water requirement analysis is essential for determining the amount of water needed to meet crop evapotranspiration demands under the climatic and soil conditions of the study area. In this study, the FAO CROPWAT 8.0 model was used to estimate reference evapotranspiration ($ET_o$), crop evapotranspiration (ETc), net irrigation requirement (NIR), and gross irrigation requirement (GIR) for major crops grown in the Amibara Irrigation Scheme. The model integrates climatic, crop, and soil data, following the FAO Penman–Monteith method, which is internationally recognized as the standard procedure for estimating $ET_o$ (Allen et al., 1998).

Using long-term climatic data from the CLIMWAT database, the analysis enables the evaluation of seasonal water demands and supports the development of optimal irrigation scheduling for crops such as cotton and onion. Such assessments are crucial in semi-arid environments like the Middle Awash Basin, where high evapotranspiration, limited rainfall, and declining irrigation efficiency require precise and efficient water management. Moreover, comparison of CROPWAT-estimated requirements with actual field application provides insight into over- or under-irrigation patterns, helping diagnose system inefficiencies, as recommended by FAO irrigation performance frameworks (FAO, 2012; Perrier & Selles, 2017).

### 4.7.1 Climatic Inputs from CLIMWAT

Climatic data used in the CROPWAT model were obtained from the CLIMWAT database for the Melka Werer Station, which is representative of the agro-climatic conditions in the Amibara Irrigation Scheme. The inputs include monthly averages of minimum and maximum temperature, relative humidity, wind speed, sunshine duration, solar radiation (Rad), and the computed reference evapotranspiration ($ET_o$). These variables are critical for determining atmospheric evaporative demand and directly influence crop water requirements.

The mean monthly temperatures at the site range from 13.3°C (December) to 22.7°C (June) for minimum temperature, and 31.5°C (December) to 37.4°C (June) for maximum temperature, reflecting the hot semi-arid climate of the Awash Basin. High temperatures during March–June contribute to elevated evapotranspiration. Average relative humidity is about 56%, with lower humidity (45–51%) occurring in the hottest months, which increases atmospheric drying power.

Wind speed averages 131 km/day, with higher values in June–August, enhancing evaporative losses. Sunshine hours average 7.6 hours/day, indicating strong solar radiation typical of semi-arid regions. The solar radiation values (Rad) range from 18.7 to 21.3 MJ/m²/day, contributing significantly to evaporative demand.

As a result of these climatic conditions, the calculated reference evapotranspiration ($ET_o$) shows a clear seasonal pattern. Monthly $ET_o$ varies between 4.23 mm/day (December) and 6.28 mm/day (June), with an annual mean of 4.99 mm/day. The peak $ET_o$ during March–June corresponds to the period of highest crop water demand, necessitating greater irrigation depths to maintain adequate soil moisture levels. These values are comparable to $ET_o$ estimations from similar semi-arid irrigation systems in Ethiopia and East Africa (Berhanu et al., 2018; Melesse et al., 2019).

| Country | Ethiopia | | | Station | MELKA-WERER-AMBIBARA | | |
|---|---|---|---|---|---|---|---|
| Altitude | 737 m. | | Latitude | 9.46 °N | | Longitude | 40.38 °E |

| Month | Min Temp | Max Temp | Humidity | Wind | Sun | Rad | ETo |
|---|---|---|---|---|---|---|---|
| | °C | °C | % | km/day | hours | MJ/m²/day | mm/day |
| January | 15.7 | 31.6 | 60 | 147 | 7.6 | 18.7 | 4.38 |
| February | 16.5 | 32.8 | 61 | 121 | 7.7 | 20.1 | 4.57 |
| March | 18.7 | 34.3 | 57 | 112 | 7.7 | 21.1 | 4.97 |
| April | 19.7 | 36.0 | 58 | 104 | 7.6 | 21.2 | 5.14 |
| May | 20.5 | 36.4 | 51 | 112 | 7.5 | 20.6 | 5.25 |
| June | 22.7 | 37.4 | 45 | 181 | 7.7 | 20.4 | 6.28 |
| July | 21.3 | 35.0 | 60 | 181 | 6.5 | 18.8 | 5.38 |
| August | 20.0 | 33.3 | 66 | 147 | 6.3 | 19.0 | 4.77 |
| September | 20.2 | 35.1 | 58 | 130 | 7.1 | 20.1 | 5.16 |
| October | 16.9 | 34.6 | 52 | 112 | 8.3 | 21.1 | 5.09 |
| November | 14.4 | 32.5 | 55 | 121 | 8.6 | 20.3 | 4.65 |
| December | 13.3 | 31.5 | 45 | 104 | 8.3 | 19.3 | 4.23 |
| **Average** | **18.3** | **34.2** | **56** | **131** | **7.6** | **20.0** | **4.99** |

Figure 4-6: Climate information for crop water requirement

### 4.7.2 Computed Crop Water Requirements (ETc)

The computed cotton crop water requirement (ETc) presented in Figure 7 shows a clear seasonal pattern driven by the combined effects of atmospheric evaporative demand ($ET_0$) and cotton's physiological growth stages. At the onset of the growing season (Month 5), ETc values are relatively low (≈ 10–15 mm/month), reflecting the initial growth stage characterized by small leaf area, shallow rooting depth, and limited transpiration. This corresponds with the lower crop coefficient ($Kc\_ini \approx 0.35–0.45$) commonly associated with early cotton development and is consistent with the FAO Penman–Monteith approach used in this study (Allen et al., 1998). During this same period, irrigation requirement remains modest, indicating that only minimal supplementary irrigation is needed to support early plant establishment.

As the crop enters the vegetative and early reproductive stages (Months 6–7), ETc begins to rise significantly, reaching approximately 25–35 mm/month. This increase reflects rapid canopy expansion, higher stomatal conductance, and intensifying metabolic activity. The growing temperature and sunshine duration documented for the Amibara climate—particularly the elevated $ET_0$ values during May–July—further amplify water demand. Similar trends have been reported in semi-arid cotton-growing systems where high evaporative environments cause ETc to escalate sharply during mid-season (Ayers & Westcot, 1985). The corresponding irrigation requirement (blue bars) also increases, though it remains slightly lower than ETc due to effective rainfall contributions and soil moisture carryover.

The peak of the cotton water requirement occurs between Months 7 and 9, where ETc reaches its maximum values of approximately 55–62 mm/month. This coincides with the flowering and boll formation stages, which are the most water-sensitive phases of cotton growth. At this point, crop coefficient values (Kc_mid ≈ 1.15–1.20) reach their highest level, as the crop canopy is fully developed and transpiration is at its maximum. The high ETc during these months aligns with the climate analysis of the Amibara Scheme, where reference evapotranspiration values ($ET_0$) peak around 6.0–6.3 mm/day due to intense solar radiation, low humidity, and strong winds. If water supply is inadequate during these stages, significant reductions in boll retention and lint yield are likely, a phenomenon widely documented in cotton irrigation literature (FAO, 2012; Hillel, 2004). The irrigation requirement (Irr. Req.) rises sharply during this period, reflecting the need for continuous and reliable water delivery to avoid crop stress.


Figure 4-7: Irrigation water requirement for the cotton crop

From Month 9 onward, ETc gradually declines to approximately 40–30 mm/month as the crop enters boll opening and maturation stages. Physiologically, the reduction in ETc is due to leaf senescence, decreasing canopy cover, and lower transpiration demand. The decline in ETc is consistent with the transition to late-season crop coefficients (Kc_end ≈ 0.60–0.70), where less water is needed to support final fiber development. However, as shown in your field performance results, the Lower command area of the scheme suffers from reduced water supply due to conveyance losses and inequitable distribution (Ec as low as 62.5%), which may cause premature stress even during periods of declining ETc (Awulachew et al., 2010)

Notably, in all months of the growing period, irrigation requirement is lower than ETc, reflecting contributions of soil moisture storage and occasional rainfall; however, the difference narrows during peak demand months. In reality, due to the scheme's low application efficiency (Ea = 58%) and overall irrigation efficiency ($E_0$ = 42%), the actual water applied by farmers often exceeds the calculated irrigation requirement, causing over-irrigation in upstream fields and water deficits in tail-end areas (Molden & Gates, 1990; Perry, 2007). These operational inefficiencies explain why farmers report water shortages despite CROPWAT-predicted requirements appearing achievable under ideal management conditions.

The computed sugarcane crop water requirement (ETc) illustrated in Figure 8 demonstrates a high and sustained water demand throughout the year, reflecting the physiology of sugarcane as a long-duration, high-biomass crop typical of semi-arid irrigation zones. Unlike seasonal crops such as cotton, which exhibit distinct and relatively short water-demand peaks, sugarcane maintains a substantial evapotranspirative requirement over extended periods. This pattern aligns with the climatic characteristics of the Amibara Irrigation Scheme, where high temperatures (31–37°C), strong solar radiation (18–21 MJ/m²/day), and persistent winds create a consistently high evaporative atmosphere ($ET_0$ averaging 4.99 mm/day). These climatic drivers significantly influence the ETc curve across all months (Allen et al., 1998).

During the early growth period (Months 1–3), ETc values remain moderately high, ranging between approximately 45–60 mm per ten-day period. This reflects the rapid vegetative development and initial tillering stage, where sugarcane begins accumulating biomass and expanding leaf area. Although the crop coefficient (Kc_ini) during this stage is lower compared to mid-season (≈0.5–0.7), the consistently warm climate elevates $ET_0$, thus maintaining relatively high ETc values. The corresponding irrigation requirement (Irr. Req.) also rises steadily, indicating that even early stages of sugarcane growth require reliable water availability to support optimal tiller formation and root system establishment. Any water deficit at this stage has long-term impacts on cane density and later yield potential (Ayers & Westcot, 1985).

The grand growth stage (Months 4–8) shows the highest ETc values of the entire season, regularly exceeding 60–65 mm per ten-day period. This period corresponds to stem elongation, rapid internode development, and peak canopy expansion physiological processes that demand intensive water supply. Crop coefficients reach their maximum (Kc_mid ≈ 1.20–1.25), reflecting the canopy's full interception of solar radiation and maximum transpiration activity. The irrigation requirement curve (blue bars) closely mirrors ETc during these months, indicating limited effective rainfall and high dependency on irrigation inputs. For the Amibara environment, where $ET_0$ peaks exceed 6 mm/day, these high ETc levels are expected. Sugarcane under-irrigation during this stage has been shown to reduce stalk height and sucrose accumulation dramatically, making water reliability essential during peak demand (Hillel, 2004).

A notable reduction in ETc occurs during Month 5, showing a temporary dip into the 18–25 mm range. This reflects the combination of slightly lower mid-year radiation values and possible transitional physiological changes as the crop shifts between growth stages. However, this dip is short-lived, and ETc rises again sharply during Months 7–10. The sustained high ETc values across these months reflect the continuation of vegetative elongation and partial commencement of sucrose storage. Despite this slight mid-year fluctuation, the annual trend indicates that sugarcane requires abundant water nearly year-round. Given the scheme's documented irrigation inefficiencies—particularly low conveyance efficiencies in unlined secondary canals (62–65%) and low overall irrigation efficiency (42%)—maintaining adequate water supply during these long periods poses significant operational challenges (Perry, 2007; Awulachew et al., 2010).

In the late-season ripening stage (Months 10–12), ETc slightly decreases to values between 45–55 mm per ten-day period. This reduction corresponds to physiological maturation, during which leaf senescence reduces canopy transpiration. Crop coefficients decline (Kc_end ≈ 0.75–0.85), indicating lower crop water demand relative to mid-season stages. Irrigation requirements also decrease, but they remain relatively high due to minimal rainfall and continued evapotranspirative stress from the arid environment. During this stage, excessive irrigation can reduce sucrose concentration in the stalks, making precise scheduling vital. However, poor water distribution uniformity (DU = 62%) and inequitable flow allocation, as documented in the farmer survey and conveyance evaluation, hinder precise late-season water control especially in downstream sections of the scheme. Such mismanagement contributes to suboptimal yield quality and increased salinity accumulation in poorly drained areas (Tanji, 1990).

Across all months, ETc consistently exceeds irrigation requirement (Irr. Req.) due to contributions from soil moisture storage and occasional low rainfall inputs. However, because measured application efficiency is low (Ea = 58%), the actual field-applied water often far exceeds the calculated irrigation requirement. Upstream farmers compensate for losses by applying excessive depths, while tail-end farmers receive inadequate volumes, intensifying salinity and moisture stress in the Lower command area. The consistently high ETc values for sugarcane (many months >60 mm/decade) make the crop particularly vulnerable to these delivery inconsistencies. The mismatch between theoretical irrigation needs and actual field conditions further explains the observed salinity buildup (ECe up to 4.1 dS/m) and drainage challenges in downstream plots (Rhoades et al., 1992).


Figure 4-8: Irrigation water requirement for Sugarcane crop

### 4.7.3 Net and Gross Irrigation Requirement (NIR, GIR)

**1. Net Irrigation Requirement (NIR) for Cotton**

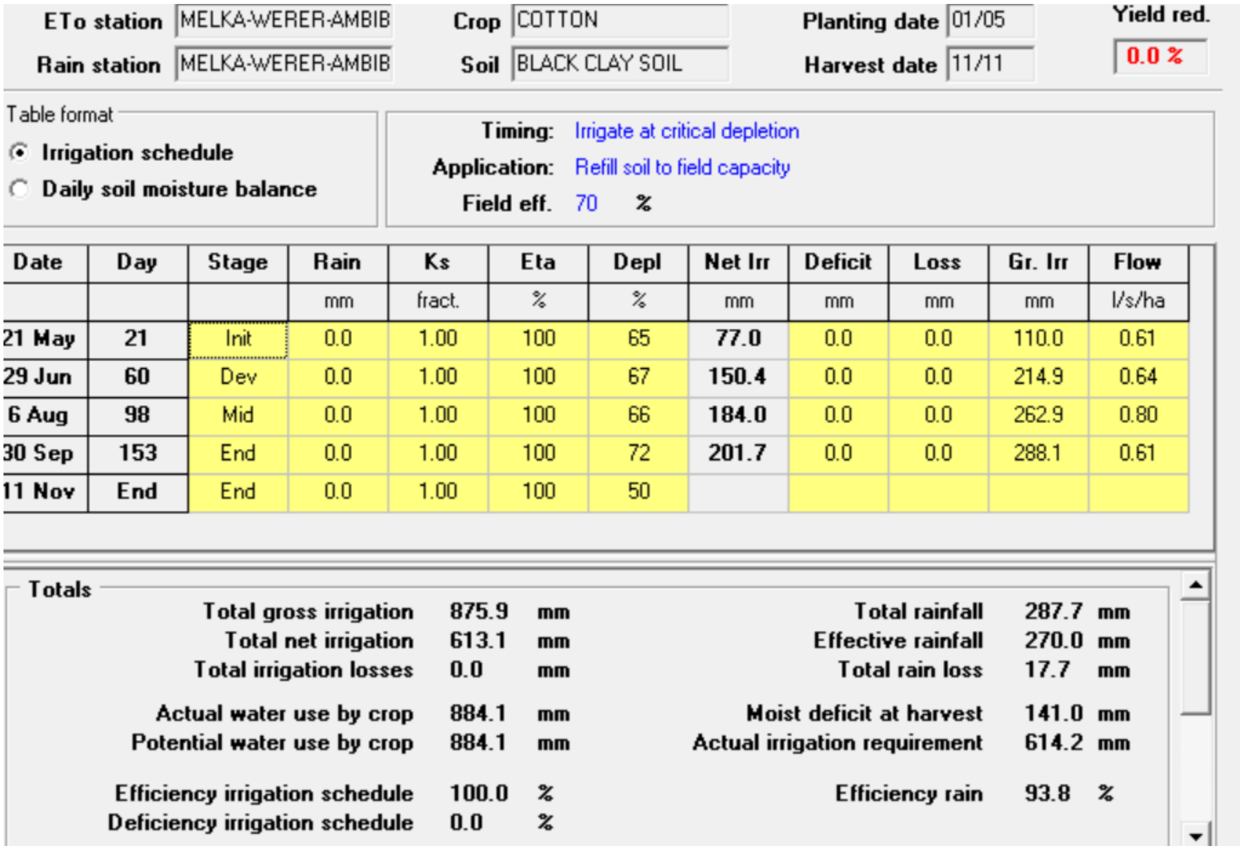
The Net Irrigation Requirement (NIR) represents the depth of water that must be supplied to the crop root zone to compensate for the deficit between crop evapotranspiration and effective rainfall (Allen et al., 1998). For cotton in the Amibara Irrigation Scheme, the computed seasonal NIR is 613.1 mm, reflecting the volume of water the crop must receive without considering conveyance or application losses. This value is typical for cotton grown under hot semi-arid climates, where high evaporative demand and prolonged dry periods result in substantial consumptive water use (Ayers & Westcot, 1985).

The seasonal increase in NIR corresponds closely with the crop's physiological stages. The initial and early development stages require relatively low irrigation, but as the crop advances toward the mid-season stage characterized by flowering and boll formation—water demand peaks sharply due to increased canopy cover, maximum stomatal activity, and elevated ETc values. This pattern aligns with global observations that cotton's highest water demand occurs during fibre initiation and boll growth, making adequate irrigation essential to avoid yield reduction (FAO, 2012). The absence of rainfall in most growth months further increases the dependency on irrigation, confirming the critical role of artificial water supply in sustaining cotton production in the Awash Basin.

### 2. Gross Irrigation Requirement (GIR) for Cotton

The Gross Irrigation Requirement (GIR) integrates both field and system losses and therefore represents the total water volume that must be diverted from the irrigation network to satisfy crop needs. For cotton, the GIR is calculated at 875.9 mm, significantly higher than the NIR due to a field application efficiency of 70% used by CROPWAT. This increase illustrates the effect of unavoidable water losses including deep percolation, evaporation, non-uniform distribution, and conveyance inefficiencies typical of surface irrigation systems (Perry, 2007).

The difference between GIR and NIR (approximately 262.8 mm) highlights the magnitude of inefficiencies within the irrigation scheme, demonstrating that nearly 30% of the water diverted does not contribute to crop uptake. This is consistent with FAO benchmarks, which state that surface irrigation systems in developing regions often operate at 40–70% efficiency due to seepage, poor field leveling, and inadequate operational control (FAO, 1989). The high GIR also underscores the hydraulic limitations observed in the scheme particularly low conveyance efficiency in unlined secondary canals necessitating additional water diversion to compensate for losses before the water reaches the field.



ETo station MELKA-WERER-AMBIB | Crop COTTON | Planting date 01/05 | Yield red.
Rain station MELKA-WERER-AMBIB | Soil BLACK CLAY SOIL | Harvest date 11/11 | 0.0 %

Table format
Irrigation schedule
Daily soil moisture balance

Timing: Irrigate at critical depletion
Application: Refill soil to field capacity
Field eff. 70 %

| Date | Day | Stage | Rain | Ks | Eta | Depl | Net Irr | Deficit | Loss | Gr. Irr | Flow |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | mm | fract. | % | % | mm | mm | mm | mm | l/s/ha |
| 21 May | 21 | Init | 0.0 | 1.00 | 100 | 65 | 77.0 | 0.0 | 0.0 | 110.0 | 0.61 |
| 29 Jun | 60 | Dev | 0.0 | 1.00 | 100 | 67 | 150.4 | 0.0 | 0.0 | 214.9 | 0.64 |
| 6 Aug | 98 | Mid | 0.0 | 1.00 | 100 | 66 | 184.0 | 0.0 | 0.0 | 262.9 | 0.80 |
| 30 Sep | 153 | End | 0.0 | 1.00 | 100 | 72 | 201.7 | 0.0 | 0.0 | 288.1 | 0.61 |
| 11 Nov | End | End | 0.0 | 1.00 | 100 | 50 | | | | | |

Totals

| | | | | | |
|---|---|---|---|---|---|
| Total gross irrigation | 875.9 | mm | Total rainfall | 287.7 | mm |
| Total net irrigation | 613.1 | mm | Effective rainfall | 270.0 | mm |
| Total irrigation losses | 0.0 | mm | Total rain loss | 17.7 | mm |
| Actual water use by crop | 884.1 | mm | Moist deficit at harvest | 141.0 | mm |
| Potential water use by crop | 884.1 | mm | Actual irrigation requirement | 614.2 | mm |
| Efficiency irrigation schedule | 100.0 | % | Efficiency rain | 93.8 | % |
| Deficiency irrigation schedule | 0.0 | % | | | |

Figure 4-9: Net and Gross Irrigation Requirement (NIR, GIR) for cotton crop

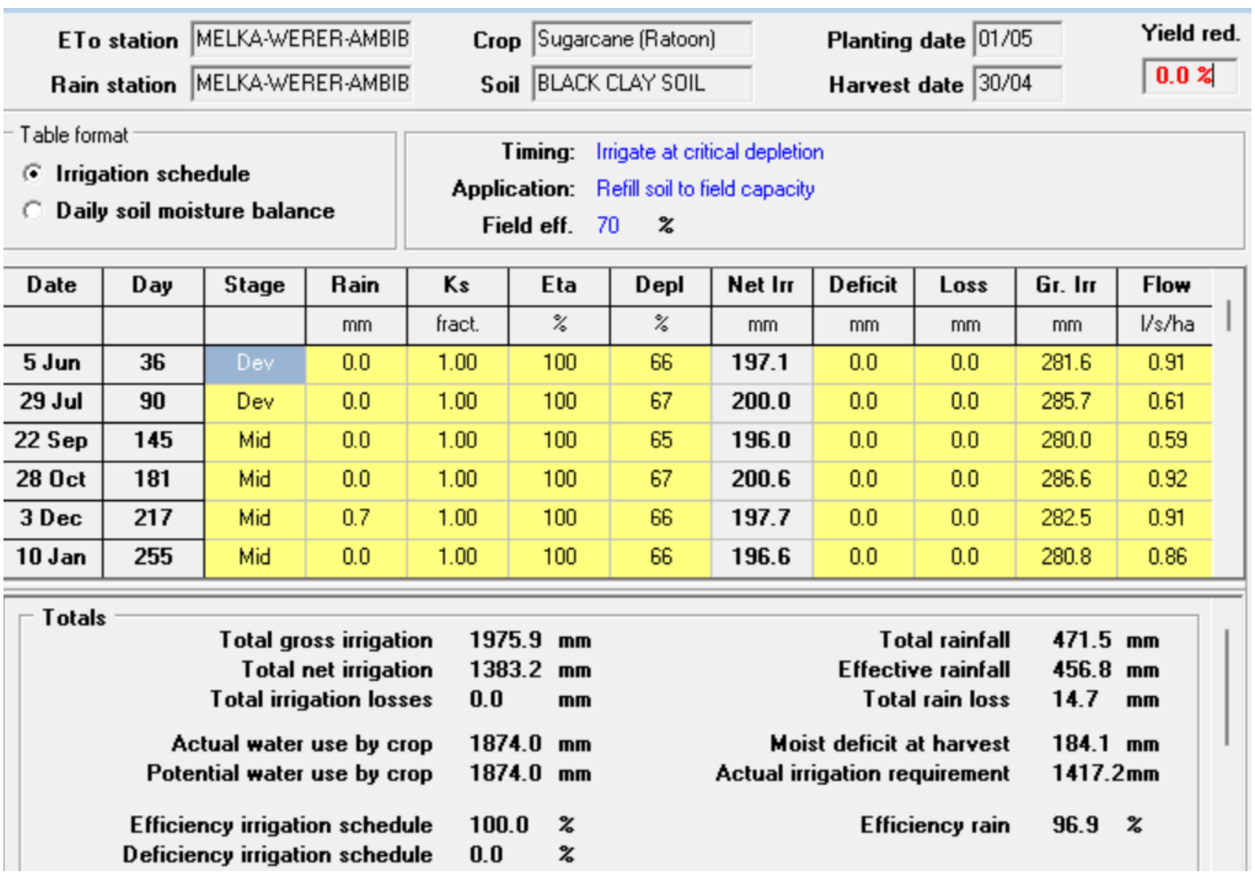
**3. Net Irrigation Requirement (NIR) for Sugarcane**

Sugarcane, being a long-duration and high-biomass crop, exhibits significantly higher consumptive water use than most seasonal crops. In the present study, the seasonal NIR for ratoon sugarcane is 1383.2 mm, more than double that of cotton. This elevated requirement reflects sugarcane's extended growth cycle, large leaf area index, and high transpiration rates under the hot climatic conditions of the Middle Awash Basin. Literature reports similarly high NIR values ranging between 1200–1800 mm in semi-arid irrigation systems, depending on climate and crop variety (Inman-Bamber & Smith, 2005).

The persistent high NIR throughout the growth period corresponds to sugarcane's physiological characteristics. The crop maintains substantial ETc during tillering, grand growth, and ripening stages, with the grand growth stage showing peak demand due to rapid internode elongation and biomass accumulation. The limited contribution of effective rainfall (456.8 mm out of 471.5 mm total rainfall) is insufficient to offset the crop's intense water requirement, reinforcing sugarcane's dependence on reliable irrigation throughout its cycle (FAO, 2012). This is especially important in the Awash Basin, where rainfall is poorly distributed, erratic, and often negligible during critical growth months.

### 4. Gross Irrigation Requirement (GIR) for Sugarcane

The Gross Irrigation Requirement (GIR) for sugarcane is estimated at 1975.9 mm, which is substantially higher than its NIR due to the integration of system-level inefficiencies. The difference between GIR and NIR (approximately 592.7 mm) reflects significant water losses that must be compensated by additional withdrawals from the irrigation network. These losses arise from seepage in unlined canals, evaporation, operational wastage, and non-uniform water application—conditions widely documented in Ethiopian surface irrigation schemes (Awulachew et al., 2010; IWMI, 2011).




| Date | Day | Stage | Rain | Ks | Eta | Depl | Net Irr | Deficit | Loss | Gr. Irr | Flow |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | mm | fract. | % | % | mm | mm | mm | mm | l/s/ha |
| 5 Jun | 36 | Dev | 0.0 | 1.00 | 100 | 66 | 197.1 | 0.0 | 0.0 | 281.6 | 0.91 |
| 29 Jul | 90 | Dev | 0.0 | 1.00 | 100 | 67 | 200.0 | 0.0 | 0.0 | 285.7 | 0.61 |
| 22 Sep | 145 | Mid | 0.0 | 1.00 | 100 | 65 | 196.0 | 0.0 | 0.0 | 280.0 | 0.59 |
| 28 Oct | 181 | Mid | 0.0 | 1.00 | 100 | 67 | 200.6 | 0.0 | 0.0 | 286.6 | 0.92 |
| 3 Dec | 217 | Mid | 0.7 | 1.00 | 100 | 66 | 197.7 | 0.0 | 0.0 | 282.5 | 0.91 |
| 10 Jan | 255 | Mid | 0.0 | 1.00 | 100 | 66 | 196.6 | 0.0 | 0.0 | 280.8 | 0.86 |

Figure 4-10: Net and Gross Irrigation Requirement (NIR, GIR) for sugarcane crop

The GIR for sugarcane also illustrates the vulnerability of the crop to water shortages. Given the scheme's overall irrigation efficiency of only 42%, the effective water reaching the root zone is far below the diverted volume, creating a mismatch between crop demand and actual supply. Sugarcane's high GIR, combined with the scheme's low conveyance and application efficiencies, helps explain the salinity buildup and yield constraints observed in downstream sections. FAO guidelines emphasize that when GIR significantly exceeds NIR—as seen here—substantial improvements in canal lining, field leveling, and irrigation scheduling are essential to safeguard crop productivity and water sustainability (FAO, 2010).

#### 4.7.4 Comparison of Actual Water Application with CROPWAT Results

The comparison between CROPWAT-estimated irrigation requirements and the actual field water application in the Amibara Irrigation Scheme reveals substantial differences arising from system inefficiencies and field-level constraints. CROPWAT provides theoretical crop water requirements based on reference evapotranspiration ($ET_o$), crop coefficients (Kc), and soil water balance under ideal irrigation conditions using the FAO Penman–Monteith method (Allen et al., 1998). These calculations assume that water reaches the field with minimal losses, that application is uniform, and that drainage conditions are adequate. However, real irrigation systems particularly surface irrigation in semi-arid regions frequently perform below these assumptions (FAO, 2012). Thus, while CROPWAT-generated net irrigation requirement (NIR) and gross irrigation requirement (GIR) for cotton (613 mm and 876 mm, respectively) and sugarcane (1383 mm and 1976 mm) appear reasonable under ideal conditions, the actual water delivered to the crops is significantly lower.

One of the primary reasons for the mismatch is the low conveyance efficiency observed in the scheme's canal network. CROPWAT assumes conveyance efficiency at or above 80%, consistent with international design standards for lined canals (FAO, 1986). In contrast, Amibara's unlined canals exhibit efficiencies of only 62–72%, and even the secondary canals show further deterioration with efficiency values as low as 62.5%. Such seepage, leakage, and structural losses substantially reduce the volume of water available at field inlets. Similar findings have been widely reported in African and Asian surface irrigation systems, where unlined earthen canals commonly achieve conveyance efficiencies of only 50–70% (Perry, 2007; Awulachew et al., 2010).

Consequently, even when the irrigation authority releases volumes that match CROPWAT GIR, farmers particularly those at the tail end—receive far less water than the model assumes.

In addition to conveyance losses, field-level application efficiency further exacerbates the discrepancy between modelled and actual irrigation. The measured application efficiency in Amibara is 58%, indicating that 42% of the water applied to fields is lost through deep percolation, runoff, or uneven infiltration. CROPWAT, however, uses an assumed application efficiency of about 70% for surface irrigation to compute GIR under standard FAO procedures (FAO, 1998). The lower actual efficiency in the scheme is attributed to inconsistent soil texture, poor field leveling, prolonged irrigation times, and improper cut-off practices. These challenges are characteristic of smallholder surface irrigation systems in semi-arid climates and are known to significantly reduce the effective water available for crop evapotranspiration (Molden & Gates, 1990; Adugna et al., 2019). Because of these inefficiencies, upstream farmers tend to over-irrigate to compensate for perceived shortages, whereas downstream farmers receive insufficient amounts, creating spatial disparities in crop water availability despite satisfying CROPWAT GIR on paper.

Storage efficiency (71%) and distribution uniformity (62%) also indicate that the root-zone water available to crops is considerably lower than what CROPWAT assumes. The model presumes uniform wetting and homogeneous soil conditions; however, the scheme's soils range from clay loam in upper areas to sandy loam and sand in lower areas. Such heterogeneity results in rapid deep percolation in sandy zones and excessive ponding in finer-textured sections. Similar observations are reported by Hillel (2004), who notes that spatial variation in infiltration capacity contributes to uneven soil moisture distribution, reducing effective root-zone storage. Low distribution uniformity (<70%) is particularly detrimental because it guarantees that a portion of the field remains under-irrigated even when the average applied irrigation matches the calculated requirement (Howell, 2001). These conditions help explain the observed crop stress, especially in downstream sugarcane and cotton fields, even when farmers follow irrigation schedules derived from CROPWAT outputs.

Drainage limitations and salinity buildup further widen the gap between modeled and actual water availability. CROPWAT assumes adequate drainage and effective leaching, but field measurements show waterlogging levels of up to 22% and soil salinity (ECe) ranging from 3.7 to 4.1 dS/m in downstream areas values approaching or exceeding thresholds for cotton and sugarcane yield reduction (Ayers & Westcot, 1985). The shallow groundwater table (0.55–0.65 m) in the lower section contributes to capillary rise and surface salt accumulation, further reducing crop water uptake even when soil moisture appears sufficient. Numerous studies confirm that inadequate drainage systems and high evaporative demand in arid irrigation schemes amplify salinity problems, significantly lowering the effective irrigation requirement beyond what CROPWAT predicts (Rhoades et al., 1992; Tanji, 1990). Thus, part of the irrigation depth that CROPWAT considers available for ETc is actually lost to salinization and waterlogging, making the real net irrigation requirement much higher.

For sugarcane, whose water demand is consistently high throughout its long growing cycle, the gap between CROPWAT requirements and actual field application becomes even more pronounced. Sugarcane ETc frequently exceeds 60–65 mm per ten days during the grand growth stage, requiring a highly reliable supply of irrigation water (FAO, 2012). However, due to low conveyance, poor uniformity, and drainage constraints, the effective water that sugarcane receives is far below the modelled requirement. Similar observations have been documented in Egypt, Ethiopia, and India, where sugarcane production in semi-arid irrigation systems often suffers from mid-season water deficits despite apparently adequate scheduling based on ET models (El-Shafie, 2014; Melesse et al., 2019). These deficits restrict stalk elongation and sucrose accumulation, explaining the lower productivity reported in Amibara's downstream sections.

Overall, the comparison clearly demonstrates that CROPWAT estimates provide a baseline for ideal irrigation requirements but do not account for real-world system constraints such as conveyance losses, poor field application, limited storage, poor distribution uniformity, waterlogging, soil salinity, and shallow groundwater. These factors significantly reduce the volume of irrigation water that ultimately becomes available for crop evapotranspiration. Consequently, although CROPWAT-derived GIRs for cotton and sugarcane appear adequate under theoretical conditions, the effective irrigation delivered to fields—particularly in downstream areas—is substantially lower. This justifies the field-observed water shortages, yield variability, salinity buildup, and drainage issues. The findings underscore the importance of combining CROPWAT-based planning with field performance assessments to design realistic irrigation schedules and improve water productivity in semi-arid irrigation schemes.

# CHAPTER FIVE

# 5 CONCLUSION AND RECOMMENDATIONS

## 5.1 Conclusions

This study set out to evaluate the irrigation and drainage performance of the Amibara Irrigation Scheme, with the aim of identifying key technical, operational, and environmental factors affecting water use efficiency and agricultural productivity. The assessment revealed that the current irrigation system operates below expected standards due to substantial conveyance losses, poor application practices, and non-uniform water distribution across the command area. These challenges hinder the effective delivery and productive use of irrigation water, particularly in downstream sections of the scheme.

The study also examined drainage conditions and found that inadequate drainage infrastructure, shallow groundwater levels, and inefficient water removal contribute to persistent waterlogging and soil salinity problems. These constraints negatively affect soil health, crop performance, and the long-term sustainability of irrigated agriculture in the area. The analysis of soil characteristics further highlighted spatial variability that influences water retention, infiltration, and irrigation response, underscoring the need for location-specific management.

Finally, the comparison between actual irrigation practices and crop water requirements indicated that the current system does not consistently meet crop needs due to operational inefficiencies and inequitable water distribution. Insights from farmers and key informants confirmed systemic issues related to maintenance, governance, and water allocation.

Overall, the research concludes that both irrigation and drainage systems in the Amibara Scheme require significant technical and managerial improvements. Without corrective interventions, the scheme will continue to face declining water productivity, worsening soil conditions, and reduced agricultural output.

## 5.2 Recommendations

Based on the findings of this study, several measures are recommended to improve the performance and sustainability of the Amibara Irrigation Scheme. The recommendations focus on addressing both technical and institutional challenges, enhancing water use efficiency, and mitigating drainage-related problems. Implementing these measures will support equitable water distribution, maintain soil health, and optimize crop productivity. Key recommendations include:

- Rehabilitate and properly maintain the irrigation and drainage infrastructure to improve water conveyance, application efficiency, and overall system performance.
- Strengthen water governance and institutional capacity, particularly the Water Users Association, to ensure equitable water distribution and effective scheme-level management.
- Improve field-level water and soil management practices, including better irrigation scheduling, field leveling, and salinity mitigation to enhance crop performance and soil health.
- Establish regular monitoring and data-based decision-making systems for groundwater levels, salinity conditions, and irrigation performance to support timely and adaptive management.

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## Appendix

## 6 FGD Questions (Farmers)

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**A. Water Availability and Distribution**

1. How would you describe the availability of irrigation water in your area?
2. Do all farmers receive water equally, or are there differences between upstream and downstream plots?
3. What problems do you face in accessing water according to the irrigation schedule?
4. How often do you have to wait longer than your scheduled turn to receive water?

**B. Drainage and Soil Conditions**

5. Have you observed areas in your farm that remain waterlogged for long periods?
6. Have you noticed any signs of soil salinity, such as stunted growth, yellowing of crops, or reduced yield?
7. Which areas of the command (Upper, Middle, Lower) are most affected by waterlogging and salinity?

**C. Maintenance and Infrastructure**

8. How often are canals cleaned and gates or other structures repaired?
9. What challenges do you face in performing routine maintenance of the irrigation system?
10. Are there collective efforts among farmers to maintain canals, and if so, how effective are they?

**D. Agricultural Impacts**

11. How do water availability and drainage problems affect your crop yields?
12. Have you abandoned any plots due to waterlogging or salinity issues?

## KII Questions (Experts, WUA Leaders, Extension Agents, Scheme Managers)

**A. Irrigation System Performance**

1. How would you assess the overall water delivery performance of the main and secondary canals?
2. What factors contribute to variability in water supply along the command area?
3. How is water rotation enforced among farmers, and what challenges exist in compliance?

**B. Drainage and Salinity Management**

4. What are the current drainage capacities in the scheme, and are they sufficient to prevent waterlogging?
5. Have you observed increasing soil salinity? If so, what areas are most affected and why?
6. What measures (e.g., leaching, flushing irrigation) are being taken to control salinity, and are they effective?

**C. Maintenance and Institutional Management**

7. How often are maintenance activities performed on canals and gates?
8. What are the main constraints for implementing routine maintenance?
9. How active and effective are Water Users Associations in managing water distribution and infrastructure?

**D. Farmer Capacity and Training**

10. What training programs exist for farmers on irrigation scheduling and water management?
11. How do farmers' irrigation practices (over- or under-irrigation) affect overall scheme performance?

**E. Socio-Technical Challenges**

12. Are there external factors (e.g., livestock, floods, vandalism) that affect canal operation?
13. How does governance, funding, and technical support influence irrigation and drainage effectiveness?