Mekelle University

Ethiopian Institute of Technology – Mekelle

Faculty of Civil and Environmental Engineering

MSc in Civil Engineering (Irrigation and Drainage Engineering)

Sustainability Assessment of Small-Scale Irrigation Scheme, in Gumselassa Irrigation Scheme, Southeastern Zone, Tigray Region, Northern Ethiopia.

By

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A Master's Thesis Submitted to the Faculty of Civil and Environmental Engineering in
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in
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Advisor: Haddush Goitom (Phd)
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Board of Examiners' Approval

We, the undersigned members of the Board of Examiners for the final open defense of **Mebrahtom Leake Mesfin**, have read and evaluated the thesis entitled "**Sustainability Assessment of Small-Scale Irrigation Scheme, in Gumselassa Irrigation Scheme, Southeastern Zone, Tigray Region, Northern Ethiopia**" and assessed the candidate's performance. We hereby certify that the thesis has been accepted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering, with specialization in Irrigation and Drainage Engineering.

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Declaration

I declare that all information on this thesis entitled **“Sustainability Assessment of Small-Scale Irrigation Scheme, in Gumselassa Irrigation Scheme, Southeastern Zone, Tigray Region, Northern Ethiopia”** is my own work and has been obtained and presented according to the academic rules and ethical conduct under the guidance. I’m also the principal author of this research work.

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Dedication

This thesis manuscript is dedicated to my family: Father Keshi Leake Mesfin, Mother Kbra Semere, and my wife Embeba Redae for their endless and generous support.

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Abstract

Small-scale irrigation plays a crucial role in addressing the problems of food insecurity, poverty reduction, and adapting to climate variability in Ethiopia. However, many irrigation schemes operate below their design capacity due to multidimensional challenges, raising concerns about their long-term functionality and sustainability. This study tried to assess the sustainability of the Gumselassa community-managed small-scale irrigation scheme in Tigray using the FAO's Sustainability Assessment of Food and Agriculture (SAFA) framework. In addition to this, the long term effects of irrigation practices on soil properties were examined using selected soil health indicators. A mixed- methodological approach was employed, combining household surveys (n = 74), focus group discussions, key informant interviews, field measurement and observations, and laboratory analysis of 36 soil samples from two soil depths (0-30, 30-60). The long-term effects of irrigation on soil health was done by comparing to the nearby non-irrigated farm lands. The overall sustainability score of the irrigation scheme was 2.98, which indicates a moderate sustainability level with moderate good governance (2.92), good environmental integrity (3.67), moderate economic resilience (2.81), and moderate social well-being (2.50). The soil health index was higher on irrigated fields (0.88) than that of rain-fed fields (0.65), which was 35.4% higher at (0-30) cm soil depth and (0.83) on irrigated fields and (0.61) than the rain fed fields at (30-60) cm soil depth, which was 36.1% higher at irrigation field than the rained fields. Reservoir siltation is the main challenge for the sustainability of the irrigation scheme. Inclusive decision making, community participation and integrated management practices through the irrigation scheme, reservoir and catchment area will ensure the sustainability of the irrigation scheme.

Keywords: Small-scale irrigation, Sustainability, SAFA framework, Soil health.

Table of contents

List of Figures

List of Tables

Abbreviations and Acronyms

ANOVA	Analysis of Variance
ArcGIS	Arc Geographic Information System
ASTM	American Society for Testing and Materials
EC	Electrical Conductivity
FAO	Food and Agriculture Organization
GPS	Global Positioning System
LSD	Least Significant Difference
pH	Percentage of Hydrogen
SAFA	Sustainability Assessment of Food and Agriculture System
SAR	Sodium Adsorption Ratio
SHI	Soil Health Index
SOC	Soil Organic Carbon Content
SPSS	Statistical Package for Social Sciences
SSA	Sub-Saharan African
SSI	Soil Structural Stability Index
SSIS	Small-Scale Irrigation Schemes
TP	Total Porosity
UNESCO	United Nations Educational, Scientific, and Cultural Organization
USDA	United States Department of Agriculture
WUA	Water User Association

1. Introduction

1.1. Background of the Study

Small-scale irrigation schemes (SSIS) are vital for improving food security, increasing income, and adapting to climate change in Ethiopia. Small-scale irrigation in East Africa comprises low-cost, often manual systems that utilize surface water sources, such as rivers and rainwater harvesting, to improve the productivity of smallholder farmers with simple, gravity-fed, or basic mechanized technologies (Nakawuka et al., 2018). Sub-Saharan African (SSA) community-managed irrigation schemes faced common problems: lack of access to financial capital, technical failure of physical infrastructure, limited market availability and extension services, failure of managing organizations, low level of technology adoption, and declining water availability and quality (Bjornlund et al., 2020). Furthermore, small-scale irrigation schemes in Sub-Saharan Africa face critical water management challenges and are proven to be highly unsustainable (Mutambara et al., 2016). Most of the developed irrigation projects in SSA are performing below their design expectations and are depleted before their design lifetime due to complex problems of technical, socio-economic, institutional, and environmental aspects (Embaye et al., 2020).

Ethiopia is regarded as having food insecurity due to its very unpredictable and variable rainfall, as well as its high likelihood of both intra-seasonal dry spells and annual droughts (Amede, 2015). The Ethiopian government has made the development and promotion of small-scale irrigation a top priority to address the issues of food insecurity and water scarcity (Hagos et al., 2011). Irrigation is believed to be the main agricultural practice that would be useful to increase land productivity by producing market-oriented crops during the dry period (Haile, 2015). Due to ongoing efforts by the public, governmental, and non-governmental groups, irrigation is currently becoming more widespread (Tesfahunegn et al., 2016). Ethiopian SSIS, commonly defined as irrigation systems with a command area of less than 200 hectares (Haile, 2015). Ethiopia's small-scale irrigation schemes are underperforming compared to their design, which leaves large areas unirrigated (Yohannes et al., 2017a). Awulachew et al., (2011) reported that less than 50% of the expected irrigation users have benefited from irrigation schemes developed in Ethiopia due to watershed degradation, lack of sustainable funding for operation and maintenance, failure of hydraulic structures, and poor extension services of the irrigation schemes.

Studies indicate that Tigray has an estimated irrigation potential of approximately 250,000 hectares, most of which is suitable for small-scale irrigation development (Hagos, 2005). By 2010, the total irrigated area in the region was estimated at about 83,000 hectares, with more than 70% of this area accounted for by small-scale irrigation schemes (MoFED, 2010). Over the past decades, more than 100 small-scale irrigation schemes have been constructed across the region, benefiting over 22,000 farming households, mainly through reservoir-based and river diversion systems (Hagos et al., 2011). Despite these investments, the performance of many schemes remains below their design capacity (Yohannes et al., 2017a). Key challenges include reservoir sedimentation resulting from catchment degradation, weak institutional arrangements, inadequate operation and maintenance, and limited technical support services (Berhe et al., 2022). Similar to many long-established small-scale irrigation schemes in Tigray, Gumselassa has experienced challenges related to reservoir sedimentation, water management inefficiencies, and institutional sustainability, which pose significant risks to its long-term performance (Yohannes et al., 2019). Due to these challenges Gumselassa was selected as a suitable site for assessing the sustainability of small-scale irrigation schemes and for evaluating the long-term effects of irrigation practices on soil health.

Studies adopt the sustainability assessment of food & agriculture Systems (SAFA) method to evaluate the sustainability of irrigation systems in different countries (Olsson et al., 2014). SAFA was developed by the FAO (Food and Agriculture Organization of the United Nations) in 2012 to evaluate the sustainability of agricultural systems and provide private and public entities with a set of indicators that are useful to identify challenging issues and identify alternative solutions (FAO, 2013). Some studies show a comparison between the SAFA methodology and other tools to assess sustainability in irrigation (De Olde et al., 2016; Gasso et al., 2015), and the authors have reported that the wide range of topics measured by the SAFA methodology is a strong point, but at the same time, it can determine an excess of qualitative information. SAFA is a multi-criteria sustainability assessment tool (FAO, 2014) that was developed for analyzing the sustainability of agriculture sectors with four dimensions, namely, governance, environment, economy, and social (Bonisoli et al., 2019; Soldi et al., 2019). A wide spectrum of sustainability issues is considered in the evaluation, along with the fact that it is easy for producers and decision-makers to implement and understand, and offers the consequential possibility of identifying precise measures to enhance sustainability in the short term (Bonisoli et al., 2019).

Many of the irrigation sustainability aspects are connected to the condition of the soil (Gelaw et al., 2015). A combination of the physical, chemical, and biological characteristics of soil that are easily adaptable to changes in soil conditions is known as soil health (Weldewahid et al., 2023). Changes in crop rotation, application frequency, management practices, and chemical dosages applied to the soil result in changes to the physical, chemical, and biological properties of the soil (Cardoso et al., 2013). The goal of sustainable irrigation is to provide for current requirements without lowering the potential for future generations' productivity (Alaoui et al., 2022). According to Gebeyehu & Soromessa (2018) and Olsson et al. (2014), the increased input of crop residue from irrigation practices has a positive effect on the soil's organic carbon content. On the other hand, Getaneh et al. (2007) indicated that irrigation affects negatively several soil properties, particularly soil organic carbon content. Therefore, this study tried to a) analyze the sustainability of a community-managed small-scale irrigation scheme using FAO’s SAFA framework following a bottom-up approach and b) evaluate the long-term effects of irrigation practices on selected soil properties.

1.2. Problem of Statement

The success of current and future small-scale irrigation projects aimed at reducing poverty and progressively ensuring food security depends mainly on sustainability (Asmamaw et al., 2021; Hagos, 2005). However, in terms of social, economic, and environmental concerns, as well as effective governance, the sustainability of irrigation systems is being questioned (Hagos, 2005). The term "sustainability" refers to the conservation, utilization, and management of natural resources to ensure their continued availability for future generations (FAO, 2013). Sustainability can also refer to a condition that allows the needs of the present generation to be satisfied without compromising the ability of future generations (Borsato et al., 2020). Indicators that represent an irrigation system's performance from both an economic viability and loss-free water delivery perspective are frequently used to characterize the sustainability of irrigation systems (Juwana et al., 2012).

Small-scale irrigation schemes are expected to play a crucial role to achieving food security, adapting climate change, and raising household incomes of smallholder farmers (Amede, 2015). Though investments and efforts have been made for the development of small-scale irrigation schemes in Ethiopia, many of these schemes are performing far below their design expectations, leaving huge areas and many beneficiaries out of irrigation (Berhe et al., 2022). The underperformance and failure of small scale irrigation schemes in Ethiopia is attributed to issues with design, implementation, operation, and maintenance (Berhe et al., 2022; Yami, 2013; Yohannes et al., 2019). Many community-managed irrigation schemes are not viable for the duration of their design due to poor scheme wide management practices the results in soil salinity and waterlogging (Gebremeskel et al., 2018). Sustainable irrigation schemes are essential to reducing poverty and progressively ensuring food security of small holder farmers (Asmamaw et al., 2021; Hagos, 2005). Beneficiary engagement and management concerns must indeed be taken into account to ensure sustainable output from irrigated schemes; otherwise, the scheme's sustainability may be endangered (Yohannes et al., 2017a).

Though much research has been done on the management practices of community-managed small-scale irrigation schemes, the sustainability issues of those schemes is not addressed comprehensively. Sustainability of SSIS in Tigray was assessed following a top-down approach that extends from experts to irrigation scheme committees (Berhe et al., 2025). This study uses a bottom-up approach to identify locally prioritized management strategies to ensure the functionality and sustainability of the irrigation scheme. Additionally, the soil health of the irrigated area was compared with nearby non-irrigated farmlands to evaluate the long-term effects of irrigation practices on soil properties. Hence, this study is intended to address the sustainability issues of community managed irrigation scheme by integrating a bottom-up and field measurement approaches by identifying existing problems and users prioritized management practices.

1.3. Objectives

1.1.1. General Objective

The general objective of this study is to assess the sustainability of small-scale irrigation schemes using sustainability indicators.

1.1.2. Specific Objectives

1. Assessing the sustainability of community-managed small-scale irrigation schemes using the SAFA framework through a bottom-up approach.
2. Evaluating the effects of small-scale irrigation practices on selected soil properties using soil health indicators.

3. To assess the sustainability challenges and recommend alternative solutions for the Gumselassa small-scale irrigation scheme.

1.4. Research Questions

1. How sustainable are community-managed small-scale irrigation schemes in Tigray?
2. Does irrigation practices affect soil health?
3. What alternative options are there to ensuring the sustainability challenges of small-scale irrigation schemes?

1.5. Scope and Limitation of the Study

This study assessed the sustainability of Gumselassa small-scale irrigation using the SAFA tool and the sustainability of the irrigation scheme regarding the four dimensions, which are good governance, environmental integrity, economic resilience, and social well-being. The effect of irrigation practice on selected soil health indicators and its contribution to the sustainability of the irrigation scheme were assessed. 74 sample household heads were selected randomly from the household lists prepared in the study area to analyze the sustainability of the irrigation scheme. It focused on household heads who have been using irrigation for agricultural production from the dam water. Thirty-six soil samples were collected from the study (18 from irrigable land and 18 from rain-fed agriculture) to analyze the effect of irrigation practice on soil health.

The study has been conducted in Woreda Hintalo-Wejerat, in the selected sample area of Gumselassa small-scale irrigation schemes. The following conditions can be considered limitations of the study. This study is limited to assessing the sustainability of Gumselassa small-scale irrigation. As compared to the study population of 350 irrigation households, the sample household, limited to 74, may affect the degree of representation. There are indeed different woreda where irrigation is practiced in the Tigray region; had there been limited resources (including workforce, time, and finance), this study would have been conducted in the Gumselassa irrigation scheme. To conduct this study, data have been collected through field laboratory tests, field observation, household questionnaires, interviews, and focus group discussions.

2. Literature Review

2.1. Irrigation Development and Management Practice in Ethiopia

In Ethiopia, irrigation has been practiced since ancient times for producing subsistence food crops. However, modern irrigation systems were started in the 1960s with the main goal of producing industrial crops in the Awash Valley (Hagos et al., 2011). Ethiopia has around 3.7 million hectares of estimated total potential irrigable land (Nakawuka et al., 2018). Nowadays, significant focus is given to the development of small-scale irrigation schemes to overcome food insecurity and rural poverty (Oates et al., 2020; Yami, 2013).

Ethiopian irrigation schemes were classified in three ways (Table 2.1): (1) size, (2) technology use, and (3) management system (Hagos et al., 2011). The first classification, which is based on the size of the command area of the scheme, can be classified as small (less than 200 ha), medium (200 to 3,000 ha), and large-scale (over 3,000 ha) schemes (Haile, 2015). The SSIS can be further categorized into two main types: modern schemes and traditional schemes (Berhe et al., 2022). The water control and diversion structures in modern schemes are typically fixed; in contrast, traditional schemes do not have fixed diversion structures since their diversion weirs are usually constructed from local materials and are rebuilt annually. The second classification is based on the technology used to control and divert water, which has implications on water availability, water loss, establishment, and operation & maintenance costs. The third classification is based on the management system, namely traditional, modern, public, and private (Yami, 2013). (Hagos et al., 2011) reported that around 103 irrigation schemes were developed in Tigray regional state, with a total of 4,932.8 hectares of irrigated area, of which 3,956.8 hectares are small-scale and 976 hectares are medium-scale, with 22,632 beneficiaries reported. Reports on the current status of irrigation development are different and conflicting with each other.

Irrigation development is considered an important cornerstone to improve agricultural productivity in many African countries, as well as in Ethiopia. Irrigation development is a key to sustainable and reliable agricultural development, which leads to overall development in Ethiopia (Berhe et al., 2022). Despite the government’s commitment and effort in investing in irrigation development, farmer-managed irrigation schemes have performed below their design expectations in Ethiopia (Hagos et al., 2011; Haile, 2015). The Ethiopian irrigation scheme’s failure and under-performance are mostly related to problems during design and implementation and/or operation and maintenance, low level of community participation during project study and design phases (Haile, 2015; Tesfahunegn et al., 2016), lack of site-specific reliable hydrological data (Embaye et al., 2020; Gurmu et al., 2019), high construction costs Yigzaw et al., (2019) and delayed project completion Annys et al., (2020) are among the major problems during the design and implementation phases of irrigation projects. A top-down approach that excludes local experiences and community needs is commonly practiced during irrigation development (Berhe et al., 2022). Due to this approach, community participation is highly limited during project initiation and implementation phases Annys et al., (2020). In practicing irrigation development, gender mainstreaming and participation are often ignored (Yami, 2013).

The functionality and sustainability of small irrigation schemes are poor water management and institutional arrangements Yohannes et al., (2017a), excessive siltation, poor agronomic and water management practices, and the failure of local institutions to sustainably manage the small-scale irrigation schemes (MoFED, 2012). This has resulted in water and yield loss, and undesirable environmental impacts (Yohannes et al., 2017a). The total irrigated land in Tigray increased from 4000 ha in 2004 to 83,000 ha in 2009 (MoFED, 2010). However, poor irrigation water management has been one of the major factors challenging the success and sustainability of these efforts in the region (Hagos, 2005). Small-scale irrigation schemes face common problems with their different water sources, which disturb their performance and sustainability (Berhe et al., 2022). Over-application of irrigation water beyond crop demands is a common problem in irrigation schemes whose source of water is from reservoirs, diversion headworks, lakes, and groundwater (Adela et al., 2019).

Table 2.1. Classification of irrigation schemes in Ethiopia

Classification Criteria	Category	Description	References
Size of command area	Small-scale	Command area less than 200 ha.	(Haile, 2015)
	Medium scale	Command area 200 to 3000 ha.	
	Large scale	Command areas greater than 3000 ha	
History of establishment and management system	Traditional	Communal management system, diversion weirs are not permanent and are constructed with local material, initiated and operated by irrigators.	(Berhe et al., 2022) (Yami, 2016)
	Modern communal	Communal management system, robust concrete diversion structures or dams, lined main canals, constructed by government or development partners, managed and operated by community elected members and/or water users association (WUA) or cooperatives, with the support of government agencies	
	Modern private	Permanent diversion structures, privately owned	
	Modern public	Constructed, operated, and maintained by government enterprises, mostly large-scale schemes for sugarcane cultivation	

2.2. Role of Small-Scale Irrigation in Food Security

Drought and climate-related hazards have severely affected Ethiopia, leaving millions of people without food every year. Irrigation plays a key role in stabilizing agricultural production and mitigating the negative impacts of variable or insufficient rainfall, and it also has the potential to increase both yields and cropping intensity (Ahmed, 2019). According to some, one of the most fundamental ways to reduce poverty and enhance food security in Ethiopia is through irrigation (Gebrehiwot et al., 2015). A strategy used to reduce poverty, stabilize agricultural output and lessen the detrimental effects of irregular rainfall, ensure food security for households, and enhance communal livelihood situations is small-scale irrigation (Assefa et al., 2022). If efforts are focused on revitalizing and upgrading the current traditional small-scale irrigation schemes, with support to enhance access to input supply, output marketing, and extension to facilitate access to information and innovations, irrigation investments can have broader effects on food security and poverty reduction (Ahmed, 2019).

Water is considered by the current Ethiopian administration as an entry point to development. It is identified as an important policy instrument to stimulate economic growth and rural development in general and in ensuring food security in particular (Hagos et al., 2011). Agriculture is the foundation of rural communities' livelihoods, and irrigation systems are crucial policy alternatives selected by the government to reduce poverty and ensure food security in Ethiopia (Habtamu et al., 2014). In terms of income, irrigation users have a strong impact over non irrigation users (Gebrehiwot et al., 2015). According to Ahemed (2019) the crop production under irrigated area is about twice that of under rain-fed farming systems, and the household income and consumption is also much higher in irrigated farms than in rain-fed.

2.3. Sustainability of Irrigation Schemes

Sustainability is a topic that is at the center of current discussions in the political, economic, social, and environmental fields Soldi et al., (2019),which is needed an integral and multidisciplinary vision for its analysis (Bonisoli et al., 2019; Leknoi et al., 2023). Hagos, (2005) reported that to achieve sustainable production from irrigated schemes, the managerial and participation of beneficiaries' issues must indeed be taken into account, otherwise the sustainability of the scheme will be endangered. Community involvement, which is characterized as involving scheme users in the decision-making procedures for the planning and implementation of irrigation projects, is essential to the irrigation schemes' sustainability (Asmamaw et al., 2021).

The sustainability of irrigation is a major concern for researchers, farmers, and policymakers (Yohannes et al., 2017a). Although the Ethiopian government is building a variety of water harvesting structures to solve the country's water scarcity, sustainability is not given as much consideration. According to Hagos (2005), the current performance of the irrigation scheme is environmentally unsustainable. Most Ethiopian institutions that manage irrigation are challenged by multiple problems, such as inferior institutional set-ups, limited financial capacity, low managerial skill, unclear physical boundaries, and managerial roles that remain unsolved even after the modernization of traditional small-scale irrigation schemes (Berhe et al., 2022). According to reports of many researchers, community-managed small-scale irrigation schemes in Tigray are performing far below their design expectations due to management practices, water scarcity, waterlogging, salinity other related problems, questioning for sustainability of irrigation schemes (Bekele & Tilahun, 2007; Berhe et al., 2022; Yohannes et al., 2019). Adequate policy solutions could be adopted by evaluating irrigation's sustainability (strong and poor) using appropriate sustainability indicators (Borsato et al., 2020).

2.3.1. Institutional/Governance Sustainability of Irrigation Scheme

In many of the small-scale irrigation schemes in Ethiopia, scheme managing institutions are either unavailable or weak (Berhe et al., 2022). Within small-scale irrigation projects, water user associations (WUAs) are seen as crucial intermediaries between outside entities and the surrounding community (Yami, 2013). WUAs are registered as cooperatives in most schemes (Oates et al., 2020; Yami, 2013) with expectations to abide by the rules and regulations of the cooperatives agency. According to research results and reports, the major reasons risking the sustainability of irrigation schemes are poor water management and institutional arrangements (Yohannes et al., 2017a), excessive siltation, poor agronomic and water management practices, and the failure of local institutions to sustainably manage the small-scale irrigation schemes (MoFED, 2012).

Experiences in managing traditional small-scale irrigation schemes with community by-laws enforced by locally elected water distributors contribute to the existence of centuries-old traditional irrigation schemes (Yami, 2013); while many newly developed small-scale irrigation schemes in the same area failed due to low community participation, non-transparent communication, and the top-down approach in setting by-laws for WUAs (Annys et al., 2020). Insufficient WUA functioning results in poor community by-law enforcement, insufficient monitoring, and ineffective irrigation system control (Amede, 2015). Most of Ethiopia's small-scale irrigation schemes, community by-laws set rules for water distribution and allocation, infrastructure maintenance, canal cleaning, fee collection, settling disputes among beneficiaries, and monetary sanctions for by-law-violating members (Yami, 2013). In some irrigation schemes, the water use rights of individuals are dependent on owning irrigation land near the irrigation scheme (Berhe et al., 2022), and membership in cooperatives is restricted to land-holders. In such small-scale irrigation schemes, landless sharecroppers' participation in WUA committee positions is highly restricted (Oates et al., 2020).

In Ethiopia, decisions about irrigation water management differ from one irrigation scheme to another, even though individual users decide on crops and irrigation technologies at their farm level. The decision-making actors in the management and operation of community irrigation schemes in Ethiopia are individual users Berhe et al., (2022), community-elected water fathers Abera et al., (2019), and WUAs (Adela et al., 2019). In some irrigation schemes, operation and maintenance decisions are made by more than one of the decision-making actors without clear boundaries and management roles (Amede, 2015; Mulugeta, 2019). During the decision-making process, farmers are also reluctant to freely express their opinions due to the influence of local political leaders and experts (Abera et al., 2019). According to Amede (2015) the development of physical infrastructure receives more funding and attention than social and institutional issues, with a belief that farmers will be the ones to maintain and operate the infrastructure.

2.3.2. Environmental and Technical Sustainability of Irrigation Schemes

Irrigated agriculture is a key policy issue in many countries since it is the major user of water and land resources, while it also affects environmental sustainability (Özerol et al., 2012). In many irrigation schemes of arid and semi-arid areas, crop yields are reduced and even land is abandoned due to environmental hazards such as waterlogging, salinity, erosion, and sedimentation of reservoirs (Berhe et al., 2022; Habtu et al., 2020). Salinization of irrigation schemes is an ever-increasing problem in the Ethiopian Rift Valley (Awulachew et al., 2011). This is due to the utilization of saline lakes for irrigation (Awulachew et al., 2007), poor irrigation management practices (Abera et al., 2019), lack of proper drainage facilities (Berhe et al., 2022), and groundwater rise due to over-irrigation (Gebrehiwet et al., 2021). According to (Abera et al., 2019; Oates et al., 2020; Yohannes et al., 2017b), salinization is also among the main problems that constrain the yield production of community-managed irrigation schemes located outside of the Rift Valley basin. After assessing the salinity level of nine irrigation schemes in the Tigray region, Gebremeskel et al. (2018) reported that more than 60% of community-managed small-scale irrigation schemes are affected by salinity problems. In Ethiopia, the main causes of huge potential areas remaining unirrigated are increasingly due to the combined effects of salinity and waterlogging issues. The environmental impacts of small-scale irrigation systems may be reduced by implementing appropriate irrigation water management, operating and maintaining them, and managing drainage infrastructures properly.

In developing countries, many of the irrigation strategies are traditional and are based on farmers' local knowledge (Asmamaw et al., 2021). This indicates that when water is available, farmers irrigate their fields without any gauging mechanism, and crops are watered more than they require (Berhe et al., 2022). Most of the farmers irrigate their fields by flooding, though flood irrigation is known to be a traditional irrigation method due to its inefficient water use (Beyene et al., 2018). Farmers do not get enough expert advice regarding when, how, and how much water to irrigate (Asmamaw et al., 2021). The scheduled irrigation used by the water user association does not consider the type of crops irrigated and the size of the fields, but it only considers the number of water users (Beyene et al., 2018). The technical application of the right amount of water to the crop at the right time is a big concern in various irrigation schemes, which need local solutions (Hagos, 2005). Beyene et al. (2018) argued that in Ethiopia, many irrigation schemes do not perform according to the design expectations, most probably due to over-irrigation practices, which means Water productivity is lower than the optimum. The application efficiency of the different irrigation methods varies and depends on design, management, and operation (Adane, 2012). Undoubtedly, well-designed and correctly used irrigation systems will have the highest efficiency and water distribution levels, which can result in good production and high product quality.

2.3.3. Socio-Economic Sustainability of Irrigation Schemes

The implementation of development policies, programs, and projects that will not maximize one type of gain at the expense of others is necessary to achieve sustainable irrigation systems, which entail balancing economic, social, and environmental benefits. The assessment of the socio-economic sustainability of the irrigation system includes different factors: total physical product per hectare, profitability (net farm income), gross revenue, total farm assets, total hectare farmed, crop value per hectare, gross revenue per person, labor cost per hectare, and economic constraints such as land loss, crop or production loss, transport and market problems, unemployment, and community willingness (Adane, 2012). Leza et al. (2020) try to analyze and compare the effect of irrigation on income among the farmers' irrigation users and non-users. The result shows that the irrigation users are 26% better off than the non-users. (Mekuriaw et al., 2017) Also cited is the finding of Azemer (2006) shows the impact of small-scale irrigation on food security and the economic status of the household, and the result of the study demonstrated better performance of irrigated agriculture in crop production and productivity than rain-fed agriculture.

A key component of Ethiopia's efforts to reduce poverty and provide food security is irrigation development, which has been recognized as a powerful tool for promoting rural development and economic growth. Results, as reported in (Hagos et al., 2011), indicate that irrigation systems generate an average revenue of about US$323/hectare (ha) under small-scale irrigation, while rain-fed systems yield an average income of US$147/ha. A gross margin of US$1,308/ha and US$400/ha, respectively, was determined for medium- and large-scale systems. According to Leza et al. (2020), the mean annual income of a household from the cropping income of irrigation users was birr 36,111 and birr 17,166 for non-irrigating users from an average area of 0.34 hectare.

2.4. Sustainability Assessment Tools

Over the past two decades, numerous sustainability assessment frameworks have been developed to address the complex interactions of institutional, environmental, economic, and social dimensions in agriculture. Among the most cited are the Sustainability Assessment of Food and Agriculture Systems (SAFA), Response-Inducing Sustainability Evaluation (RISE), Multi-Attribute Sustainability Calculator (MASC), Land Degradation Assessment in Drylands (LADA), Sustainability Monitoring and Assessment Routine (SMART), and the Public Goods (PG) Tool. Each of these frameworks was designed to respond to particular sustainability questions, scales of application, and stakeholder needs.

The study of (Alaoui et al., 2022) tries to compare the six sustainability assessment frameworks (SAFA, RISE, MASC, LADA, SMART, and PG), and its result showed that they have different characteristics concerning their assessment methodologies, time and data requirements to operate, and different outcomes with different accuracy and level of complexity. For global-scale assessments, two primary frameworks are available: SAFA and LADA (Alaoui et al., 2022). While both operate at this level, they differ in scope and coverage. SAFA extends beyond land degradation to assess food systems as a whole, whereas LADA focuses primarily on land degradation (FAO, 2013). Moreover, SAFA addresses all four dimensions of sustainability: environmental, economic, social, and governance, while LADA excludes the sociocultural dimension at the individual level and incorporates only a limited set of economic themes (Alaoui et al., 2022). SAFA is designed as a comprehensive tool for identifying, developing, and evaluating the sustainability of agricultural systems, practices, and policies (Zarbà et al., 2025). So SAFA's broader coverage makes it particularly well-suited for the assessment of irrigation schemes that require a holistic view across sustainability dimensions.

2.4.1 Sustainability Assessment of Food and Agriculture System (SAFA Framework)

The Sustainability Assessment of Food and Agriculture System (SAFA) is a multi-criteria sustainability assessment tool developed by the Food and Agriculture Organization (FAO) of the United Nations (FAO, 2014) for evaluating sustainability performance throughout agricultural activities. The SAFA tool has been widely used for assessing the sustainability of agriculture in developing and developed countries (Leknoi et al., 2023). FAO's SAFA framework is structured based on different hierarchical levels: dimensions, themes, sub-themes, and indicators (Soldi et al., 2019). At its more general level, SAFA includes four dimensions of sustainability: good governance, environmental integrity, economic resilience, and social well-being (FAO, 2014). SAFA comprises 21 sustainability themes, which are defined by 58 sub-themes (Table 2.2). At a more specific level, each sub-theme includes a total of 116 indicators, measured with a performance score on a scale from 1 to 5 (FAO, 2013). On an increasing scale, in conjunction with a traffic light color code, sustainability practices are defined as unacceptable (red), limited (orange), moderate (yellow), good (light green), and best (dark green) (Bonisoli et al., 2019).

SAFA has four procedures: mapping, contextualization, indicators, and reporting (FAO, 2014).

1. **Mapping** is the first step of the SAFA framework procedures, which indicates setting goals and scopes of the study.
2. **Contextualization** is the second step, which deals with selecting themes, sub-themes, and rating conditions for indicators that were defined based on the context of the study area for the sustainability performance of a small-scale irrigation scheme.
3. **An indicator** is a step of selecting indicators. After selecting the indicators, quantitative and qualitative data were collected from the study area, which was rated against the contextualization defined in the previous step. The rating score, ranging from best to unacceptable, was illustrated in five different colors: dark green, green, yellow, orange, and red, respectively.

4. **Reporting** is the final stage of the assessment that is performed in the SAFA sustainability polygon to reflect the complete indicator list result.

Table 2.2. Overall SAFA structure (FAO, 2013)

Dimension	Themes	Sub-themes	Indicators
Good Governance	5	14	19
Environmental Integrity	6	14	52
Economic Resilience	4	14	26
Social Well-being	6	16	19
Total	21	58	116

2.5. Irrigation Practices and Soil Health

Soil health is the soil's capacity to perform its ecological functions effectively, supported by balanced physical, chemical, biological, and socio-economic attributes essential for sustainable agriculture and environmental health (Adejumobi et al., 2016). Increasing world population and the demand to ensure food security have made irrigated agriculture a significant contributor to the world’s food (Adejumobi et al., 2014). However, the increased application of irrigation technology, though with the expected results in terms of crop and water productivity, has been reported to have a far-reaching negative impact on the ecological regime, particularly the environment (Adejumobi et al., 2016). Globally, about two-thirds of agricultural lands have been degraded within the last century, and around 1 to 2 % of irrigated land has been lost annually as a result of salinity-related problems, especially in semiarid and arid regions (Guarnieri et al., 2005). The success of irrigation management (soil, crop, water, etc.) to sustain soil health is a function of the knowledge of how soils respond to irrigation use and practices over time (Weldewahid et al., 2023). Thus, irrigation can have adverse effects on soil properties and functions (Adejumobi et al., 2016; Getachew et al., 2012).

The modification of the soil matrix by irrigation could alter the overall soil health due to changes in soil properties and processes (Adejumobi et al., 2016). The overall soil health was classified in to five classes based on their soil health index value (Aprisal et al., 2019) (Table 2.3). Nowadays, soil is seen as one of the most valuable resources on Earth, given its essential elements to sustain and maintain life and received increasing attention under the environmental indicators and typically includes physical, chemical, and biological aspects (Karlen et al., 2019). Sustainability of irrigation systems is an important issue, and many of the issues are related to soil health (Gelaw et al., 2015). Soil health is a combination of soil physical, chemical, and biological properties that can change readily in response to variations in soil conditions (Weldewahid et al., 2023).

Table 2.3. Soil health classification (Aprisal et al., 2019)

Soil health	Soil health index	Class
Very Good	0.8-1	1
Good	0.6-0.79	2
Fair	0.35-0.59	3
Bad	0.2-0.34	4
Very Bad	0-0.19	5

Global and specific area studies also reported changes in soil physico-chemical properties upon adoption of irrigation agriculture have controversial results. Researchers such as Gebeyehu & Soromessa (2018) and Olsson et al. (2014) reported that irrigation positively influenced some soil health indicators, mainly soil organic carbon (SOC) content, due to increased inputs from crop residues. The results of these scholars indicated a 1–35% annual increment in SOC compared to the corresponding soils under a rain-fed production system. In contrast, studies such as (Getaneh et al., 2007) confirmed 13% of organic matter (OM) and 7% total nitrogen reduction in soil because of long-term irrigated fields. Moreover, Rotenberg et al. (2005) reported that irrigation of vegetable crops caused an over 18% decline in SOC stocks. According to Amacher et al., (2007) the soil health index and its associated soil property threshold values was assessed (Table 2.4).

Table 2.4. Soil health index and its associated soil property threshold values (Amacher et al., 2007)

Soil Health Variables Indicators	Soil Property Level	Soil Property Threshold	SH Index
Soil pH	<3.0	Severely acidic, almost no plants can grow in this environment	0
	3.01 to 4.0	Strongly acidic – only the most acid-tolerant plants can grow in this pH range	
	4.01 to 5.5	Moderately acid – growth of acid-intolerant plants is affected depending on levels of extractable aluminum (Al) and other metals.	
	5.51 to 6.8	Slightly acid – optimum for many plant species, particularly more acid-tolerant species	1
	6.81 to 7.2	Near neutral – optimum for many plant species except those that prefer acid soils	
	7.21 to 7.5	Slightly alkaline – optimum for many plant species except those that prefer acid soils, possible deficiencies of available P and some metals (for example, Zn)	
	7.51 to 8.5	Moderately alkaline – preferred by plants adapted to this pH range, possible P and metal deficiencies	
	>8.5	Strongly alkaline – preferred by plants adapted to this pH range, possible B and other oxyanion toxicities	0
Soil EC (dS m^{-1})	<4.0	Normal	1
	4 to 8	Slightly saline	
	8 to 16	Moderately saline	
	16 to 40	Strongly saline	0
	>40	Very strongly saline	
Soil organic carbon (SOC) (%)	>5	High organic carbon levels in soil provide excellent benefits for plant growth and soil health	1
	1 to 5	Moderate - adequate levels	
	<1.00	Low organic carbon levels in soil could indicate a potential loss of organic carbon due to erosion or other processes	0
Total Nitrogen (TN) (%)	>0.5	High - excellent reserve of nitrogen	1
	0.1-0.5	Moderate - adequate levels	
	<0.1	Low - could indicate loss of organic N	0
Phosphorus (P) (Mg kg^{-1})	>30	High levels of available phosphorus (P) in slightly acidic-to-alkaline soils can provide an excellent reserve for plant growth	1
	10 to 30	Moderate - adequate levels for plant growth	
	<10	Low-P deficiencies are likely	0
Exchangeable Sodium Percentage (ESP) (%)	>15	High-sodic soil with associated problems	1
	≤15	Adverse effects unlikely	0
Sodium Adsorption Ratio (SAR)	>13	High-sodic soil with associated problems	0
	≤13	Adverse effects unlikely	1
	>1.5	Possible adverse effects	0

Bulk Density (BD) (Mg m−3)	≤1.5	Adverse effects unlikely	1
Percentage Base Saturation (PBS) (%)	<40	Low soil fertility	0
	40 to 60	Moderate soil fertility	1
	>60	High-fertility soil	
Cation Exchange Capacity (CEC) (cmolc kg−1)	<25	Low-high leaching of basic cations	0
	25 to 40	Moderate levels of basic cations in soil could indicate that there are adequate levels of essential nutrients, such as calcium, magnesium, potassium, and sodium, available for plant uptake	1
	>40	High—excellent reserve of basic cations	
Soil Structural Stability Index (SSI) (%)	<9%	Low levels of basic cations in soil can indicate a high risk of soil structural degradation. Basic cations play a key role in maintaining soil stability and structure by promoting aggregation and reducing soil erosion	0
	>9%	High levels of soil organic carbon (OC) can indicate that there is sufficient organic matter present in the soil to help maintain soil structural stability. Organic matter plays a crucial role in promoting soil aggregation, improving water infiltration and retention, and enhancing overall soil structure	1

2.6. Challenges and Problems of Small-Scale Irrigation

Community-managed small-scale irrigation systems are facing multiple problems and are poorly performing in terms of livelihood improvement, cost recovery, and scheme sustainability (Abera et al., 2019; Amede, 2015). Poor scheme management practices (Abera et al., 2019; Adela et al., 2019), deterioration of infrastructures (Berhe et al., 2022), exclusiveness in development and management decision-making (Berhe et al., 2022; Oates et al., 2020; Yami, 2013), and limited capacity of governing institutions are the major problems of small-scale irrigation schemes in Ethiopia. Due to these problems and challenges, many community-managed small-scale irrigation schemes in Ethiopia are irrigating below half of their design potential, which indicates leaving more than half of the expected users out of irrigation (Amede, 2015).

Small-scale irrigation schemes in Ethiopia face common problems with their different water sources, which affect their performance and sustainability. Over-application of irrigation water beyond crop demands is a common problem in irrigation schemes whose source of water is from reservoirs, diversion headworks, lakes, and groundwater (Adela et al., 2019). Upstream catchment erosion, reservoir sedimentation, and salinization are common problems of irrigation schemes from natural lakes and built dam reservoirs (Berhe et al., 2022). In some irrigation schemes, water distribution among beneficiaries is under pressure from illegal water pumping from water sources and distribution systems (Amede, 2015). Though there are technical support and extension services from governmental and non-governmental organizations during irrigation operation and maintenance, their interventions are not tailored to local contexts (Abera et al., 2019; Embaye et al., 2020; Oates et al., 2020).

2.7. Top-down and Bottom-up Approaches in irrigation Scheme Sustainability

In the study of sustainability of small-scale irrigation schemes, researchers emphasize the importance of integrating both bottom-up and top-down analytical approaches to capture the composite relationship between local decision making and broader institutional structures. Bottom-up approaches foreground farmers’ practices, knowledge, and participation, showing how community engagement and self-organization in water management can enhance adaptive capacity and sustain irrigation performance, especially when local users actively contribute to operation and maintenance decisions (Amina et al., 2023). In contrast, top-down approaches are oriented toward formal policy frameworks, institutional support, and centralized planning by government or external agencies that shape infrastructure development, extension services, and regulatory environments that influence scheme adoption and long-term viability (Girard et al., 2015).

In the Ethiopian context, studies on small-scale irrigation sustainability highlight the connection between community-level participation (bottom-up) and policy/institutional support (top-down) approaches. Participatory development programs in Ethiopia, involving local farmers and Water Users’ Associations in planning and management, have been shown to enhance ownership, social sustainability, and resilience of small-scale irrigation systems (Berhe et al., 2025). Research on irrigation development further indicates that traditional, indigenous institutional arrangements and locally respected rules contribute positively to scheme success and sustainability Amina et al., (2023), whereas a predominantly top-down planning system that overlooks local knowledge and participation often results in weak community ownership and reduced sustainability outcomes (Mekonen Ayana, 2021). Overall, the Ethiopian evidence suggests that sustainability in small-scale irrigation benefits most from a combination of bottom-up local participation and top-down policy coherence, institutional capacity, and extension support, which are crucial for enhancing adoption, productivity, and long-term viability of irrigation schemes (Berhe et al., 2025).

3. Materials and Methods

3.1. Description of the Study Area

3.1.1. Location and Accessibility

The study was conducted in the Gumselassa irrigation scheme, which is found at Hintalo Wejerat Wereda, southeastern zone of the Tigray region, Northern Ethiopia. The irrigation scheme is specifically located between $13^{0}13'$ to $13^{0}15'$ N and $39^{0}31'$ to $39^{0}32'$ E (Figure 3.1). Gumselassa is approximately 35 km south of Mekelle city and is accessible by an all-weather gravel road branching from the Mekelle-Adigudem main road. The major water source for Gumselassa irrigation is a micro-dam that was constructed in 1995 by the Regional Government with a reservoir design capacity of 1.9 Mm^3 (million cubic metres) of water, with 110 ha planned command area. The second water source of Gumselassa irrigation is seepage water that comes from the reservoir (through the bed and earthen dam body), which is diverted to a canal and used for irrigation. According to (Yohannes et al., 2017b), about 12–35% of the total irrigated area was covered by seepage water.

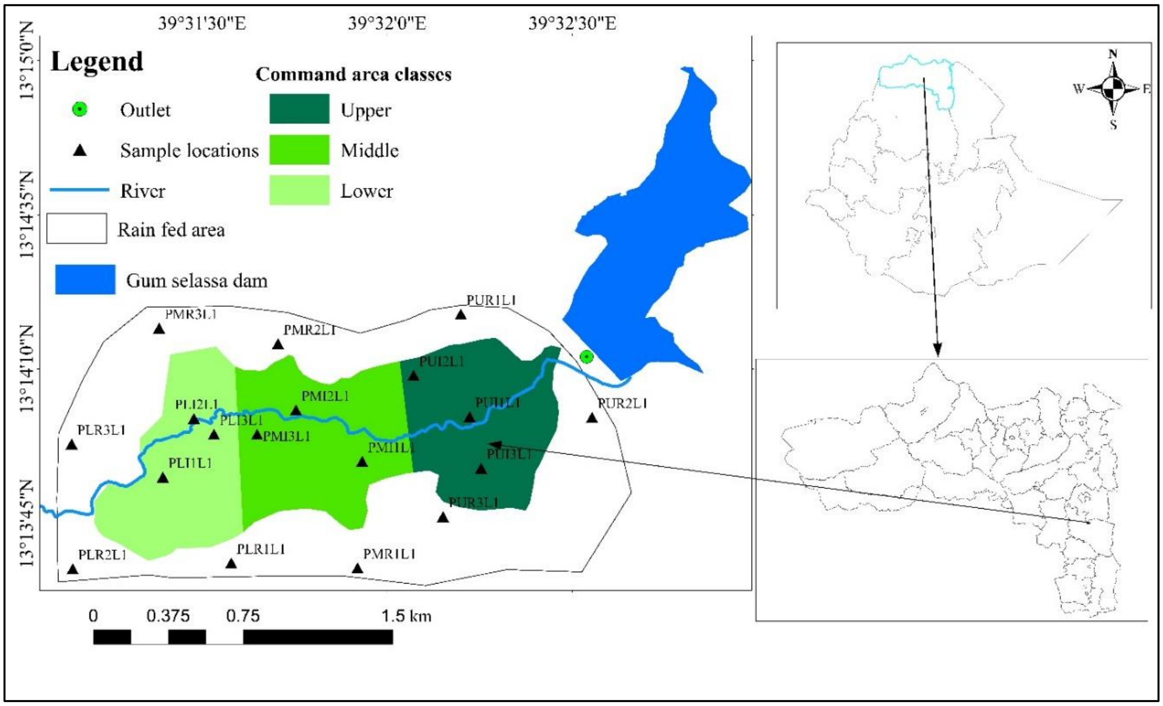


Figure 3.1. Location of the Gumselassa irrigation scheme

3.1.2. Climate

The climate in the study area is characterized by low and erratic rainfall. The area experiences low and highly variable rainfall, with a unimodal rainfall pattern concentrated mainly between June and September. The average annual rainfall of the area is 500 mm, which indicates that the area is typically semi-arid (Amede, 2015; Hagos, 2005). Mean annual temperatures range between 15°C and 25°C, with relatively high evapotranspiration rates throughout the year. The long dry season and frequent dry spells during the rainy season make agricultural production highly dependent on irrigation. As a result, small-scale irrigation plays a critical role in stabilizing crop production and improving household food security in the area.

3.1.3. Topography

The topography of the Gumselassa watershed is generally undulating, with elevation variations ranging from approximately 2,100 to 2,300 meters above sea level (Hagos, 2005) . The irrigation command area is located in a relatively gentle slope downstream of the reservoir, which allows gravity-based water conveyance through canals. However, the surrounding catchment area consists of moderately steep slopes, which contribute to surface runoff and soil erosion during intense rainfall events. This topographic condition has significant implications for reservoir sedimentation and long-term sustainability of the irrigation scheme, as reported in several studies conducted in Tigray (Yohannes et al., 2017b).

3.1.4. Land Use Land Cover

Land use and land cover (LULC) of the Gumselassa watershed were analyzed using 2024 land use land cover satellite image on GIS techniques to classify and quantify the major categories within the total area of 24.23 km² (Table 3.1) (Figure 3.2). The results indicate that rangeland dominates the watershed, covering 17.37 km², which accounts for 71.69% of the total area, rangeland includes vegetation cover, shrub land, grass land, bare land and other. Cropland represents the second most extensive category, occupying 6.08 km² or 25.09% of the watershed. Other land cover types are relatively limited in extent. Water bodies account for 0.67 km² (2.77%), while settlement areas occupy only 0.11 km² (0.45%). These findings of GIS software emphasize the need for integrated watershed management strategies that enhance vegetation cover, promote soil and water conservation practices, and ensure sustainable use of land resources in the Gumselassa watershed.

Table 3.1. Land use and land cover of the Gumselassa watershed

Land use	Area in square km	Percentage
Water body	0.67	2.77
Crop land	6.08	25.09
Settlement	0.11	0.45
Rangeland	17.37	71.69
Total	24.23	100

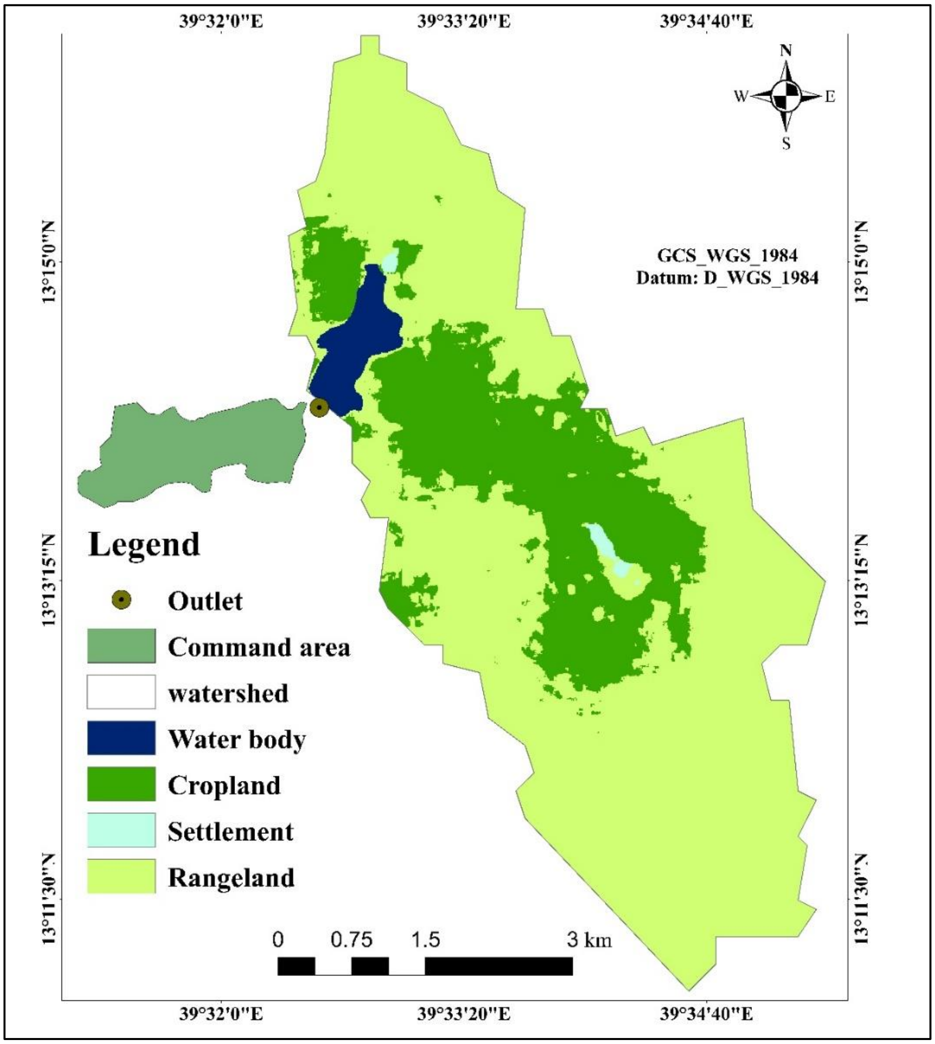


Figure 3.2. Land use and land cover of 2024GC of the study area.

3.1.5 Socio-Economic Characteristics

The livelihood of households in the Gumselassa area is predominantly based on subsistence agriculture. The majority of the population depends on small landholdings for crop production and livestock rearing. The irrigation scheme was designed to serve more than 350 households organized by 12 members of irrigation water users' associations (WUAs) with 2 Abomays. The irrigation scheme plays a crucial role in improving household income, food availability, and employment opportunities, particularly during the dry season. Farmers practicing irrigation are able to cultivate high-value crops and achieve multiple cropping cycles per year, which significantly enhances their economic resilience compared to rain-fed farming households.

3.2. Materials

The research was conducted using different materials:

- ✓ **GPS** was used to take the location of soil samples.
- ✓ **A digger** was used to dig deep into the ground to collect soil samples.
- ✓ **A hammer** was used to push core samplers into hard or compacted soil.
- ✓ **A measuring tape** was used to measure the depth of soil samples.
- ✓ **A plastic bag** was used to collect disturbed soil samples.
- ✓ **A core sampler** was used to collect an undisturbed soil sample.
- ✓ **Oven dry** was used to determine the soil physical properties by oven drying at 105^0C for 24 hours.
- ✓ **A sieve** was used to separate the soil larger than 2 mm during the determination of soil texture.
- ✓ **A hydrometer** was used for the determination of soil texture proportions less than 2 mm in diameter.
- ✓ **A stopwatch** was used to control time.

3.3. Methods

3.3.1. Data Source and Data Collection

To assess the sustainability of small-scale irrigation schemes, both qualitative and quantitative data were employed. The data used for the analysis of this research were collected through field measurement, field observation, laboratory test, questionnaires, group discussion, and key informant interviews.

Qualitative data were used to capture data pertaining to local perception and opinions on the sustainability of a small-scale irrigation scheme using focus group discussions and key informant interviews (Appendix 1).

Quantitative data were used to quantify the household's resources, income status, food security status, demographic characteristics, and other basic information was collected from sample households using a structured questionnaire as well as field laboratory tests (Appendix 3).

Primary data were collected using various instruments such as key informant interviews using expert interviews, structured questionnaires, laboratory tests, focus group discussions, and field observation events in the irrigation scheme.

Secondary data were used published and unpublished documents that were collected from formal sources such as the Bureau of Agriculture and Rural Development, Woreda Agriculture, Rural Development office reports.

3.3.2. Sampling Technique and Sample Size Determination

3.3.2.1. Household Size Determination

The total household heads who used irrigated agriculture at the Gumselassa small-scale irrigation scheme is 350 (Mr. Teshale, kebele rural development expert). A total of 74 sample households were selected (Equation 3.1) using random sampling from the irrigation users, 20 females and 54 male households, and the questionnaire was translated to local language (Tigrigna) for data collection from respondent. Each sample household was selected randomly from the prepared list of household heads in the study area since April 2025. The numbers of representative sample sizes of the respondents were calculated by using Equation (3.1), which was developed by (Kothari, 2004). The Sample size determination is computed as:

$$n = \frac{Z^2 * P * Q * N}{P^2(N-1)} + Z^2 * P * Q \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \text{(Equation 3.1)}$$

Where: n: Sample size, N: Number of households=350, P: Level of precision =5%

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

Z = 1.96 for confidence interval 95% (Using Excel Sheet)

3.3.2.2. Soil Sample Determination

The soil samples for the determination of physical, chemical, and biological properties of the soil were collected from a site close to the location selected for the measurement of soil health indicators. Thirty six soil samples were collected from two layers of the surface (0–30 and 30-60 cm) of three sites randomly chosen at the upper, middle, and lower parts (Weldeabezgi, 2023) of the irrigation scheme (Figure 3.1) and rain-fed agricultural area, with three replications.

3.3.2.3. Experts Sample Determination

The evaluation of challenges and alternative solutions for the Gumselassa small-scale irrigation scheme was conducted based on expert feedback. There was 5 experts on Gumselassa irrigation scheme and for this study all of the experts are included. The experts were rated for challenges/problems (3 = highly severe problem, 2 = moderately severe problem, 1 = less severe problem) and for alternative solutions (3 = highly important alternative, 2 = moderately important alternative, 1 = less important alternative) (Appendix 2). The expert's average rate for challenges/problems and alternative solutions for the Gumselassa irrigation scheme was indicated as 1.0-1.7 for less severe/important, 1.71-2.3 moderate severe, and 2.31-3.0 highly severe/important (Goshu, 2024).

3.3.3. Sustainability of Small-Scale Irrigation Scheme

To assess the sustainability of small-scale irrigation schemes, the SAFA framework was selected in this study using data that was obtained from primary sources through field observation, laboratory tests, questionnaires, Focus group discussions, GIS software, and secondary sources extracted from government agency reports and organizational records. As shown in (Table 3.2) the dimensions as well as the themes with their method of delivery was listed.

Table 3.2. Selected SAFA themes.

Dimensions	Themes	Methods how was Deliver
Good governance	G2. Accountability	questionnaire survey
	G3. Participation	questionnaire survey
	G4. Rule of Law	questionnaire survey and KII
	G5. Holistic Management	KII and documents of rural development
Environmental integrity	E2. Water	questionnaire survey, field observation, and literature
	E3. Land	questionnaire survey, laboratory result, field observation, and literature
	E4. Biodiversity	questionnaire survey, KII, field observation, and literature
	E5. Materials and Energy	KII, field observation, and literature
Economic resilience	C1. Investment	questionnaire survey, KII, literature
	C2. Vulnerability	questionnaire survey and field observation
	C3.Product Quality and Information	questionnaire survey, KII, literature
	C4. Local Economy	KII
Social well-being	S1. Decent Livelihoods	questionnaire survey and literature
	S2. Fair Trading Practices	questionnaire survey
	S3. Labor Rights	questionnaire survey and KII
	S4. Equity	questionnaire survey and KII
	S5. Human Health	Literature

Where KII=key informant interview

3.3.4. Soil Sampling and Analyses

The collected soil data were checked before analysis for normality and subjected to statistical analysis using analysis of variance (ANOVA) in SPSS software version 25.0. Variations in soil quality between land use types (irrigated and rain-fed) were tested using the independent t-test. Variations between means were tested with the least significant differences (LSD) method at 5%

level of significance. The overall indicators that were used to analyze the effect of irrigation practice on soil health are summarized in the table below (Table 3.3).

Table 3.3. Soil health indicators and analysis methods applied

Indicators	Method	Reference
Soil texture	Hydrometer method	(Bouyoucos, 1962)
Total porosity	Brady and Weil method	(Brady and Weil, 2008)
Bulk density (Mg. m^{-3})	oven-dry	(Blake & Hartge, 1986)
PH	PH meter	(Rhoades, 1982)
EC (dS.m^{-1})	Electrical Conductivity meter	(Rhoades, 1982)
OC (%)	Walkley-Black methods	(Walkley-Black, 1934)
Ca & Mg (cmolc.kg^{-1})	Atomic absorption spectrophotometer	(Black, 1965)
Na & K (cmolc.kg^{-1})	Flame emission spectrophotometry	(Black, 1965)
N (%)	Kjeldahl digestion method	(Bremmer & Mulvaney, 1982)
CEC (comlc.kg^{-1})	Ammonium acetate extraction buffered at pH = 7	(Rhoades, 1982)

PH Percentage of hydrogen, EC electric conductivity, OC organic carbon, N total nitrogen, Na Sodium, K Potassium, Ca Calcium, Mg Magnesium, CEC cation exchange capacity.

Soil structural stability index (SSI) is a statistic used to assess how durable and adaptable the soil composition is, taking into account variables like the percentages of clay and silt as well as the soil organic carbon content (SOC) (Serme et al., 2016).

$$\mathbf{SSI} = \frac{\mathbf{1.724SOC}(\%)}{\mathbf{clay}(\%)+\mathbf{silt}(\%)} * \mathbf{100} \qquad \text{(Equation 2)}$$

Total Porosity (TP) The term "total porosity" (TP) describes the volume of pore space in a soil and is mostly influenced by the soil's structure. Total porosity (TP) was calculated using (Equation 3) (Brady & Weil, 2008)

$$\boldsymbol{TP}(\%) = \left(\mathbf{1} - \frac{\boldsymbol{\rho}\mathbf{b}}{\boldsymbol{\rho}\mathbf{s}}\right) * \mathbf{100} \qquad \text{(Equation 3)}$$

Where ρb is the bulk density of the soils in Mgm^{-3} and ρs is the particle density, which is 2.65 Mgm^{-3}(Richards, 1954).

SOC and N Stocks were calculated using the model developed and proposed by (Ellert & Bettany, 1995), using a volume fraction of coarse fragments > 2 mm (Si), as in the following (Equation 4).

$$SOCst.(tha^{-1}) = SOC(\%) * BD(gcm^{-3}) * (1 - Si) * D(cm) \quad \text{(Equation 4)}$$

$$Nst.(tha^{-1}) = N(\%) * BD(gcm^{-3}) * (1 - Si) * D(cm) \quad \text{(Equation 5)}$$

Where SOC/N St. = Soil organic carbon or nitrogen stock (t ha^{-1}), SOC/N (%). = the percentage of soil organic carbon (%) or nitrogen, ρb = bulk density (g cm^{-3}), and D = depth or soil layer (cm), and Si is the volume fraction of coarse fragments > 2 mm. Nonetheless, the majority of the fragment fraction was less than 2 mm, which were considered fine particles and were not included in the calculation. Carbon sequestration was calculated by conversion factors of 3.67 as Carbon sequestration = SOC stock × 3.67 (Ellert & Bettany, 1995).

Sodium Adsorption Ratio (SAR) is a quantity that indicates the proportion of sodium ions to the total amount of calcium and magnesium ions in the soil, using the following (Equation 6), as suggested by (Richards, 1954).

$$\boldsymbol{SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}}} \quad \text{(Equation 6)}$$

Exchangeable sodium percentage (ESP) is the proportion of sodium ions that are present on the soil surface. ESP can be calculated using the empirical formula that follows (Equation 7):

$$\mathbf{ESP} = \frac{\textbf{Exchangeable Na}}{\boldsymbol{CEC}} * \mathbf{100\%} \quad \text{(Equation 7)}$$

Percentage base saturation (PBS) is the ratio of the total exchangeable bases (Ca, Mg, K, and Na) by the CEC of the soil and multiplied by 100%. PBS can be estimated by the (Equation 8):

$$\mathbf{PBS} = \frac{\textbf{Basic Cations}}{\textbf{CEC}} \times \mathbf{100\%} \quad \text{(Equation 8)}$$

Soil health index (SHI) is a tool used to assess and quantify the overall health of soil in all land uses or environmental systems. It offers a thorough assessment of the numerous properties of soil as well as the variables that affect the function and performance of soil. The process of creating a soil quality index usually entails selecting and integrating a number of indicators that represent various aspects of soil production and health. The dataset was reduced, and the most important soil properties were chosen for the SHI calculation by the model using principal component analysis (PCA). PCA is a widely used method to identify the main variables that significantly influence the total variation in a dataset. Consequently, PCA was utilized to generate a minimum data set (MDS) to lower the indicator load in the model and prevent data redundancy, as well as to remove high-loading elements by statistically combining soil properties into major principal components (PCs) (Yu et al., 2018). Only soil physicochemical parameters showing significant differences were chosen for the complete dataset selection process. In essence, only those indicators demonstrating significant variations or differences across the land uses were considered for analyses from the total samples of measured soil properties (Fadl et al., 2024).

The most important components in principal component analysis that account for the majority of the variability in the data are often the principal components (PCs) with eigenvalues greater than 1 (Weldewahid et al., 2023). The process for selecting indicators with assigned scores based on their implications for soil quality in the MDS involved several steps (Selmy et al., 2021). Descriptive statistics of the studied soil characteristics include the minimum, maximum, arithmetic mean, and standard deviation, which were computed using SPSS version 25. The Shapiro–Wilk test was used to assess the normal distribution of the data. The Pearson correlation coefficient (r) was used to examine the linear relationships between the variables. Microsoft Excel and SPSS version 25 were used to conduct the principal component analysis (PCA). These PCs explain most of the variation present in the original variables of the selected indicators. After that, the soil health index was calculated using (Equation 1) (Mohamed et al., 2021).

$$SHI = \sum_{i=1}^{N} Wi * Si \qquad \text{(Equation 9)}$$

Where Wi is the relative weight of each indicator and has values ranging between 0 and 1, and Si is the value of each soil indicator, which is transformed into a standard normal distribution using

$$f(x) = \frac{1}{\sqrt{2\pi}} e^{-(\frac{z^2}{2})} \qquad \text{(Equation 10)}$$

Where e and z refer to the natural logarithm, equal to approximately 2.718, and the standard soil indicator scores, respectively.

A spatial distribution map of the soil health indicators was generated using ordinary kriging interpolation in ArcGIS software version 10.4, where the kriging method was applied to predict the values of variables in unsampled locations and to interpolate the spatial soil properties using Equation 11 (Cafarelli et al., 2015)

$$Z*(Xo) = \sum_{i=1}^{N} \lambda i\, Z(Xi) \quad \text{(Equation 11)}$$

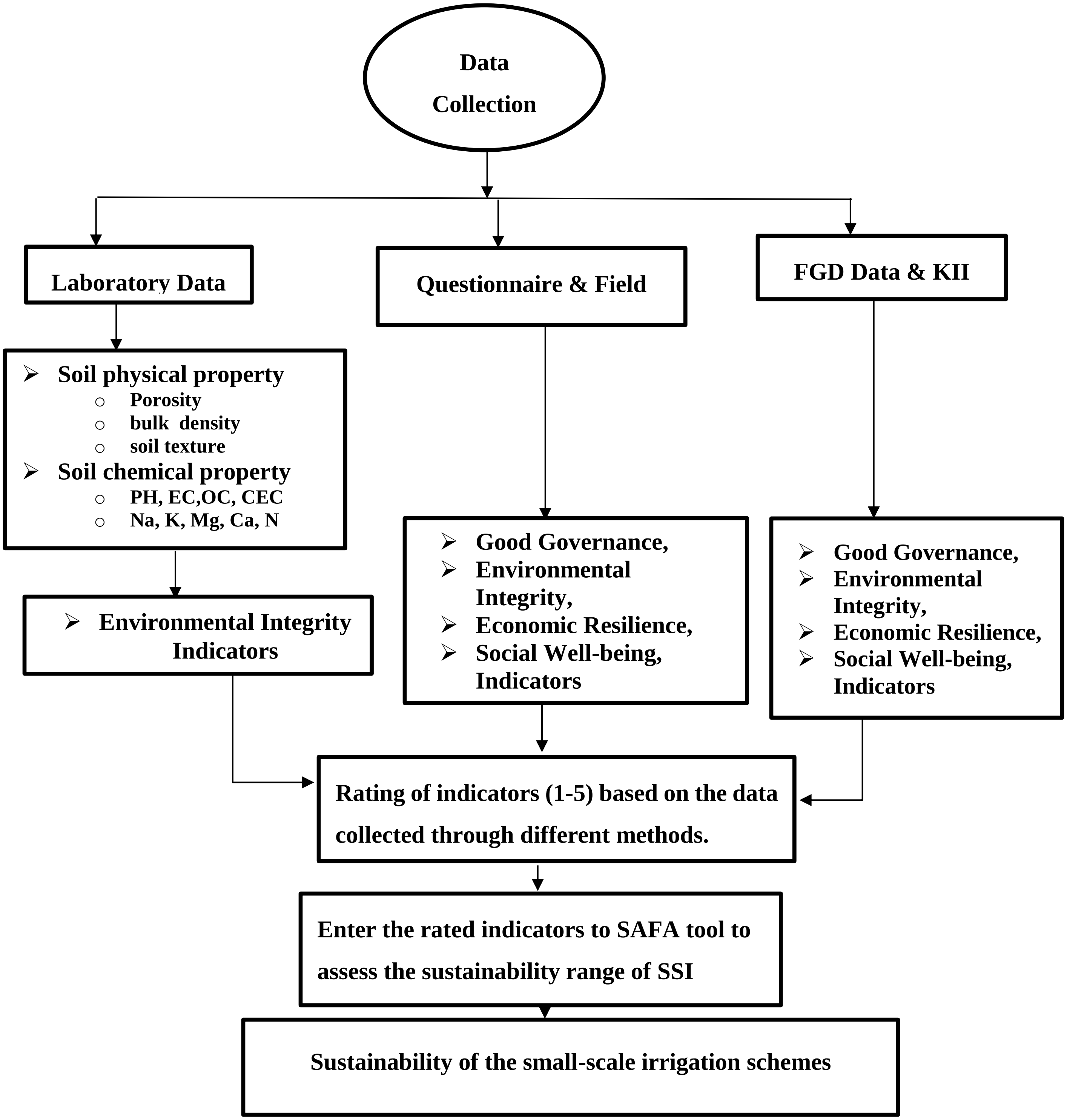
Where Z*(xo) is an estimated variable at location xo, Z(Xi) is the value of an inspected variable at location Xi, i is the statistical weight that is attributed to Z*(Xi) for a sample located near xo, and N is the number of observations in the neighborhood of the inspected point.

3.4. Data Analysis

The data that was collected from the field through questionnaires, focus group discussions, field observation, laboratory tests, and secondary sources extracted from government agency reports and organizational records were analyzed and prepared as input for the SAFA framework. Finally, the sustainability of the small-scale irrigation scheme was plotted with the four dimensions using the SAFA framework tool. The collected soil data were checked before analysis for normality and subjected to statistical analysis using analysis of variance (ANOVA) in SPSS software version 25.0. An independent t-test was used to test soil health variations between land use types (irrigated and rain-fed). Variations between means were tested with the least significant differences (LSD) method at a 5% level of significance. The respondents' answers for each indicator were also averaged using Microsoft Excel, and the average result translates to the SAFA guideline (Goshu, 2024) (Table 3.4).

Table 3.4. Rating scale interpretation: Corresponding categories for 5-point and 3-point Likert Scales (Goshu, 2024)

5-scale		3-scale	
Respondents Average Value	SAFA Category	Respondents Average Value	SAFA Category
1-1.80	Unacceptable	1-1.70	Less
1.81-2.6	Limited	1.71-2.3	Moderate
2.61-3.4	Moderate	2.31-3.0	High
3.41 -4.20	Good		
4.21-5	Best		



FGD focus group discussion, KII key informant interview, PH percentage of hydrogen, EC electric conductivity, OC organic carbon, N total nitrogen, Na Sodium, K Potassium, Ca Calcium, Mg Magnesium, CEC cation exchange capacity.

Figure 3.3. Overall workflow of the study

4. Results and Discussion

4.1. Sustainability of Gumselassa Irrigation Scheme: The SAFA Framework

The sustainability assessment of the Gumselassa irrigation scheme was evaluated across four key SAFA sustainability dimensions (Good Governance, Environmental Integrity, Economic Resilience, and Social Well-being) comprehensively. Each dimensions also contains different themes and sub-themes that was listed in the tables 4.1 up to 4.4. The SAFA polygons indicates the result of each themes whereas the values of each themes (1-3) indicates the data accuracy only, which indicates 1= low data quality, 2=moderate data quality 3=high data quality (FAO, 2013) (Figure 4.1). Example let's take one theme, participation, the SAFA polygon result for participation indicates at light green that shows moderate sustainability level, the data accuracy for participation was 3, indicate high data quality (Figure 4.1).

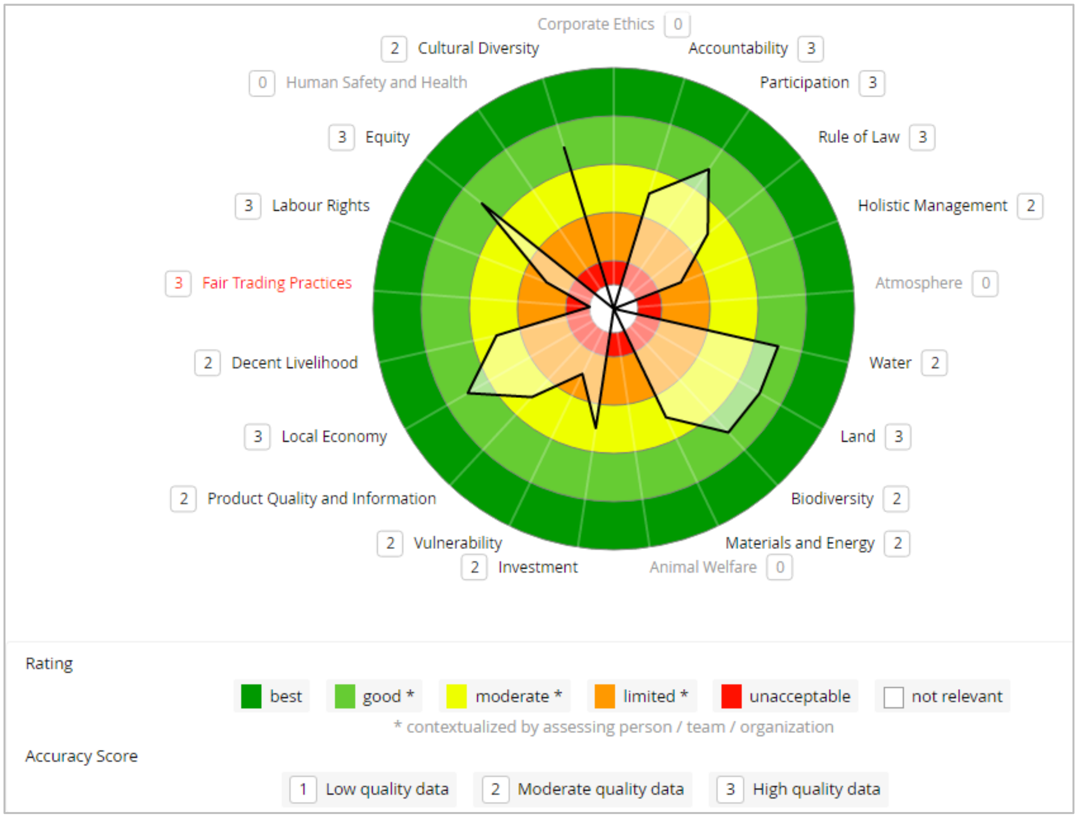


Figure 4.1. Gumselassa irrigation scheme sustainability polygon. FAO's SAFA score values: 4–5 (Best); 3–4 (Good); 2–3 (Moderate); 1–2 (Limited); 0–1 (Unacceptable)

4.1.1. Good Governance

The governance dimension of the irrigation scheme was evaluated using the SAFA (Sustainability Assessment of Food and Agriculture systems) guidelines developed by FAO. The Governance (GG) dimension of the Gumselassa irrigation scheme obtained an overall score of **2.92,** which indicates a moderate level of good governance sustainability. In this study, the accountability, participation, rule of law, and holistic management themes were considered (Table 4.1).

Table 4.1. Good governance themes and sub-themes score

Dimension	**Themes**	**Sub-themes**	**Respondents average sub-theme score**	**SAFA sub-theme score**	**SAFA theme score**	**Dimension score**
Good Governance	Accountability	Holistic Audits	1.00	1	3	**2.92**
		Responsibility	2.92	3		
		Transparency	4.33	5		
	Participation	Stakeholder Dialogue	3.83	4	3.67	
		Grievance Procedures	3.00	3		
		Conflict Resolution	3.57	4		
	Rule of Law	Legitimacy	3.00	3	3	
		Remedy, Restoration, and Prevention.	2.00	2		
		Civic Responsibility	3.00	3		
		Resource Appropriation	3.42	4		
	Holistic Management	Sustainability Management Plan	3.00	3	2	
		Full-Cost Accounting	1.00	1		

The score for the accountability theme was (3.00), which indicates a Moderate sustainability level according to the SAFA score (Figure 4.1). This score shows that mechanisms for responsibility and transparency exist. At Gumselassa irrigation scheme, the committee structures ensure some oversight, but systematic documentation and feedback mechanisms are lacking. The same is true informal practices often dominate irrigation scheme management in Ethiopia, with limited written records and weak financial reporting (Van Koppen et al., 2020). The absence of clear accountability structures can lead to mismanagement and reduced trust among stakeholders (Adela et al., 2019). SAFA notes accountability requires transparency of decision-making, availability of information, and mechanisms for holding leaders responsible (FAO, 2014). Strengthening accountability through transparent reporting and clear delineation of responsibilities could enhance the scheme's governance system.

The participation theme of good governance was scored (3.67) from (Table 4.1), which was a good sustainability level, indicating good involvement of farmers in decision-making and scheme management. Previous studies at the Gumselassa irrigation scheme highlight that participatory irrigation scheduling and farmer-led planning significantly improved water-use efficiency and crop productivity (Mekonen et al., 2011; Mekuriaw et al., 2017). High participation of irrigation users aligns with SAFA’s emphasis on inclusiveness and legal decision-making in good governance systems (FAO, 2014). Research indicates that active participation leads to better management outcomes and increased satisfaction among stakeholders (Berhe et al., 2025). Enhancing participatory approaches, such as involving community members in planning and operational decisions, could improve scheme governance systems and sustainability.

The score for the rule of law theme for the Gumselassa irrigation scheme was (3.00) which was a moderate level of sustainability. In the Gumselassa irrigation scheme, the rules and regulations exist, but enforcement is often inconsistent. Ethiopian water governance frameworks legally recognize WUAs and their rights to manage irrigation systems (FDRE, 2014). Studies have shown that effective enforcement of rules is essential for the sustainable management of irrigation systems (Berhe et al., 2025). Strengthening legal frameworks and ensuring consistent enforcement could improve governance outcomes.

Holistic management scored the lowest score out of all good governance themes, which was (2.00) which indicating a limited sustainability level, which reflects insufficient integration of the sustainability management plan. Gumselassa irrigation scheme management largely focuses on technical and operational tasks, while broader concerns such as catchment conservation, climate risks, and long-term planning are less systematically addressed. This result aligns with the findings of (Mekuriaw et al., 2017), at the Gumselassa irrigation scheme, upstream watershed degradation and lack of adaptive planning have been reported as recurrent challenges. Addressing these issues requires multi-year strategic planning, watershed rehabilitation programs, and participatory monitoring systems.

4.1.2. Environmental Integrity

The environmental integrity dimension of the Gumselassa irrigation scheme was assessed using four themes; Water, Land, Biodiversity, and Materials & Energy (Figure 4.1). The Environmental Integrity (EI) dimension of the Gumselassa irrigation scheme obtained an overall score of **3.67** (Table 4.2), which indicates a good level of environmental integrity sustainability (Figure 4.1). Even though the overall environmental sustainability level Gumselassa irrigation scheme was good, it requires interventions such as watershed rehabilitation and conservation practice, soil improvement practice, and participatory water allocation mechanisms. The results are consistent with previous findings in Tigray, where irrigation has improved food security and productivity, but faces long-term sustainability risks if environmental challenges are not addressed (Hagos et al., 2011; Mekuriaw et al., 2017).

Table 4.2. Environmental integrity themes and sub-themes score

Dimension	Themes	Sub-themes	Sub-theme score	SAFA sub-theme score	SAFA theme score	Dimension score
Environmental Integrity	Water	Water Withdrawal	3.67	4	4.00	**3.67**
		Water Quality	3.76	4		
	Land	Soil Quality	4.65	5	4.00	
		Land Degradation	3.00	3		
	Biodiversity	Ecosystem Diversity	4.20	4	3.67	
		Species Diversity	3.25	3		

		Genetic Diversity	3.80	4		
	Materials and Energy	Material Use	3.25	3	3.00	
		Energy Use	2.75	3		

The water theme of the environmental integrity dimension score is (4.00), (Table 4.2), and indicates a good sustainability level (Figure 4.1). Even though the theme sustainability level was good, the watershed degradation upstream of the reservoir contributes to siltation and reduces water storage capacity. The result of the theme relates to the studies of (Mekonen et al., 2011), while participatory irrigation scheduling has improved water use efficiency, water scarcity during dry seasons, and conflicts over allocation persist at the Gumselassa irrigation scheme.

The score recorded for the land theme was (4.00), see Table 4.2. According to the SAFA guideline, the sustainability level of the theme was categorized under a good sustainability level, Figure 4.1. This result indicates that there is effective use of soil and agricultural land, but the land conservation practice is not good in the upstream catchment. This aligns with evidence that irrigated agriculture in Tigray contributes to improved soil fertility management and land productivity, especially when irrigation is complemented with soil and water conservation measures (Hagos, 2005; Mekuriaw et al., 2017).

The biodiversity theme sustainability score was (3.67), indicating a good sustainability level according to the SAFA guideline see Figure 4.1. The material and energy theme score a (3.0) (Table 4.2), which indicates a moderate sustainability level according to the SAFA guideline that reflects relatively efficient use of farm inputs and energy resources. Gumselassa irrigation users primarily rely on gravity-based irrigation, which minimizes energy consumption compared to mechanized pumping systems, and this result aligns with (Bekele & Tilahun, 2007) the limited use of chemical fertilizers and pesticides, and application of water through gravity in Tigray reduces environmental risks.

4.1.3. Economic Resilience

The economic resilience dimension of the Gumselassa irrigation scheme was assessed using four themes: investment, vulnerability, product quality and information, and local economy (Figure 4.1). The economic resilience (ER) dimension of the Gumselassa irrigation scheme obtained an overall score of **2.81** from Table 4.3, which indicates a moderate level of sustainability (Figure

4.1). The economic resilience assessment shows that Gumselassa irrigation plays an important role in sustaining the local economy, but structural weaknesses in investment, market systems, and risk management limit its long-term resilience. Targeted interventions in infrastructure investment, market integration, and risk management systems would strengthen economic resilience and ensure more sustainable benefits from the scheme.

Table 4.3. Economic resilience themes and sub-themes score

Dimension	**Themes**	**Sub-themes**	**Sub-theme score**	**SAFA sub-theme score**	**SAFA theme score**	**Dimension score**
Economic Resilience	Investment	Internal investment	2.92	3	2.75	**2.81**
		Community investment	4.00	4		
		Long-ranging investment	1.50	1		
		Profitability	3.09	3		
	Vulnerability	Stability of production	3.03	3	2.00	
		Stability of supply	1.24	1		
		Stability of the market	1.05	1		
		Risk management	2.87	3		
	Product Quality and Information	Food safety	2.00	2	3.00	
		Food quality	4.00	4		
	Local Economy	Value creation	4.00	4	3.50	
		Local procurement	3.00	3		

The investment theme of economic resilience dimension score is (2.75), see Table 4.3, and indicates a Moderate sustainability level according to the SAFA guideline (Figure 4.1). The investment score of the Gumselassa irrigation scheme indicates limited reinvestment capacity in infrastructure, technology, and productive assets. While farmers contribute labor and fees for operation and maintenance, larger investments such as reservoir rehabilitation, canal lining, or improved storage facilities are heavily dependent on external support from the government or NGOs. This reflects broader constraints in Ethiopia, where smallholder farmers face limited access to credit, extension services, and irrigation technologies (Awulachew et al., 2011).

The vulnerability theme of the economic resilience dimension score was (2.00), see Table 4.3, and indicates a limited sustainability level according to the SAFA guideline (Figure 4.1). The irrigation users of the Gumselassa irrigation scheme are vulnerable to market fluctuations and instability of crop prices, particularly for vegetables that spoil quickly, like onions and tomatoes, which dominate irrigated production. Without crop insurance, savings mechanisms, or diversified income sources, households are unable to buffer against shocks. The SAFA framework considers vulnerability reduction as essential for resilience, emphasizing adaptive capacity, diversification, and access to safety nets (FAO, 2014).

The product quality and information theme of the economic resilience dimension score was (3.0), see Table 4.3, and indicates a moderate sustainability level according to the SAFA guideline (Figure 4.1). This score reflects gaps in market information systems, product quality assurance, and value chain linkages. Irrigation users at Gumselassa often sell produce at the farm gate or local markets without access to reliable price information, grading systems, or storage facilities, and this reduces bargaining power and income stability. Similar challenges are reported across Ethiopian smallholder irrigation schemes, where lack of infrastructure and market integration limit the potential benefits of irrigation (Van Koppen et al., 2020). Improving extension services, market information systems, and cooperative marketing structures could raise this score significantly.

The local economy theme of economic resilience dimension score was (3.50), (Table 4.3), and indicates a good sustainability level according to the SAFA guideline (Figure 4.1). The relatively high score reflects the significant role of Gumselassa irrigation in supporting household incomes, employment, and local markets. Irrigation in Tigray has been shown to enhance household food security and stimulate rural economies through crop diversification and year-round production (Mekuriaw et al., 2017). In Gumselassa, the production of cash crops such as onions and tomatoes contributes to the local economy by creating market linkages and opportunities for off-farm activities. This aligns with SAFA’s emphasis on local economic contribution as a key indicator of economic resilience (FAO, 2014).

4.1.4. Social Well-being

The assessment of social well-being sustainability in the Gumselassa irrigation scheme using the SAFA guideline revealed variations across the five key themes (Table 4.4), which include decent livelihoods, fair trading practices, labour rights, equity, and cultural diversity. The social well-being dimension of the Gumselassa irrigation scheme obtained an overall score of **2.50** from Table 4.4, which indicates a moderate level of sustainability.

Table 4.4. Social well-being theme and sub-themes score

Dimension	Themes	Sub-themes	Sub-theme score	SAFA sub-theme score	SAFA theme score	Dimension score
Social Well-being	Decent Livelihoods	Quality of life	2.46	2	2.00	**2.50**
		Capacity development	2.13	2		
		Fair access to means of production	2.28	2		
	Fair Trading Practices	Responsible buyers	1.00	1	1.00	
		Rights of suppliers	1.00	1		
	Labour Rights	Employment relations	2.00	2	2.00	
		Forced labour	3.00	3		
		Child labour	1.83	2		
		Freedom of Association and right to bargaining	1.00	1		
	Equity	Non-discrimination	4.08	4	4.00	
		Gender equality	4.83	5		
		Support to vulnerable people	3.00	3		
	Cultural Diversity	Indigenous knowledge	3.00	3	3.50	
		Food sovereignty	4.00	4		

The score of the themes' livelihoods, fair trading practices, labor rights, equity, and cultural diversity was 2.00, 1.00, 2.00, 4.00, and 3.50 (Table 4-8) respectively, which indicates limited, unacceptable, limited, good, and good sustainability levels according to the SAFA guideline see figure 4.1. The lowest score was recorded for fair trading practices, unacceptable sustainability level, indicating serious unsustainability. This result indicates absence of farmer cooperatives or contract-farming arrangements prevents producers from accessing fair markets. This reflects larger issues in Ethiopia, where farmers are frequently not connected to fair value chains by irrigation programs (Awulachew et al., 2011). In order to address this deficiency and guarantee that farmers obtain fair returns, producer cooperatives, market connections, and pricing information systems must be strengthened.

Labor rights were assessed as “limited,” reflecting weak enforcement of fair labor standards. In Gumselassa, family labor dominates, and formal contracts are rare. Similar patterns are observed across small-scale irrigation in Ethiopia, where informal labor dominates without regulatory oversight (Hagos et al., 2011). To improve this score, the scheme must promote awareness of labor rights, fair wage structures, and social safety nets for vulnerable groups.

Equity emerged as a strength of the Gumselassa irrigation scheme. Water allocation is relatively fair, with community rules ensuring both upstream and downstream users receive shares. Gender representation, though not equal, has improved, as women participate in water user meetings and benefit directly from irrigated plots. This aligns with studies showing that equitable access to irrigation water significantly reduces rural poverty (Mekuriaw et al., 2017). The “good” rating indicates progress, though continued efforts are needed to achieve gender equality and support vulnerable households.

The irrigation scheme supports cultural diversity, as it encourages collective decision-making through traditional institutions such as Water user associations and Abomays. These institutions help resolve disputes and maintain local customs in water allocation. Farmers’ traditional knowledge is respected and integrated into water management. Similar findings in Tigray emphasize that irrigation schemes succeed when indigenous knowledge complements formal governance (Kassahun & Aregawi, 2020). This good score reflects strong social cohesion and cultural identity.

4.1.5. Sustainability of Gumselassa Small Scale Irrigation Scheme

The sustainability assessment of the Gumselassa irrigation scheme was evaluated across four key SAFA sustainability dimensions: Good Governance, Environmental Integrity, Economic Resilience, and Social Well-being (Figure 4.2). The SAFA assessment indicated that the Gumselassa irrigation scheme achieved a **Moderate** sustainability level, which is **2.98/5,** see figure 4.2. The sustainability level results indicate variation in sustainability scores between the dimensions, with environmental integrity scoring the highest, 3.67, and social well-being recording the lowest score, 2.50, and good governance and economic resilience, 2.92 and 2.81 sustainability level respectively.

The governance dimension of the irrigation scheme was evaluated using the SAFA (Sustainability Assessment of Food and Agriculture systems) guidelines developed by FAO. The Governance (GG) dimension of the Gumselassa irrigation scheme obtained an overall score of 2.92/5 from table 4.1, which indicates a moderate level of good governance sustainability (Figure 4.2), which suggests that while certain governance practices are present at the Gumselassa irrigation scheme, they are not fully developed or systematically applied. The good governance results are presented in terms of different themes (Table 4.1), which are (1) Accountability, (2) Participation, (3) Rule of Law, and (4) Holistic Management.

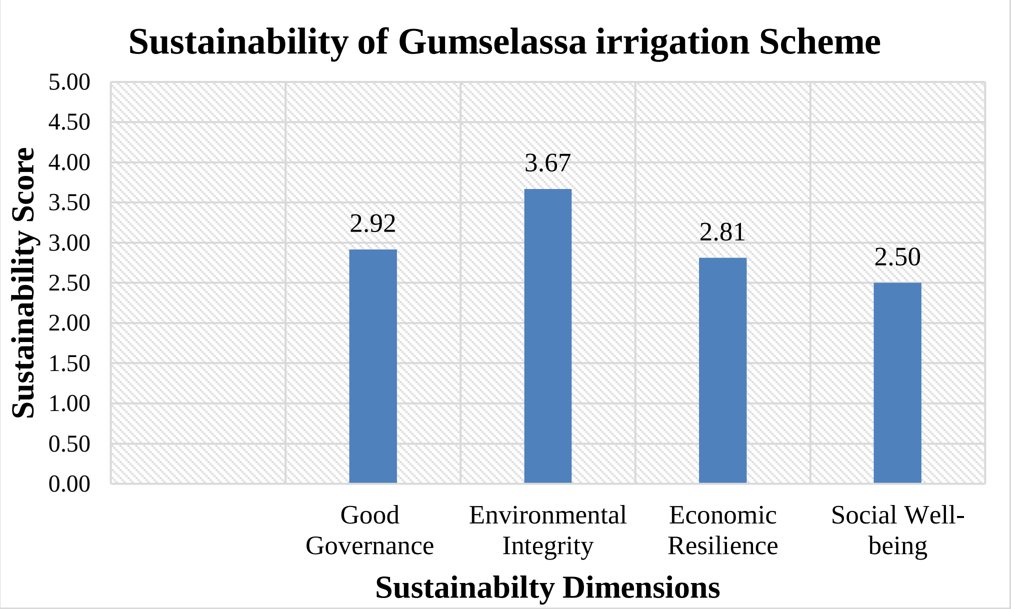


Figure 4.2. Gumselassa irrigation scheme sustainability dimension chart. FAO's score values: 4–5 (Best); 3–4 (Good); 2–3 (Moderate); 1–2 (Limited); 0–1 (Unacceptable)

The high score of the sustainability level of environmental integrity was **3.67/5,** suggesting that the irrigation scheme has effectively maintained ecological functions, water quality, and resource conservation within the project area. Even though the environmental integrity and sustainability level of the Gumselassa irrigation scheme was good and moderate respectively, it requires interventions such as watershed rehabilitation and conservation practice, soil improvement practice. The results are consistent with previous findings in Tigray, where irrigation has improved food security and productivity, but faces long-term sustainability risks if environmental challenges are not addressed (Hagos et al., 2011; Mekuriaw et al., 2017). Also, the finding aligns with studies that highlight how well-managed irrigation systems can enhance ecosystem services through soil conservation, improved vegetation cover, and water-use efficiency (FAO, 2017).

Economic resilience of the Gumselassa irrigation scheme was scored (2.81/5), which is a moderate sustainability level, suggesting that while the irrigation scheme may contribute to agricultural productivity, it faces challenges in ensuring stable and diversified incomes for beneficiaries. The same finding was also reported by Berhe et al. (2025); the production, market, and supply stability of Tigray irrigation schemes were severely affected by the war and siege in Tigray. Without targeted interventions, such as promoting value addition, market linkages, and financial literacy programs, the long-term economic sustainability of the scheme may remain constrained.

The social well-being of the Gumselassa irrigation scheme recorded the lowest sustainability level score (2.5/5), reflecting potential shortcomings in areas such as fair trading practices, and improvements in quality of life for the community. The lowest score was recorded for fair trading practices, unacceptable sustainability level, indicating serious unsustainability. This result reflects larger issues in Ethiopia, where farmers are frequently not connected to fair value chains by irrigation programs (Awulachew et al., 2011). In order to address this deficiency and guarantee that farmers obtain fair returns, producer cooperatives, market connections, and pricing information systems must be strengthened.

4.2. Effect of Irrigation Practice on Selected Soil Health Indicators

The soil type of the study area was clay for both land uses and soil depths (Table 4.5).

Table 4.5. Soil particle size distribution (%) of the study area

Soil depth (cm)	Irrigation					Rain fed				
	% sand	% sand	% clay	Texture (USDA)	OM (%)	% sand	% sand	% clay	Texture (USDA)	OM (%)
0-30	26	24	50	Clay	2.103	23	24	45	Clay	1.841
30-60	24	25	51	Clay	1.672	21	32	47	Clay	1.607

4.2.1. Effect of Irrigation Practice on Selected Soil Physical Indicators

The irrigation fields in the study area did not show any significant difference in total porosity and bulk density (BD) compared to the rain-fed fields. The soil bulk density in the irrigation fields ranged from 1.29 to 1.46 Mg m^{-3} and 1.3 to 1.44 Mg m^{-3} at the 0-30 cm and 30-60 cm respectively, while in the rain fed fields it ranged from 1.37 to 1.52 Mg m^{-3} and 1.36-1.45 Mg m^{-3} for the 0-30 cm and 30-60 cm depths respectively (table 4.6 and figure 4.3a, 4.4a). The result appears that long-term irrigation practice in the study area resulted in a 2.6% and 3.4% reduction in soil bulk density for depths 0-30 cm and 30-60 cm, respectively, compared to the corresponding soils from rain-fed fields. Similarly, there was a 3.45% reduction in soil bulk density reported in irrigated fields compared to rain-fed fields in Damietta Governorate, Egypt (Fadl et al., 2024). Similarly 5.5% decrease in soil bulk density was reported in irrigated fields of May-Negus small-scale irrigation field, Tigray, Ethiopia, as compared to that of rain-fed farms (Weldewahid et al., 2023). Based on (Amacher et al., 2007), the classification guideline, soils of irrigation fields and rain-fed fields are categorized into no adverse effects on soil structures. Table 4.6 shows the difference in soil bulk density at both 0 - 30 cm and 30 - 60 cm depths for both land uses. The bulk density shows a reduction of 2.36% and 1.5% in irrigation fields and rain-fed fields as the depth increases. Similarly 1.23% reduction in soil bulk density 0-10 cm and 10-20 cm was reported by (Serme et al., 2016).

The irrigated fields shows a 2.8% increase in total porosity (TP) from 0-30 cm depth and a 1.8% increase from 30-60 cm soil depth. This is because of irrigated fields produce more root biomass from crops grown twice a year, which results in a relatively higher soil organic matter content and lower soil bulk density (Adejumobi et al., 2022). The higher bulk density observed in rain-fed fields (1.52 g cm^{-3}) compared to the corresponding irrigation fields (1.46 g cm^{-3}) indicates that the soil in the rain-fed areas has a larger mass per unit volume, depending on some factors. Thus, the variations in bulk density and porosity between irrigation and rain-fed fields highlight the importance of soil management practices that support the creation of root biomass, soil structure, and organic matter content in order to enhance soil health and overall agricultural productivity (Fadl et al., 2024).

The SSI showed a significant increase of 5.6% in 0-30 cm soil depth and 9.87% in 30-60 cm soil depth in the study area (Table 4.6). The higher values of SSI indicates a lower risk of soil structural degradation (Amacher et al., 2007; Serme et al., 2016). Conversely, the lower SSI value on rain-fed soils was also an indicator of inadequate replenishment, continuous removal of nutrients, and loss of organic matter from the soils, which contribute to increased erosion rates (Amacher et al., 2007; Fadl et al., 2024; Serme et al., 2016; Weldewahid et al., 2023). For sustainable agriculture, soils with stable structures and good physical quality are crucial because they provide a favorable environment for plant growth, water infiltration, and nutrient availability (Fadl et al., 2024).

Irrigation practices can enhance the long-term health and production of soil by strengthening its structural stability (Adejumobi et al., 2016).

Table 4.6. Comparison of physical soil indicators between irrigation and rain-fed soils.

Soil Indicator	Land Use	Number of Samples	(0-30) cm		(30-60) cm	
			Mean	Sig	Mean	Sig
Bulk Density g/cm3	Irrigation	9	(1.388 ±0.058)	0.201	(1.356 ±0.042)	0.184
	Rain fed	9	(1.423 ±0.046)		(1.402 ±0.025)	
Total Porosity	Irrigation	9	(47.631±2.174)	0.197	(46.221 ±2.129)	0.177
	Rain fed	9	(46.291 ±1.739)		(45.401 ±1.297)	
Soil Structural Stability Index	Irrigation	9	(2.508+0.206)	0.041[a]	(2.148 ±0.183)	0.034[a]
	Rain fed	9	(2.376+0.324)		(1.955 ±0.293)	

±, standard deviation; [a] Shows the difference between irrigated and rain-fed is statistically significant, values indicated by ±in brackets =standard deviation.

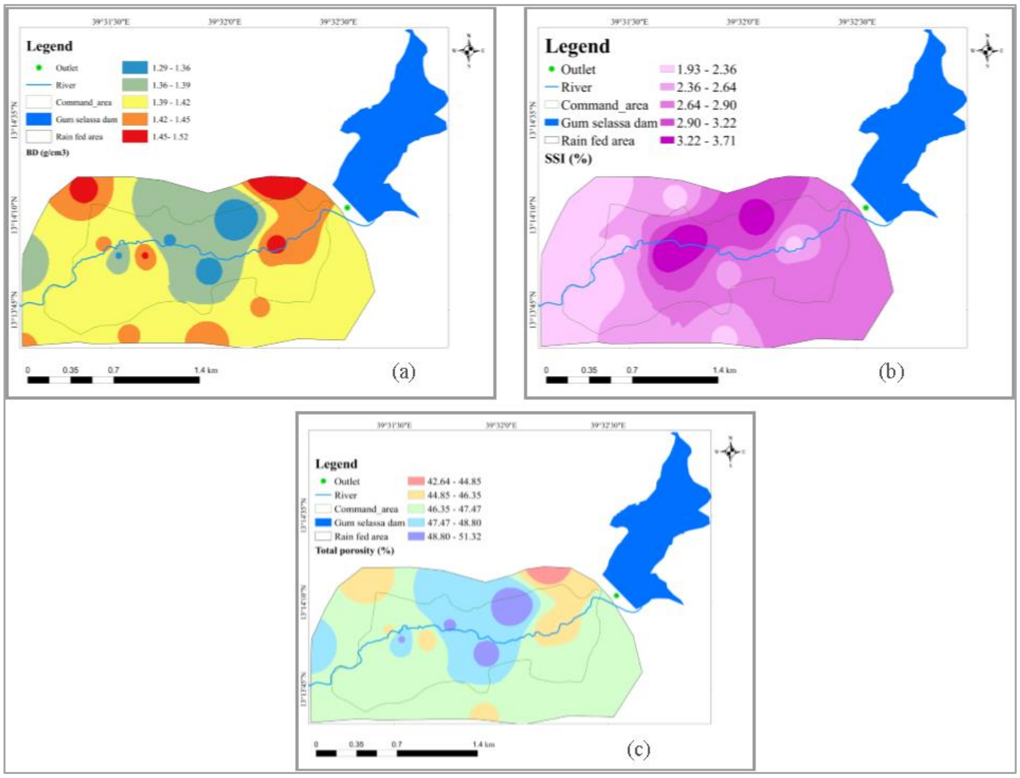


Figure 4.3. Bulk density (BD) (a), soil structural stability index (SSI) (b), and total porosity (c) at (0-30) cm soil depth distribution in the study area.

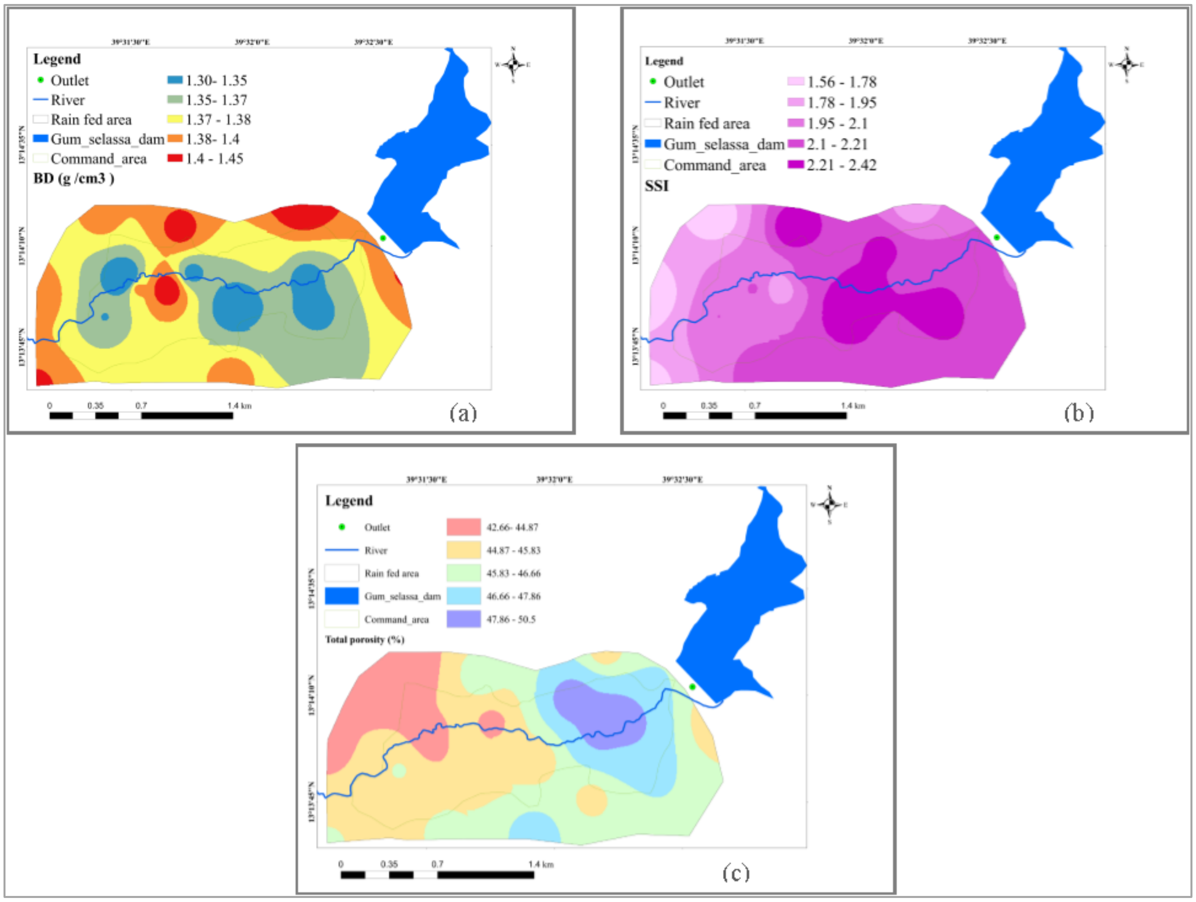


Figure 4.4. Bulk density (BD) (a), soil structural stability index (SSI) (b), and total porosity (c) at (30-60) cm soil depth distribution in the study area.

4.2.2. Effect of Irrigation Practice on Selected Soil Chemical Indicators

The irrigated field in the study area has significantly higher levels of soil organic carbon (SOC), total nitrogen (TN), and available Phosphorus (P) as compared to the surrounding rain-fed farm plots. Table 4.7, Figures 4.5 and 4.6 summarizes the comparison of soil chemical properties of irrigated and rain-fed farm plots in the study area. Long-term irrigation was found an increase in SOC and TN by 14.03 and 20.88% at 0-30 cm soil depth and 11.34% and 18.67% at 30-60 cm soil depth, respectively. This corresponds with the finding of Weldewahid et al (2023) that reported a 21% increase in SOC and 37% increase in TN on the irrigation fields. This indicates that irrigation practice has improved the retention of crop residues in the soil, leading to higher organic carbon and nitrogen contents (Adejumobi et al., 2014). The lower SOC and TN contents in the rain-fed fields were also associated with the crop rotation and history of farm input supply. On the rain-fed soils, crop rotation was less practiced because the cropping system was dominated by monoculture

Teff, and only mineral fertilizer was applied. Moreover, crop harvesting practice on rain-fed soils regularly removes all the above-ground biomass for fuel wood and animal forage, which results in low soil organic matter content (Weldewahid et al., 2023).

The available phosphorus P content in irrigated fields was 26.95 % higher at 0-30 cm soil depth and 19.76 % higher at 30-60 cm soil depth compared to that of rain-fed soils. This is related to the additional inputs like animal manure, compost, and household wastes like ashes supplied on soils of irrigated fields at least twice a year, as compared to applying chemical fertilizer to rain-fed farm soils only once. These added inputs potentially increase soil organic matter content in soils, which in turn increases phosphorous concentration (Gebeyehu & Soromessa, 2018; Getaneh et al., 2007; Weldewahid et al., 2023). According to Amacher et al., (2007), the calculated available phosphorous, soils in both land uses are categorized into moderate potential soils with adequate levels of available P for plant growth at the 0-30 cm of soil depth, whereas with the 30-60 cm of soil depth, the available P are categorized into low P deficiencies likely on both land uses.

The carbon-to-nitrogen ratio (C: N) was also considerably lower in irrigated soils than in rain-fed soils. This is consistent with the results of (Weldewahid et al., 2023), which showed that irrigated farms had a lower carbon to nitrogen ratio than their nearby rain-fed farm plots. According to Aweke et al. (2014), irrigated soils with higher nitrogen content also have higher soil organic matter and soil moisture contents for the optimum decomposition of soil organic matter.

The long-term irrigation practice in the study area led to a 0.55% increase in soil pH compared to those soils under rain-fed production. The pH of the soils increased from (8.11 to 8.16) at 0-30 cm soil depth and (8.19-8.2) at 30-60 cm soil depth upon adopting irrigation, as shown in table 4.6. This is in line with the findings of Mon et al. (2007) for Argentina's pampa region, which reported that the adoption of irrigation caused a slight increase in pH (from 6.13 to 6.45) and a small decreasing from the study of (Gebremeskel et al., 2018) at Gumselassa irrigation scheme which is 8.64 from the upper soil layer 0-15 cm soil depth. This increase in pH can be attributed to the increased application of soil organic matter (Adejumobi et al., 2022). The study area's soils are classified as moderately alkaline, which is preferred by plants that are adapted to this pH range with possible P and metal deficits, according to the mean soil pH (8.11–8.20) of both soil depths and land uses (Amacher et al., 2007).

Table 4.7. Comparison of selected soil chemical indicators between irrigated and rain-fed soils

Soil Indicator	Land Use	Number of Samples	(0-30)cm		(30-60)cm	
			Mean	p Value	Mean	p Value
PH	Irrigation	9	(8.156±0.167)	0.009[a]	(8.200±0.15)	0.116
	Rain fed	9	(8.111±0.334)		(8.189±0.267)	
EC (dSm^{-1})	Irrigation	9	(0.263±0.144)	0.0001[a]	(0.403±0.298)	0.004[a]
	Rain fed	9	(0.117±0.035)		(0.132±0.069)	
OC (%)	Irrigation	9	(1.219±0.292)	0.006[a]	(1.026±0.119	0.035[a]
	Rain fed	9	(1.069±0.134)		(0.921±0.056)	
TN (%)	Irrigation	9	(0.131±0.029)	0.002[a]	(0.109±0.018)	0.009[a]
	Rain fed	9	(0.109±0.013)		(0.092±0.01)	
P (mg.kg $^{-1}$)	Irrigation	9	(13.458±0.259)	0.004[a]	(9.604±1.172)	0.012[a]
	Rain fed	9	(10.601±0.904)		(8.02±0.323)	
C:N	Irrigation	9	(9.520±2.171)	0.032[a]	(9.514±1.686)	0.732
	Rain fed	9	(9.839±1.006)		(10.099±1.343)	
TN Stock (mg N ha−1)	Irrigation	9	(5.44±1.144)	0.017[a]	(4.47±0.718)	0.032[a]
	Rain fed	9	(4.65±0.585)		(3.88±0.400)	
SOC Stock (mg C ha−1)	Irrigation	9	(50.59±11.527)	0.038[a]	(41.72±5.059)	0.041[a]
	Rain fed	9	(45.60±6.505)		(38.42±2.422)	
Soil Health Index (SHI)	Irrigation	9	(0.88±0.021	0.025[a]	(0.83±0.020)	0.001[a]
	Rain fed	9	(0.65±0.049)		(0.61±0.062)	

±, standard deviation; [a] Shows the difference between irrigated and rain-fed is statistically significant; values indicated by ±in brackets =standard deviation.

In irrigated fields, the electrical conductivity (EC) was found to be significantly higher, with a 125.71% at 0-30 cm soil depth and 205.04% at 30-60 cm soil depth compared to adjacent rain-fed fields, as shown in table 4.7. These results are in good agreement with (Phogat et al., 2020), who found that long-term irrigation practice increases concentrations of soluble salt in the soil solution rapidly. The relatively higher concentration of base-forming cations and soil pH contribute to the increased soil EC due to a continuous enrichment of dissolved calcium with irrigated water (Fadl et al., 2024). According to the (Amacher et al., 2007) classification, the soil EC in both soil depths and land uses is categorized as non-saline. The most likely reason for having low EC even in the irrigated fields could be attributed to the acceptable irrigation water quality (Phogat et al., 2020; Weldewahid et al., 2023), and heavy rainfall during the rainy season, which may contribute to timely leaching of salts from the root zone (Phogat et al., 2020). The finding of EC in the Gumselassa irrigation indicates decreases from the finding of Yohannes et al., (2019), and the decreasing may be due to variation of data taking since the soil data was taken before the beginning of irrigation and the irrigation gaps due Tigray war at the irrigation scheme.

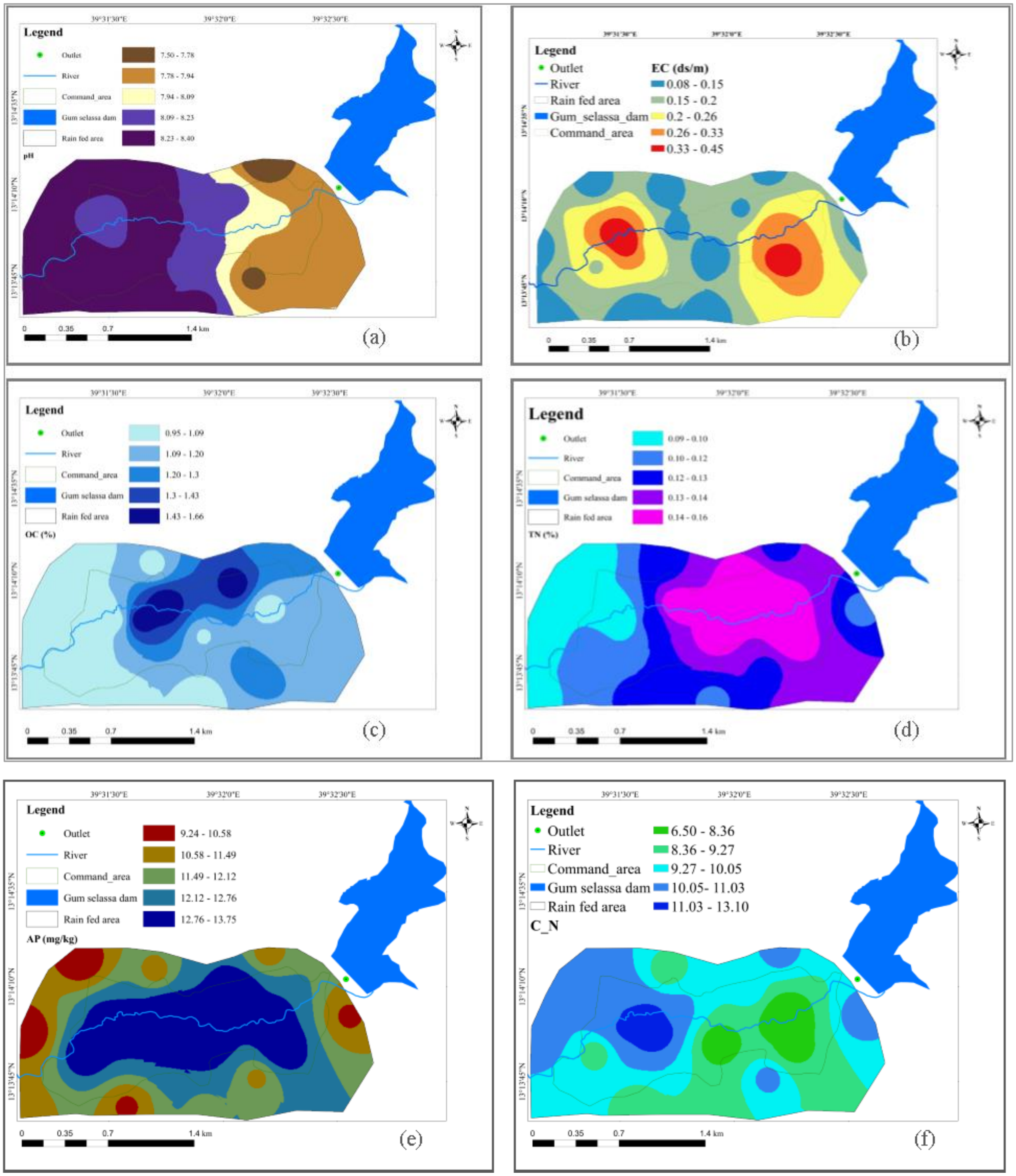


Figure 4.5. Soil chemical characteristics distribution (0-30) cm soil depth in the study area: PH (a), EC (b), OC (c), TN (d), p (e), and C: N(f).

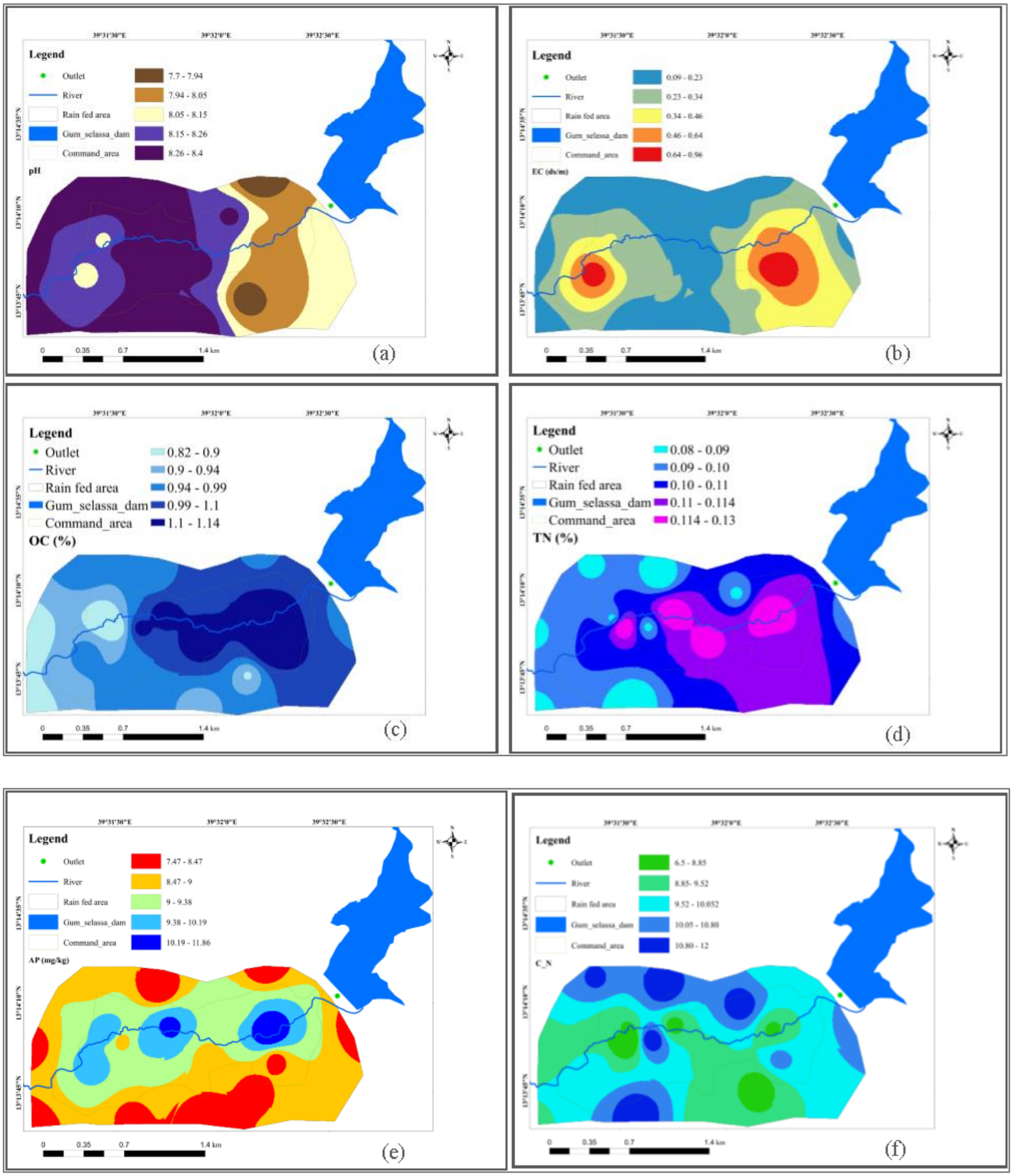


Figure 4.6. Soil chemical characteristics distribution (30-60) cm soil depth in the study area: PH (a), EC (b), OC (c), TN (d), P (e), and C: N(f).

The mean soil organic carbon and nitrogen stock were higher on irrigated fields compared to rain-fed fields, as presented in Table 4.6. The irrigated soils had a soil organic carbon stock of 50.59 Mg C ha−1 and a nitrogen stock of 5.44 Mg N ha−1 at (0-30) cm soil depth and 41.72 Mg C ha−1 and 4.47 Mg N ha−1 at (30-60) cm soil depth, while the rain fed fields had a soil organic carbon stock of 45.60 Mg C ha−1 and a nitrogen stock of 4.65 Mg N ha−1 at (0-30) cm soil depth and 38.42 Mg C ha−1 and 3.88 Mg N ha−1. This indicates approximately 10.9% and 17.1% at (0-30) cm soil depth and 8.6% and 15.2% at (30-60) cm soil depth, increased the SOC and N stocks due to the long-term irrigation practice respectively. (Weldewahid et al., 2023) also reported that an increase in SOC and N stock by a magnitude of 14.1% and 29.9%, respectively. Similarly, Gebeyehu & Soromessa (2018) found a 3.4% and 2.0% increase in SOC stock and total nitrogen stock, respectively.

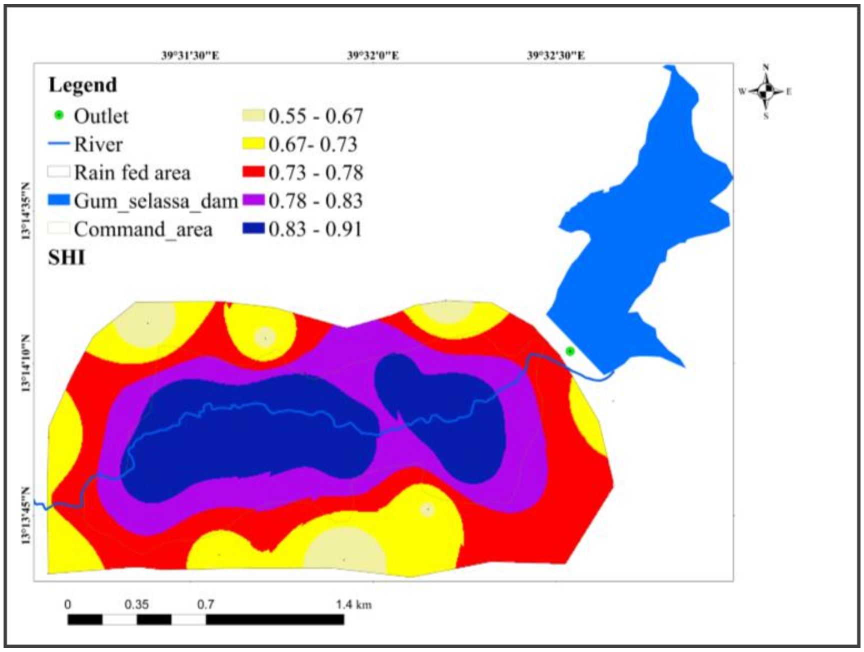


Figure 4.7. Soil health index distribution of (0-30) cm depth in the study area.

The soil quality index was higher on irrigated fields (0.88) than that of rain-fed fields (0.65), which was 36.2% higher at (0-30) cm soil depth and (0.83) on irrigated fields and (0.61) on rain-fed fields at (31-60) cm soil depth, which was 37.5% higher. The increased usage of crop rotation (cereal-vegetable-cereal) and moisture content on irrigated soils, which in turn led to an increase in soil organic matter availability (Aweke et al., 2014; Gebeyehu & Soromessa, 2018). However, in rain-fed fields, the presence of continuous cultivation, the addition of minimal inputs, and the removal of crop residues play a role in soil redistribution and soil structure (Gebeyehu & Soromessa, 2018). According to (Aprisal et al., 2019), soil quality classification, the soil quality of the study area was classified as very good in irrigation fields and good in the rain-fed fields at both soil depths.

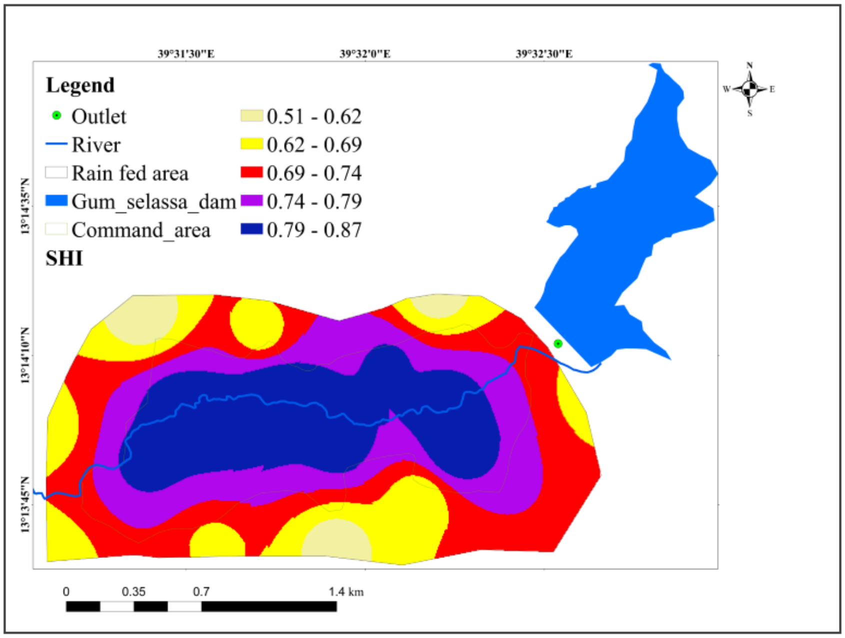


Figure 4.8. Soil health index distribution of (30-60) cm soil depth in the study area.

4.2.3. Effect of Irrigation Practice on exchangeable bases, cation exchange capacity

The results of exchangeable bases, cation exchange capacity, and related soil parameters for both irrigated and rain-fed fields at both soil depths are indicated in table 4.8. All parameters significantly increased upon irrigation practice except for CEC and exchangeable. Long-term irrigation, increased Potassium, Calcium, Magnesium, Sodium, sodium absorption ratio (SAR), exchangeable sodium percentage (ESP), and percent base saturation (PBS) by 43.9%, 24%, 18.1%, 32.2%, 20.6%, 21.8 and 5.8% at (0-30) cm soil depth and by 38.9%, 23.9%, 11.7%, 19.2%, 9.1%, 12.4 and 7.8% at (30-60) cm soil depth respectively as compared to the rain fed farm soils. The increase in these parameters is consistent with the findings of (Weldewahid et al., 2023) that argued irrigation development brings about large-scale changes in the local geo-hydrological regime, which often results in the mobilization of these cations. This is due to the addition of organic materials and to the improved mobility of the cations in soil (Fadl et al., 2024). According to the findings of (Mon et al., (2007) and (Phogat et al., (2020), irrigation water could increase the amount of base cations, like sodium in soils without increasing the overall salt content, which could also be due to modification of the proportion of exchangeable cations rather than an increase in total salt content.

Table 4.8. Comparison of exchangeable bases, cation exchange capacity, and related parameters between irrigated and rain-fed soils.

Soil Indicator	Land Use	Number of Samples	(0-30) cm		(30-60) cm	
			Mean	p Value	Mean	p Value
Ex. K^{+} (cmolc.kg^{-1})	Irrigation	9	(0.721±0.138)	0.009[a]	(0.639±0.08)	0.013[a]
	Rain fed	9	(0.501±0.019)		(0.46±0.032)	
Ex. Ca^{+2} (cmolc.kg^{-1})	Irrigation	9	(20.678±0.749)	0.033[a]	(18.312±1.393)	0.006[a]
	Rain fed	9	(16.679±1.605)		(14.784±0.625)	
Ex. Mg^{+2} (cmolc.kg^{-1})	Irrigation	9	(12.036±0.736)	0.013[a]	(11.051±1.118)	0.002[a]
	Rain fed	9	(10.194±1.659)		(9.89±2.362	
Ex. Na^{+} (cmolc.kg $^{-1}$)	Irrigation	9	(0.338±0.076)	0.005[a]	(0.256±0.045)	0.027[a]
	Rain fed	9	(0.256±0.033)		(0.214±0.024)	
SAR	Irrigation	9	(0.084±0.019)	0.004[a]	(0.068±0.012)	0.014[a]
	Rain fed	9	(0.07±0.007)		(0.062±0.007)	
CEC (cmolc.kg^{-1})	Irrigation	9	(41.056±1.445)	0.173	(39.84±2.04)	0.272
	Rain fed	9	(36.53±2.236)		(36.056±1.429	
ESP (%)	Irrigation	9	(0.858±0.2222)	0.025[a]	(0.683±0.109)	0.019[a]
	Rain fed	9	(0.705±0.129)		(0.608±0.061)	
PBS (%)	Irrigation	9	(80.476±2.756)	0.034[a]	(76.128±5.943)	0.02[a]
	Rain fed	9	(76.027±8.41)		(70.648±10.39)	

[a] Shows the difference between irrigated and rain-fed is statistically significant. Ex. K^{+}=Exchangeable Potassium, Ex. Ca^{+2} =Exchangeable Calcium, Ex. Mg^{+2} =Exchangeable Magnesium, Ex. Na^{+} =Exchangeable Sodium, SAR =Sodium Observation Ratio, CEC =cation exchange capacity, ESP =Exchangeable Sodium Percentage, PBS =Percent Base Saturation, values indicated by ± in bracket =standard deviation.

The long-term irrigation resulted in a considerable increase in SAR (from 0.07 to 0.084) at (0-30) cm soil depth and (from 0.062 to 0.068) at (30-60) cm soil depth, which agrees with the findings of (Phogat et al., 2020) that reported a rapid increase in SAR upon irrigation adoption. The SAR values less than 13 indicate that an adverse effect of sodicity is unlikely (Amacher et al., 2007). The long-term irrigation in the study area also increased ESP from 0.71 to 0.86% at (0-30) cm soil depth and 0.61 to 0.68% at (30-60) cm soil depth. This is aligns with the findings of (Weldewahid et al., 2023) that reported a slight increase in ESP (from 0.61 to 1.71%) upon irrigation adoption. The calculated ESP values were below their threshold value (<15% is non-sodic) in both soil depths and land uses (Amacher et al., 2007).

Overall, the increase in PBS (from 76 to 80.5%) at (0-30) cm soil depth and (from 70.7 to 76.1%) at (30-60) cm soil depth indicates improved soil fertility status in the both soil depth of irrigated fields, high soil fertility in both land uses and soil depths (Amacher et al., 2007). The CEC of soils at both land uses and soil depths is classified into the moderate category, which could indicate adequate levels of basic cations. The increased application of animal manure, retention of crop residues, and increased soil moisture availability on irrigated soils also led to numerically increased soil CEC 12.4% at upper soil and 10.5% at lower soil depth, which in turn enhances the availability of Ca^{+2}, K^{+}, and Mg^{+2} (Phogat et al., 2020).

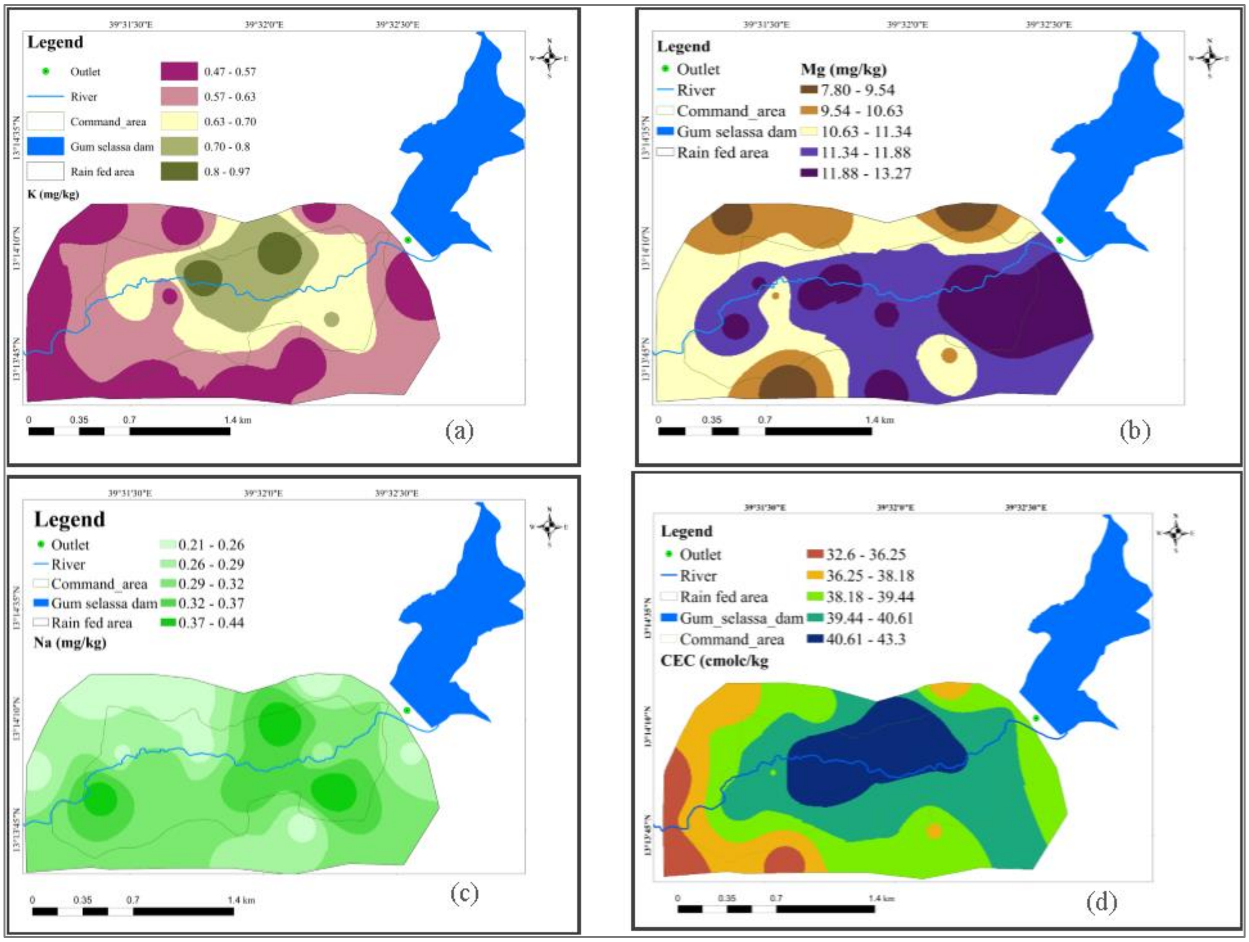


Figure 4.9. Soil exchangeable bases, CEC, and related parameters distribution (0-30) cm soil depth in the study area: K (a), Mg (b), Na (c), CEC (d).

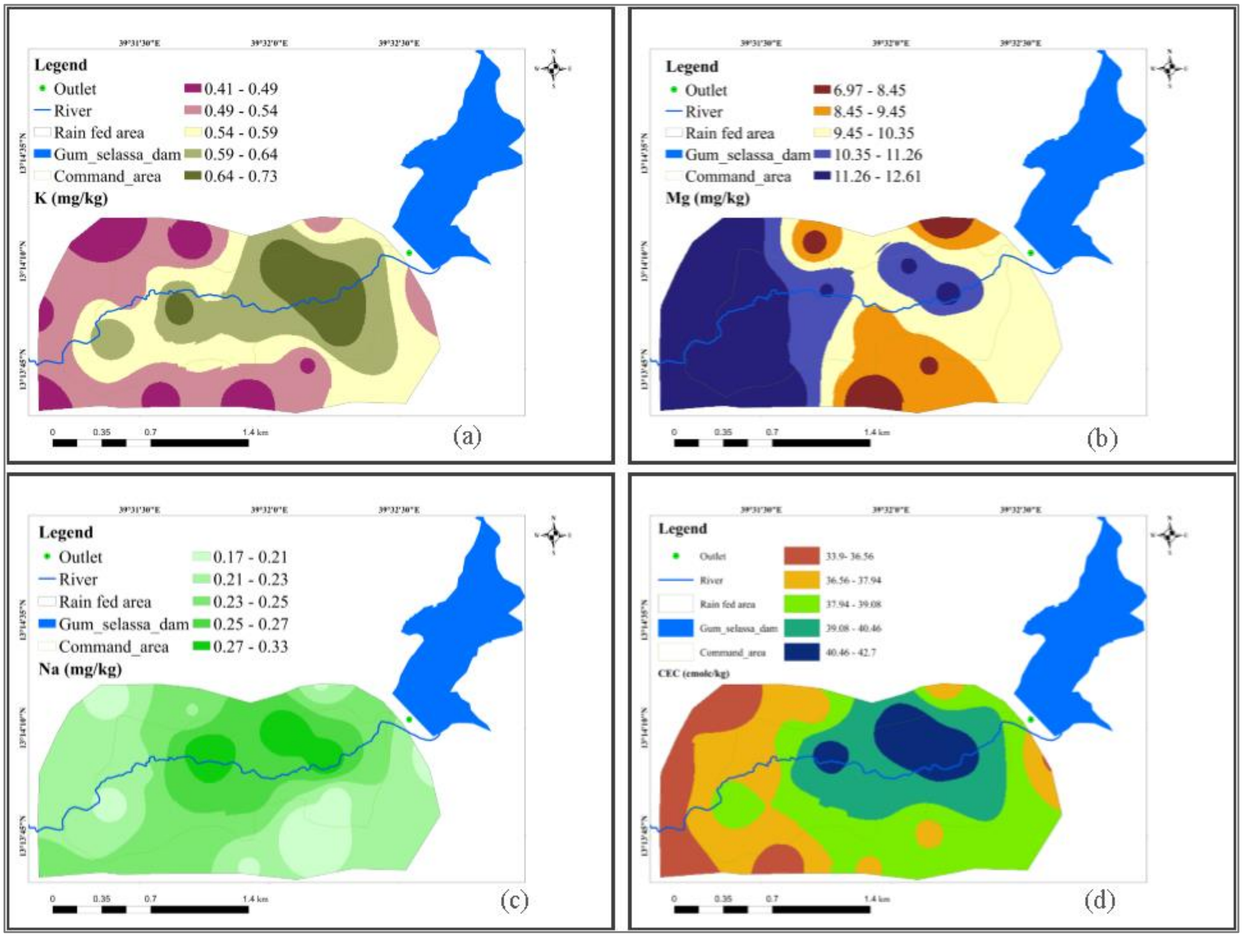


Figure 4.10. Soil exchangeable bases, CEC, and related parameters distribution (30-60) cm soil depth in the study area: K (a), Mg (b), Na (c), CEC (d).

4.3. Irrigation Sustainability Challenges and their Alternative Solutions

4.3.1. Sustainability Challenges of Gumselassa Irrigation Scheme

The challenges/problems of Gumselassa irrigation scheme was rated (Figure 4.11) by the experts as highly severe challenges reservoir siltation (2.8), lack of adequate data for reservoir design, soil salinity, low technical and managerial capacity of managing scheme institutions, low financial capacity for operation and maintenance costs, low irrigation efficiency, and insufficient water availability for irrigation (2.6), and poorly treated watersheds, sedimentation of conveyance structures, lack of irrigation water metering, and poor irrigation scheduling practices (2.4), as moderately severe challenges seepage loss from reservoirs, structural damage on conveyance structures, lack of appropriate irrigation water tariffing system, high maintenance cost, low irrigation water productivity, low awareness of irrigation water users about irrigation, problems on irrigable land redistribution among users (2.2), waterlogging (2), insufficient flow to reservoirs, structural failure on dam body and its appurtenant structures, conveyance loss, neglecting community knowledge and experience in decision making, irrigation users' low willingness to pay for irrigation water, low crop yield, and ambiguities in ownership of irrigation system infrastructures (1.8) and as less severe challenges unavailability of irrigation water users' association, neglecting women in decision making, conflict between irrigation users and non-users (1.6), inequitable water sharing among users, and poor soil and crop management practices (1.4).

The challenges identified in the Gumselassa irrigation scheme are largely consistent with findings from similar small- and medium-scale irrigation schemes in Ethiopia and other developing countries. The highly severe challenge of reservoir siltation (mean = 2.8) for Gumselassa SSIS agrees with numerous studies that identify sedimentation as a critical factor reducing reservoir storage capacity and scheme performance. Haregeweyn et al., (2015) reported that severe watershed degradation and poor upstream land management in the Ethiopian highlands significantly accelerate sediment inflow into reservoirs, thereby shortening their design life. Similar observations were made by Yohannes et al., (2019), who emphasized that inadequate consideration of sediment yield during reservoir design is a major weakness of small-scale irrigation schemes. The lack of adequate data for reservoir design and insufficient water availability (mean = 2.6) also aligns with Awulachew et al., (2011), many irrigation schemes in Ethiopia were designed using limited hydrological and meteorological data, leading to overestimation of available water and subsequent supply deficits.

The moderately severe challenges identified in Gumselassa SSIS, including poorly treated watersheds, sedimentation of conveyance structures, lack of water metering, and poor irrigation scheduling practices (mean = 2.4), are supported by Awulachew et al.,(2007), noted that the absence of irrigation water measurement devices and weak scheduling practices often lead to inequitable water distribution and inefficient water use. Challenges such as waterlogging, low crop yield, users' low willingness to pay, and ambiguities in ownership of irrigation infrastructure (mean ≈ 1.8–2.0), are also comparable with findings Hagos et al., (2011), reported that unclear ownership arrangements and weak enforcement of water fees reduce farmers' sense of responsibility for system maintenance, ultimately affecting productivity.

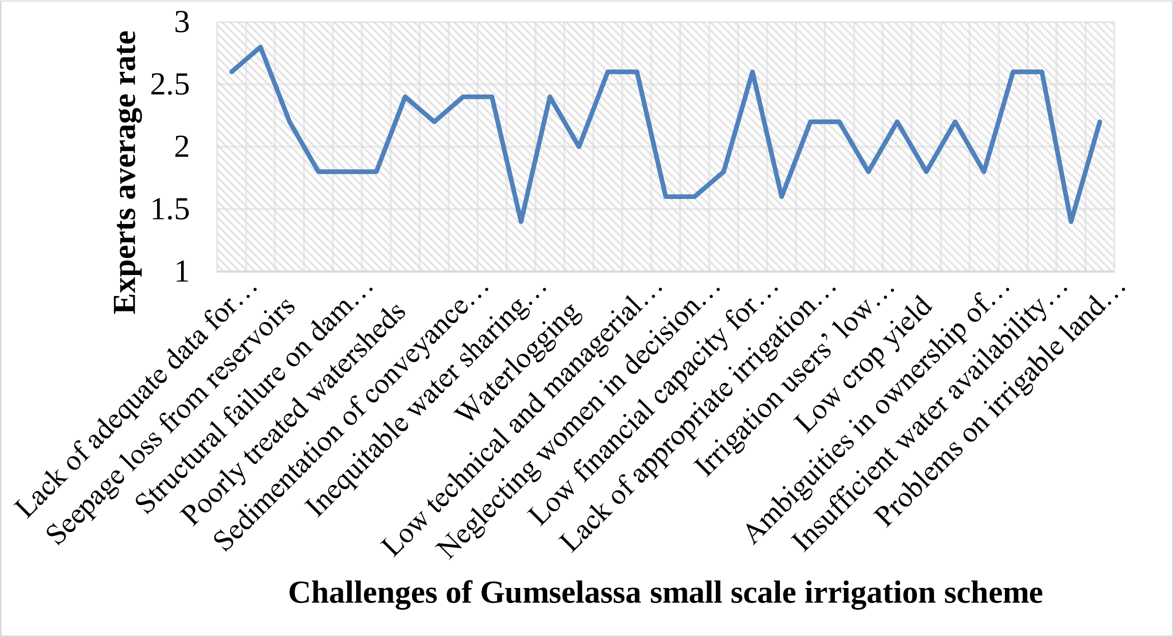


Figure 4.11. Challenges of the Gumselassa small-scale irrigation scheme (experts' response)

4.3.2. Alternative Solutions for Challenges of Gumselassa irrigation Scheme

The alternative solution for Gumselassa irrigation scheme was ranked (Figure 4.12) as highly important alternative inclusive community participation in planning, development, and management of irrigation schemes (3), implementation of watershed management practices in the upstream reaches of reservoirs, establishing irrigation water users' associations (2.8), sediment removal from reservoirs (2.6), setting routine maintenance schedule for irrigation infrastructures, accounting local community knowledge and experiences in decision making processes, training and capacity building of irrigation water users, development workers, and other stakeholders, land reclamation practices (2.4), as moderately important alternative implement conjunctive use of reservoir water and other sources of water for irrigation, working on awareness raising of irrigation users, and improve soil and crop management practices, and as less important alternative introduction of water tariffing and pricing systems, and implementation of irrigation water metering (1.6).

The highest-ranked alternative solution for Gumselassa SSIS is inclusive community participation in the planning, development, and management of irrigation schemes (mean = 3.0), strongly aligns with findings of Yohannes et al., (2019), small-scale irrigation schemes in northern Ethiopia, emphasized with strong farmer participation and shared decision-making tend to show better operation, maintenance, and conflict resolution. The implementation of watershed management practices in upstream reservoir catchments and the establishment of irrigation water users' associations (mean = 2.8) are also well supported by the studies conducted in Tigray have repeatedly shown that integrated watershed management significantly reduces sediment inflow into reservoirs and improves their longevity (Haregeweyn et al., 2015). The ranking of sediment removal from reservoirs (mean = 2.6) as a highly important solution is also consistent with findings from Tigray, as Yohannes et al., (2019) documented that many reservoirs in the region have lost a substantial portion of their designed capacity within a short period of operation.

Alternatives ranked as moderately important (mean = 2.4), including routine maintenance of irrigation infrastructure, incorporation of local knowledge, capacity building, and land reclamation practices are similarly emphasized with the study of Amede (2015) noted that weak maintenance culture and inadequate technical skills among users and development agents are persistent constraints in small-scale irrigation schemes. The low ranking of water tariffing, pricing systems, and irrigation water metering (mean = 1.6) is consistent with observations from other Ethiopian studies. Awulachew et al., (2011) and Yohannes et al., (2019) reported that introducing formal water pricing and metering in smallholder-dominated irrigation schemes often faces resistance due to low income levels, weak institutional enforcement, and limited technical capacity.

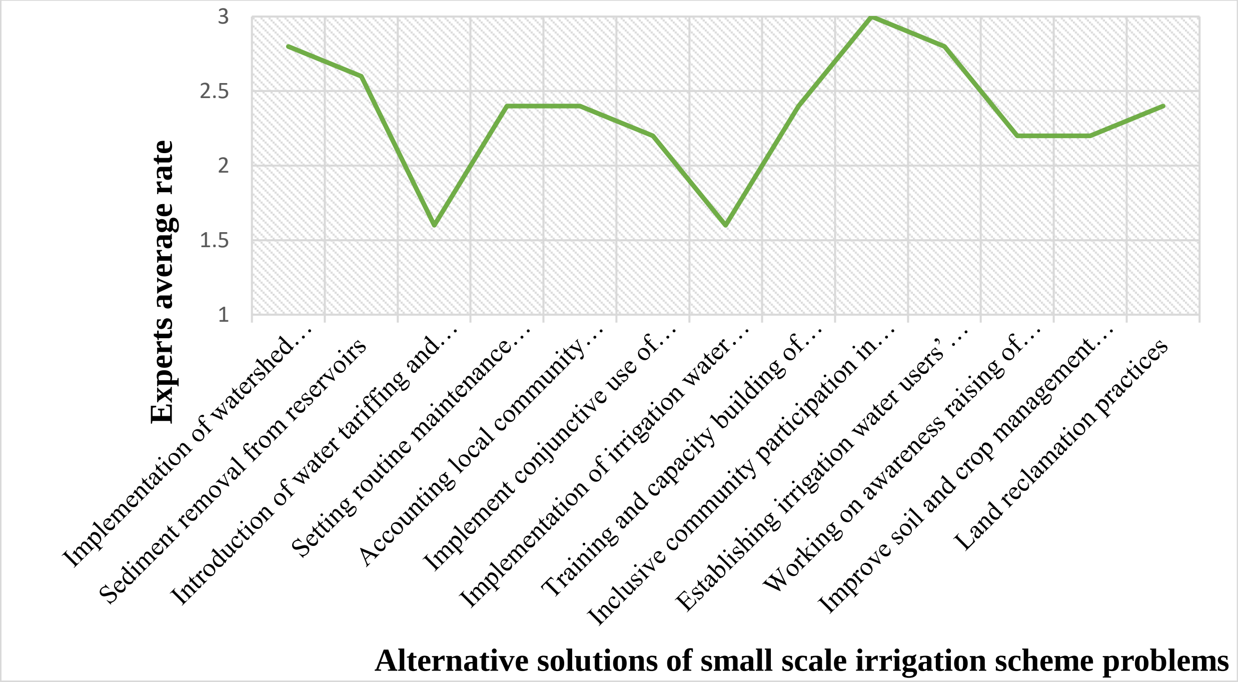


Figure 4.12. Alternative solutions for the problems of the Gumselassa SSIS

5. Conclusions and Recommendations

5.1. Conclusion

This study assessed the sustainability of the Gumselassa small-scale irrigation scheme in Tigray, Ethiopia, using the FAO SAFA framework, and selected soil health indicators. The sustainability was assessed based on four dimensions: good governance, environmental integrity, economic resilience, and social well-being. The overall sustainability level of the Gumselassa irrigation scheme was 2.98, which indicated a moderate sustainability level. The score for each dimension of the irrigation scheme was also a good sustainability level of environmental integrity 3.67, moderate sustainability level of good governance 2.92, economic resilience 2.81, and social well-being 2.50. These findings suggest that while irrigation contributes positively to livelihoods, income, and soil fertility, weaknesses in governance structures, institutional arrangements, and social inclusiveness remain critical barriers to long-term sustainability.

The soil health analysis shows that irrigation practices improved several soil properties compared to rain-fed agriculture. The soil health index was higher on irrigated fields 0.88 than on rain-fed fields 0.65, which was a 35.4% increase at (0-30) cm soil depth and 0.83 on irrigated fields and 0.61 on rain-fed fields at (30-60) cm soil depth, which was a 36.1% increase at the irrigation field than the rain-fed fields. The consistent improvement across both surface and subsurface soil layers underscores the potential of irrigation practices to sustain soil productivity and long-term agricultural performance within the irrigation scheme.

Reservoir siltation was identified as a highly severe challenge of the Gumselassa small-scale irrigation scheme. Inclusive decision making and users participation during operation and maintenance would play an important role in solving the sustainability challenges of the irrigation scheme.

5.2. Recommendations

Based on the study findings, the following recommendations are made:

- **Strengthening the institutional set-up and governance of the irrigation scheme**
    - ✓ Enhance the capacity, transparency, and accountability of Water User Associations (WUAs).
    - ✓ Encourage participatory decision-making, equitable water distribution, and clear enforcement of bylaws.
    - ✓ Introduction of irrigation water pricing to improve the financial sustainability of the scheme, considering the operation and maintenance costs.
- **Improving soil health and reducing environmental impacts**
    - ✓ Promote efficient irrigation methods and scheduling practices to reduce waterlogging and salinity problems.
    - ✓ Integrate soil conservation practices that considers the entire irrigation system components to minimize reservoir siltation.
- **Policy and research support**
    - ✓ Government and development partners should prioritize the sustainability of existing schemes rather than focusing only on the construction of new projects.
    - ✓ Further research should be conducted on long-term soil health monitoring and climate change resilience of small-scale irrigation schemes.

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Appendix

Apendix-1. Questionnaire for experts and household heads, and group discussion.

1. To be filled by household heads of irrigation users.

Introductory note: Dear respondents, the objective of this household survey questionnaire is to assess the sustainability of the small-scale irrigation scheme, Case of Gumselassa small-scale irrigation scheme, Tigray. The study focuses on assessing sustainability dimensions like governance, economic context, environmental integrity, and social well-being of the irrigation scheme. Therefore, your active participation and honest responses are very important in meeting the intended objectives of the study. I kindly request your active cooperation in responding to the questionnaires. The study is fully for academic research purposes, and any information you provide will be kept confidential.
Many thanks for your valuable time and information
Mebrahtom Leake (Mekelle University Master's Student)

A. General

1. Irrigable land location from water source: [1] Upper [2] Middle [3] Lower
2. Household head [1] Male [2] Female
3. Age in years [1] 18-30 [2] 30-45 [3] 46-65 [5] above 65
4. Educational status [1]: Illiterate [2]: Elementary school [3]: High school [4]: diploma and above

B. Resource availability and its potential utilization

1. Size of your irrigation land? [1] <0.25ha [2] 0.26-0.5ha [3] 0.51-1 ha [4] >1ha
2. Source of water used for irrigation [1] from reservoir [2] from seepage [3] from groundwater wells through pump [4] 1 &2 [5] 1& 3 [6] 2 &3
3. What type of crops are you growing in your irrigation land? [1] Fruits [2] Vegetables [3] Food crops [4] Cash crop [5] any other specify ___________________________
4. How do you improve your farm land fertility? [1] Animal manure [2] Soil mulching [3] Artificial fertilizer [4] other specify__________________________
5. How much fertilizer (manure or artificial one) do you use per year?______________kg/year
6. What kind of tools and farming methods are you using? [1] Manpower only [2] Oxen and man power [3] Improved or mechanized method [4] Other, specify ________________
7. If using a mechanized method or tractors? Since when? __________, ____________________.

C. Sustainability Questionnaire

I. Good Governance/ Institutional Sustainability of Irrigation Scheme

1) Does the scheme managing WUA provide information about the irrigation scheme to irrigation users? (G 2.3.1 Transparency) [1] Yes [2] No

2) How do you see the participation of irrigation users during the decision-making process? (G 3.1.2 Stakeholder engagement)
[1] Unacceptable [2] Limited [3] Moderate [4] Good [5] Best

3) Do you believe the land redistribution after the construction of the irrigation scheme was fair? [1] yes [2] no

4) If the answer for the number is 3 is no. What was the main limitation of the land redistribution? ______________________

5) How do you rate the access to irrigation water among irrigation users of the scheme?
[1] Unfair [2] fair [3] equitable

6) If for the answer for the above question was unfair what is the reason___________________

II. Environmental sustainability of small-Scale Irrigation Schemes

1. Does your irrigable land get enough water? [1] Yes [2] No
2. If your answer to the above question is “No,” what is the reason? [1] Irrigation land expansion [2] Water scarcity in the source [3] Water distribution failure [4] Management problems, and water theft [5] Nearness to the source
3. How was the quality of irrigation water (according to farmers' understanding and to be supported from literature) [1] Unacceptable [2] Limited [3] Moderate [4] Good [5] Best
4. Percentage of area lost due to poor irrigation water quality (to be supported by transect walks). [1] No lost [2] very low [3] low [4] high [5] very high
5. How do you rate the activities that are taken in the prevention of water pollution (E2.2.2 Water pollution prevention practices)?
   [1] Unacceptable [2] Limited [3] Moderate [4] Good [5] Best
6. How does the overall irrigation water management practice? (Indicator: E 2.1.2 Water conservation practice)
   [1] Unacceptable [2] Limited [3] Moderate [4] Good [5] Best
7. Is soil salinization a problem on your irrigable land? [1] Yes [2] No (to be supported by literature)
8. How was the soil erosion risk at your irrigable land? (to be supported by a transect walk)
   [1] Very low [2] low [3] moderate [4] high [5] very high
9. Is there a waterlogging problem in your irrigable land? (to be supported by a transect walk)
   [1] Yes [2] No
10. If yes above, what area is lost due to the waterlogging problem?
    [1] None [2] Small [3] medium [4] high [5] very high

III. Economic Sustainability of Small-Scale Irrigation Schemes

1. Annual costs that you pay for:

Items that pay for	Annual cost
Costs for energy (if there is pump irrigation)	
Cost for irrigation water (if they have a tariff system)?	
Operation and maintenance cost	

Crop production cost of major crops cultivated (at least the last three years)	
Cost for operators	
Penalty payment (if any)	

2. Are you achieving economic profitability from the irrigation schemes? [1] Yes [2] No
3. If your answer is yes, how much was your annual profit? _________________________
4. Does the WUA have market linkage to minimize the risk of production price? [1] Yes [2] No
5. Do you produce more than one product, species, or variety of crops for income generation in your farm area? (C 2.1.2 Production Diversification) [1] Yes [2] No
6. Did the WUA take actions and mechanisms to access alternative marketing channels? (C2.3.1. Stability of the market) [1] Yes [2] No

IV. Social Sustainability of Small-Scale Irrigation Schemes

1. Do you have time for family, rest, and culture, and the ability to care for their needs, such as maintaining adequate diets? (S 1.1.1 Right to quality of life) [1] Yes [2] No
2. How do you rate the opportunities that you get to increase your skills and knowledge, to advance within the enterprise in which you work? (S 1.2.1 Capacity development)
   [1] Unacceptable [2] Limited [3] Moderate [4] Good [5] Best
3. Do primary producers have access to the means of production, meaning the knowledge, facilities, and equipment necessary for the enterprise owners and employees to maintain a decent livelihood? (S 1.3.1. Fair access to means of production) [1] Yes [2] No
4. Do buyers, through their policies and practices, recognize and support suppliers' rights to fair pricing and fair contracts and agreements (S 2.1.1. Fair pricing and transparent contracts)?
   [1] Yes [2] No
5. Do buyers explicitly recognize and support suppliers' rights to freedom of association and to collective bargaining? (S2.2.1. Right of suppliers) [1] Yes [2] No
6. Does the enterprise discriminate against particular groups or by sexual identity in hiring, job allocation? (S. 4.1.1 Non-discrimination) [1] Yes [2] No
7. Does the enterprise discriminate against women in hiring, remuneration, training, and advancement, access to resources (S.4.2.1 Gender Equity)? [1] Yes [2] No
8. What was the wage of male and female laborers in the irrigation scheme
   [1] Equal [2] females lower than male [3] males lower than females
9. Females' role in scheme decision-making
   [1] Equal [2] females lower than male [3] males lower than females
10. Does the irrigation water distribution among male and female users seem fair? [1] Yes [2] No
11. The role of the irrigation scheme in societal wellbeing, such as education, health, etc.?
    [1] No role [2] positive [3] negative
12. Does the irrigation scheme affect the Tigray war (Labor, agricultural input, product marketing, etc.) [1] Yes [2] No

2. To be filled by experts.

Introductory note: This questionnaire aims at supporting data collection to identify the rate of sustainability of the Gumselassa irrigation scheme and the problems, as well as the challenges of small-scale irrigation schemes in Gumselassa, Tigray. It also tries to rank these problems and find alternative solutions to tackle these problems and challenges. Please provide your inputs in the spaces provided for each question.

Many thanks for your valuable time and information

Part One: Experts' experiences

1. Educational status: [1] BSc [2] MSc [3] PhD [4] Another

2. Your experiences in irrigation project design, development, and/ or management in years

[1] Less than five years [2], five to ten years [3], ten to fifteen years [4], fifteen to twenty years [5], more than twenty years

3. Your role in irrigation development and/or management (multiple answers are possible)

[1] Design [2] Supervision [3] Management [4] Research [5] Another (please specify)______________

4. Which part of the reservoir-based irrigation system is your priority area as an expert? (Multiple answers are possible)

[1] In the catchment (Watershed management related)
[2] In the water source part (reservoir, embankment, spillway, etc.)
[3] In the conveyance and distribution system (primary and secondary canals, crossing, etc.)
[4] In the irrigation farm plots (field canals, land levelling, irrigation methods, etc.)
[5] Irrigation scheme governance system (irrigation water management, establishment of WUA, and related)
[6] Others, please specify ________________________

Part Two: Challenges and problems of small-scale irrigation schemes

Problems and challenges of small-scale community irrigation schemes in Gumselassa, Tigray, were identified from different reports by considering the entire irrigation system (i.e., the catchment area, the water source of the system, and the irrigated command area including its conveyance and distribution system, drainage facilities, and the governance issues) as a single management unit (Table 1).

1. Which additional problems of reservoir-based irrigation schemes would you suggest occurring in Gumselassa, Tigray? Please add them in the space provided in Table 1.
2. Could you rank these problems according to their degree of severity for the sustainability of reservoir-based irrigation schemes in Tigray? Please put your ranking of these problems in Table 1 under ‘Rank’ (Ranking Remark: 3 = highly severe problem, 2 = severe problem, 1 = less severe problem).

Table 1: Problems of reservoir-based irrigation schemes in Tigray

S.No	Problems of the Gumselassa small-scale irrigation scheme	Rank
1	Lack of adequate data for reservoir design (e.g., Sediment, hydro-meteorological data, etc.)	
2	Reservoir siltation	
3	Seepage loss from reservoirs	
4	Insufficient flow to reservoirs	
5	Structural failure of the dam body and its appurtenant structures	
6	Conveyance loss	
7	Poorly treated watersheds	
8	Structural damage to conveyance structures	
9	Sedimentation of conveyance structures	
10	Lack of irrigation water metering	
11	Inequitable water sharing among users	
12	Poor irrigation scheduling practices	
13	Waterlogging	
14	Soil salinity	
16	Low technical and managerial capacity of the managing scheme institutions	
17	Unavailability of the irrigation water users' association	
18	Neglecting women in decision-making	
19	Neglecting community knowledge and experience in decision-making	
20	Low financial capacity for operation and maintenance costs	
21	Conflict between irrigation users and non-users	
22	Lack of an appropriate irrigation water tariffing system	
23	High maintenance cost	
24	Irrigation users' low willingness to pay for irrigation water	
25	Low irrigation water productivity	
26	Low crop yield	
27	Low awareness of irrigation water users about irrigation	
28	Ambiguities in ownership of irrigation system infrastructures	
29	Low irrigation efficiency	
30	Insufficient water availability for irrigation	
31	Poor soil and crop management practices	
32	Problems with irrigable land redistribution among users	
33		

Part three: Alternative solutions for problems and challenges of small-scale irrigation schemes

Some alternative solutions are identified from different literature sources (Table 2). Please add more possible solutions to tackle the problems and challenges of reservoir-based irrigation systems in Tigray, considering the entire spatial scale of such irrigation schemes.

1. Which additional alternative solutions do you recommend to solve the problems and challenges identified in part two above? Please mention your additional alternative solutions according to their importance.

2. Could you rank the alternative solutions in Table 2 according to their importance? (**Ranking Remark:** 3 = highly important alternative, 2 = moderately important alternative, 1 = less important alternative)

Table 2: Alternative solutions to problems of reservoir-based irrigation schemes

S.No	**Alternative solutions to problems of small-scale irrigation schemes**	**Rank**
1	Implementation of watershed management practices in the upstream reaches of reservoirs	
2	Sediment removal from reservoirs	
3	Introduction of water tariffing and pricing systems	
4	Setting a routine maintenance schedule for irrigation infrastructures	
5	Accounting for local community knowledge and experiences in decision-making processes	
6	Implement the conjunctive use of reservoir water and other sources of water for irrigation.	
7	Implementation of irrigation water metering	
8	Training and capacity building of irrigation water users, development workers, and other stakeholders	
9	Inclusive community participation in planning, development, and management of irrigation schemes	
10	Establishing irrigation water users' associations	
11	Working on awareness raising of irrigation users	
12	Improve soil and crop management practices.	
13	Land reclamation practices	
14		

You can add any additional comments about problems, challenges, and alternative solutions of small-scale irrigation systems in Tigray below:

Thank you for your time!

3. Checklist for Group Discussion (with concerned group)

1. Organization, management performance, and weaknesses of the WUAs committee.
2. Water management in the irrigation systems.
3. Major problems in water management or principal areas of users' complaints.
4. Support was given from the local irrigation office and local governance.
5. Conflict and conflict management in the irrigation scheme.
6. Technical problems of the irrigation schemes.
7. Socioeconomic viability of the irrigation system: Compatibility of irrigation with the farming system/socioeconomic environment (market, family labor allocation, and choice of crops, etc.).
8. Farmer's perception about the benefits of irrigation and its sustainability.
9. Activities that are taken in the watershed and command area.

Appendix 2. Expert's response to challenges/problems and their alternative solutions

No	**Challenges/problems of the Gumselassa small-scale irrigation scheme**	**Experts**					**Average rate**
		1	**2**	**3**	**4**	**5**	
1	Lack of adequate data for reservoir design (e.g., Sediment, hydro-meteorological data, etc.)	2	3	3	2	3	2.6
2	Reservoir siltation	3	3	3	2	3	2.8
3	Seepage loss from reservoirs	3	3	2	1	2	2.2
4	Insufficient flow to reservoirs	2	3	2	1	1	1.8
5	Structural failure of the dam body and its appurtenant structures	2	2	1	1	3	1.8
6	Conveyance loss	1	2	2	3	1	1.8
7	Poorly treated watersheds	2	3	3	1	3	2.4
8	Structural damage to conveyance structures	2	2	2	3	2	2.2
9	Sedimentation of conveyance structures	3	2	3	3	1	2.4
10	Lack of irrigation water metering	2	3	3	3	1	2.4
11	Inequitable water sharing among users	2	1	2	1	1	1.4
12	Poor irrigation scheduling practices	3	3	3	1	2	2.4
13	Waterlogging	2	2	1	3	2	2
14	Soil salinity	2	3	3	3	2	2.6
16	Low technical and managerial capacity of the managing scheme institutions	3	2	2	3	3	2.6
17	Unavailability of the irrigation water users' association	1	2	1	1	3	1.6
18	Neglecting women in decision-making	1	2	2	1	2	1.6
19	Neglecting community knowledge and experience in decision-making	2	2	2	1	2	1.8
20	Low financial capacity for operation and maintenance costs	3	3	3	3	1	2.6
21	Conflict between irrigation users and non-users	2	2	2	1	1	1.6
22	Lack of an appropriate irrigation water tariffing system	2	3	2	3	1	2.2
23	High maintenance cost	3	3	2	1	2	2.2
24	Irrigation users' low willingness to pay for irrigation water	1	3	3	1	1	1.8
25	Low irrigation water productivity	2	2	3	2	2	2.2
26	Low crop yield	1	2	2	2	2	1.8
27	Low awareness of irrigation water users about irrigation	2	1	2	3	3	2.2
28	Ambiguities in ownership of irrigation system infrastructures	2	2	2	1	2	1.8
29	Low irrigation efficiency	3	3	3	2	2	2.6
30	Insufficient water availability for irrigation	3	2	2	3	3	2.6
31	Poor soil and crop management practices	1	2	1	2	1	1.4
32	Problems with irrigable land redistribution among users	2	2	2	3	2	2.2
No	**Alternative solutions to small-scale irrigation scheme problems**	**1**	**2**	**3**	**4**	**5**	**Average**
1	Implementation of watershed management practices in the upstream reaches of reservoirs	3	2	3	3	3	2.8
2	Sediment removal from reservoirs	2	3	3	3	2	2.6
3	Introduction of water tariffing and pricing systems	1	2	2	1	2	1.6
4	Setting a routine maintenance schedule for irrigation infrastructures	2	2	2	3	3	2.4

5	Accounting for local community knowledge and experiences in decision-making processes	2	2	3	3	2	2.4
6	Implement the conjunctive use of reservoir water and other sources of water for irrigation	2	3	2	2	2	2.2
7	Implementation of irrigation water metering	1	2	2	1	2	1.6
8	Training and capacity building of irrigation water users, development workers, and other stakeholders	2	2	2	3	3	2.4
9	Inclusive community participation in planning, development, and management of irrigation schemes	3	3	3	3	3	3
10	Establishing irrigation water users' associations	2	3	3	3	3	2.8
11	Working on awareness raising of irrigation users	1	3	3	2	2	2.2
12	Improve soil and crop management practices	2	2	2	3	2	2.2
13	Land reclamation practices	3	2	2	3	2	2.4

Appendix 3. Some pictures during data collection