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By

Kedrala Wabela Hussen

Title

Enhancing Small Scale Irrigation Water Management in the Ethiopian Rift Valley: Performance Evaluation and Strategies to Improve Water Management and Productivity

Jury Members:

Pr Ali Hammani	IAV Hassan II-Rabat	Thesis director
Dr Sirak Tekleab	EIWR, Addis Abeba University- Ethiopia	Member of thesis committee
Dr Abdelilah Taky	Ex-IAV Hassan II-Rabat	Member of thesis committee
Pr Zeleke Agide	EIWR, Addis Abeba University- Ethiopia	Rapporteur
Dr Rachid Mrabet	National Institute of Agricultural Research-Morocco	Rapporteur
Pr Marcel Kuper	UMR G-EAU, CIRAD, Montpellier – France	Rapporteur
Pr Moha El Ayachi	IAV Hassan II-Rabat	Examiner
Dr Bassou Bouazzama	INRA	Examiner

July, 2024

Thesis Director:

Prof. Ali Hammani

Institute of Agronomy and Veterinary (IAV), Hassan II, Rabat, Morocco

Thesis committee members:

Dr. Abdelilah Taky

Institute of Agronomy and Veterinary (IAV), Hassan II, Rabat, Morocco

Dr. Sirak Tekleab

Ethiopian Institute of Water Resources (EIWR), Addis Ababa University, Addis Ababa, Ethiopia

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Abstract

The influence of climate change and an increasing demand for water from different sectors affect the availability of water for agricultural production. Thus, effective management of the available agricultural water is essential to ensure water, food, energy, and environmental sustainability. The main objective of this study is to investigate scheme-level institutional and on-farm irrigation water management practices and develop approaches for effective irrigation water management to ensure sustainable production and enhance water productivity in the small-scale irrigation (SSI) schemes in the Ethiopian Rift Valley.

In this study, the farmers' perceptions on technical and irrigation water user associations' (IWUAs) management performance of four SSIs were assessed. Data were collected using scheme performance reports, household surveys, key informant interviews (KII), focus group discussions (FGD) with various stakeholders, and field observations. Results indicated that although the severity of the problems varies between the schemes, the operation, maintenance, and water allocation systems of all schemes were unsatisfactory. Lack of training and financial constraints affected the IWUA's ability to manage the schemes properly. In addition, field experiments and secondary data were used to evaluate the on-farm performance of two (Furfuro and Bedene) SSI schemes. Results showed that the overall efficiencies of the schemes were below the minimum permissible values. The relative irrigation and total water supply of the Furfuro scheme indicated that there was surplus water diverted to the command area during the study season; however, crops grown at the tail end of the scheme experienced a water shortage. The relative irrigation and water supply of Bedene indicated that the scheme was water deficient. The Soil and Water Assessment Tool (SWAT) model and the Jensen crop water production function were integrated to develop a simulation-optimization model for optimizing the irrigation scheduling in the study area. The result indicated that optimizing irrigation scheduling based on moisture-stress-sensitivity levels can save up to approximately 26% of irrigation water in the study area, with insignificant yield reduction. On the other hand, the Soil Water Atmosphere Plant (SWAP), a physically based agrohydrological model, was used to investigate the water productivity (WP) and water balance in the Furfuro irrigation scheme, Ethiopian Rift Valley. Two groups of field experiments (the researcher plot and the farmer plot) were conducted within the command area of the scheme using the main irrigated crops. Results showed that in all crops, the percolated depth of the farmers' plot was greater than the researcher's plot. The physical and economic WP of researcher plots was greater than that of farmer plots at all water balance components.

Keywords: Irrigation scheme, IWUA, SWAT, SWAP, Irrigation scheduling optimization, Crop water productivity, Rift Valley, Ethiopia

Résumé

L'impact du changement climatique et de la demande en eau croissante de différents secteurs affecte la disponibilité de l'eau pour la production agricole. Ainsi, une gestion efficace de l'eau agricole est essentielle pour garantir la durabilité de l'agriculture irriguée, de l'alimentation, et de l'environnement. L'objectif principal de ce travail de recherche est d'étudier les pratiques de gestion de l'eau d'irrigation au niveau institutionnel et à l'échelle de l'exploitation agricole, et de développer des approches pour une gestion efficace de l'eau d'irrigation afin d'assurer une production durable et d'améliorer la productivité de l'eau dans les petits systèmes d'irrigation (SSI) de la vallée du Rift éthiopien.

Dans cette recherche, les perceptions des agriculteurs sur la performance de gestion technique et des associations d'usagers de l'eau d'irrigation (AUWEI) de quatre Petits Systèmes d'Irrigation (SSI) ont été évaluées. Les données ont été collectées à l'aide de rapports des études de performance de ces systèmes, des enquêtes exploitation agricole, d'entretiens avec des cadres et des responsables clés, des focus groups de divers acteurs ainsi qu'à l'aide d'observations sur le terrain. Les résultats ont montré que bien que l'importance des problèmes varie entre les systèmes, le fonctionnement, la maintenance et les méthodes d'allocation de l'eau de tous les systèmes étaient non satisfaisants. Le manque de formation et les contraintes financières ont affecté la capacité des AUWEI à gérer correctement les systèmes. De plus, des expérimentations et des données secondaires ont été utilisées pour évaluer les performances sur le terrain de deux petits systèmes d'irrigation (Furforo et Bedene). Les résultats ont montré que les efficiences globales des systèmes étaient inférieures aux valeurs minimales admissibles. L'irrigation relative et l'approvisionnement total en eau du projet de Furfuro ont indiqué qu'il y avait un surplus d'eau détourné vers la zone de commandement pendant la période de l'étude ; cependant, les cultures cultivées à la fin du projet ont connu une pénurie d'eau. L'irrigation relative et l'approvisionnement en eau de Bedene ont indiqué que le système souffrait d'un déficit en eau. Le modèle Soil and Water Assessment Tool (SWAT) et la fonction de production d'eau de culture de Jensen ont été intégrés pour développer un modèle de simulation-optimisation pour optimiser le calendrier d'irrigation. Le résultat a indiqué que l'optimisation de la planification de l'irrigation en fonction des niveaux de sensibilité au stress hydrique peut permettre d'économiser jusqu'à 26 % d'eau d'irrigation dans la zone d'étude, avec une réduction insignificative du rendement. D'autre part, le modèle agrohydrologique SWAP (Soil Water Atmosphere Plant), basé sur la physique, a été utilisé pour étudier la productivité de l'eau (WP) et le bilan hydrique dans le système d'irrigation Furfuro. Deux groupes d'expérimentation de terrain (la parcelle de recherche et la parcelle de l'agriculteur) ont été menés dans la zone de commande du système en utilisant les cultures irriguées principales dans la zone d'étude. Les résultats ont montré que dans toutes les cultures, la profondeur au niveau de percolation de la parcelle de l'agriculteur était supérieure à celle de la parcelle de recherche. La WP physique et économique des parcelles de rechercheur était supérieure à celle des parcelles d'agriculteurs pour tous les composants du bilan hydrique.

Mots clés: Schéma d'irrigation, IWUA, SWAT, SWAP, Optimisation de la programmation de l'irrigation, Productivité en eau des cultures, Vallée du Rift, Éthiopie.

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Abbreviations

BCM	Billion cubic meter
CE	World Cereal Equivalent
CU	Christiansen uniformity
CWR	Crop water requirement
DAAD	German Academic Exchange Service
DAP	Days after planting
DEM	Digital Elevation model
Ea	Irrigation application efficiency
Ec	Conveyance efficiency
ENMSA	Ethiopian National Meteorological Service Agency
Ep	Overall efficiencies
EPIC	Environmental Policy Integration Calculator
ETa	Actual evapotranspiration
ETc	Crop evapotranspiration
ETm	Maximum Evapotranpiattion
ETo	Reference evapotranspiration
ETp	Potential evapotranspiration
FAO	Food and Agricultural Organization
FDRE	Federal Democratic Republic of Ethiopia
FGD	Focus Group Discussions
GA	Genetic algorism
GDP	Gross Domestic Product
GTP	Growth and Transformation Plan
HRU	Hydrologic response units
IFAD	International Fund for Agricultural Development
IFC	International Finance Corporation
IR	Irrigation ratio
IWUA	Irrigation Water User Associations
Kc	Crop coefficient
KII	Key Informant Interviews

LAI	Leaf area index
LSD	Least significant difference
MoA	Ministry of Agriculture
MoFED	Mistry of Finance and Economic Development
MoWE	Ministry of Water and Energy;
NGO	Non-Governmental Organizations
NSE	Nash-Sutcliffe model efficiency
OAT	One-At-a-Time
PASDEP	Plan for Accelerated and Sustained Development to End Poverty
Pe	Effective rainfall
RF	Annual rainfall
RMSE	Root Mean Square Errors
RVLB	Rift Valley Lake Basin
SSA	Sub-Saharan Africa
SSI	Small Scale Irrigation
SWAP	Soil Water Atmosphere Plant
SWAT	Soil and Water Assessment Tool
UNDP	United Nations Department of Population Division
USDA.SC	United States Department of Agriculture and Soil Conservation service
USGS	United States Geological Survey
WOFOST	World Food Studies
WP	Water productivity

CHAPTER I: General Introduction

1.1 Irrigation in Sub-Saharan Africa

The world population is projected to rise to 8.5 billion in 2030, 9.7 billion in 2050, and 10.9 billion in 2100, with the greatest population growth is expected in Sub-Saharan Africa over the coming decades. During these periods, a population increase of 2.0 billion is predicted between 2019 and 2050, of which 1.05 billion (52 percent) is estimated to be added to countries in sub-Saharan Africa (UNDP 2019). In the same period, the food requirement for the World Cereal Equivalent (CE) is predicted to be about 10,094 million tons in 2030 and 14,886 million tons in 2050 (Islam and Karim 2020). The combined effect of high population growth and the need for improved living standards has increased the demand for food production. However, agricultural production is seriously affected by recurrent droughts and unpredictable rainfall (Lebdi 2016; Kafle et al. 2020). For nations in Africa, the continent with the fastest population growth and where 25% of the population experiences severe food insecurity, the "business as usual" scenarios will be even worse (Stellmacher and Kelboro 2019; Pawlak and Kołodziejczak 2020). Particularly in Sub-Saharan Africa (SSA), food shortages, poverty, and a lack of resilience to climate change impacts are immense. Therefore, improving agricultural yields in this region is essential to addressing food insecurity and climate change impacts. In this regard, irrigation agriculture is important for improving crop production and meeting rising food demands (Diao and Pratt 2007; MoA 2011; Passarelli et al. 2018; Ahmed 2019). Moreover, for sustaining crop production under unpredictable and increasingly variable climatic conditions, a well-planned irrigation system could be a critical response for subsistence and commercial farmers (Oates et al. 2015; Muluneh et al. 2017; Balana et al. 2020).

There are significant differences between world regions in the extent of irrigated land. More than 30% of the irrigated farmland in the world is in South Asia, and nearly 40% is located in East Asia and the Pacific. These two regions combined account for more than 70% of the world's irrigated cropland, compared to only 5% in SSA (Ringler 2017). In 2000, 41% of the cultivated land in Asia was irrigated, which is ten times more than the irrigated land in the SSA in the same year (Portmann et al. 2010). Clearly, with such a small percentage of irrigated land, SSA's irrigation development lags far behind that of other regions of the world.

Agricultural production accounts for 87% of total SSA water withdrawals (FAO 2011). However, as depicted in Figure 1.1, the total equipped irrigation area was less than that of the

Northern African region in 2020. This indicates that the total water withdrawal in SSA is low compared with other regions. Projections indicate that by 2050, the area equipped with irrigation in SSA can grow to 9.4 million ha, leading to a 21% increase in water withdrawal. Therefore, a concrete road map for a water supply strategy, appropriate irrigation sector policy for Agenda 2063, capacity building of irrigation institutions, and promoting a programs for effective irrigation water management, water saving, and water accounting are necessary to maintain food security (Lebdi, 2016).

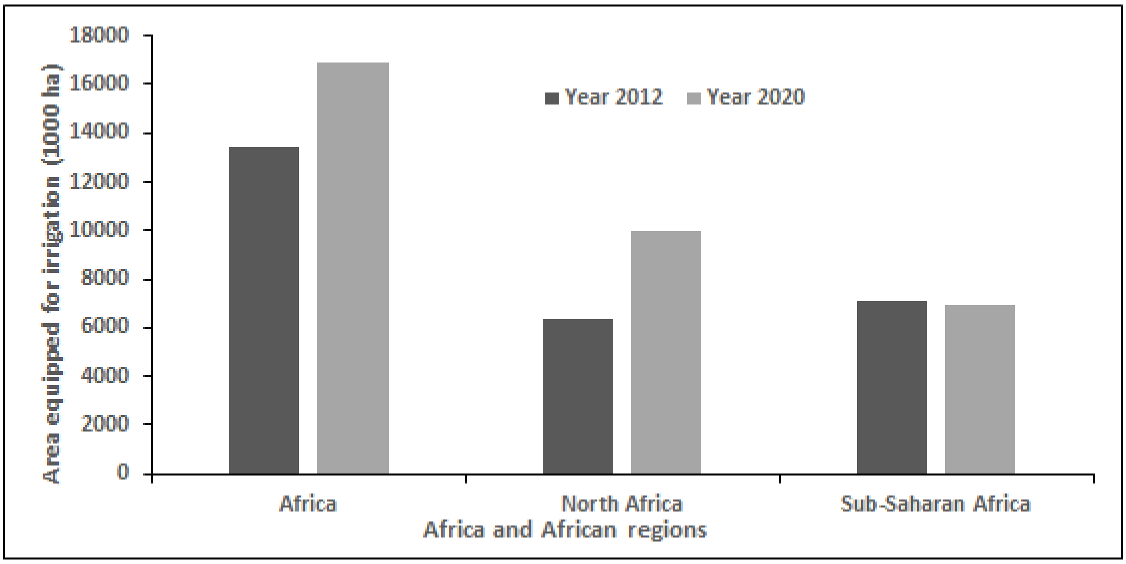


Figure 1.1: Irrigation-equipped area in Africa and African regions

Source: (FAOAQUASTAT, 2022)

1.2 Irrigation Agriculture in Ethiopia

Ethiopia is an agricultural country. The agricultural sector contributes about 44 percent to the national gross domestic product (GDP) and accounts for about 70 percent of the export commodities (FAO and IFC 2015; World Bank 2016). The estimated annual growth rate of the Ethiopian population is about 2.3% (UNDP 2014), placing it second in Africa next to Nigeria. According to the World Bank World Population Database, the Ethiopian population in 2022 was 123.4 million (WorldBank 2022). On the other hand, the agricultural system in the country is dominated by small-scale and rainfed farming systems and has inadequate access to improved technologies and institutional support services (FAO 2014; FAO and IFC 2015; Stellmacher and Kelboro 2019). Furthermore, the erratic rainfall distribution, recurrent drought, insufficient agricultural input, and land degradation have been impacting the food security system of the country (Mekuria 2018; Worqlul et al. 2019; Zerssa et al. 2021). Thus, the productivity of the agricultural sector has not kept up with the population growth rate of the country.

Irrigation agriculture is a vital strategy for food self-sufficiency in many arid and semi-arid regions. Heavy dependence on rainfed farming systems in the current climate change and recurrent drought conditions affects the agricultural yields and economies of nations like Ethiopia. Asian countries such as Malaysia, South Korea, Singapore, Thailand, Taiwan, Hong Kong, Indonesia, and Vietnam have principally attributed the development of irrigation systems and enhanced agricultural technologies to their successful food security and economic growth (Hussain and Hanjra 2004; FAO 2006). Irrigation in an improved agricultural water management manner could provide the chance to mitigate the impact of climate change and improve productivity per unit of land (Awulachew and Merrey 2006). According to Mukherji et al. (2009), the importance of irrigated agriculture in agricultural production can be described in three ways. First, it stabilizes the yield variations with associated enhancements in average yields. Second, in the case of an efficient water management system, two or more crop cultivations may be possible. Third, there is the possibility of the application of new technologies such as improved seeds, new farming technologies, and the application of chemical fertilizer. The fact that about 40% of food production in the world comes from irrigated land demonstrates the central role of irrigation in meeting global food demand (Molden et al. 2010; Nagaraj et al. 2021). Furthermore, irrigation can provide sustainable agricultural development, can be a source of employment for smallholder farmers, and can contribute to the overall economy (Molden 2007; Adugna et al. 2014; Alemu 2017; Woodhouse et al. 2017; de Bont et al. 2019).

In developing countries such as Ethiopia, the necessity of irrigation development, mainly in the farmer sub-sector, needs prime consideration to increase crop production and ensure food security at the domestic level. Furthermore, irrigated agriculture is an important source of raw materials for local and international industries as well as a means of earning foreign currency (Hagos et al. 2009; MoA 2011; FAO and IFC 2015). Clear and primary reasons for evolving the irrigation sector in Ethiopia include improving the productivity of land and labour, which is predominantly important to reducing food insecurity and minimizing reliance on the rain-fed production system (Awulachew et al. 2007; Awulachew et al. 2010). The sector can be used to lessen the risks associated with drought-related crop failures in the country. However, despite the appreciation of the significant role of irrigation in ensuring food security and intensifying crop production, well-organized irrigation development focusing on medium- and large-scale irrigation schemes started only a few years ago in the country (Gebul 2021). Several reasons, including a shortage of capacity, a lack of market value chain development (Scheumann et al. 2017), weak governance and environmental impacts (World Bank, 2007), and poor performance of already developed irrigation schemes, are the most important challenges for the sector in SSA, including Ethiopia. The achievement of a successful irrigation system generally requires the collaboration of all stakeholders, such as governmental institutions, extension workers and farmers, financial institutions, and planning bodies. Furthermore, physical, environmental, social, and political factors also affect the development of the irrigation sector.

Despite its enormous advantages, irrigation development has negative impacts on soil and water regimes, water quality, and, in some situations, the socioeconomic circumstances of the people (Verma 1986). Diversion and reservoir construction, along with the infrastructure needed for water distribution and land preparation for irrigation, come at an enormous capital expense. The sustainability of such massive investments must be heavily reliant on whether or not the development satisfies public expectations and the environment. Furthermore, negative impacts of irrigation include public health risks from water-related diseases, displacement of people as a result of new irrigation development, irrigation-induced land and water degradation, loss of biodiversity, and river health risks from increased river water withdrawals for irrigation (Hussain 2007; Asayehegn 2012b). However, the majority of possible negative effects of irrigation are not caused by irrigation water use, but rather by institutional and managerial shortcomings and their inability to solve them (Hussain 2007).

The Ethiopian government has regarded irrigation development as a key strategy to attain food security, reduce poverty levels, and promote economic growth in the country (Hagos et al. 2009; Amede 2015). The irrigation development strategy of the country has been classified into three scales based on the size of the irrigation project command area. Accordingly, command areas with less than 200 ha are categorized under small-scale irrigation (SSI) scheme; command areas between 200 and 3,000 ha are termed as medium-scale irrigation; and command areas greater than 3,000 ha are grouped under large-scale irrigation systems. SSI schemes can be further classified into traditional and modern SSI schemes. Traditional SSI schemes are typically constructed, managed, and executed by local communities, whereas modern SSI schemes are constructed with available technologies and aided by the government and non-governmental institutions (MoA 2011). SSIs have great importance for increasing production during periods of low rainfall and can help improve the overall living standard of the rural population by meeting social needs and reducing poverty (Asayehegn 2012a; Belay and Bewket 2013). The Ethiopian irrigation development plan and implementation strategy is given in Table 1.1.

Table 1.1: Ethiopian irrigation development plan and implementation road map

Key points	Activities to be carried out	Federal	Regional/ zonal	Local	Waterworks
Plan delivery	Ensure liability through irrigation water task force	*	*	+	
	Enable systematic project prioritization	*	*	*	
Performance of the scheme	Encourage research on irrigation, water resources, climate change impact	*	*	+	
	Develop the skills of farmers and expertise in irrigation and business case	+	*	*	
	Improve the contract management system	*	*		+
Scale up of the system	Enhance business case, cost retrieval if possible	*	*	*	+
	Develop and retain expertise for irrigation sector (e.g., engineers)	*	*		*
	Encourage and provide support to local small/medium private sector	*	*	*	+
Sustainability	Enable sustainability of groundwater resources/schemes	*	*	+	+
	Include watershed and environmental management as part of irrigation interventions	*	*	*	+

Note: * implies the leading role, + implies supporting role

Source: (Awulachew et al. 2010)

1.3 Problem definition

In the last two decades, the Ethiopian government has given more consideration to the irrigation sector to achieve the food security goals of the country. The development of irrigation facilities has been increasing, particularly with SSI, aiming to intensify crop production (Awulachew and Merrey 2006; Awulachew et al. 2010). Particularly, in the development programs of " Plan for Accelerated and Sustained Development to End Poverty (PASDEP)" and "Growth and Transformation Plan (GTP)", significant achievements have been noted in terms of expansion of irrigated land (Gebul 2021). As the primary strategy of the government development programs in the country, the cumulative area equipped for SSI has grown from 64,000 ha in 1991 to 2,528,000 ha in 2019. In addition, the area under medium- and large-scale irrigation schemes has increased from 30,400 ha in 1991 to 539,726 ha in 2019 (Figure 1.2) (Gebul 2021). During these development program periods, in addition to the government, the contribution of non-governmental organizations (NGOs) in developing SSI was encouraging. For instance, the International Fund for Agricultural Development (IFAD) has built 121 SSI schemes in four regions of the country, which has increased the total irrigation area by more than 12,000 ha (IFAD 2018). Several NGOs have introduced manual pumps, such as rope and washer pumps and treadle pumps, which are used for surface water and groundwater irrigation (Nakawuka et al. 2018). The FAOAQUASTAT (2022) data on areas equipped for general surface irrigation in the country is given in Figure 1.3. Since 2006, there has been a noticeable growth in the area equipped for surface irrigation, as shown in Figure 1.3. The impact of SSI on domestic life has not been extensively studied at the national level. However, it has been discovered that SSI has a positive and significant impact on household food security at various locations in the country (Gebregziabher et al. 2009; Yigzaw et al. 2019; Jambo et al. 2021; Kassie and Alemu 2021).

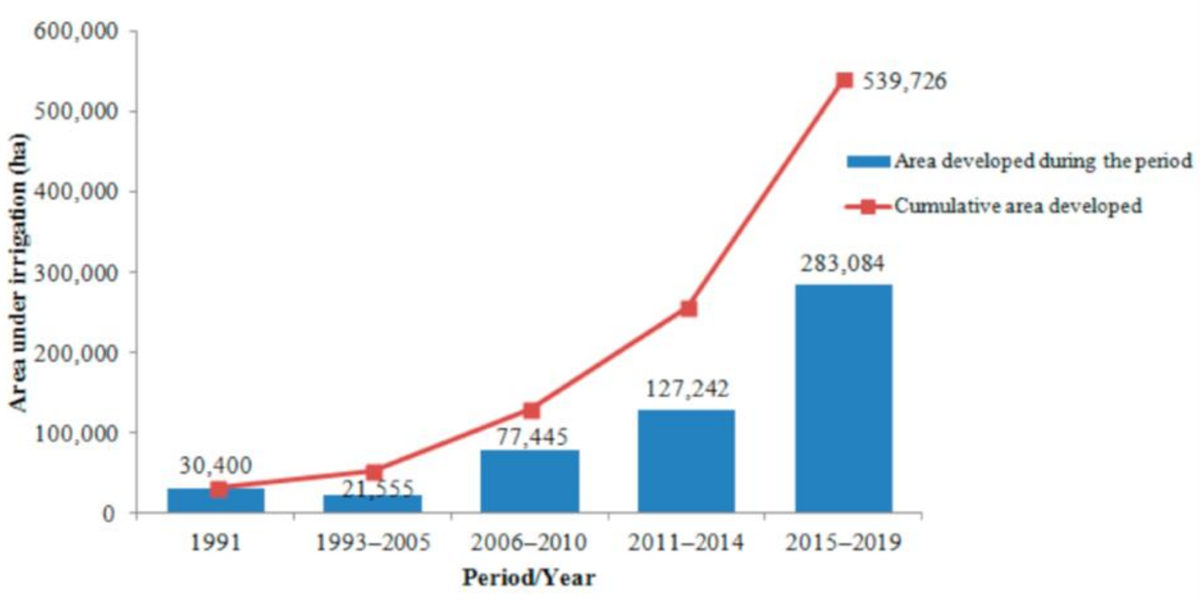


Figure 1.2: Area equipped for medium and large-scale irrigation over three decades

Source: (Gebul 2021).

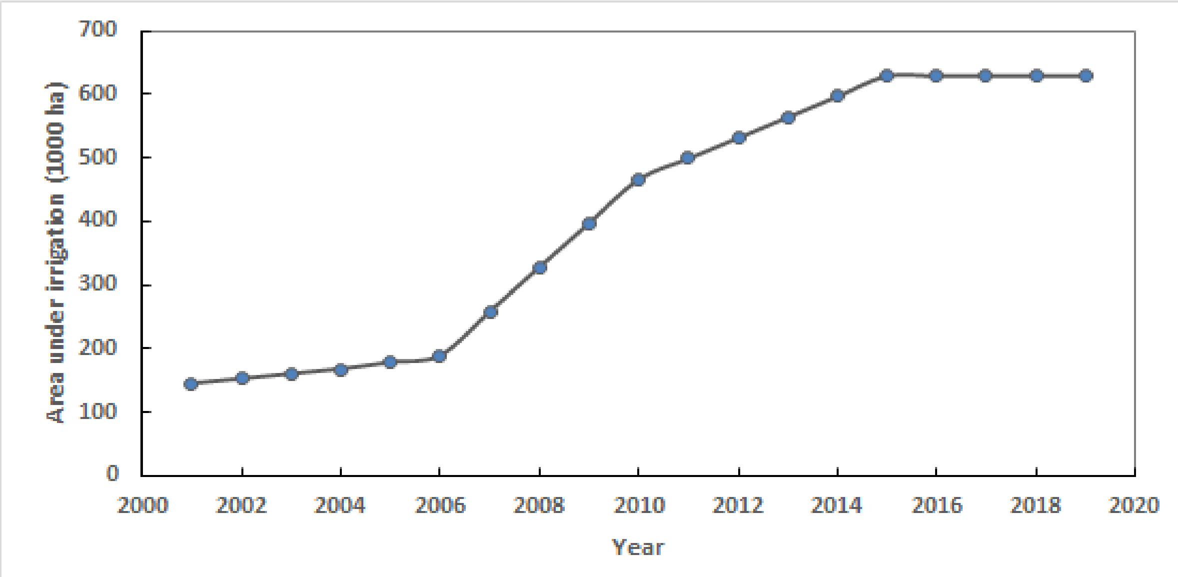


Figure 1.3: Trend area equipped for surface irrigation (2001-2019)

Source: (FAOAQUASTA, 2022)

The Ethiopian government has prioritized irrigation development mainly through the promotion of SSI in order to achieve primarily food self-sufficiency. As a result, since 1991, Ethiopia has made enormous investments and efforts to expand irrigated land and, consequently, to improve crop production (Figures 1.2 and 1.3). However, the community managed SSI confronted several problems associated with water management, operation and maintenance, and sustainability. Several unfunctional and underperforming SSI schemes exist in various regions of the country (Amede 2015; Abera et al. 2019; Gurmu et al. 2019; Aseres et al. 2020; Habtu et al. 2020). Water availability, institutional management, on-farm water management, and agronomic practices are the major challenges of the SSI schemes in the country. These problems affect their viability, and as a result, the benefits gained were below expectations.

The irrigation scheme deals with the infrastructure for water delivery and the institutions managing it (Agide et al. 2016), while the irrigation system is composed of physical, cropping, economic, and socio-organizational components (Mwendera and Chilonda 2013). The Ethiopian government has declared several regulations to ensure the effective management of water and irrigation systems at different times. The most recent proclamation for organizing irrigation water user associations (IWUAs) in a place where irrigation schemes have been built was declared in 2014. The proclamation is aimed at organizing IWUAs for the objectives of maintaining and operating irrigation schemes, ensuring fair and equitable irrigation water allocation among users, and collecting water fees from users (FDRE 2014). The members and managers of the associations are farmers who have land around the irrigation shemes. District level institutions (state representatives at the lower administration level), such as the district irrigation office, district cooperative office, and kebele administration, have the responsibility to organize and supervise the IWUA. However, studies indicate that these institutions have not been functioning at their full capacity to provide a sustainable service to the irrigation community (Yami and Snyder 2012; Amede 2015; Haileslassie et al. 2016b; Berhe et al. 2022).

On-farm irrigation water mismanagement and poor irrigation scheduling systems are identified as major challenges affecting crop production and the performance of the SSI schemes in the country (Haileslassie et al. 2016a; Abshiro and Singh 2018; Yohannes et al. 2019). In several irrigation schemes, the proper amount of water applied to the crop at the right time is a major concern that requires local solutions. In some SSI schemes, water is traditionally applied to the fields without taking into account the needs of the crops at mutually agreed-upon and fixed irrigation turns, while in others there is a serious water shortage. These imbalances in water demand and supply problems seriously impacted their benefits and challenged their overall sustainability.

Studies indicate that the situation is more severe in the Rift Valley Lakes Basin (RVLB), which is one of the largest basins in Ethiopia with subsistence agriculture activities. Water demand is continuously growing in the basin (Molla et al. 2019), whereas the sustainability of water resources has been decreasing as a result of climate change (Girma and Awulachew 2007; Orke and Li 2021). On the other hand, irrigation water scarcity is further complicated in the SSI schemes in the basin due to institutional and on-farm management issues (Van Halsema et al. 2011; Etissa et al. 2014; Ulsido and Alemu 2014; Tebeba and Ayana 2015; Teshome et al. 2018; Feleke et al. 2020). Poor irrigation scheduling has led to significant amounts of water and crop yield losses and environmental impacts, which have become serious concerns in several SSI schemes.

Therefore, enhancing the performance of SSI schemes under different interventions is an important aspect to be considered for improved productivity of irrigation land and water. This PhD research concerns the institutional and on-farm management performance evaluation of selected SSI schemes in the Ethiopian RVLB and recommendations for improving water management and productivity. The institutional arrangement and the types of problems are different from one scheme to another, and the solutions would also be different based on the nature of the problems. Based on farmer perceptions and stakeholder discussions on the service delivery performance and the general managerial condition of the schemes, recommendations that would improve the reliability and equity of the water need to be made. The assessment of scheme performances based on pertinent performance indicator approaches would be helpful in determining ideal water supply and demand conditions and the best operational water management configurations. In addition, irrigation scheduling optimization based on crop water stress sensitivity and scheme level water productivity assessment would assist in improving water productivity and enhancing scheme performance. Thus, it is essential to evaluate site-specific and scheme-level irrigation water management practices and propose and develop practical techniques for effective water management to save irrigation water and improve crop yield and water productivity.

1.4 Research questions

The competition for water in the RVLB has been increasing from time to time due to population pressure and climate change, and it is highly likely that in the upcoming years, the basin will experience increased water shortages, especially during the dry season. Irrigation water management within the SSI schemes is problematic and is characterized by poor performance and low inefficiencies. Potential water management interventions that could assure improved performance, efficiencies, and overall irrigation water management are thought to involve practical and effective system operation strategies. Therefore, this research attempts to address the following scientific research questions:

- How do the existing institutional irrigation water management practices affect the availability of water for irrigation water users?
- What does the on-farm irrigation management system look like in the selected SSI schemes, and how does it affect productivity and outputs?
- Will an alternate intervention, crop water stress-based irrigation scheduling optimization, improve the water management practice by saving irrigation water?
- How do traditional irrigation water management practices affect the water productivity of the SSI schemes?

1.5 Research hypothesis

Increasing water demand for irrigation and a reduction in annual rainfall have been dropping the surface water level in the Ethiopian RVLB. The sustainability of the community-based SSI schemes in the basin is being questioned in terms of economic and environmental perspectives.

Identifying and adopting locally viable irrigation practices and systems in combination with best management approaches can enhance irrigation water management. The hypothesis of this study is that effective institutional and on-farm irrigation water management practices can enhance the performance and productivity of SSI schemes. Irrigation water management practices such as irrigation scheduling optimization and application of water based on crop water demand are used to save irrigation water and enhance water productivity.

1.6 Research objectives

The general objective of this study is to investigate scheme-level institutional and on-farm irrigation water management practices and propose and develop approaches for effective irrigation water management to enhance water productivity and ensure sustainable production in the SSI schemes in the Ethiopian Rift Valley.

The specific objectives are:

- To assess the farmers' perception on the technical and irrigation water user associations' management performance of four SSI schemes and propose approaches to enhance irrigation water management
- To evaluate the on-farm performance of two SSI schemes and provide evidence for decision-makers and the local community to take remedial action to enhance the performance of schemes for improved production
- To develop a simulation optimization model for potato and wheat irrigation scheduling for saving irrigation water and maximizing yield
- To analyze the water productivity of the main crops based on water balance components for saving irrigation water and improving scheme productivity

1.7 Description of Ethiopia and study area

Ethiopia is a least developed and landlocked country located in eastern Africa. The country covers a total area of 1.1 million km^2, with three major agroecological zones based on annual rainfall amount and type of agricultural system: the high rainfall zone (> 800 mm/year), the low rainfall zone (< 600 mm/year with mixed agricultural system), and the pastoralist zone (< 600 mm/year with livestock-based agricultural system). The country receives a substantial amount of rainfall annually, even though its distribution is erratic. The annual rainfall amount ranges from 2275 mm in the western highlands to 141 mm in the northeast, east, and southeast parts of the country (Berhanu et al. 2014). According to FAOAQUASTAT, (2016), the annual rainfall of Ethiopia varies from 2000 mm in the southwest to less than 100 mm in the east of the country, with a national average of 848 mm. The country has 12 river basins with an annual surface runoff volume of 122 billion m^3 and an estimated 2.6–6.5 billion m^3 of groundwater potential (Awulachew et al. 2007). However, rainfall in the country is extremely erratic and unevenly distributed, which increases the likelihood of both annual droughts and intra-seasonal dry spells. Therefore, irrigation agriculture is a vital strategy to ensure food security in the country.

Potentially irrigable land in the country is estimated to be about 3.7-5.3 million ha (Awulachew et al. 2010; GTP 2016), with an economic irrigation production potential of (availability of water, land, technology, and finance) about 2.7 million ha (FAOAQUASTAT 2016) (Table 1.2). Several annual and perennial rivers with suitable landscapes for irrigation allow the production of diversified crops. The country has a significant land area suitable for surface irrigation using groundwater. A river basin-based potential study indicated that the Abay, Rift Valley, and Omo-Gibe River basins have high irrigation potential using groundwater, with 21186, 10512, and 8235 km^2 of potentially irrigable land, respectively (Worqlul et al. 2017). An administrative region-based potential study for the development of small-scale irrigation showed that Amhara, Oromia, and the former Southern Nations Nationality People regions have 0.47, 0.45, and 0.12 million ha of irrigable land, respectively (Xie et al. 2021).

Table 1.2: Economic irrigation potential by river basins

Major drainage system	River basin	Economic irrigation potential (1000 ha)
Nile basin	Abbay (Blue Nile)	523
	Baro-Akobo	600
	Setit-Takaze/Atbara	189
	Mereb	0.5
Rift valley	Awash	205.4
	Afar-Denakil	3
	Omo-Gibe	384
	Rift Valley	139.3
Sheballi-Juba	Wabi-Shebelle	204
	Genale-Dawa	423.3
North-East Coast	Oogaden	0
	Gulf of Aden	0
Total		2 671.5

Source: (FAOAQUASTAT 2016)

Ethiopia's climatic distribution is mostly a tropical monsoon with a wide topographic-induced variation. The agricultural production system also varies across altitudes. In parts of the southern, southeast, northeast, and eastern parts of the country, the annual rainfall amount is small. The agricultural system in these regions is an agropastoral mixed type. In these regions, irrigation could increase food production and improve the livelihoods of society. Half of the western and southern parts (area of this study based) of the county has one rainy season (the main rainy season, which is usually from June to October), and in these regions, shifting cultivation is commonly practiced. In these areas, irrigation would be another source of livelihood and improve food resilience. In the south and southwest of the country, a mixed farming system with a prolonged humid period and a bimodal rainfall system (*Mehr* and *Belg* in the local language) is adopted. Irrigation in these regions serves as supplementary production to intensify productivity. The most common irrigated crops in Ethiopia are vegetables, cereals, cotton, sugarcane, and potatoes. Although it is rare, fruit crops such as citrus, mango, and avocado and pulse crops such as haricot bean and groundnut are being cultivated using irrigation.

RVLB is geographically situated in the administrative regions of Oromiya, Central Ethiopia, South Ethiopia, and Sidama with a total area coverage of 52,739 km^2 (Figure 1.4). RVLB supplies water for more than 15 million people, with subsistence farming being the primary source of income (Abraham et al. 2021). From the 12 river basins, only two, namely the Awash River and the rivers of RVLB, flow within the country, while the remaining rivers are transboundary. The central part of RVLB (the area where this study was conducted) is formed by a Pliocene-aged faulted caldera, caused by the fractured volcano (Woldegabriel et al. 1990). It has several lakes of varying sizes and hydrological and hydrogeological settings (Alemayehu et al. 2006). Several small-to-medium-sized watersheds drain into eight freshwater lakes within the basin (Abraham et al. 2021). This basin is one of the highest irrigation potential areas with an estimated mean annual surface flow of 5.6 billion m^3 and a groundwater potential of 0.1 billion m^3 (Awulachew et al. 2007). It is characterized by a semi–arid climatic condition, with the annual movement of the intertropical convergence zone within the main part of the East African rift. The mean daily minimum temperature varies between 10.5 °C and 16.4 °C, and the mean daily maximum temperature ranges from 25.7 °C to 30.1 °C. The average annual rainfall in the basin is 700 mm, of which 75% is precipitated in the main rainy season from June to October. Commonly adopted irrigated crops in RVLB are vegetables, cereals, and potatoes. In addition, fruit crops such as citrus, mango, and avocado are being cultivated using irrigation.

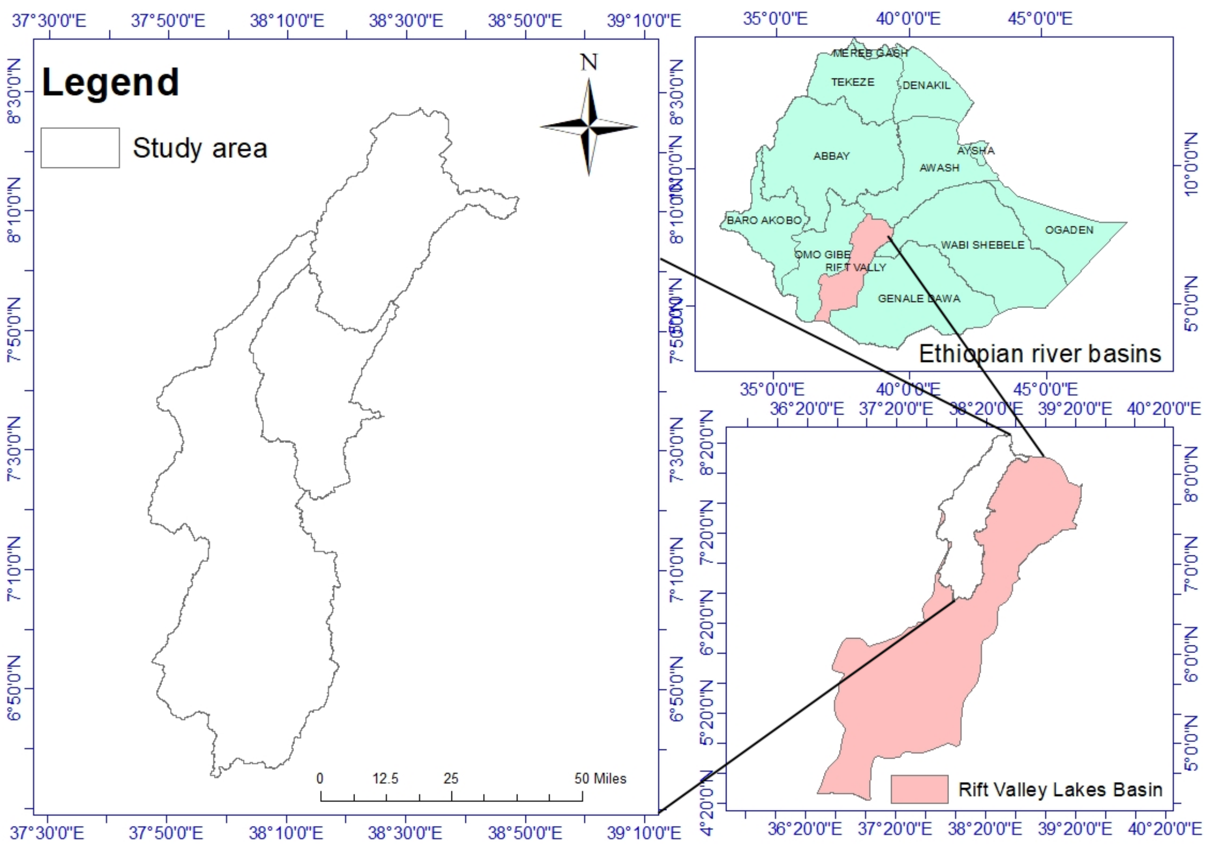


Figure 1.4: Location map of the study area

1.8 General methodology

In this thesis, a variety of methodologies were applied to meet the research objectives (Figure 1.5). The investigation began by surveying the performance of institutional irrigation water management practices in selected SSIs in the Ethiopian Rift Valley. There is a growing need for the investigation of farmers' practices and opinions and adaptation and mitigating approaches to deal with irrigated agriculture challenges at local and regional levels. Understanding farmers' perceptions allows the sharing of experiences and aids in the development of efficient adaptation strategies for the sustainability of agricultural systems. In this study, household surveys, key informant interviews (KII), focus group discussions (FGD), performance reports, and field visits were used to collect data on the institutional management performance of four selected SSI schemes. Interviews were conducted with local communities, experts, and water managers to gather their perspectives and insights regarding the management of SSI schemes. The questionnaires were mainly based on the reliability and water delivery performance, the fairness and equitability of irrigation water allocation, and the maintenance and protection of irrigation structures. Field experiments were also conducted in two selected SSIs to evaluate the on-farm performance of the schemes. Given the many components of an agricultural system, it seems challenging to address all performance-related issues at once. Identifying some pertinent performance criteria and finding indicators that can provide information on the status of the schemes are necessary for improving the performance of irrigation schemes (Dejen et al. 2012).

Water now becomes a finite resource that needs to be allocated in both time and space. Optimization of irrigation scheduling is an important approach for saving irrigation water, improving the productivity of water, and enhancing the benefits to farmers (Sun and Ren 2014; Li et al. 2018). Crop water stress sensitivity level identification at different growth stages is essential to saving water by applying deficit irrigation in water scarce areas. Potato and wheat are popularly cultivated crops in this study area with irrigation and rainfed agriculture. A simulation-optimization model was developed to optimize irrigation scheduling for these two crops using climate, crop, soil, and irrigation data. The model integrated the Soil and Water Assessment Tool (SWAT) and the Jensen crop water production function. Agricultural water productivity indicators can provide a clear picture of where and when water can be saved. Knowledge of water balance components at the field level can provide information on the water productivity of individual crops grown in irrigation schemes. Therefore, it is essential to figure out the associations among water hydrological components such as transpiration, evaporation, and percolation to enhance water management and productivity. The water productivity of the main irrigated crops in a scheme was assessed using the physically based agrohydrological model, the Soil Water Atmosphere Plant (SWAP). Field experiments were conducted to collect data on irrigation practices in the study area. The water productivity of the main crops in the study area was analyzed based on SWAP simulated water balance components.

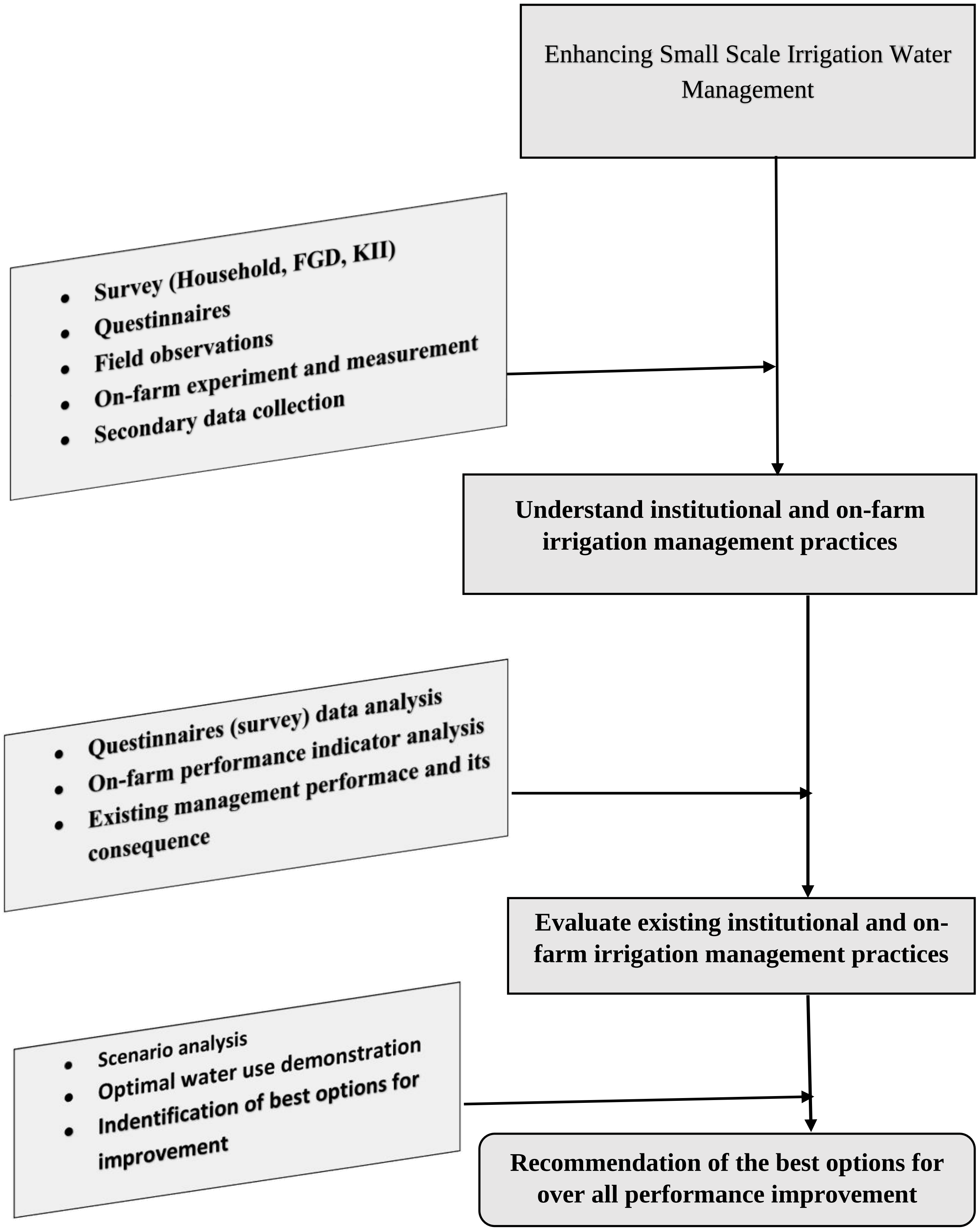


Figure 1.5: Methodological framework followed in the research

1.9 Thesis outline

The thesis is composed of six chapters, in which Chapter One presents the general introduction and problem statement. Chapters Two to Five give and discuss the results of the research, and Chapter Six provides a summary and general conclusion and recommendations. The thesis contains three published scientific articles (Chapters Two, Three, and Four), while Chapter Five has been presented at a conference for publication. In order for them to form comprehensible ensembles, objectives, as mentioned in Section 1.6, are dispatched within these chapters. In Chapter two, farmers' perceptions on the technical and institutional irrigation water management performance were assessed in four selected SSI schemes in the Rift Valley using a household survey, key informant interviews, and focus group discussions. In Chapter Three, the on-farm performance of two selected SSI schemes was evaluated based on field experimental and secondary data using internal and external process approaches. In Chapter Four, the watershed level irrigation scheduling optimization model for potato and wheat was developed based on soil, water, crop, and climatic data using the SWAT and the Jensen crop water production function model. In Chapter Five, traditional and improved irrigation water management practices were evaluated and water productivity was analyzed based on field experimental data. The final chapter summarizes the key findings from the earlier chapters and offers a reflection on the objectives of the study. In this chapter, the summaries of the problem statement, methodologies followed in chapters two to five, and the main findings in the subsequent chapters are given. Finally, general conclusion and recommendations are given at the end of this chapter.

CHAPTER II: Farmers' Perception on Technical and Irrigation Water User Associations (IWUAs) Performance of Selected Small-Scale Irrigation Schemes in the Ethiopian Rift Valley

This chapter covers the survey results regarding the farmers' perceptions on the technical and institutional irrigation water management performances, particularly the irrigation water user associations (IWUAs). The chapter aimed to evaluate the management performance of the irrigation institutions in the study area, particularly the IWUAs, in light of their organizational setup. Farmers' insights, expert opinions, performance reports, and field observation data were used to reach sound conclusions about the general management performance of four selected SSI schemes in the Ethiopian Rift Valley. There is an increasing need for research into farmers' perspectives and approaches to develop adaptation and mitigation strategies to address the challenges associated with irrigated agriculture. Understanding farmers' perceptions allows the sharing of experiences and aids in the development of efficient adaptation strategies for the sustainability of agricultural systems. In this chapter, interviews and discussions about the reliability and water delivery performance of the schemes and the fairness of the water distribution among farmers were conducted with farmers and stakeholders. Discussions were also carried out on problems that challenge the farmer in the irrigation system of production. Farmers and stakeholders pointed out potential causes of the poor performance of SSI schemes, and possible recommendations were suggested. The interviews and discussion were analysed, and a conclusion was made about the general management performance of institutions in the study area. This Chapter has been published in the journal of Sustainable Water Resource Management (Springer publisher).

Based on:

Wabela, K., Hammani, A., Tekleab, S. et al. Farmers' perception on technical and irrigation water user associations (IWUAs) performance of selected small-scale irrigation schemes in the Ethiopian Rift Valley. Sustain. Water Resour. Manag. 10, 9 (2024). https://doi.org/10.1007/s40899-023-00989-x

2.1 Introduction

In Ethiopia, modern irrigation was started in the 1950s by a Dutch company in the Upper Awash Valley to produce industrial crops (MoA 2011). However, traditional irrigation has been practiced in the highlands for centuries, primarily for producing smallholder food crops. Irrigation development needs prime consideration, particularly at the smallholder level, to increase crop production and ensure food security at the household level (Magistro et al. 2007; MoA 2011; Amare and Simane 2017). Furthermore, irrigated agriculture can be important in delivering raw materials in sufficient quantity and quality for domestic industries and foreign currency earnings. The vulnerability to the effects of climate change hazards can also be mitigated through irrigated agriculture (Bekele 2014; Amede 2015; Ostad-Ali-Askari et al. 2017; Balana et al. 2020). Irrigation agriculture is a cornerstone of development policies in Ethiopia, aiming to ensure food security in the current climate change scenario. Thus, sustainable improvement in food production has been projected to be possible through the optimal development of water resources for irrigation, land, and human resources (Awulachew et al. 2007).

The Ethiopian government has prioritized the development of irrigated agriculture to combat climate change and ensure food security, which has been primarily achieved by expanding SSI (MoFED 2010). Consequently, significant efforts and investment have been placed into water resource potential studies, irrigation system design, and infrastructure development. Particularly in the last two decades, in the programs "Plan for Accelerated and Sustained Development to End Poverty (PASDEP)" and "Growth and Transformation Plans (GTP)," significant achievements have been recorded in terms of the expansion of SSI (Gebul 2021). Along with the government, several international donors, including the International Fund for Agricultural Development (IFAD), have made considerable contributions, particularly in the development of SSI (IFAD 2018).

Local irrigation institutions, such as IWUAs, are important for the effective management and sustainability of SSI schemes. Handover of the developed SSI schemes by local farmer institutions can reduce operating and maintenance costs, increase the farmers' sense of ownership, and enhance irrigation water management (Lempériere et al. 2014). Wang et al. (2010) presented five key principles for the establishment and management of IWUA. First, access to sufficient irrigation water supply and well-developed infrastructure should be ensured; second, the leaders of the IWUA should be elected from the farmers (no local administration interference); third, the IWUA should be organized within defined hydraulic boundaries; fourth, the allocated irrigation water should be measured volumetrically; and fifth, the IWUAs should fairly assess and collect an irrigation water fee from their members. For better irrigation scheme management, organizing, establishing the necessary legal framework, and increasing the capacity of irrigation institutions are crucial (Yami and Snyder 2012).

The Ethiopian government have approved national declarations aiming to establish and manage local IWUAs in locations where modern and traditional irrigation schemes developed. According to the Federal Democratic Republic of Ethiopia (FDRE 2014) proclamation, the main objectives of organizing IWUAs are maintaining and operating irrigation schemes, ensuring fair and equitable irrigation water allocation among users, collecting fees from irrigation water users, protecting the scheme from erosion, salinity, and pollution, and resolving disputes between irrigation water users. The members and managers of the associations are farmers who have land around the irrigation shemes. District level institutions (state representatives at the lower administration level), such as the district irrigation office, district cooperative office, and kebele administration, have the responsibility to organize and supervise the IWUA.

Although significant achievements have been noted in terms of expansion, several SSI schemes in the country are underperforming due to a lack of a proper management system (Amede 2015; Agide et al. 2016; Haileslassie et al. 2016b). Despite its importance in ensuring irrigation benefits, the management of irrigation schemes is largely overlooked. Thus, poor irrigation water allocation systems, low production capacity, and early deterioration of irrigation structures are common irrigation scheme problems in Ethiopia (Yami 2013; Haileslassie et al. 2016b; Gebul 2021). The Rift Valley Lakes Basin (RVLB) is one of the most densely populated areas in Ethiopia, with intensive agricultural activities. Subsistence rainfed farming systems are the main means of generating income for the vast majority of the people in the basin. Over the past two decades, irrigated agriculture has developed significantly, most importantly using SSI schemes. However, similar to other parts of the country, several SSI schemes have been performing poorly at various locations in the basin (Belete et al. 2008; Van Halsema et al. 2011; Tebeba and Ayana 2015; Feleke et al. 2020). The community-based SSI schemes in the basin appear to have limited viability in terms of the economy and environment. Poor scheme protection, inefficient watershed management, waterlogging, deforestation, soil salinity, and soil acidity are a few examples of factors that contribute to the low performance of irrigation schemes in the basin (Ulsido et al. 2013). Therefore, in order to develop appropriate strategies for enhancing the performance of IWUAs and irrigation production, it is essential to evaluate site-specific and scheme-level irrigation water management practices, farmers' perceptions, challenges, and adaptation measures. Therefore, this study aimed to assess the farmers' perception on the technical and management performance of four SSI schemes in the Ethiopian Rift Valley. The study was focused mainly on IWUA's activities and performance in light of their organizational objectives.

2.2 Conceptual framework of the study

The end goal of this study is to evaluate the institutional management performance of four SSI schemes in the Ethiopian Rift Valley. The evaluation was based on the perception of the irrigation user communities, performance reports, expert opinions, field visits, and the prescribed FDRE 2014 proclamation of the IWUAs. The FDRE 2014 IWUAs proclamation was designed to organize IWUAs primarily for the objectives of maintaining and operating irrigation schemes, ensuring fair and equitable irrigation water allocation between users, collecting fees from water users, protecting the schemes from any hazards, and resolving disputes between water users. In the proclamation, the structure of the IWUAs comprises a general assembly at the head and management, control, and dispute resolution committees set up afterward. Evaluations of the performance of IWUAs in light of their organizational objectives were made in this study. The involvement of the local community in irrigation system administration could make it easy to assess the management performance of the schemes. Irrigation users articulated their level of satisfaction with the management of SSI schemes based on the reliability and water delivery performance, the fairness and equitability of irrigation water allocation, and the maintenance and protection of irrigation structures. In addition, during irrigation periods, canal systems and irrigation fields were continuously monitored, and informal discussions with farmers and daily labourers were conducted to support the conclusion. The conceptual framework of the study is given in Figure 2.1.

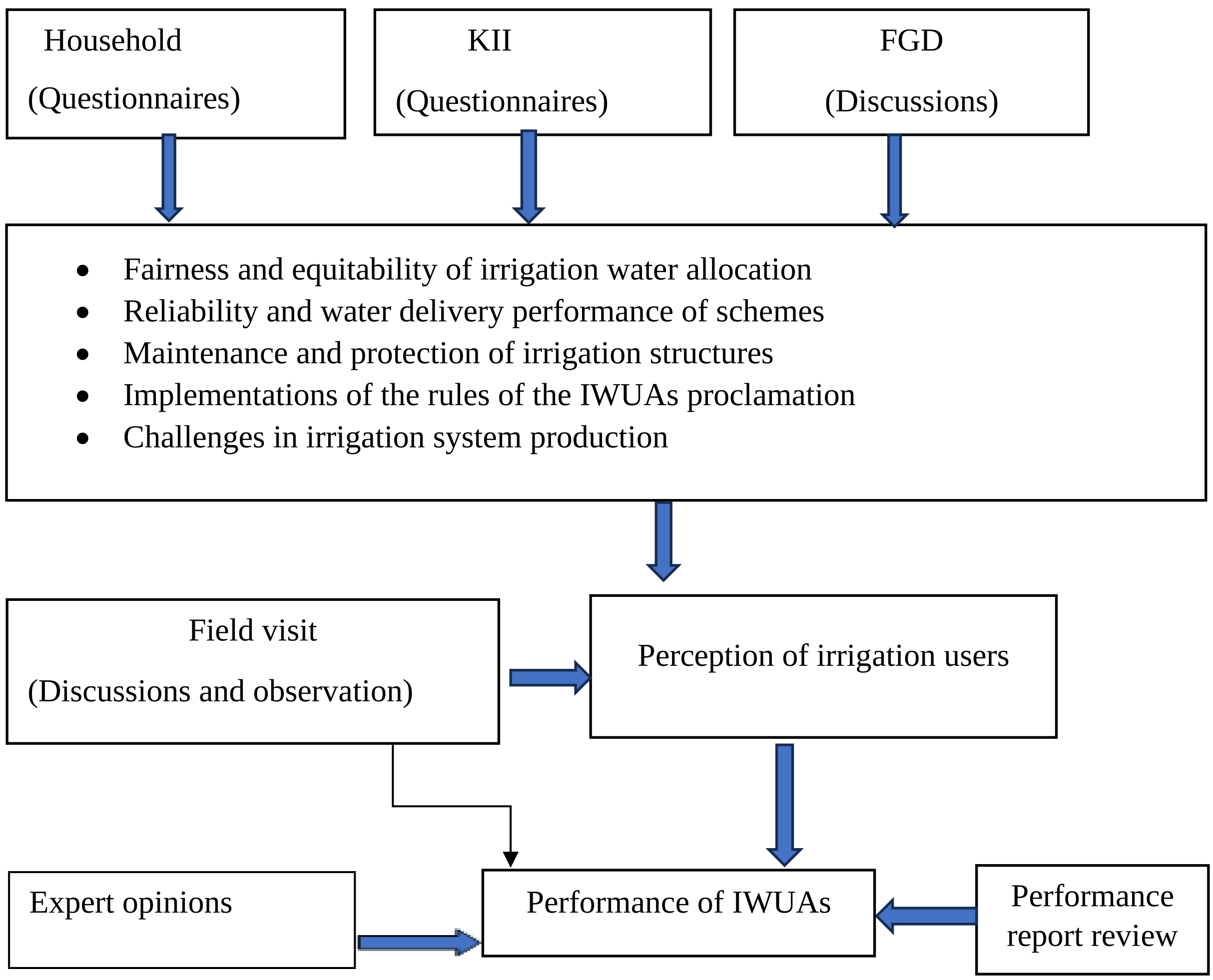


Figure 2.1: Conceptual framework of the study

2.3 Materials and Methods

2.3.1 Study area description

Ethiopia has twelve river basins, which produce an estimated annual runoff of approximately 125 billion cubic meters (BCM), and the groundwater potential of the country varies from 2.6 to 13.5 BMC (Awulachew et al. 2010). The estimated irrigation development potential of the country is about 3.7 million ha (Awulachew et al. 2007), with an economic irrigation production potential of 2.7 million hectares (FAOAQUASTAT 2016). RVLB is one of the twelve river basins in Ethiopia. The basin is endowed with several lakes of varying sizes with high environmental significance. It has a considerable land area for rainfed-based crop production, substantial rangeland size, and irrigation potential for its great economic and social importance. The irrigation potential of the basin is estimated to be 139,300 ha (Awulachew et al. 2007), of which only 10% has been developed (Ulsido and Alemu 2014). The surface SSI system dominated the irrigated agriculture in the basin. The basin is characterized by a semi-arid climate with an annual movement of the intertropical convergence zone within the main part of the East African rift valley (Sagri et al. 2008). The mean daily minimum temperature varies between 10.5 °C and 16.4 °C, and the mean daily maximum temperature ranges from 25.7 °C to 30.1 °C. The average annual rainfall in the basin is 700 mm, of which 75% is precipitated in the main rainy season from June to October.

2.3.2 Location map of the study area and description of the selected schemes

RVLB is located between the latitudes of 07°00' and 08°30' N and the longitudes of 38°00' and 39°30' E, with a total area coverage of 52,739 km^2. The basin covers parts of the southern and southeastern parts of the country. The four selected irrigation schemes are located in three different administration zones in southern Ethiopia. Furfuro and Murtute are located in Siltie zone Wulbareg and Silti districts, respectively; Bedene is located in Alaba zone Wera district; and Sibisto is situated in Gurage zone South Sodo district (Figure 2.2). The description of the selected irrigation schemes is given in Table 2.1.

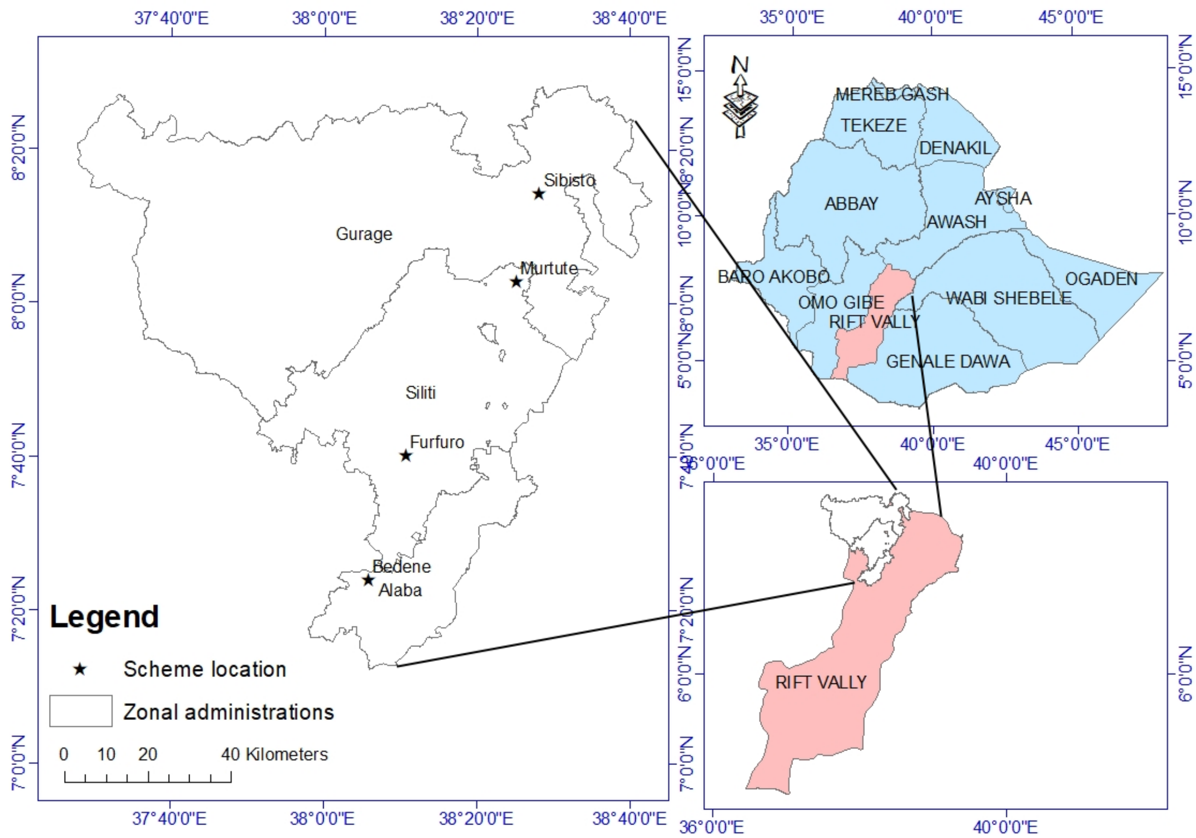


Figure 2.2: Location map of the study area

Table 2.1: Description of the selected irrigation schemes

Scheme	Command area (ha)	No of beneficiaries	Source of water	Diversion type	Is there IWUA?
Furfuro	200	326	Furfuro river	Modern	yes
Murtute	60	160	Stream	Modern	yes
Bedene	200	265	Bilate river	Modern	yes
Sibisto	-	-	Stream	Traditional	yes

2.3.3 Selection criteria of the irrigation schemes

The selection criteria for the schemes include administrative location, availability of formally organized IWUA, typology, and agroecology. The selected irrigation schemes are located in three different administrative zones, which allowed us to gather information from various managerial sources to draw general conclusions about the performance of IWUAs. In Ethiopia, several SSI schemes have no legally formed irrigation institutions (Haileslassie et al. 2016b). Some of them are managed by local governments, while others are governed by local informal institutions. In this study, the existence of a formally organized IWUA was the criterion for selecting the schemes. The selection criteria also included the typology of the schemes. Among the selected schemes, Furfuro, Murtute, and Bedene SSI schemes have modern diversion structures, whereas farmers at the Sibisto SSI scheme use a traditional earthen diversion system. Agroecology, or crop diversity, was used as a criterion to select schemes. In Furfuro, onion, tomato, and wheat are majorly cultivated crops. The most important crops in Bedene are wheat, potato, onion, and haricot beans; in Murtute, tomato, cabbage, wheat, onion, and carrot; and in Sibisto, maize, onion, tomato, carrot, and chili.

2.3.4 Data collection method

2.3.4.1 Document review

This study focused more on qualitative approaches. Secondary documents involving FDRE IWUAs proclamations, regulations, and policies were reviewed. A review of the literature on the establishment, management performance, and roles of IWUA in the Ethiopian irrigation system was carried out. Specific data collected includes the objectives of IWUAs, procedures for organizing IWUAs, guiding principles of the IWUAs, and scopes of application of the rules. Pertinent project development documents, performance reports, baseline data, and beneficiary assessment information were reviewed for each selected SSI scheme.

2.3.4.2 Field visit and observation

The farmers' field, command area, and canal systems were continuously observed during irrigation periods. Informal discussions with farmers, daily labourers, youths, and experts were held during the observation to gather more information. During the field visit, data was collected on how irrigation water was distributed between users, the irrigation water allocation control system, the maintenance and operations of the irrigation system, irrigation scheduling, and how the local communities perceived the institutional management system of the schemes.

2.3.4.3 Household and Key Informant Interview (KII)

Household and KII surveys were conducted to collect data on service delivery performance and the status of institutional irrigation management in the four SSI schemes. The survey data were collected for four months (January to April 2022) with the help of agricultural research experts. Men and women-headed irrigation user households were included in the survey to collect the required data. During respondent selection, stratified sampling techniques were used to find homogeneous information at all reaches of the irrigation schemes. Each irrigation scheme was stratified into head, middle, and tail reach strata with respect to the diversion structure. At each stratum, respondents were then selected using a probability sampling technique. Semi-structured questionnaires were prepared, and data were collected primarily focusing on the reliability and water delivery performance of the schemes; the equity and fairness of the irrigation water allocation; the water allocation plans between users; the implementation of the rules of IWUAs; challenges in irrigation system production; and the general perception of institutional irrigation management performance. The respondents were also interviewed about the adaptation measures they have been applying during irrigation water scarcity. The questionnaires were of open-ended and closed-ended mixed types to enable the respondents to give free-form responses.

2.3.4.4 Focus group discussion (FGD)

FGDs were held with local elders, experts (development agents), local leaders, and IWUA leaders at each scheme to find out more information regarding the management of the schemes. During FGD member selection, the proportion was used to obtain representative participants from men and women. In addition, discussions were conducted with higher-level water managers and irrigation experts at district and zonal-level institutions regarding the overall irrigation management performance. Data were collected specifically on the IWUAs' assistance, market accessibility, input supply facilitation, and training on irrigation water management. The level of support provided to IWUAs was also discussed with district- and zonal-level institutions.

2.3.5 Data analysis and interpretation

Data associated with irrigation institutions are primarily qualitative, and analysis and interpretations are based on a qualitative comparison and descriptive statistics of relevant information (Yami 2013; Haileslassie et al. 2016b). The qualitative data analysis can be used to understand relations among the variables by carefully organizing the information and giving consideration to the local conditions, opinions, perceptions, and preferences of farmers and institutions. The data collected from household surveys was analysed using the Statistical Package for Social Science (SPSS) software. The percentage of responses for each question was calculated. The data collected from the household survey, FGD, KII, and field observation at each SSI scheme was analysed, interpreted more reasonably, and compared to each other to determine the weaknesses and strengths of the irrigation management systems in the study area.

2.4 Result and discussion

2.4.1 Historical declarations for water resource and irrigation management in Ethiopia

Water Resources Utilisation Proclamation No. 92/1994: It is the first official water law in Ethiopia, published in 1994. This proclamation controls how water resources are used by demanding a government permit for all but the most minor and conventional uses. The proclamation also specifies the fundamental standards that permit-granting authorities must follow when evaluating permit applications. The permits have a set duration, can be renewed when they run out, and can be changed, suspended, revoked, or transferred in accordance with the statute's specified conditions (FDRE 1994). However, it didn’t state anything about water resource management. The stakeholders' existence and their roles were not incorporated. It also failed to consider a river basin as the proper planning unit. Finally, it was changed by Proclamation No. 197/2000.

Ethiopian Water Resources Management Proclamation No. 197/2000: This proclamation was issued in order to maximize the social and economic benefits of Ethiopia's water resources through development, protection, and utilization. With some exceptions, the proclamation emphasizes the management of water resources through permits (FDRE 2000). Article 12(1)(a) of this proclamation states that permission is not required to dig water wells by hand, use water from hand-dug wells, or use water for traditional irrigation. The Ministry of Water Resources and Energy was given the majority of the authority and responsibility for planning, managing, using, and protecting water resources under this proclamation. The proclamation motivates organizing the water user associations so that water can be used productively based on user demand.

River Basin High Councils and Authorities Proclamation No. 534/2007: This proclamation aims to put integrated water resource management into practice using a river basin planning strategy. The management of water resources was intended to be more effective, well-organized, and sustainable. In order for basin authorities and regional states to implement integrated water resource management more successfully, the proclamation transferred some of the Ministry of Water Resources and Energy's authority to them.

Irrigation Water Users' Associations Proclamation No. 841/2014: Local irrigation institutions, such as IWUAs, are crucial in providing equitable and sustainable irrigation system functions. The previous Ethiopian legal framework (FDRE 1998 proclamations of cooperatives and associations) regarding local irrigation institutions was unable to offer an appropriate legal foundation for IWUAs (Lempériere et al. 2014). In order to establish and run the IWUAs, a new type of proclamation was therefore approved in 2014. This proclamation aims to establish IWUAs to manage an irrigation and drainage system within their service area and to fairly distribute water among their members for agricultural use. The new proclamation states that the IWUAs are responsible for operation and maintenance, taking appropriate action against erosion, salinity, and pollution, collecting membership fees from members, and providing training for members on irrigation water management and agronomic practices (FDRE 2014).

2.4.2 Performance of selected SSI in the Ethiopian Rift Vally

Four SSI schemes were selected to evaluate the farmers' perception on the technical and management performance of IWUAs in the respective schemes. Scheme performance reports, household and KII surveys, FGDs with various stakeholders, and field observations were used to collect data on the current managerial provision of the schemes. A total of 197 households were interviewed, of which 24 were rejected for justifiable reasons during the qualification process (Table 2.2). Of the total respondent households, 58% of them were older than 50 years, and more than 60% had irrigation experience greater than ten years. Most of the interviewed households have their own land within the scheme command area, and a few are sharecroppers or use land contracts.

Table 2.2: Participants during the data collection

Irrigation scheme	Household survey		KII	FGD
	Male	Female		
Furfuro	27	14	3	5
Murtute	32	13	3	6
Bedene	26	17	2	4
Sibisto	34	10	4	4
Total	119	54	12	19

2.4.2.1 Major irrigation management practices in the study area

The establishment of IWUAs can enhance irrigation scheme management practices, particularly in terms of canal maintenance, water allocation between users, and irrigation scheduling. In this study area, irrigation practices usually start in November, at the onset of the dry season. Each irrigation scheme under this study has a legally organized IWUA, which is responsible for coordinating the scheme management activities. The major irrigation management practices carried out in the study area include cleaning canals to remove obstructions to water flow, maintaining broken canals, allocating water, offering on-farm training on irrigation water management and agronomic practices, controlling water thefts, and resolving disputes between water users. These are among the responsibilities given to IWUAs. Based on the survey, the canal and diversion site cleaning and assistance with agricultural input supply have been coordinated by IWUA's leaders at the Furfuro and Sibisto irrigation schemes. However, local leaders and development agents execute these activities at Bedene and Murtute. In Furfuro and Sibisto, illegal water diversion (vandalism) control systems were also applied to generate suitable water allocation plans between users. Even though its execution varies between schemes, discussions have been carried out between IWUA members regarding canal protection, the water distribution system, and the fairness of water allocation at all schemes in the current study. In addition, although it was the responsibility of the IWUAs, farm-level training on irrigation water management, crop disease control systems, and general agronomic practices has been provided by district and zonal-level agriculture and irrigation institutions in the four schemes. The deteriorated canals are occasionally maintained by the regional government in the four schemes.

2.4.2.2 Reliability and water delivery performance of the schemes

Households were interviewed about their experience with the reliability and water delivery performance of the schemes. The reliability and water delivery performance of Furfuro and

Sibisto were rated as good by 52 and 41% of respondents, respectively; moderate by 26 and 34%; and poor by the rest (Figure 2.3). On the other hand, 73 and 51% of respondents at Murtute and Bedene, respectively, said that the reliability and water delivery performance are poor, and 16 and 28% rated them as moderate. These results indicate the degree to which irrigation users were content with the dependability of the irrigation water in the respective schemes. The reliability and water delivery performance of Murture were the worst of the four irrigation schemes. All irrigation schemes had problems with water supply; however, the severity varies between schemes. Household respondents and FGD members said that poor reliability and water delivery performance are primarily caused by poor maintenance and operating habits. The problems were realized during the field visit. Water loss from overtopping and deteriorated structures was significant, especially at Murtute and Bedene. Crops, particularly those at the tail reach of the schemes, experienced water scarcity and, in some cases, wilted due to inconsistent water flow. These may affect the scheme's overall efficiency and the intended production level to ensure food security. As it has been noted in different reports, the number of farmers involved in irrigation systems of production has been increasing from time to time in the study area; however, the reliability and water delivery performance of irrigation schemes are declining due to poor maintenance. These phenomena are the outcome of the weakness of irrigation institutions (Haileslassie et al. 2016b).

The FDRE 2014 IWUAs proclamation has declared the requirement for fee collection from irrigation water users, which can be used to maintain and operate irrigation schemes (FDRE 2014). However, none of the IWUAs in this study were used to collect fees from water users. As a result, they are unable to execute their responsibilities due to financial constraints. Irrigation water pricing can be used to finance irrigation schemes, improve water use efficiency, and ensure the long-term viability of irrigation services (Haileslassie et al. 2016b). The irrigation users believe that the government is responsible for canal maintenance. This indicates the need for awareness creation regarding the rules and regulations of the IWUAs. Survey participants also stated that problems with the faulty design and construction are another reason for the inconsistent flow, particularly at Murtute. Numerous research findings indicated that the study and design errors are an important challenge to irrigation development and management in Ethiopia (Amede 2015; Yohannes et al. 2017; Gurmu et al. 2019; Meja et al. 2020). In fact, the amount of abstracted water from the source has been declining due to climate change and annual rainfall reductions (Tekle 2015), and increasing competition for water, particularly at Bedene. This might be another factor contributing to inconsistent water flow in the schemes. Various scholars have noted unreliable water flow and poor delivery performance of irrigation schemes in the Ethiopian Rift Valley. For instance, Van Halsema et al. (2011) stated severe irrigation water unreliability in Dodicha SSI in the central Rift Valley. Ulsido and Alemu (2014) described an unreliable irrigation water supply in irrigation schemes in the Rift Valley due to illegal water users and malfunctioning irrigation infrastructure.

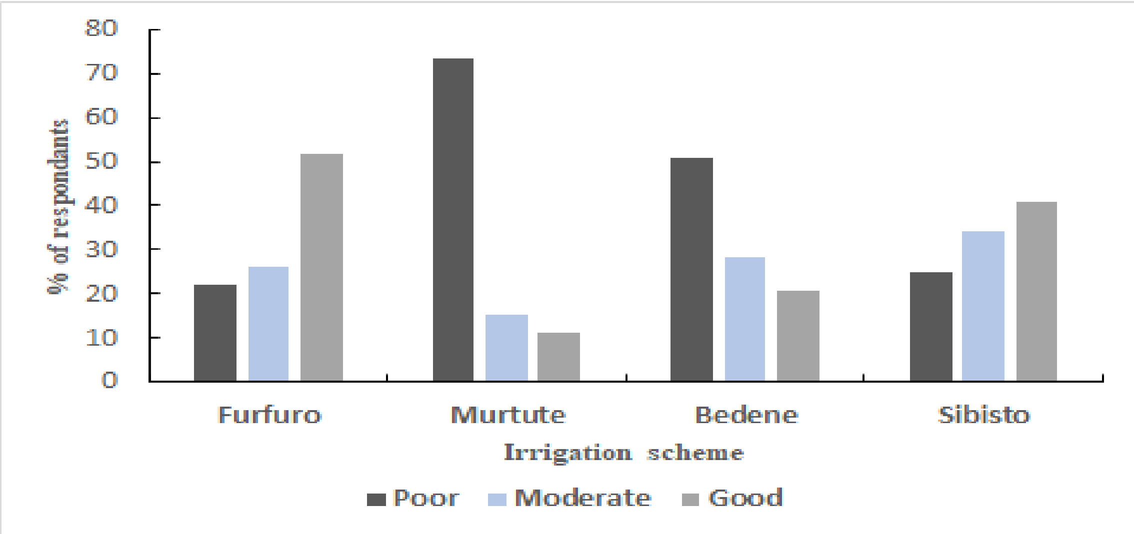


Figure 2.3: Reliability and water delivery performance of irrigation schemes

2.4.2.3 Fair and equitability of water allocation

The FDRE 2014 IWUA proclamation states that one of the objectives of establishing IWUA is to deliver irrigation water fairly and equitably for the members for agricultural purposes (FDRE 2014). A fair and equitable distribution of irrigation water for users is a key performance indicator for IWUAs (Haileslassie et al. 2016b). As depicted in Figure 2.4, all irrigation schemes under the current study experience some degree of unfair water distribution. In Murtute and Bedene, 32 and 37% of respondents, respectively, thought that the water allocation was seriously unfair, and 50 and 43% said that they occasionally see unfairness. In Furfuro and Sibisto, 20 and 22% of respondents, respectively, mentioned seriously unfair water allocation, and 38 and 29% of them said sometimes they observe unfairness in irrigation water distribution. The results indicated that Furfuro and Sibisto have better fairness than Murtute and Bedene in water allocation. In these two schemes the water allocation was based on prescribed plans, though this was not always the case.

The survey participants indicated that there was no inclusive schedule to allocate water to users at Murtute and Bedene; instead, the schedule was largely determined by the personal interests of the IWUA leaders. In addition, there was no limit on the size of irrigation land in the four irrigation schemes. The tail reach users stated that head residents are privileged to water and could cultivate relatively large land sizes. This situation negatively affected the water distribution system, resulting in unfair water allocation between head and tail reach residents. Comparable results were reported in the Chelelek a watershed in the Central Rift Valley, Ethiopia (Teshome et al. 2018). The other factor contributing to the unfair irrigation water distribution is the inconsistent water flow in the canals, which is brought on by poor canal maintenance. Participants in the survey stated that the unfairness was also due to corruption and dishonesty. Such power abuse and unfairness by IWUAs have been reported in various irrigation schemes in Ethiopia (Haileslassie et al. 2016b; Teshome et al. 2018). Even though it is difficult to expect irrigation schemes to be free of challenges, according to the survey respondents, rules and regulations regarding irrigation water distribution must be respected in order to lessen the problems. The FGD members also suggested the formulation of comprehensive water allocation plans, controlling water consumption, and imposing restrictions on irrigation land size to improve the water allocation system in the schemes.

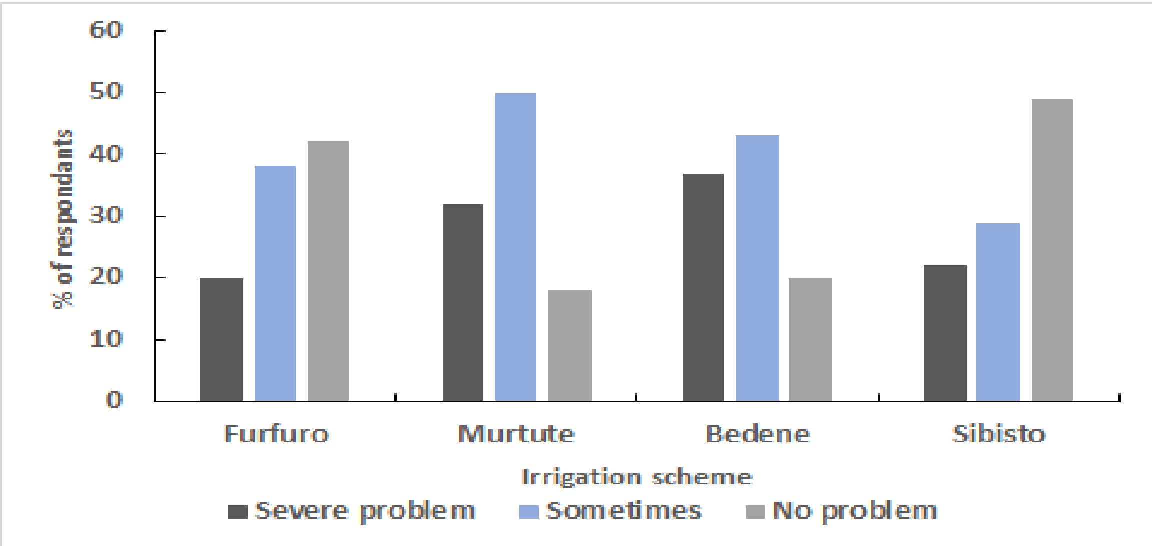


Figure 2.4: Fairness and equitability of water allocation

2.4.2.4 Perception on the performance of irrigation institutions in the study area

The survey results on the overall performance of institutions working in irrigation management in the four SSI schemes are presented in Figure 5. The respondents were interviewed about the general managerial provisions of the schemes, mainly focusing on canal protection, on-farm training, rules for controlling water consumption and water thefts, and facilitating the maintenance of depreciated irrigation structures. The IWUAs in the respective schemes have the responsibility to manage these activities. However, during the survey, respondents were interviewed not only about the managing performance of the IWUAs but also about the district and zonal level institutional supports since, based on the FDRE 2014 IWUAs proclamation, they are responsible for assisting the IWUAs. Results indicated that 23, 44, 48, and 19% of respondents in Furfuro, Murtute, Bedene, and Sibisto, respectively, said the overall management performance of the institutions was poor, and 38, 13, 17, and 29% of respondents thought that the performance was good (Figure 2.5). Application of some management activities such as internal regulations for controlling water theft and a plan for water allocation at Furfuro and Sibisto, made them better than Murtute and Bedene. In all irrigation schemes, household respondents and FGD participants emphasized the importance of weak canal protection, poor maintenance habits, and unpredictable irrigation water allocation systems. In addition, since illegal water diversion and subsequent free riding cannot entirely be avoided in surface irrigation systems, membership in the IWUA should be required (FDRE 2014). However, the majority of the irrigation users were unaware of the rules for being membership in all schemes in this study.

Generally, the existing IWUAs fail to meet the standards of self-governing institutions as declared by FDRE (2014). In fact, in a top-down governing system, the existing irrigation institutions are not given the authority to self-govern (Yami 2013). According to Lempériere et al. (2014), irrigation institutions have three major tasks to accomplish: operation and maintenance, governance, and financial management. The IWUAs in this study area were unable to achieve these tasks properly. According to the FDRE 2014 IWUAs proclamation, the supervising body for IWUAs is required to organize and create awareness about the implementation of the rules and regulations. However, during the FGD, participants from all schemes stated that the IWUAs have not received any training on the guidelines and implementations of the IWUA's proclamation, and there is no formally assigned supervising body to follow up on their status. Therefore, a shortage of awareness of management principles might have an impact on the poor performance of the IWUAs.

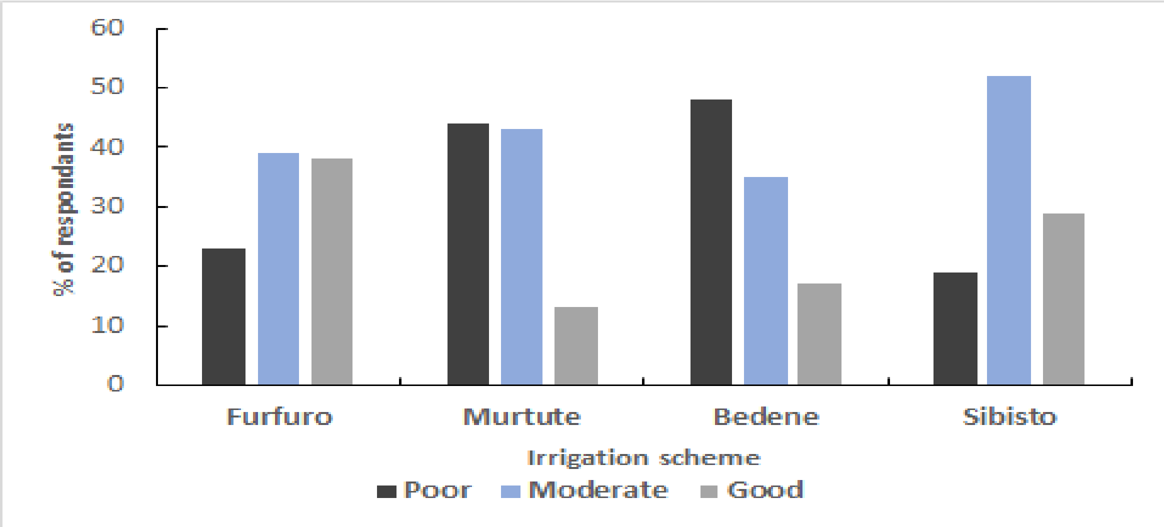


Figure 2.5: Perception on institutional management performance

2.4.3 Adaptation/mitigation strategy of irrigation water scarcity in the study area

Farmers in the study area adopt quite a few types of strategies to mitigate irrigation water scarcity. Farmers at the Murtute irrigation scheme use shallow groundwater for irrigation during the recession of the canal water. In all of the schemes in this study, crop shifting from a diverse range to a few moisture-stress-tolerant crops, as well as the use of early-maturing crop varieties, have been adopted during irrigation water stress. Farmers in northern Ethiopia use a similar strategy to mitigate irrigation water scarcity (Yohannes et al. 2017). Shifting the planting time is another strategy used by farmers to escape the severe moisture stress periods. Particularly, respondents from Furfuro and Bedene stated that they have been using the planting time of early November. This is due to the fact that after the cessation of the main rainy season *(Kiremt)* in October, they can use recession moisture for land preparation and planting for the next irrigation season. The other benefit of planting in early November is that crops can escape the severe moisture stress periods in later growth stages.

2.4.4 Major problems of irrigation production in the study area

Respondents were interviewed about major problems they confronted during irrigation system production. The pair-wise comparison of the problems indicated that the low price of agricultural products was perceived as the first challenging factor, followed by the high cost of production inputs and the shortage of water access (Table 2.3). According to the respondents, the costs of agricultural inputs such as fertilizer, seed, fuel, and pesticides have been increasing regularly, while crop products have low selling prices. During the FGD, participants, particularly from Murtute and Sibisto irrigation schemes, revealed that the reason for the low selling price is that farmers plant the same type of crops and produce a similar product at the same time of the year, which makes the product beyond the capacity of the local markets and causes low selling prices. Since most farmers in the study area are smallholders with land sizes of 0.25 to 0.5 ha, they believe that their crop product is not big enough to be transported to a better market area, like Addis Abeba. A shortage of market information and dealers' misleading information affect the farmer's decision on the market. This is due to weak linkages and integration between value chain actors. Yami (2016) reported that the productivity of irrigation is hampered by inadequate market access and the expensive cost of input supplies in various regions of the country. Selling price volatility and a scarcity of market access are almost always cited as major constraints to irrigated agriculture in Ethiopia (Kassie 2020). In many cases, middlemen earn much higher marketing margins than the farmers, which reduces the farmers' incentives to increase their production (Emana et al. 2015).

The other major constraints perceived by respondents were water access-related problems. As discussed in sections 4.2.2 and 4.2.3, irrigation water reliability and fairness in allocation are important issues that need to be considered in this study area. Crop disease and pests are other important factors affecting farmers' yields. Vegetable crops, in particular, are much more susceptible to crop disease and pests, which raise production costs by demanding the use of pesticides. Generally, weak technical capacity, a poor value chain and crop marketing system, a shortage of water access and land tenure, and a lack of financial and credit systems are barriers to irrigation development in Ethiopia (FAO and IFC 2015; Kassie 2020).

Table 2.3: Pair-wise comparison of the irrigation problems and ranking

Problems	WA	HIC	LPP	LS	CDP	Score	Rank
Water access (WA)	*	HIC	LPP	WA	WA	2	3
High input cost (HIC)		*	LPP	HIC	HIC	3	2
Low product price (LPP)			*	LPP	LPP	4	1
Land shortage (LS)				*	CDP	0	5
Crop disease and pest (CDP)					*	1	4

2.4.5 Ways to improve the benefits of the farmer from SSI

The government and stakeholders can make SSI more effective by improving how they intervene in several situations. First, strengthening local irrigation institutions should be given priority in order to succeed in irrigation development. The local IWUAs can play an important role in operating the whole task of the SSI schemes. However, they require awareness and training on irrigation system management and implementation principles. The implementation of the IWUAs proclamation has several advantages. For instance, fee collection from irrigation water users has three benefits. First, it increases the local people's ownership of irrigation infrastructure; second, the collected fee can be used to operate and maintain the schemes; and third, it improves irrigation water management efficiency. In addition, strengthening the IWUAs can improve irrigation water reliability and solve unfairness problems. The other important issue that needs government intervention is market value chain development. This could be carried out by strengthening market connections by promoting high-value and off-season crops, providing farmers with up-to-date market information, and connecting farmers to particular markets. In addition, updating farmers with regional and national market information could assist them in adjusting planting times in accordance with market demand. Consulting the community at all stages of the irrigation development plan can also be helpful. The planning, development, and management of irrigation schemes should include farmers. Encouraging irrigation water management and irrigation agronomy research should be used to advance the farmer's indigenous knowledge.

2.5 Conclusion

In this study, the technical and management performance of four SSI schemes in the Ethiopian Rift Valley was assessed using household surveys, FGD, KII, and field observations. IWUAs have been formally organized in the four irrigation schemes to execute and coordinate irrigation management practices. The evaluation result indicated that the IWUAs were unable to manage the schemes in accordance with the rules and regulations. In all irrigation schemes, there was a problem with inconsistent water flow and unfair water allocation between users; however, Furfuro and Sibisto performed better than Murtute and Bedene. Some internal rules, such as water theft control regulations and water allocation plans, were implemented in Furfuro and Sibisto. However, some irrigation users were not satisfied. Inconsistent water flows in the schemes were caused by poor maintenance and operating habits. Although the FDRE 2014 IWUAs proclamation has declared fee collection for irrigation water, none of the IWUAs in this study collect fees from irrigation users. Therefore, they were unable to maintain deteriorated canals by themselves due to financial constraints. A lack of inclusive irrigation water allocation plans caused unfair water distribution between users. Crops, particularly those at the tail reach of the schemes, suffered from water scarcity due to inconsistent water flow and unfair water allocation. The problems were severe in the cases of Murtute and Bedene. Although the degree of the problems varies between schemes, the institutional management of all irrigation schemes under the current study was unsatisfactory. Due to a lack of training, guidance on execution principles, and supervision, the IWUAs were unable to perform effectively. These imply the need for closely supervising and strengthening the IWUAs to improve their management performance. Moreover, inadequate market access and value chain development, high costs of agricultural inputs, and inefficient irrigation management affected farmers' production in the irrigation system in the study area. Generally, in order to achieve the goals of ensuring food security and enhancing farmers’ income, emphasis should be given to the management of irrigation schemes and value chain development for irrigation products.

CHAPTER III: On-farm Performance Evaluation of Small-Scale Irrigation Schemes in the Ethiopian Rift Valley: Internal and External Performance Process Approach

Chapter three of the thesis contains the findings of the on-farm performance evaluation of two selected SSI schemes in two different districts. The two selected schemes were included in the survey in Chapter Two. This chapter aimed to evaluate the on-farm performances of the selected schemes using both internal and external performance indicators. Filed experiments were conducted within the two SSI schemes command area, and irrigation water, crop, and secondary data were used for the evaluation. Internal performance indicators such as conveyance efficiency, application efficiency, and application uniformity, and external performance indicators such as agricultural, water use, and physical sustainability performance indicators were used. The outcomes presented in this chapter validated the field survey findings in Chapter Two. Based on the findings, possible measurements were recommended to improve on-farm irrigation water management. This Chapter has been published in the journal of Irrigation and Drainage (Wiley Online Library publisher).

Based on:

Wabela, K., Hammani, A., Taky, A. & Tekleab, S. (2024) On-farm performance evaluation of small-scale irrigation schemes in the Ethiopian Rift Valley: Internal and external performance process approach. Irrigation and Drainage, 1–13. Available from: https://doi.org/10.1002/ird.2960

3.1 Introduction

Globally, irrigated agriculture is the largest consumer of freshwater and accounts for 70% of all freshwater withdrawals (Michelon et al. 2020). However, although irrigation uses the largest percentage of freshwater, the amount of available freshwater is insufficient to meet the demand for growing irrigation needs on a global scale and is projected to decline more in the near future due to climate change and increasing competition with other sectors (Singh 2012; Wang et al. 2017). As the world's population grows at an exponential rate, pressure is mounting on both land and water, which are the most essential resources for irrigation agriculture. In addition, irrigated agriculture has been expanding with poor water management systems, which has aggravated the shortage of water for irrigation (Amede et al. 2014; Amede 2015).

Agriculture is the cornerstone of the Ethiopian economy. It serves as a source of food, a source of employment for 85% of the population, and an input material for industries, and it contributes to 43% of the gross domestic product (GDP) (FAO 2012). However, production is susceptible to climate change and recurrent droughts (Hagos et al. 2009; Mirzakhail et al. 2012; Asrat and Anteneh 2019). Irrigated agriculture has been considered a tool for sustaining food security and enhancing agricultural production in the country (Awulachew et al. 2007; Asres 2016). The infrastructure for irrigated agriculture has expanded widely throughout the country to mitigate the effects of climate change and enhance food security. The expansion has been implemented primarily through small-scale (< 200 ha) community-managed irrigation schemes (Awulachew and Ayana 2011; Gebul 2021), which are relatively easy to construct in terms of financial and time requirements. Small-scale irrigation (SSI) schemes are run and controlled by local water users' associations with little or no government intervention. In Ethiopia, the roles of SSI schemes in enhancing food security and improving the income of rural people have not been studied in detail at the national level; however, some scheme-level studies indicated that there is a positive impact on ensuring food security (Yigzaw et al. 2019; Jambo et al. 2021; Kassie and Alemu 2021). The SSI can also help to improve the overall living standard of the rural population by meeting social needs and reducing poverty (Asayehegn, 2012; Belay & Bewket, 2013).

Although the government has been building numerous irrigation schemes, several SSI schemes are underperforming, and some of them have stopped providing services (Amede 2015; Gebul 2021). Water loss through seepage and deteriorated structures, poor operation and maintenance systems, weak institutional strength, and poor awareness of on-farm irrigation water management practices are the causes of poor performance (Abera et al., 2019; Ayele et al., 2021; Belay et al., 2022; Teshome et al., 2018). Nonuniformity in on-farm water distribution, poor irrigation scheduling, inappropriate duration of irrigation, etc., are some of the causes contributing to poor on-farm irrigation water management (Haileslassie et al. 2016a). Crop production sustainability in an irrigation system is influenced by several factors, including the water conveyance capacity of irrigation structures, institutional strength, operation and maintenance systems, and land and water resources (Dejen et al. 2012; Gebrehiwot 2018). The Ethiopian government have made several efforts to improve the performance of irrigation schemes, which include farmer participation in different scheme management aspects, starting with project planning, administration, and water distribution (Awulachew et al. 2007). However, the lack of incessant improvement and performance evaluation systems has made it difficult to achieve sustainable production.

On-farm performance evaluation of SSI schemes is an essential task for identifying the root causes of problems and examining management solutions that can improve performance and revive failed irrigation schemes. Identifying some pertinent performance criteria and identifying indicators that can provide information on the status of the schemes are necessary for improving the performance of irrigation schemes. The choice of indicators is based on the objectives of the evaluation being conducted (Small and Svendsen, 1990). Given the many components of an agricultural system, it seems challenging to address all performance-related issues at once. There are two groups of performance indicators for irrigation schemes. The first is an external performance indicator, which is based on the output-input relationship from and to an irrigated system (Molden et al. 1998). The output is the total revenue obtained from irrigated crops in each scheme. The second indicator is an internal performance indicator, which relates the performance of the scheme to internal management targets. Although internal performance indicators are essential for evaluating irrigation system performance in relation to operational targets, they cannot provide much information in terms of scheme benefits. On the other hand, external performance indicators can provide information about the revenue attained from irrigation systems in relation to inputs; however, they provide little information about the internal indicators that result in outputs. Therefore, the combination of these two performance indicators is most relevant for gathering sufficient information on the status of irrigation schemes. This study aimed to evaluate the on-farm performance of two SSI schemes in the Ethiopian Rift Valley using both internal and external performance indicators. The findings of this study provide evidence for decision-makers and the local community to take remedial action to enhance the performance of schemes for improved production.

3.2 Materials and Methods

3.2.1 Description of the Study Area

The selected SSI schemes are located in two different administration zones in the Ethiopian Rift Valley. Furfuro is located in the Wulbareg district, Siltie zone, and Bedene is located in the Wera district, Alaba zone (Figure 3.1). Each scheme has a command area of 200 ha. The source of water for the Furfuro is the Furfuro River, which is sourced from a stream in the western escape of the Dijo watershed, while the Bedene scheme abstracts water from the Bilate River. The two schemes use modern diversion structures to supply irrigation water to the command area. The study area shares a similar pattern of humid and subhumid climate conditions with bimodal rainfall (short and main rainy seasons) (Figure 3.2). The short rainy season (*Belg*) usually starts in March, continues through May, and is used to supplement irrigated crops. The main rainy season (*Kiremt*) begins in June and lasts until October. The meteorological data show that the annual average rainfall of the area ranges between 560 and 1300 mm (Wabela et al. 2022). The mean minimum and maximum temperatures of the study area are 9 and 27 °C, respectively. Irrigation agriculture is being practiced in the area during the longest dry season, which typically lasts from November to March. The most common crops cultivated in the schemes are onions, tomatoes, potatoes, wheat, and other small vegetables. Most land use activities involve intensively cultivated agriculture, with Vertisols, Leptosils, Nitosols, and Cambisols as the dominant soil types.

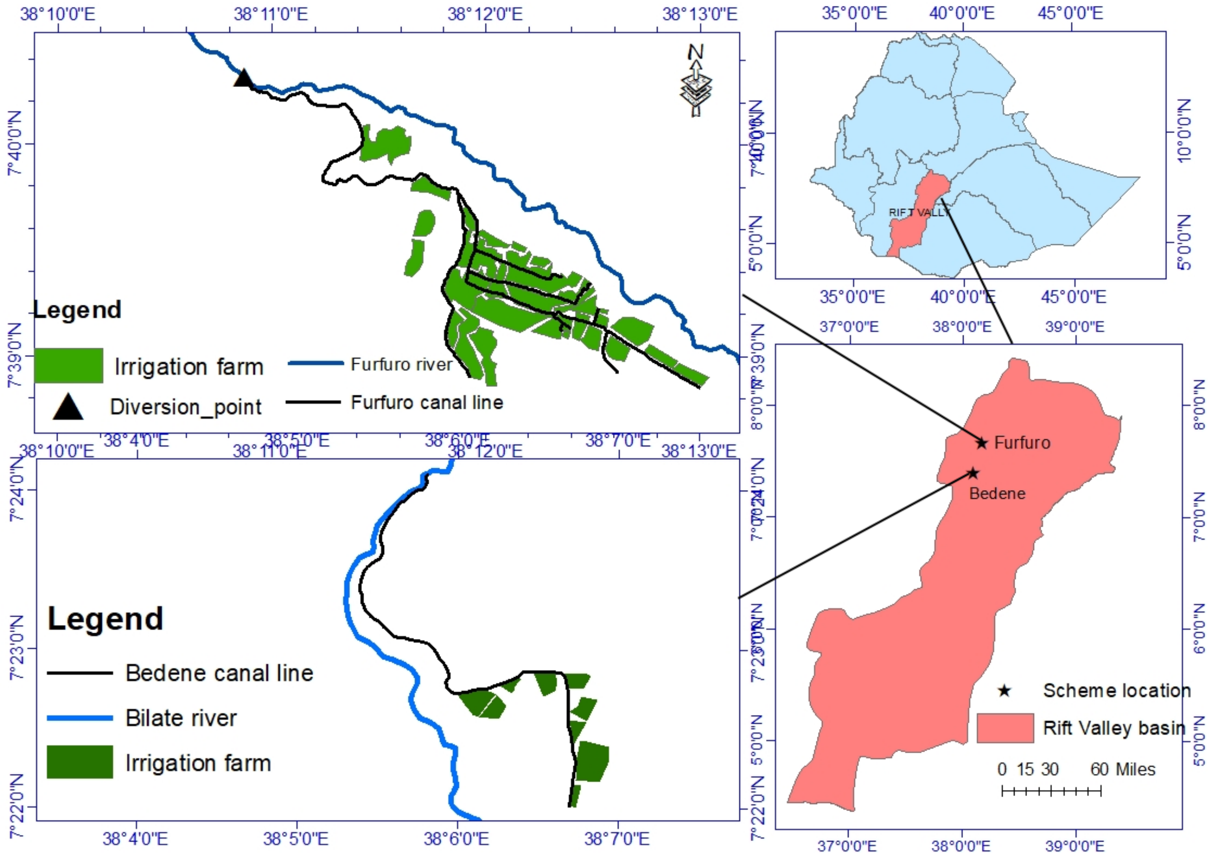
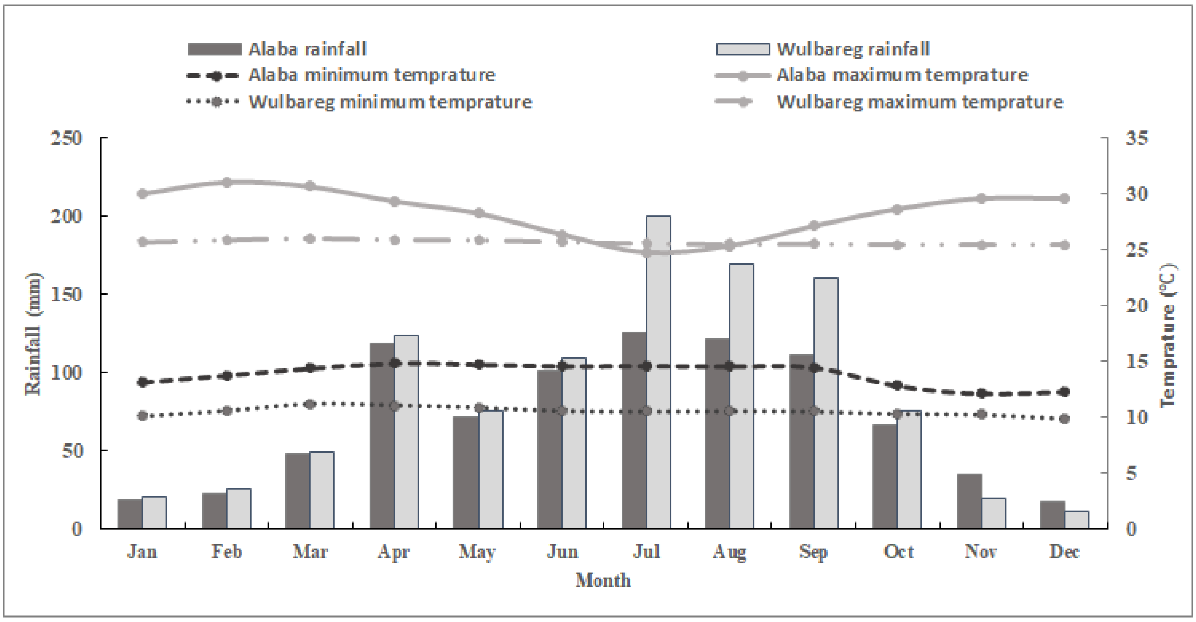


Figure 3.1: Location map of the study area



Notes: Alaba station is near the Bedene scheme, while Wulbareg station is near the Furfuro scheme

Figure 3.2: Mean monthly rainfall and temperature of the study area

3.2.2 Field Experimental Data Collection

Internal and external performance indicators were used to evaluate the on-farm performance of the schemes. Climate, soil, water, crop, irrigation, and yield data were among the most important data collected for this study. Field experiments were conducted within the command area of the two schemes in the 2021/22 and 2022/23 dry seasons (from mid-December to the end of March). The cross-sectional area of canals was measured at different sites in the two schemes to determine the conveyance efficiency. The velocity of the water in the canals was measured at various locations using floating methods. Three crop fields (wheat, onion, and tomato) at Furfuro and three crop fields (wheat, onion, and potato) at Bedene were used to measure the irrigation water application depth. The amount of irrigation water applied to the fields was measured using a 5.08×90 cm cutthroat flume (Figure 3.3). Equivalent depths of a 5.08×90 cm cutthroat flume was used from discharge tables to determine the discharges of irrigation applied to the fields. To calculate the soil water content using the gravimetric method (Hillel 1998) (Figure 3.4), soil samples were taken before and after irrigation to a depth of 80 cm with 20 cm intervals in all fields using an auger.

Figure 3.3: Measuring the irrigation water depth using the cutthroat flume

Figure 3.4: Soil moisture content mearing in laboratory

3.2.3 Description of the CROPWAT and determination of crop water requirement

In this study, the crop water requirement (ETc) was calculated using the CROPWAT model. CROPWAT is a computer model developed by the FAO that is used for the calculation of ETc based on soil, climate, and crop data (FAO 2020). The ETc is the quantity of water that crops need to compensate for the loss of evapotranspiration from the cropped field. The CROPWAT model has been extensively applied in computing appropriate irrigation schedules and calculating water footprints. The model is also used to calculate the irrigation water required for crops in different cropping patterns in a particular land area. ETc is the product of the crop coefficient (Kc) and reference evapotranspiration (ETo). Kc is a crop characteristic that varies during the growing period. Differences in vegetation and ground cover indicated that Kc varied during the growth stage (Allen et al. 1998).

$$ETc = ETo * Kc \tag{3.1}$$

The reference evapotranspiration is a climatic parameter that represents the evaporating power of the atmosphere (Katerji and Rana 2011). Climatic data such as maximum and minimum temperature, relative humidity, sunshine hours, and wind speed are needed to calculate the ETo in CROPWAT. The CROPWAT model computes the ETo based on the Penman–Monteith method:

$$ET_o = \frac{0.408\Delta(R_n - G) + \Upsilon \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \Upsilon(1 + 0.34u_2)} \quad 3.2$$

where R_n is the net radiation at the crop surface [MJ m^{-2} day^{-1}], G is the soil heat flux density [MJ m^{-2} day^{-1}], T is the mean daily air temperature at 2 m height [°C], es is the saturation vapour pressure [kPa], u_2 is the wind speed at 2 m height [m s^{-1}], e_a is the actual vapour pressure [kPa], e_s-e_a is the saturation vapour pressure deficit [kPa], γ is the psychrometric constant [kPa $°C^{-1}$], and Δ is the slope of the vapour pressure curve [kPa °C−1].

The climatic data for this study were obtained from the Ethiopian National Meteorological Service Agency (ENMSA). Kc values reported in the Central Rift Valley by Bossie et al. (2009) for onion and by Dirirsa et al. (2017) for tomato were used. For wheat and potato, the Kc values from FAO Irrigation and Drainage Paper No. 56 were used (Allen et al. 1998). The United States Department of Agriculture and Soil Conservation Service (USDA S.C.) method was used to calculate the effective rainfall. Based on the data collected on the proportion of the main irrigated crop area, 53%, 36%, and 11% for wheat, onion, and tomato, respectively, at Furfuro, and 75%, 15%, and 10% for wheat, onion, and potato, respectively, at Bedene were considered for cropping patterns. Agronomic practices such as ploughing, land levelling, weeding, and fertilization were carried out properly. Irrigation scheduling was calculated based on the crop growth stage water demands; however, its application was not always respected due to water shortages and a lack of scheme-level scheduling, particularly in Bedene. Thus, schedule rearrangements were made based on water availability. All field management and irrigation practices were carried out by farmers; however, the researchers measured the amount of applied irrigation water based on a pre-established schedule.

3.2.4 Secondary Data Collection

Secondary data were also collected from various sources. Scheme-level data on crop yield, irrigated area, and incomes generated from irrigation users were collected from the respective district agricultural offices. Yield-selling price data from local markets were collected during the harvesting period (March to April 2022 for Bedene and March to April 2023 for Furfuro), and the average values were used. Scheme performance reports were assessed to gather the necessary information. Furthermore, interviews were carried out with farmers and development agents regarding irrigation water application techniques, income generated from irrigation, and cropping intensity and patterns.

3.2.5 Internal Performance Indicators

Conveyance efficiency (Ec): The cross-sectional area of the canals and the average flow velocity of the water were used to calculate the inflow and outflow discharge through the canals. Water depth in the canal and canal width were measured to obtain the cross-sectional area. Water flow velocity in the canal was measured several times using floating objects, and average values were used. Conveyance efficiency provides information about the loss of diverted water through conveyance canals due to seepage or evaporation (Kassa and Ayana 2019). It is calculated as:

$$E_c = \frac{Q_{out}}{Q_{in}} * 100 \qquad 3.3$$

where, Q_{in} is the discharge of diverted water (inflow) to the canals (m^3/s), and Q_{out} is the discharge of leaving water (outflow) from the outlets of the canals (m^3/s).

Irrigation application efficiency (E_a): This parameter is an important long-term performance indicator (Kijne et al. 2003b). It signifies the proportion of the mean irrigation depth stored in the root zone of the plant after irrigation to the mean irrigation application depth (Bos et al. 2005). Soil samples were taken before and after irrigation, and the amount of stored water in the soil root zone was determined using the gravimetric method. The gravimetric soil water content is then converted to depth using the soil bulk density, density of water, and soil sampling depth. The application efficiency is computed as:

$$E_a = \frac{d_s}{d_v} * 100 \qquad 3.4$$

where d_s is the irrigation water depth stored in the plant root zone (mm) and d_v is the water depth applied to the field (mm).

The depth of the applied irrigation water to the field was calculated using the cutthroat flume equivalent depth for discharge:

$$d_v = \frac{Q * T}{A} \qquad 3.5$$

where *Q* is the field application discharge obtained from the cutthroat flume table for the equivalent depth (m^3/s), T is the elapsed time (s), and A is the area of the field (m^2).

Christiansen uniformity coefficient (CU): It measures how the applied irrigation water is uniformly distributed throughout the entire field. It was calculated by using soil samples taken at different points in the fields:

$$CU = (1 - \frac{\Sigma r}{mR}) * 100 \qquad 3.6$$

r is the absolute value of the deviation of the individual observations from the mean (mm), R is the mean depth of observations (mm), m is the number of observations

The overall efficiencies (E_p) of the schemes were calculated as:

$$E_p = E_c * E_a \qquad 3.7$$

3.2.6 External Performance Indicators

Agricultural performance indicators: Four agricultural performance indicators were considered in this study (Molden et al. 1998): output per irrigated area, command area, irrigation supply, and water consumed. The seasonal revenue (output) obtained from each scheme was calculated using the total yield of each crop and its selling prices. The irrigated area is the total area covered by crops in that season, and the command area is the scheme design area to be irrigated. The seasonal diverted irrigation water to the command area was calculated using the monthly average discharge at the diversion site and the length of the growing season. The consumed water is the seasonally available water consumed as evapotranspiration (ETc).

Output per irrigated area (OIA): It is the association between the total irrigation production value in each scheme and the actual irrigated area:

$$OIA = \frac{Procution\ value (US\$)}{Irrigated\ area\ (ha)} \qquad 3.8$$

Output per command area (OCA): It is the association between the values of total irrigation production in each scheme and the command area:

$$OCA = \frac{Production\ value\ (US\$)}{Command\ area\ (ha)} \qquad 3.9$$

Output per irrigation supply (OIS): It connects the value of production to the volume of seasonal irrigation water supplied to the command area.

$$OIS = \frac{Production\ value\ (US\$)}{Diverted\ rrigation\ water\ volume\ (m^3)} \quad 3.10$$

Output per consumed water (OCW): It relates the value of production to the actual evapotranspiration (ETc) of the cultivated crops in a specific season.

$$OCW = \frac{Production\ value\ (US\$)}{Volume\ of\ irrigation\ water\ consumed\ as\ ETc\ (m^3)} \quad 3.11$$

Water use performance indicators: Water use performance indicators are based on irrigation supply and total water supply relative to irrigation demand and crop water demand, respectively. In this group, relative water supply and relative irrigation supply indicators were considered for the two irrigation schemes based on methods given by Molden et al. (1998). The irrigation supply is the volume of seasonally diverted irrigation water to the command area, while the total water supply is the sum of the effective rainfall and irrigation supply. The total crop water demand in each scheme was obtained by multiplying the seasonal evapotranspiration need of all crops (ETc in mm) by the total irrigated area. The irrigation demand is the crop water demand minus the effective rainfall.

Relative irrigation supply (RIS): It is the ratio of the seasonal irrigation supply at the scheme level to the seasonal irrigation demand. It is an important indicator for assessing the level of irrigation water stress or abundance:

$$RIS = \frac{Seasonal\ Irrigation\ supply\ (m^3)}{Sesonal\ irrigation\ demand\ (m^3)} * 100 \quad 3.12$$

Relative water supply (RWS): The RWS is the ratio of the total seasonal water supply (irrigation plus rainfall) to the seasonal crop water demand. This parameter indicates that the total water supply is under or over the crop demand for a specific time period:

$$RWS = \frac{Total\ water\ supply\ (m^3)}{Crop\ water\ demand(m^3)} * 100 \quad 3.13$$

Physical sustainability indicators*:* Under this category, *irrigation ratio (IR*) was considered. *IR* refers to the proportion of currently irrigated area to the total design command area.

$$IR = \frac{Irrigated\ area\ (ha)}{Commnand\ area\ (ha)} \quad 3.14$$

3.3 Result and Discussion

3.3.1 Crop water requirement and irrigation practices in the study area

Irrigation agriculture has been practiced in the study area for several years. Crops such as onion, tomato, potato, and other vegetables are grown extensively. In addition, recently, wheat has become a popular cultivated crop that uses irrigation. The ETc of the major crops in the study area are presented in Table 3.1. The crop water demand can be met by rainfall and irrigation. In this study, the crop water demand was fully supplied by irrigation in the dry season of 2021/22 since there was no rainfall in the study area. In this season, the crop water demand was equal to the irrigation demand (Table 3.1). However, in the dry season of 2022/23, partial crop water demand was supplied by rainfall. During this season, the irrigation demand was less than the crop water demand.

Table 3.1: Crop and irrigation water demand of major crops in the study area

Crop type	Irrigation scheme	Cropping year	Crop water demand (mm)	Applied water (mm)				Effective rain	Irrigation demand (mm)
				ini	dev	mid	late		
Wheat	Furfuro	2022/23	384	66	111	132	65	10	374
Onion	Furfuro	2022/23	390	74	120	136	44	15	375
Tomato	Furfuro	2022/23	412	76	131	139	51	15	397
Total	Furfuro	2022/23	1186						1146
Wheat	Bedene	2021/22	397	72	110	117	25	0	397
Onion	Bedene	2021/22	402	74	110	116	28	0	402
Potato	Bedene	2021/22	449	79	121	134	32	0	449
Total	Bedene	2021/22	1249						1249

Note: In Bedene, the applied amount was less than the demand due to water shortage

Ini = initial, dev= development (crop growth stages)

3.3.2 Internal Performance Indicators

3.3.2.1 Conveyance efficiency

The conveyance efficiency of the two irrigation schemes was calculated using the data collected during the 2021/22 and 2022/23 irrigation seasons. The average conveyance efficiencies of Furfuro and Bedene were 84% and 79%, respectively. The conveyance efficiency of the Bedene scheme slightly increased due to the repair of the lined canals at several points after first-year data were recorded for this study (Table 3.2). The minimum recommended conveyance efficiency for a lined canal is 95% (Akkuzu et al. 2007). Based on this recommendation, the conveyance efficiencies of the two schemes were below the standard. Poor operation and maintenance practices and inadequate canal protection are the causes of low conveyance efficiency in the two schemes. In the study area, unprotected grazing and poor soil and water management practices have been widely observed, which have caused canal damage and low conveyance efficiencies. During the field visits, overtopping, water loss through broken canals, and high sediment accumulation were observed in both schemes. Canals at the head of the Bedene and in the middle of the Furfuro seriously cracked, and water loss at these locations was substantial. A lack of timely maintenance and regular cleaning of the canal led to the loss of significant water, particularly at Bedene. In addition, the conveyance efficiency of the Furfuro scheme was affected by extended water diversion at the head reach. This situation causes unfairness in the water distribution and affects crops grown in the tail of the scheme. The conveyance efficiencies found in this study are greater than those reported by Teshome et al. (2018) and Van Halsema et al. (2011) for adjacent watersheds in the Ethiopian Rift Valley but lower than those reported by Ahmed (2017), Alebachew & Ing (2018), and Belay et al. (2022) for different regions of Ethiopia.

The discharges of the schemes at the diversion sites were measured during the dry season. In the Bedene scheme, there was high discharge at the beginning of the dry season (November), and discharge was lower in later months. The quantity of discharge also decreased in 2022/23 compared with 2021/22. This was due to increased competition for irrigation water since several other irrigation schemes abstract water from the Bilate River, especially upstream of the river. On the other hand, the discharge to the Furfuro scheme command area was constant over the two study seasons (Table 3.2).

Table 3.2: Monthly average discharge at the diversion site

Month	Furfuro discharge (m^3/s)		Bedene discharge (m^3/s)	
	2021/22	2022/23	2021/22	2022/23
Nov	0.23	0.23	0.33	0.23
Dec	0.23	0.23	0.30	0.11
Jan	0.23	0.23	0.23	0.05
Feb	0.23	0.23	0.15	0.00
Mar	0.23	0.23	0.11	0.00
Conveyance efficiency	84%	84%	66%	79%

3.3.2.2 Irrigation application efficiency

Irrigation application efficiencies were determined at various reaches of the schemes. The irrigation application efficiencies of the Furfuro scheme were 68% (head), 52% (middle), and 56% (tail), with an average value of 59%; similarly, the application efficiencies of the Bedene scheme were 59% (head), 67% (middle), and 63% (tail), with an average value of 63%.

Differences in application efficiencies within a scheme at different locations were observed. Variations in application efficiency within a scheme show that on-farm irrigation water management practices are not directed by a scheme-level water management system but instead depend on the experiences of individual farmers (Van Halsema et al. 2011). According to Savva and Frenken (2001), a 50% to 70% application efficiency is a distinctive result for effectively designed surface irrigation. On the other hand, Smith et al. (2005) suggested that an average application efficiency of 60–70% for furrow irrigation is good. Thus, the average values of the irrigation application efficiencies for the two irrigation schemes fell within the recommended values.

However, attention should be given to extended periods of water application in the field, particularly at the head of the schemes, to enhance the application efficiency. On several farmers' fields, the irrigation depth did not follow the crop water demand, particularly at the head of the Furfuro. The application of irrigation water based on crop water requirements is important for improving irrigation efficiency (Evans and Sadler 2008; Mahmoud and El-Bably 2019). Due to a lack of scheme-level irrigation schedules, farmers irrigate their crops for extended periods of time during the periods when water is available in both schemes. Irrigation water control in the study area was performed manually, depending on the irrigator's skill. Continuous water application may result in high runoff, whereas low application rates usually cause slow water advancement, poor water distribution, and significant drainage losses (Jha et al. 2016). High runoff and deep percolation losses significantly reduce the application efficiency. Excessive loss during water application can be reduced by minimizing the amount of water per irrigation and increasing the irrigation frequency. The proper use of available irrigation water ensures the improvement of irrigation water allocation and resolves irrigation water disputes between farmers (Teshome et al. 2018).

3.3.2.3 Irrigation application uniformity

Christiansen uniformity coefficient indicates the level of uniformity of water infiltration into the soil. It is an important indicator of how well irrigation water is delivered to all points of the field. The CU of the Furfuro scheme were 55% (head), 49% (middle), and 47% (tail), with an average value of 50%, while the CU of the Bedene scheme were 50% (head), 54% (middle) and 60% (tail), with an average value of 55%. According to Hansen (1960), application uniformity below 70% is poor, that from 70% to 90% is considered good, and that above 90% is considered excellent. Based on this recommendation, the irrigation application uniformity of the two schemes was found to be poor. Knowledge of soil properties and an appropriate cut-off time during the water supply are needed to improve the uniformity of the water distribution. A low water distribution uniformity in surface irrigation systems will result in drainage losses, possibly leading to extremely inefficient water use (FAO 1989).

The overall efficiencies of Furfuro and Bedene were 49.6% and 49.8%, respectively. According to Hansen (1960), FAO (1989), and Halcrow (1992), the minimum overall efficiency of an irrigation scheme is expected to reach 60%. Therefore, the irrigation schemes in the current study were underperforming.

3.3.3 External Performance Indicators

3.3.3.1 Agricultural Performance Indicators

The ultimate goal of effective irrigation scheme management is to enhance agricultural output through the sustainable use of land and water. The performance of irrigation schemes can be demonstrated by the extent of outputs per hectare of land and cubic meters of water used. Yield production, production value, and irrigation data from the irrigation seasons of 2022/23 and 2021/22 for Furfuro and Bedene, respectively, were used to determine agricultural performance indicators in this study. In Furfuro, a weighted mean of 4.8 tons/ha yield was obtained from all irrigated crops from the total irrigated area of 143.5 ha, while in Bedene, a weighted mean of 2.95 tons/ha yield was attained from all crops from a total cropped area of 54.925 ha. The yield per command area of the two schemes was less than the yield per irrigated area, implying that the irrigation intensity in the two schemes was less than one. The OCA and OIA for Furfuro were 1396 and 1945 $/ha, respectively, and for Bedene, they were 299 and 1090 $/ha, respectively (Table 3.3). These parameters provide information on the land productivity level in the irrigation schemes.

The OIA was greater than the OCA in the two schemes because the irrigated area was less than the command area. This was due to a shortage and improper management of irrigation water to put all command areas under irrigation. This indicates how water-related issues are affecting land productivity. The variation is substantial in the case of Bedene. Due to a reduction in flow potential and high competition for water upstream of the Bilate River, the Bedene scheme faced a serious water shortage during the maximum irrigation-demanding time for crops, which caused crop failure and a reduction in yield. A lack of comprehensive scheme-level water distribution plans was another issue in both schemes. Comparable results have been noted in the northern parts of Ethiopia (Ayele et al., 2021; Belay et al., 2022). The yield per irrigated area provides information about the irrigation management practices at each irrigation scheme. Overirrigation or underirrigation directly affects the production amount, which indirectly affects the revenue per irrigated area. However, since there are other factors affecting land productivity, these parameters do not necessarily imply irrigation water management conditions (Dejen et al. 2012). The yield obtained also reflects how other agronomic practices were carried out at the scheme level. In addition, the output and consequently the productivity of the land are significantly influenced by crop variety, soil type and fertility, land suitability, and agricultural inputs (Molden et al. 1998).

Table 3.3: Yield and output per command and irrigated area

Irr. scheme	Furfuro (2022/23)	Bedene (2021/22)
Command area (ha)	200	200
Irrigated area (ha)	143.5	54.9
Average yield (tons/ha)	4.8	2.95
Production value ($)	279182	59876
OCA ($/ha)	1396	299
OIA($/ha)	1945	1090

The other agricultural performance indicators analysed in this study were the output/revenue per cubic meter of irrigation supply and consumed water. The irrigation supplies to the command areas in the dry season were 1988582 m^3 and 558472 m^3 for Furfuro and Bedene, respectively. The weighted mean yields attained from all crops in light of the irrigation supply were 0.35 kg/m^3 and 0.29 kg/m^3 at Furfuro and Bedene, respectively. The OIS and OCW for Furfuro were 0.14 and 0.16 $\$/m^3$, respectively, and they were 0.11 $\$/m^3$ for Bedene (Table 3.4). These values indicate the amount of revenue obtained per cubic meter of irrigation water diverted to the command area and per cubic meter of water consumed by crops. The figures also provide information on the scheme-level water productivity. The metrics also demonstrate how water management is effectively carried out in light of economic considerations while also accurately accounting for the water used by each scheme (Ayele et al. 2021).

Comparisons of OIS and OCW indicated that the OCW was greater in the Furfuro scheme, implying that excess water was supplied to the command area. In Furfuro, even without considering rainfall, the irrigation water supplied to the command area alone was greater than the total crop water demand in the study season. This resulted in less OIS than OCW. On the other hand, in the Bedene, the amount of irrigation supplied was less than the demand. Therefore, the supplied and consumed amounts were equal, resulting in equal amounts of OIS and OCW. The revenue obtained per irrigation supply and water consumed in this study is lower than that reported by other researchers in Ethiopia (Ayele et al., 2021; Belay et al., 2022; Dejen et al., 2012). Crop disease outbreaks were another factor, particularly in wheat during the flowering periods, which significantly reduced the yield in both schemes. Therefore, effective on-farm and scheme-level agronomic, irrigation water management, and crop disease control practices should be applied to improve crop yield and outputs per area and water used. Water loss through seepage, overtopping, and runoff can increase the amount of water lost and decrease productivity. The timely maintenance of deteriorated canals, sustainable and inclusive irrigation scheduling, and the application of irrigation water based on crop water demand can improve outputs per cubic meter of supplied and irrigated water.

Table 3.4: Yield and output per irrigation supply and water consumed

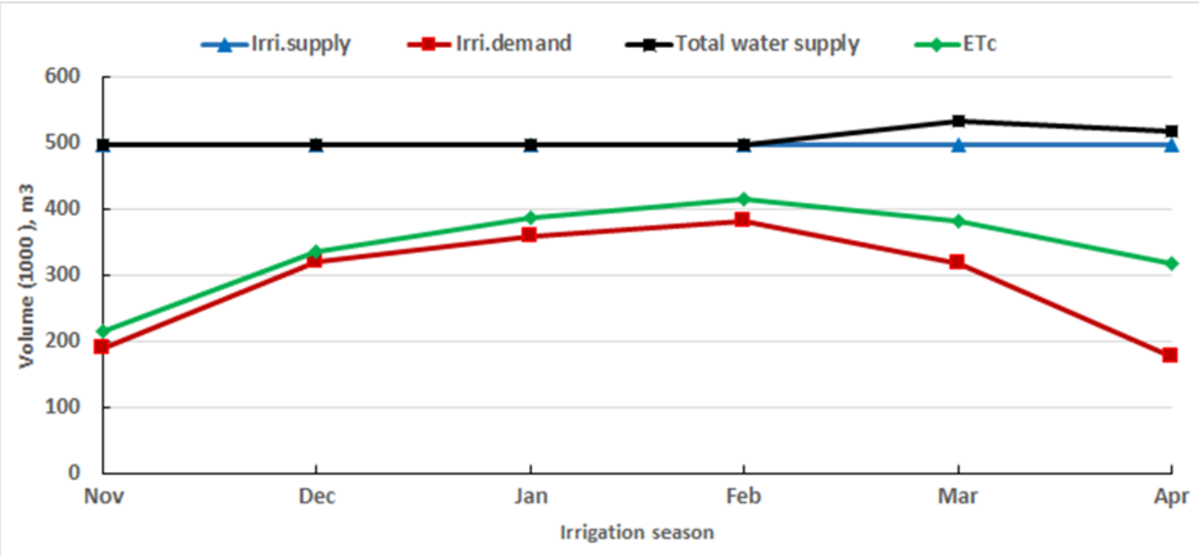
Irr. scheme	Furfuro (2022/23)	Bedene (2021/22)
Irrigation volume(m^3)	1988582	558472
Consumed volume(m^3)	1701881	558472
Average yield (kg/m^3)	0.35	0.29
Production value ($)	279182	59876
OIS ($/$m^3$)	0.14	0.11
OCW ($/$m^3$)	0.16	0.11

3.3.3.2 Water Use Performance Indicators

The values of the water performance indicators in this study showed that both the RIS and RWS for the Furfuro scheme were greater than one (Table 3.5). This implies that disregarding the uniform distribution of water in the scheme, the command area had excess water during the study period. According to the results, 21% of the irrigation water supply and 20% of the total water supply exceeded the demand in the study season. Monthly values of total water/irrigation supply/demand were also calculated for the two schemes. The monthly total water and irrigation demands for the main irrigated crops were calculated based on climatic data using the CROPWAT 8 computer model. Monthly irrigation demands were calculated as the difference between monthly total water demand and effective rainfall. The monthly demand and supply analysis for furfuro indicated that at all months, the supply exceeded the demand in the study season (Figure 3.5).

Although there was excess water in the command area, crops grown at the tail of the scheme experienced a serious water shortage during the peak irrigation demand stage (Figure 3.6). The main reason for this situation was the lack of scheme-level water allocation plans for farmers.

Particularly at the head of the scheme, there was extended time for water diversion to the fields, and the farmers themselves decided the amount of irrigation water they used. The other reason was that despite the Water User Associations' Proclamation declaring fee collection for irrigation water used (FDRE 2014), there was no fee collection in the scheme. Water fee implementation in irrigation schemes is a useful intervention that can encourage water savings and reduce the possibility of waterlogging and salinity problems caused by excessive irrigation (Dejen et al. 2012). In addition, during interviews with farmers at the tail end of the scheme, they complained about the irrigation water allocation systems. Similar results have been observed for SSI schemes in Ethiopia (Dejen et al. 2012; Shiberu et al. 2019; Ayele et al. 2021). This situation can affect the total scheme feasibility and lower water use efficiency. Strengthening local water institutions, such as irrigation water user associations, is beneficial for managing water distribution and reducing water loss.



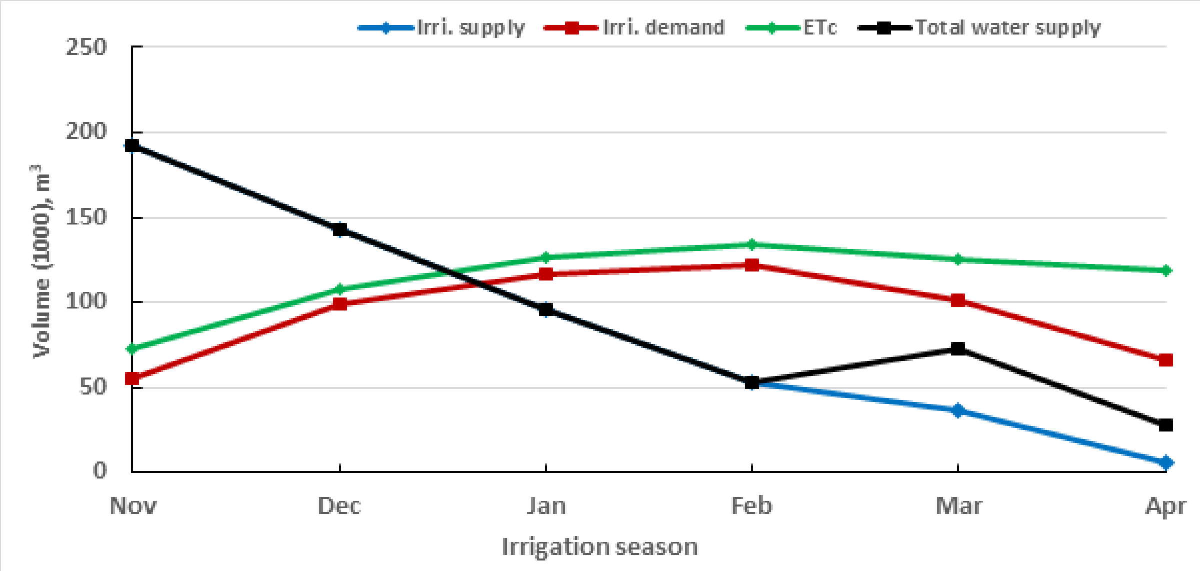
Fugure 3.5: Average monthly total water/irrigation supply/demand for Furfuro scheme for the year 2021/22 and 2022/23

Figure 3.6: Irrigation water use at Furfuro scheme

For Bedene, the seasonal RIS and RWS were less than one (Table 3.5), which showed that the supply amount was less than the demand. Similar findings have been noted in the adjacent watershed within the Rift Valley (Tesfaye et al. 2019). The monthly demand and supply analysis for Bedene indicated that for the first two dry months (November and December), the supply exceeded the demand, while in later months (after January), the supply couldn't meet the water demand of the irrigated crops (Figure 3.7). Therefore, in this scheme, water storage from excess months might be beneficial to meet crop water demand in water deficit months. The shortage of irrigation supply to the Bedene scheme is due to two important external factors. First, the potential of the Bilate River, which is a source of water for the Bedene scheme, has been declining due to climate change and a decrease in annual rainfall (Orke and Li 2021). Second, the Bilate River is the source of water for several other irrigation schemes upstream of the river. The need for irrigation water upstream is growing, which increases the demand for water. Therefore, discussions between zonal irrigation departments were required to develop inclusive irrigation schedules to ensure a fair water distribution between all irrigation schemes.

Table 3.5: Water use performance indicators

Scheme	Total water supply (m^3)	Crop water demand (m^3)	Irrigation supply (m^3)	Irrigation demand (m^3)	RIS	RWS	IR (%)
Furfuro	2045982	1701881	1988582	1644481	1.21	1.20	72
Bedene	558472	685848	558472	685848	0.81	0.81	27



Fugure 3.7: Average monthly total water/irrigation supply/demand for Bedene scheme for the year 2021/22 and 2022/23

3.3.3.3 The Physical Sustainability Indicators

The physical sustainability indicator considered in this study was the irrigation ratio, which measures how much of the command area was used for irrigation. It may also be a useful tool for determining whether any factors are causing the command area to be underirrigated (Dejen et al. 2012). The irrigation ratios for Furfuro and Bedene were 72% and 27%, respectively (Table 3.5). Several factors can affect the irrigation ratio in the study area. The irrigation ratio of the Bedene scheme is too low compared with Furfuro. Internal management factors such as poor maintenance and unpredictable water allocation plans are largely attributed to low irrigation ratios. Due to a reduction in the amount and duration of rainfall, the annual flow capacity of the Bilate River has been significantly reduced, particularly at later crop growth stages (February and March). Another factor is the absence of serious discussions between upstream and downstream stakeholders of the Bilate river to plan a basin level water allocation. The unreliability of irrigation water, the high cost of agricultural inputs, and the low selling prices of the products discourage farmers from pursuing irrigation agriculture in the study area. Effective irrigation water management and strong market value chain system development can be useful for boosting farmers' benefits from irrigated agriculture.

3.4 Conclusion

In this study, the on-farm performances of the Furfuro and Bedene irrigation schemes in the Ethiopian Rift Valley were assessed using internal and external performance indicator parameters. The findings showed that the conveyance efficiency and application uniformity of the two irrigation schemes were below the recommended values. The overall efficiencies were 49% for both schemes, which are below the minimum permissible values. This result implies that there is significant water loss in the schemes, which affects the yield production and expected revenues from the schemes. Inadequate canal protection, poor operation and maintenance habits, and a shortage of awareness of on-farm irrigation water management skills were the causes of the low efficiencies of the schemes. Therefore, timely canal maintenance, on-farm training, and experience sharing in irrigation water management practices can be useful for solving these problems. The OIA was greater than the OCA in the two schemes because the irrigated area was less than the command area. The difference was significant for Bedene. In Bedene, due to shortages and mismanagement, and in Furfuro, due to mismanagement of water, the OCA and OIS were negatively affected. In addition, crop disease significantly affected the yield and output per area of land and cubic meters of water used in the study area. On the other hand, the RIS and RWS of the Furfuro demonstrated that despite some parts of the scheme experiencing water shortages, the command area had a surplus water supply. This showed that the water distribution and irrigation scheduling systems need improvement. The RIS and RWS of the Bedene scheme indicate that the supply was below demand. A low river flow potential and an increasing need for irrigation water upstream of the river were important factors contributing to water stress in the scheme.

CHAPTER IV: Optimization of Irrigation Scheduling for Improved Irrigation Water Management in Bilate Watershed, Rift Valley, Ethiopia

This chapter concentrates on the optimization of irrigation scheduling for saving water and enhancing irrigation water use. Approach was developed in order to enhance irrigation water management in the study area, in light of the findings in Chapters Two and Three. Climatic, crop, soil, and water data were used to optimize the available water resources for improved irrigation water management. Irrigation scheduling was optimized for potato and wheat in the Bilate watershed, which is part of the Ethiopian Rift Valley, based on the SWAT model simulated crop yield and evapotranspiration and Jensen crop water production function. Deficit irrigation treatments were used to develop the Jensen crop water production function for the two crops. Based on the developed Jensen moisture stress sensitivity index, the seasonal irrigation water applied at each deficit treatment was optimized and the yield produced and irrigation water saved were compared. This Chapter has been published in the journal Water(Switzerland) (MDPI publisher).

Based on:

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4.1 Introduction

Agriculture, which uses approximately 70% of the world's freshwater withdrawals for irrigation, is the largest consumer of water resources globally (Jeong and Zhang 2020).The influence of climate change and an increasing demand for water from different sectors affect water availability for agricultural production (Mushtaq and Moghaddasi 2011; Singh 2012; Mancosu et al. 2015). Moreover, the projected increase in the rate of world population growth highlights the impending rise in food demand, which will immediately affect farming water use (Mancosu et al. 2015).

Ethiopia is dominantly reliant on agriculture for sources of food and employment. The sector plays an important role, especially for smallholder farmers, who produce 95% of the total agricultural production in the country (FAO 2012). Agriculture is a cornerstone of the community in the Ethiopian Rift Valley Lakes Basin (RVLB), as a source of food and income generation. However, the production in the basin has been impacted by climate change and frequent droughts (Girma and Awulachew 2007; Kassie et al. 2014). The Bilate watershed, which is situated in RVLB, is vulnerable to climate change, and the availability of water resources in the watershed has been deteriorating (Girma and Awulachew 2007). Due to climate change, the watershed has experienced a significant drop in rainfall amount and a rise in temperature over the last three decades. Consequently, the stream flow of the Bilate River, which is a source of water for several large, medium, and small-scale irrigation schemes, has been declining (Orke and Li 2021). Therefore, in order to cope with the scarcity of irrigation-water sources in those areas, it will be important to practice efficient irrigation water management techniques such as irrigation-scheduling optimization (Akhtar et al. 2013; Li et al. 2018; Gu et al. 2020; Li et al. 2020).

Agro-hydrological simulation models are capable of illuminating the dynamics of crop growth under different irrigation schedules and climatic conditions. These simulation models can be used to conduct scenario analysis in order to look for the most effective management approaches (Li et al. 2020). For example, Geerts et al. (2010) applied the Aquacrop simulation model to identify the optimal time interval for irrigation-water application, to evade drought stress and attain maximum water-productivity. Li et al. (2020) used a soil-water-balance simulation model to study optimal irrigation scheduling for maize in an arid region of northern China. The Soil and Water Assessment Tool (SWAT) model is a semi-distributed and physically based simulation model, and it is popular in the simulation of basin-level hydrological processes (Arnold et al. 2012). It is used to model basin-level hydrology, crop growth, the scheduling of agricultural operations, and climate-change scenarios (Neitsch et al. 2011). SWAT can simulate the effects of various irrigation-water management approaches on crop growth, yield, and hydrological processes. Fu et al. (2019) applied the SWAT model to determine optimal irrigation scheduling for corn and soybeans in dryland regions. Sun and Ren (2014) used the SWAT model to assess crop yield, and crop-water productivity, and to look at an irrigation scheduling approach that is optimal for the production of winter wheat and summer maize.

The simulation models can describe the impacts of irrigation scheduling on yield and crop growth, but they can only answer the question "What if?" (Singh 2014). This indicates that more effective irrigation scheduling depends on scenario analysis of a number of user-decision-based alternatives. In this situation, determining the most effective scheduling approach is dependent on assessments of simulated yield or water productivity. The chosen irrigation schedule, although possibly the best among the options, is probably not the exact optimal global irrigation schedule (Shang and Mao 2006). The optimum global irrigation schedule can be attained by combining the simulation- and optimization models (Singh and Panda 2013; Jamshidpey and Shourian 2021).

Optimization of irrigation scheduling is an important approach for saving irrigation water, improving the productivity of water, and enhancing the benefits to farmers (Sun and Ren 2014; Li et al. 2018; Padhiary et al. 2020). Irrigation-scheduling optimization is very helpful to achieve a fair distribution of irrigation water among users at the basin level, and it can also improve water-use efficiency. During the application of optimization methods, the irrigation system is defined by creating a sequence of mathematical equations, and the optimal solutions can be determined using optimization solution technologies (Singh 2012). Information on the yield response of crops to water conditions has been required in order to apply scheduling optimization (Li et al. 2018). The crop-water production function describes the association between the crop water used and the yield produced. These associations are complex since they must involve the impacts of crop moisture stress at different growth stages (Rao et al. 1988).

The genetic algorithm (GA), which has been introduced since the 1970s (Holland 1975), is an extensively used algorithm to optimize irrigation scheduling. It is a search algorithm that follows the procedure of natural genetics and selection, which combines the idea of survival of the fittest with genetic operators, to form a strong searching mechanism. GA solutions are based on parameter coding, searching from a population of points (strings) rather than a single point, and relying on objective function information rather than auxiliary knowledge (Golberg 1989). Selection, crossover, and mutation are the three important processes in GA that operate strings and advance to the next generation. GA is found to be useful in the application of irrigation-scheduling optimization, and it has been widely applied to solving simulation-optimization problems (Raju and Kumar 2004; Moghaddasi et al. 2010; Wen et al. 2017). Taking into account the thoughts above, the objective of this study is to develop a simulation-optimization model for potato-and wheat crop irrigation scheduling for saving irrigation water and maximizing yield. The model will integrate a SWAT crop growth simulation model and the irrigation-scheduling optimization model outlined to maximize crop yield.

4.2 Materials and Methods

4.2.1 Description of the study area

The Bilate watershed is known for its high population density in Ethiopia. Approximately 500 people live in a 1 km^2 area (Hussen et al. 2018). Geographically, the watershed is located between the latitudes of 6°38′18″ and 8°6′57″ N, and in the longitudes of 37°47′6″ and 38°20′14″ E (Figure 4.1). The watershed has a total area of 5518 km^2 , with a stream length of 197 km and an elevation range of 1176 m to 3328 m.a.s.l (Hussen et al. 2018). However, for this study, the watershed area was delineated as 5233 km^2. The initial drainage of the Bilate River starts from the Gurage highlands, passes through Siltie, Hadiya, and Kambata, and ends at Abaya Lake, which is one of the largest lakes in the RVLB. The climate in the Bilate watershed is humid and semi-arid, with bimodal rainfall-patterns (Negash 2014). The main rainy season is usually the summer monsoon, from June to August (Getahun et al. 2020). The meteorological data indicated that the mean annual-rainfall ranges from 560 mm in the rifts to 1300 mm in areas of the highlands. The average minimum and maximum temperatures are 16 and 30 degrees Celsius, respectively. The watershed is part of the western rift-margin, which is characterized by deep and wide valleys with several streams. (Megebo 2020). More than 82% of the land-use type is occupied by agricultural activities (Figure 4.2a). Nitosols, Cambisols, Vertisols and Leptosils are the major soil-groups in the watershed (Figure 4.2b).

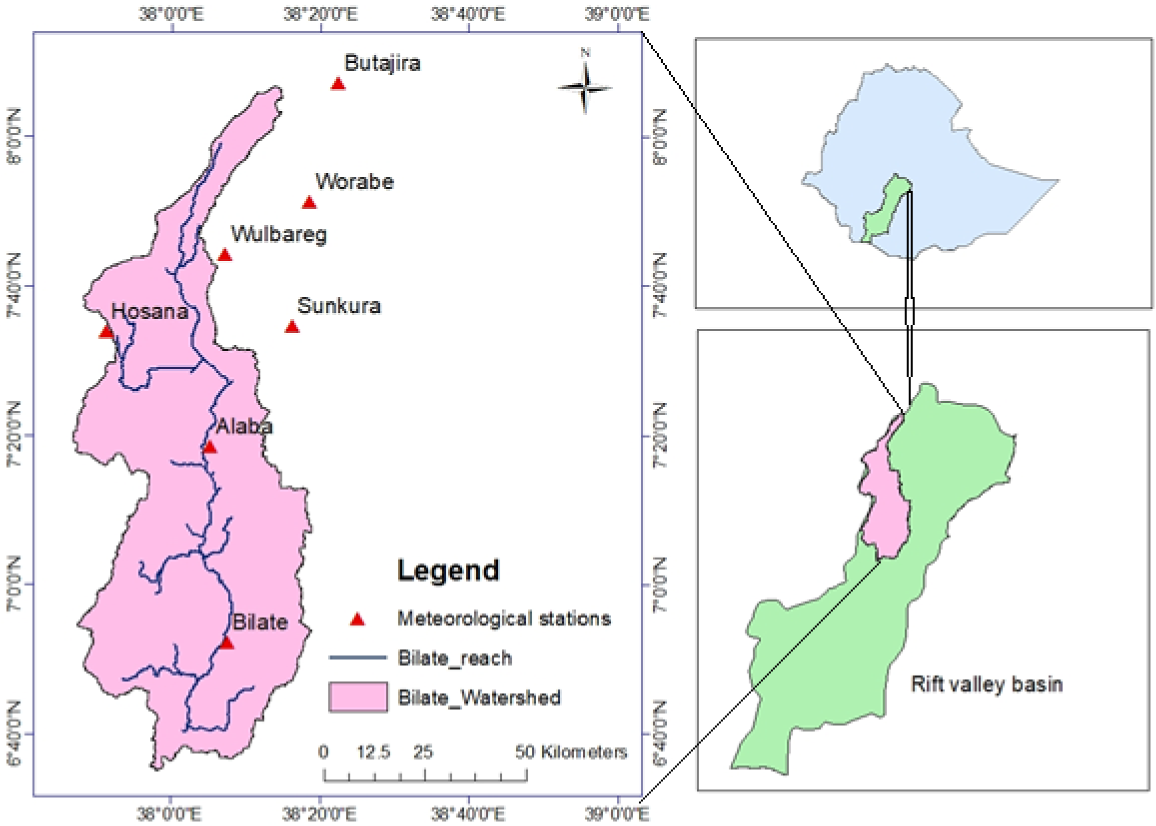

Figure 4.1: Location map of the study area

4.2.2 Available data

Temporal and spatial data were collected to establish a SWAT model in the watershed (Table 4.1). In addition, a field survey was conducted to compile information on the study area's more significant irrigation crops and current irrigation-production scenarios. The irrigation departments in the districts were communicated for additional crop-production data, seasonal crop yield, and other necessary details.

Table 4.1: Collected data

Data Type	Data Source	Resolution	
		Temporal	Spatial
Streamflow data	MoWE	Daily (1991–2008)	-
Climatic data	ENMSA	Daily (1991–2014)	-
Crop data	Zones	Annual (2001–2014)	-
Soil data	MoWE	-	30 m × 30 m
Land use and land cover	MoWE	-	30 m × 30 m
Digital Elevation Model (DEM)	USGS		30 m × 30 m

Note(s): MoWE: Ministry of Water and Energy; ENMSA: Ethiopian National Meteorological Service Agency; USGS: United States Geological Survey

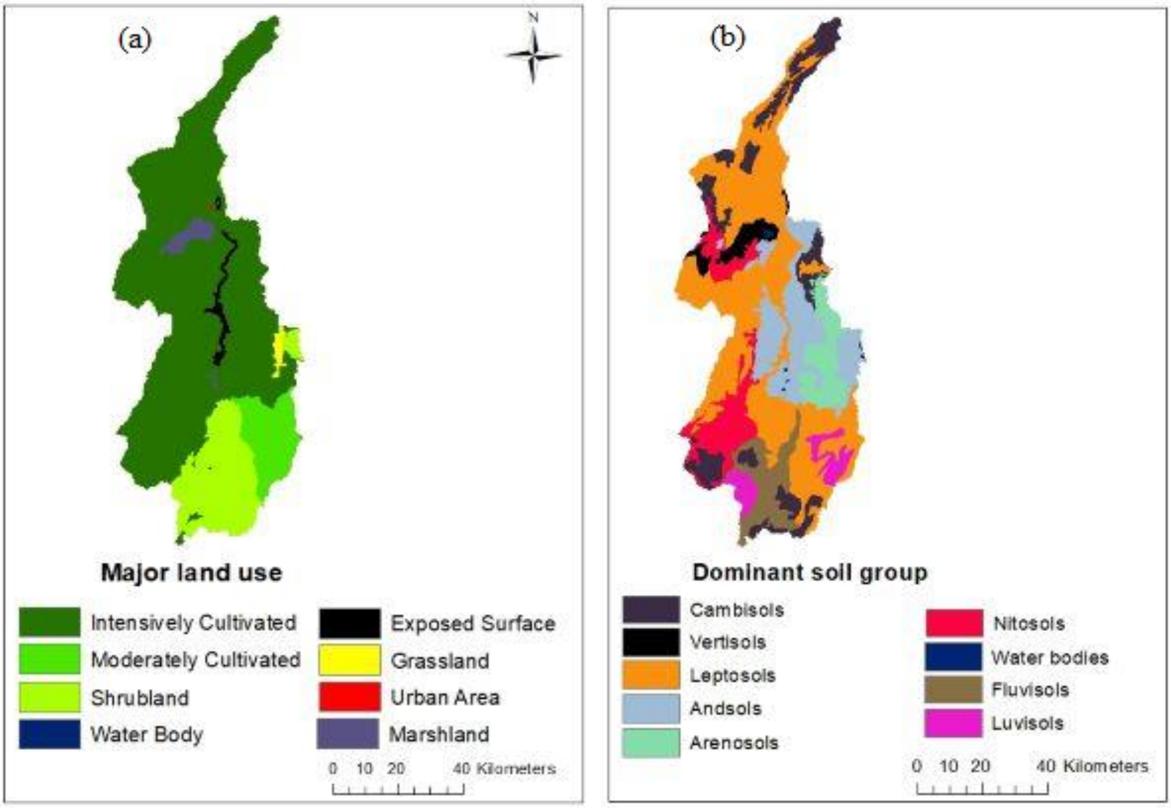

Figure 4.2: (a) Land use. (b) Dominant soil-group

4.2.3 SWAT model

SWAT is a time-continuous simulation model that can be applied to estimate how land management affects water, agricultural chemicals, and sediment, at the basin level. SWAT divides the basin into sub-basins, which are then further subdivided into pieces of units called hydrologic response units (HRU) (Arnold et al. 2012). An HRU describes a collection of similar land use and soil types, and it is the smallest unit in a basin. Water resources and agricultural management, and climate are the main components of the SWAT model. In this study, the SWAT model was built using a digital elevation model (DEM), climatic data, land use/land cover data, and soil data of the study area. The SCS curve number approach (USDA Soil Conservation Service) was applied to simulate the surface runoff. The Penman Monteith technique (Monteith 1965) was used to calculate the potential evapotranspiration (PET) and reference evapotranspiration (ETo). SWAT applies the simplified environmental policy integration calculator (EPIC) crop model (Williams et al. 1984) to calculate plant growth. The EPIC uses the above ground biomass and harvest index information to determine the crop yield on the day of harvest. The governing equation for the SWAT model is the water balance equation given by:

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \qquad 4.1$$

where, SW_t is the amount of soil water-content in mm at time t (day), SW_0 is the initial soil water-content on day 1 in mm, R_{day} is the daily rainfall on the i-th day in mm, Q_{surf} is surface discharge on the i-th day in mm, E_a is the actual evapotranspiration on the i-th day in mm, W_{seep} is the amount of water that enters the unsaturated zone on the i-th day in mm, and Q_{gw} is the amount of return flow on the i-th day,in mm.

Eighteen years of monthly stream flow and fourteen years of annual crop-yield data were used to calibrate stream flow and crop parameters, respectively. Stream-flow parameters were selected from various sources, and their ranges of parameters were fixed. The calibration process becomes more complex if the number of parameters for calibration is extensive due to the huge number of processes being taken into account (Saltelli et al. 2000). To reduce the complexity, the sensitive stream-flow parameters were identified based on one-at-a-time (OAT) and global sensitivity-analysis methods (Abbaspour 2007). Sensitivity analysis is the process of evaluating the impact of an input change on the output of a model (Arnold et al. 2012). The t-stat and *p*-values were used to select parameters for each simulation in the sensitivity analysis (Abbaspour et al. 2017). For stream-flow parameter-calibration, the program called Sequential Uncertainty Fitting-II (SUFI-2) was applied in the SWAT-CUP. SWAT-CUP provides numerous objective functions with their specified properties used for calibration. The validation process was carried out with independent observed stream-flow data on the same parameters and parameter ranges in order to be confident in the calibration. Crop parameters were calibrated manually using annual crop-yield data. Changes in crop-growth parameters and growth constraints such as nutrient stress and water stress were used to simulate actual crop-growth (Williams 1995). The crop growth parameters that have an influence on yield and ETc were identified by changing each parameter's value, one at a time. The calibration process was carried out for several iterations until the change in output value reached an insignificant level compared with observe values.

The model performance was evaluated based on statistical values including the coefficient of determination (R^2), the ratio of mean-squared-error to the standard deviation of the observed data (RSR), and the Nash–Sutcliffe coefficient (E_{NS}). The R^2 value describes the association between measure- and simulated-data, and its value is between 0 and 1. A value closer to 1 postulates the good model-performance, while a value of less than 0.6 reveals that the model has poorly performed. The value of the E_{NS} ranges from $-\infty$ to 1, and it enumerates how to fit the simulated output to the observed data. It shows how the magnitude of the measured data varies, compared with simulated data. The performance was evaluated based on recommendations given by (Moriasi et al. 2015):

$$R^2 = \frac{[\sum_{i=1}^{n}(Q_o - Q_{oavr})(Q_s - Q_{savr})]^2}{\sum_{i=1}^{n}(Q_o - Q_{oavr})^2 \sum_{i=1}^{n}(Q_s - Q_{savr})^2} \tag{4.2}$$

$$E_{NS} = 1 - \left[\frac{\sum_{i=1}^{n}(Q_O - Q_s)^2}{\sum_{i=1}^{n}(Q_o - Q_{savr}{}^2}\right] \tag{4.3}$$

$$RSR = \frac{\sqrt{\sum_{i=1}^{n}(Q_o - Q_s)^2}}{\sqrt{\sum_{i=1}^{n}(Q_o - Q_{oavr})^2}} \tag{4.4}$$

where n denotes the number of observed values, Q_o represents observed discharge-data (m^3/s), Q_s represents simulated discharge-data (m^3/s) and Q_{oavr} and Q_{savr} represent the average observed- and simulated-values (m^3/s), respectively.

4.2.4 Coupling Degree among ETc and Effective Rainfall in Irrigation Season

The coupling degree among crop water-requirement (ET_c) and effective rainfall (P_e) describes how much the effective rainfall satisfied the crop water-demand in the specific growth stages. Information on the extent of P_e to fulfill ET_c in the specific growth stage is beneficial to setting efficient irrigation-scheduling (Yang et al. 2013). ET_c depends on the crop coefficient (K_c) and reference evapotranspiration (ET_o) (Doorenboos and Pruitt 1977; Allen et al. 1998). In this study, ET_c was calculated as follows:

$$ET_c = K_c * ET_o \tag{4.5}$$

The value of K_c depends basically on the characteristics of each crop and its stage of growth and canopy dynamics. In this study area, K_c values for potato and wheat have not been determined yet. Therefore, to compute ET_c, the K_c values from FAO Irrigation and Drainage Paper No. 56 were used. ET_o is the evaporative capacity of the atmosphere, independently of crop type, crop growth-stage, and management conditions, and it is given by:

$$ET_o = \frac{0.408\Delta(R_n - G) + \Upsilon\frac{900}{T + 273}u_2(e_s - e_a)}{\Delta + \Upsilon(1 + 0.34u_2)} \qquad 4.4$$

where R_n is net radiation at the crop surface [MJ m^{-2} day^{-1}], G is soil-heat-flux density [MJ m^{-2} day^{-1}], T is mean daily air-temperature at 2 m height [°C], u_2 is wind speed at 2 m height [m s^{-1}], e_s is saturation vapor-pressure [kPa], e_a is actual vapor-pressure [kPa], e_s-e_a is saturation vapor-pressure deficit [kPa], Δ is slope of the vapor-pressure curve [kPa $°C^{-1}$], and γ is psychrometric constant [kPa $°C^{-1}$]

P_e is the portion of the rainfall that is actually stored in the soil. It is the difference between total rainfall and actual evapotranspiration. The climatic variables can be used to directly calculate P_e. There are several methods to calculate P_e. In this study, the USDA Soil Conservation Service method was applied:

$$P_e = \begin{cases} \frac{P(125 - 0.2 * P)}{125}, & P \leq 250 \text{ mm} \\ 125 + 0.1 * P, & P > \quad 250 \text{ mm} \end{cases} \qquad 4.5$$

where, P is total rainfall.

The value of the coupling degree is between 0 and 1, and it is computed as:

$$L_i = \begin{cases} 0 & Pe_i = 0 \\ \frac{Pe_i}{ETc_i} & Pe_i < ETc_i \\ 1 & Pe_i \geq ETc_i \end{cases} \qquad 4.6$$

where, L_i is the coupling degree between ET_c and P_e at growth stage i.

4.2.5 Deficit irrigation scheduling

One of the water resource management options modeled by SWAT is irrigation operation. The main purpose of irrigation operation is to evaluate the effect of irrigation scheduling on irrigation systems, crop growth, and yield. Irrigation in an HRU can be scheduled by the user (pre-defined schedule) or automatically by SWAT in response to a water deficit in the soil (Neitsch et al. 2011). In this study, irrigation-scheduling scenarios were set on the SWAT model using predefined scheduling operations. The timing and depth of the applied water were filled in by the management module. SWAT enables the scheduling of management operations by day or by the fraction of potential heat units. The model examines whether a month and day have been specified for the timing of each operation before proceeding to simulation. In this study, the irrigation scheduling in the management operation was carried out using a schedule by day. Eight irrigation treatments (one full irrigation and seven deficit irrigation treatments) were used to simulate potato and wheat yield and evapotranspiration. The deficit amount was defined based on the calculated ETc at specific growth-stages. The irrigation depth based on the ratio or percentage in Table 4.2 was filled out in the SWAT model at specific growth stages. The accumulated potential heat unit resets to zero at each calendar year. Therefore, to keep going with the calendar year heat unit, the planting date was set to January 1st. Generally, four operations were scheduled: planting time, fertilization time, irrigation depth and time, and kill/harvest time. During simulation, irrigation efficiency (IRR_EFM) and surface runoff (IRR_SQ) were considered as 70% and 10%, respectively. An auto fertilizer operation was chosen to replenish the soil nutrients.

Table 4.2: Irrigation-scheduling treatments

	Growth-Stage-Based Deficit Irrigation (% of ET_c)							
	Growth-Stage Irrigation Depth for Potato (%)				Growth-Stage Irrigation Depth for Wheat (%)			
TRT	Seedling	Vege.t	Starch a.	Maturity	Seedling	Vege.t	Grain fill.	Maturity
CK	100	100	100	100	100	100	100	100
T1	25	100	100	100	25	100	100	100
T2	100	25	100	100	100	25	100	100
T3	100	100	25	100	100	100	25	100
T4	100	100	100	25	100	100	100	25
T5	25	25	25	25	25	25	25	25
T6	50	50	50	50	50	50	50	50
T7	75	75	75	75	75	75	75	75

Note(s): TRT: Treatment; CK: Full-irrigation treatment; Vege.t: Vegetative; Grain fill.: Grain filling; Starch a: starch accumulation

4.2.6 Crop water production function

The association between applied irrigation water during specific seasons and crop yield is described by the crop water production function. An alternative definition of the production function that specifies seasonal evapotranspiration as the independent variable rather than applied irrigation water has been put forth by some agronomic studies (Doorenbos, J., Kassam 1979; Igbadun et al. 2007; Geerts and Raes 2009). There are two principles of crop water production function (Tsakiris 1982). The first one is the “Boule principle,” which expresses the multiplicative effect of moisture deficiency on yield, which occurs during different growth stages (Jensen 1968; Minhas et al. 1974). The other one is the “arithmetic principle,” which defines the additive effect of the water deficiency on yield, which occurs at the different growth-stages (Steward and Hagan 1973; Bras and Cordova 1981). Earlier studies on different crops indicated that the prediction ability of the Jensen model was better than other models (Igbadun et al. 2007; Li et al. 2022). Thus, in this study, we applied the Jensen model to compute the crop water production functions of potato and wheat in the study area. The model is given by:

$$\frac{Y_a}{Y_m} = \prod_{i=1}^{n} \left(\frac{ET_a}{ET_m}\right)_i^{\lambda_i} \quad 4.7$$

where Y_a and Y_m are actual and maximum yield from the deficit and full irrigation treatments, respectively, (kg/hm^2), ET_a and ET_m are the actual and maximum evapotranspiration from the deficit- and full-irrigation treatments respectively, (mm), i represents growth stages, n represents number of growth-stages and λ is the Jensen's moisture-sensitivity index

After simulation of yield and evapotranspiration in the SWAT model, the Jensen moisture stress sensitivity index (λ) was calculated for both crops using the Python/Jupyter notebook packages based on a multiple nonlinear-regression analysis.

4.2.7 Irrigation-scheduling Optimization Model

Optimization of irrigation scheduling between irrigation cycles for maximum yield was modeled using the computed crop water production function. The seasonal relative evapotranspiration of the deficit irrigation treatments and the number of days in each irrigation interval were used for the maximization model. During a field survey, irrigation interval days and duration of irrigation time data were collected from sample irrigation schemes in the study area. The calculated moisture stress sensitivity index was transformed into corresponding irrigation interval days using the cumulative curve of the sensitivity index. The optimal relative evapotranspiration for maximum relative yield was calculated by using the genetic algorism (GA) on the platform of MATLAB (R2020a, MathWorks Inc., Natick, MA, USA).
The irrigation-scheduling optimization model is:

$$\text{Max } Y_a = Y_m * \prod_{i=1}^{n} \left(\frac{ET_a}{ET_m}\right)_i^{\lambda_i} \quad 4.8$$

$$\text{Subject to: } \sum_{i=1}^{n} \frac{ET_{ai}}{ET_{mi}} * d - C * \sum_{i=1}^{n} d \quad 4.9$$

$$0 < \frac{ET_{ai}}{ET_{mi}} \leq 1$$

where i represents the irrigation interval considered, n represents number of irrigation cycle in the growing season, d is the number of days in one irrigation cycle, and C is the seasonal relative evapotranspiration of the deficit treatments.

4.3 General Framework of the Study

The general outline of the study is shown in Figure 4.3. First, a SWAT model was developed in the study area using DEM, climatic, soil, and land use data. Next, the SWAT model was calibrated and validated with stream flow and crop yield data. In the calibrated SWAT model, full and deficit irrigation treatments were scheduled to simulate potato and wheat yield and evapotranspiration. The Jensen moisture stress sensitivity index was then computed from simulated yield and evapotranspiration, and the Jensen crop water production function was developed for potato and wheat. The optimal irrigation scheduling was then solved using the developed crop water production function.

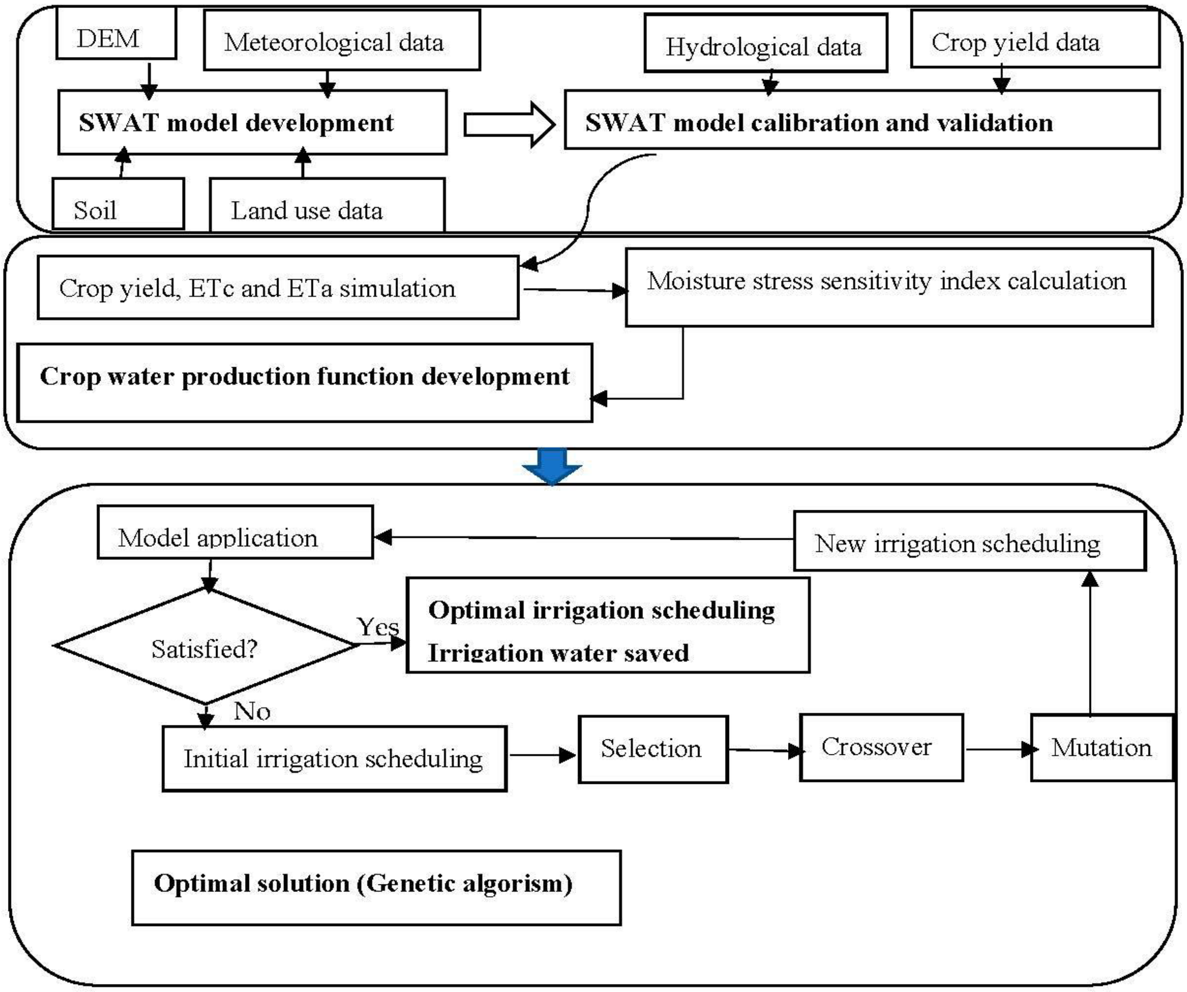

Figure 4.3: Diagrammatic representation of the study

4.4 Result

4.4.1 SWAT Model Performance

The SWAT model was calibrated and validated using 18 years (1991–2008) of monthly stream-flow data from the Bilate gauging station based on the data that was available. Of these, two years (1991–1992) of the data were allocated to model warm-up; ten years (1993–2002) of the data were used for calibration; and six years (2003–2008) of the data were adopted for validation. One-at-a-time (OAT) and global sensitivity-analysis methods were applied to identify the most sensitive parameters. The parameters with the smaller *p*-value and the absolute value of the larger t-stat value were nominated for further calibration and validation of the model. The most sensitive parameters were the curve number (CN2), groundwater-recession factor (ALPHA_BF), time taken for water to exit from beneath the root zone (GW_DELAY), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), soil-evaporation compensation factor (ESCO), available water capacity of the soil layer (SOIL_AWC), soil moist-bulk density (SOL_BD), Manning's n value for overland flow (OV_N), average slope-length of the watershed (SLSUBBSN), and deep-aquifer percolation fraction (RCHRG_DP). After simulation, the performance of the model was evaluated using performance indicators. According to the performance indicators, the agreement between measured- and simulated-stream-flow data was good. The timings of flow events (peaks and valleys) were also well estimated (Figure 4.4). The statistical values indicated that for the calibration period the values of R^2 and E_{NS} were 0.72, and the value of RSR was 0.53, while in the validation period the values of R^2, E_{NS}, and RSR were 0.72, 0.65, and 0.59, respectively. Based on Moriasi et al. (2015) criteria, the model showed good performance in the study area.

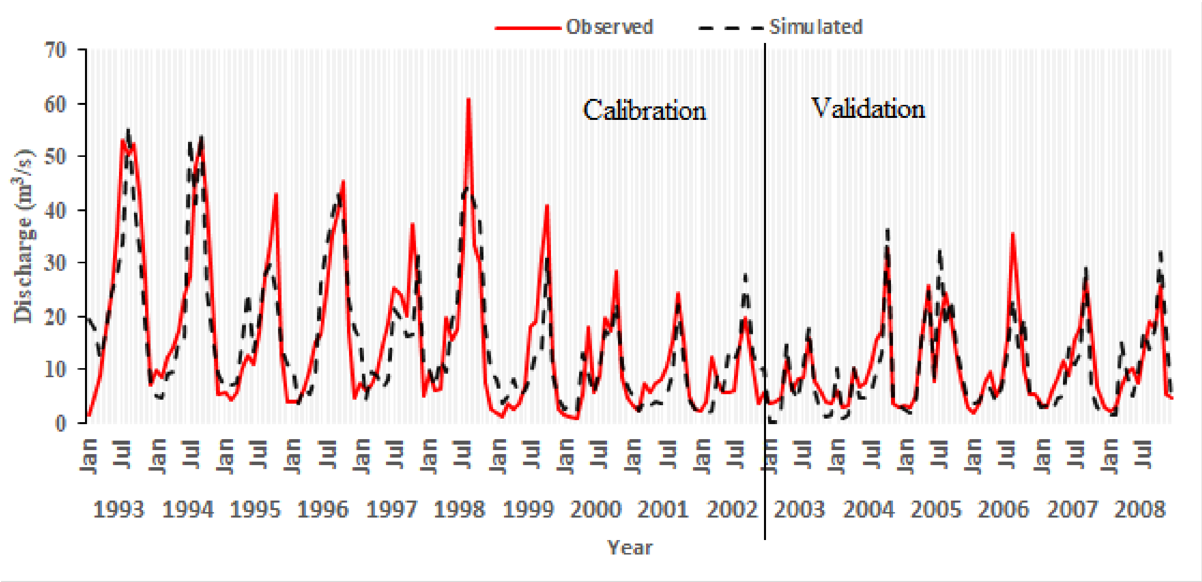

Figure 4.4: Monthly observed- and simulated-stream-flow for calibration and validation period

Crop parameters were also calibrated manually using annual average-yield data collected from different districts in the watershed. The fraction of leaf-area index, harvest index, and parameters related to growing season-length had more influence on yield and crop evapotranspiration during simulation. The identified crop parameters and their values before and after calibration are presented in Table 4.3.

Table 4.3: Adjusted crop parameters

Parameter	Parameter Description	Potato		Wheat	
		Before	After	Before	After
BLAI	Maximum leaf-area index	4	4.5	4.0	4.0
DLAI	Fraction of growing season when leaf area starts declining	0.6	0.6	0.8	0.8
LAIMX1	Fraction of BLAI at point 1	0.01	0.05	0.01	0.04
LAIMX2	Fraction of BLAI at point 2	0.95	0.90	0.95	0.84
FRGRW1	Fraction of the plant-growing season at point 1	0.10	0.15	0.15	0.10
FRGRW2	Fraction of the plant-growing season at point 2	0.5	0.45	0.5	0.45
HVSTI	Harvest index	0.95	0.90	0.4	0.35

4.4.2 The Relationship between P_e and ET_c in the Target Season

The coupling degree indicates how much the effective precipitation meets the crop water-demand in the growth stages. In this study area, the annual rainfall pattern has bimodal characteristics with a short rainy season (March–May) and the main rainy season (June–

September). Usually, irrigation agriculture is being practiced in the area from November to the start of the main rainy season. ET_o in this period is much greater than the rainfall (Figure 4.5). The coupling degree among P_e and ET_c indicated that P_e in this period could not fulfill the required amount of ET_c for potato and wheat throughout the growing season (Figure 4.6).

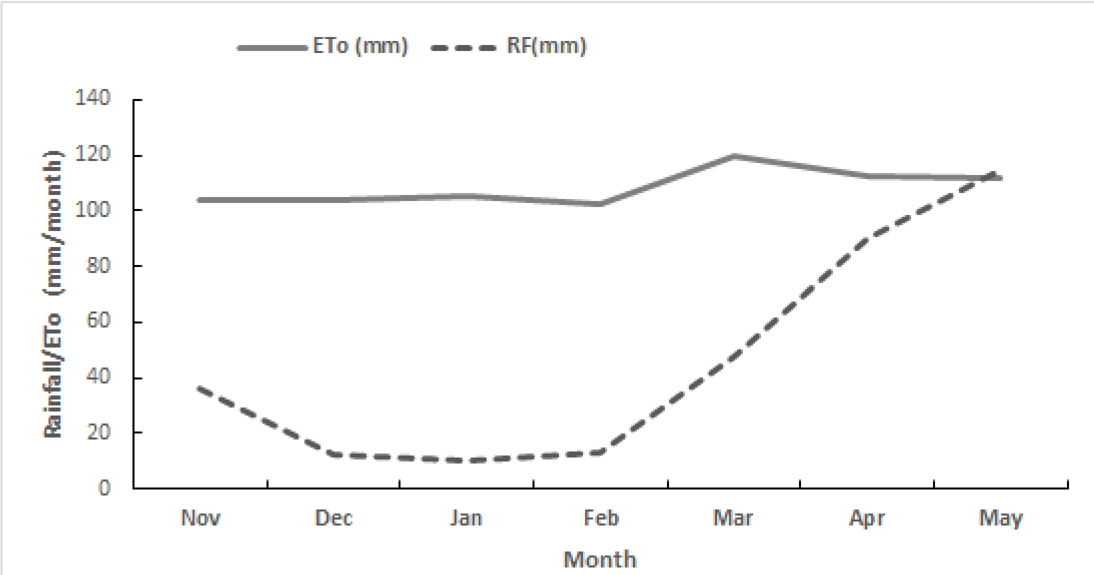

Figure 4.5: Mean monthly ET_o and rainfall in the irrigation season

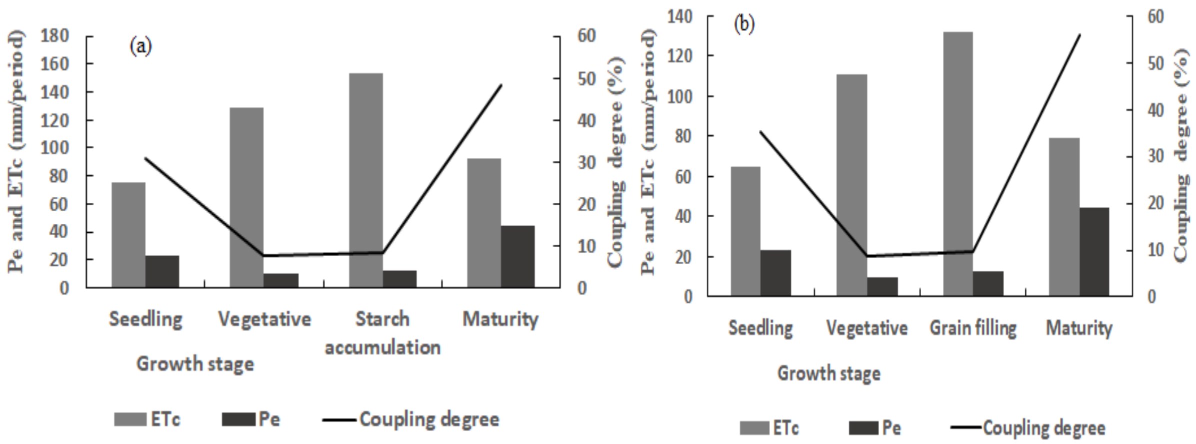

Figure 4.6: Coupling degree between P_e and ET_c in the irrigation season: (a) potato, (b) wheat

4.4.3 Statistical Analysis of the Simulated Yield

The statistical analysis of the SWAT simulated yield indicated that the yield of all deficit irrigation treatments showed a significant difference from the full irrigation in both crops. However, the significance level varies with the stage of growth at which the deficit was scheduled and the amount of the deficit. Water stress at seedling and maturity stages has less effect on yield than at vegetative and starch-accumulation/grain-filling stages. With the least significant difference (LSD) level of 288.3 and 165.7 for potato and wheat, respectively, the yield difference between the full-irrigation treatment and all deficit-irrigation treatments is presented in Table 4.4.

Table 4.4: Statistical analysis of SWAT simulated yield

Potato				Wheat			
TRT rank	Yield (kg/ha)	% of Yield Reduced	% of water saved	TRT rank	Yield (kg/ha)	% of Yield Reduced	% of water saved
CK	8056.609 [a]	-	-	CK	4501.07 [a]	-	-
T1	7308.935 [b]	9	13	T1	4060.017 [b]	10	13
T4	7252.461 [b]	10	15	T4	3986.577 [b]	11	15
T7	6742.744 [c]	16	25	T7	3678.789 [c]	18	25
T2	5825.637 [d]	28	22	T2	3056.719 [d]	32	22
T6	5576.38 [d,e]	31	50	T3	2829.889 [e]	37	26
T3	5414.225 [e]	33	26	T6	2804.272 [e]	38	50
T5	4193.523 [f]	48	75	T5	2086.153 [f]	54	75
LSD	288.3			LSD	165.7		

Note(s): There is no significant yield difference between treatments in a column with the same letter at $p < 0.05$

4.4.4 Crop Water Production Function

The Jensen moisture stress-sensitivity index was calculated using the simulated maximum and actual yield and evapotranspiration. The simulated yield and evapotranspiration data were used from HRUs in five representative subbasins based on the agro-ecology of the watershed (Figure 4.7). The moisture stress-sensitivity index varies across subbasins, particularly at vegetative and starch-accumulation/grain-filling stages (Table 4.5). In both crops, the moisture stress-sensitivity index at vegetative and starch-accumulation/grain-filling stages is greater than at seedling and maturity stages. The average regional moisture-sensitivity-index for potato is 0.05, 0.28, 0.32, and 0.06 at seedling-, vegetative-, starch-accumulation-, and maturity-stages, respectively, and the regional average moisture-sensitivity-index for wheat is 0.06, 0.36, 0.40, and 0.07 at seedling-, vegetative-, grain-filling-, and maturity-stages, respectively. For both crops, the Jensen crop-water-production function was established, using the calculated moisture stress-sensitivity index.

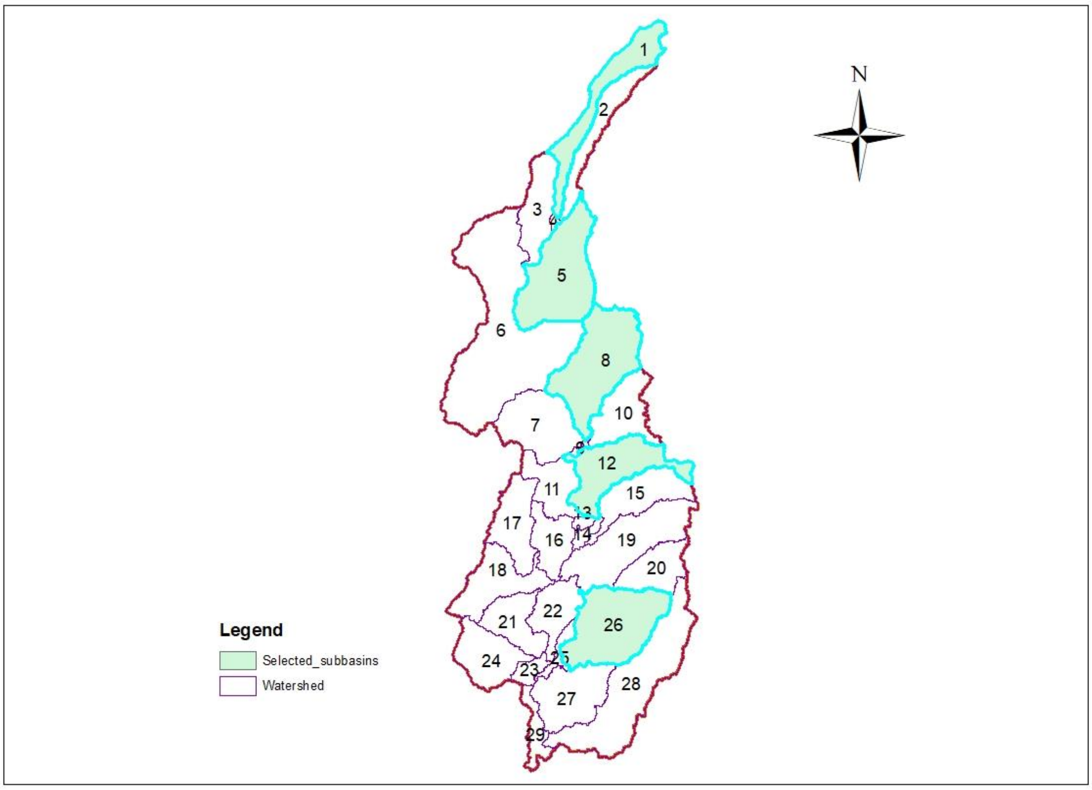

Figure 4.7: Selected subbasins for moisture sensetivitiy index analysis

Table 4.5: Moisture stress-sensitivity index in selected subbasins

Sub-Basin	Growth Stages of Potato				Growth Stages of Wheat			
	Seedling	Vege.t	Starch a.	Maturity	Seedling	Vege.t	Grain fill.	Maturity
1	0.03	0.12	0.17	0.04	0.03	0.14	0.24	0.04
5	0.05	0.11	0.17	0.02	0.02	0.11	0.19	0.04
8	0.04	0.25	0.31	0.05	0.04	0.38	0.38	0.06
12	0.06	0.26	0.30	0.04	0.07	0.38	0.38	0.06
26	0.07	0.46	0.47	0.10	0.09	0.49	0.55	0.09
Basin level	0.05	0.28	0.32	0.06	0.06	0.36	0.40	0.07

The Jensen crop-water-production function for potato in the study area:

$$\frac{Y_a}{Y_m} = \left(\frac{ET_{a1}}{ET_{m1}}\right)^{0.05} * \left(\frac{ET_{a2}}{ET_{m2}}\right)^{0.28} * \left(\frac{ET_{a3}}{ET_{m3}}\right)^{0.32} * \left(\frac{ET_{a4}}{ET_{m4}}\right)^{0.06} \qquad 4.10$$

The Jensen crop-water production function for wheat in the study area:

$$\frac{Y_a}{Y_m} = \left(\frac{ET_{a1}}{ET_{m1}}\right)^{0.06} * \left(\frac{ET_{a2}}{ET_{m2}}\right)^{0.36} * \left(\frac{ET_{a3}}{ET_{m3}}\right)^{0.40} * \left(\frac{ET_{a4}}{ET_{m4}}\right)^{0.07} \qquad 4.11$$

The developed Jensen crop-water-production function model estimated the relative yield of treatments with an R^2 of 0.99 for both crops and root mean square errors (RMSE) of 0.068 and 0.08 for potato and wheat, respectively (Table 4.6). The Jensen model predicts the relative yield accurately for less-deficit treatments (T1 and T4). For high irrigation-deficit treatments (T5), prediction accuracy is reduced. The average prediction performance of the model is good.

Table 4.6: SWAT-simulated and Jensen model predicted relative yield

TRT	Potato		Wheat	
	SWAT Simulated Relative Yield	Jensen Predicted Relative Yield	SWAT Simulated Relative Yield	Jensen Predicted Relative Yield
1	0.91	0.93	0.90	0.91
2	0.72	0.68	0.68	0.60
3	0.67	0.64	0.63	0.57
4	0.90	0.91	0.89	0.90
5	0.52	0.37	0.46	0.29
6	0.69	0.61	0.62	0.54
7	0.84	0.82	0.82	0.77
R^2	0.99		0.99	
RMSE	0.068		0.08	

4.4.5 Irrigation-scheduling Optimization

The seasonal irrigation cycles and developed crop-water-production function were used to optimize irrigation-scheduling. The calculated moisture stress-sensitivity indices were transformed into corresponding irrigation cycles using the cumulative-sensitivity-index curve (Figure 4.8) and number of days in each growth stage. In the study area, the average number of days for a full growing season of potato and wheat is 115 and 90, respectively. For potato, 10, 15, 40, 35, and 15 intra-seasonal growth-stage days for establishment, seedling, vegetative, starch accumulation, and maturity, respectively, were considered. Similarly, for wheat, 7, 8, 35, 25, and 15 intra-seasonal growth-stage days for establishment, seedling, vegetative, grain filling, and maturity, respectively, were considered. Taking into account the availability of irrigation water in the study area, a fifteen-day irrigation interval was assumed (Table 4.7).

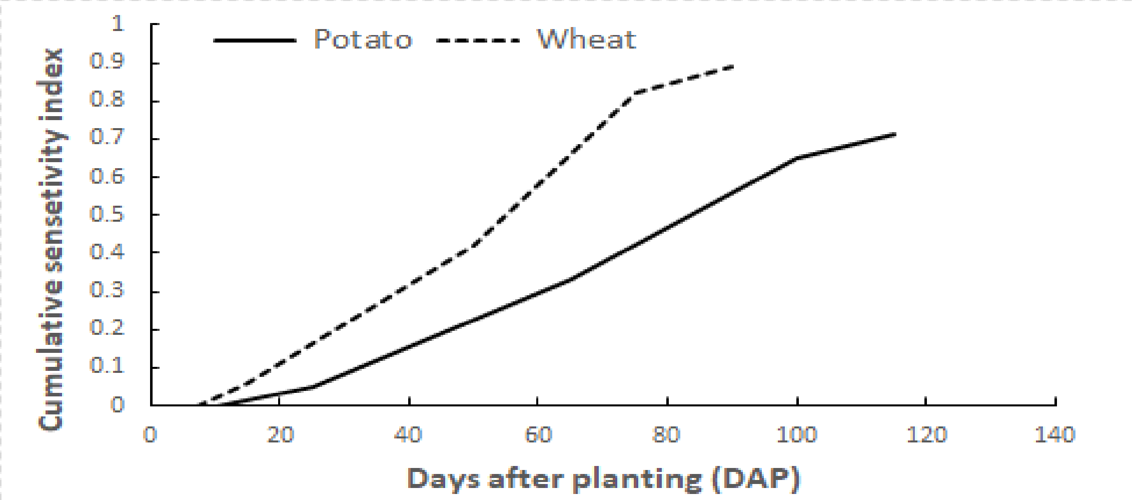

Figure 4.8: Cumulative-sensitivity-index curve

Table 4.7: Transformed moisture stress-sensitivity index into fifteen-day interval

	Potato		Wheat
DAP	Transformed Sensitivity Index	DAP	Transformed Sensitivity Index
10	0	7	0
25	0.05	15	0.06
40	0.105	30	0.154
55	0.105	45	0.154
70	0.1157	60	0.211
85	0.1371	75	0.24
100	0.1371	90	0.07
115	0.06		

The seasonal relative-evapotranspiration of the deficit-irrigation treatments was optimized in between irrigation-cycles based on the transformed moisture stress-sensitivity index. Considering the length of growing seasons, seven and six seasonal irrigation-cycles were adopted for potato and wheat, respectively. The genetic algorithm toolbox on the MATLAB 2020a platform was used to solve the optimal value of relative evapotranspiration for maximizing relative yield, and results are presented in Figures 4.9 and 4.10. The percentage of maximized yield was determined relative to the yield from prior optimization. The optimization result indicated that the seasonal evapotranspiration of all treatments showed some level of yield maximization except at T5 and T6. In both crops, the highest yield maximization was attained at T3 and T2 (Figure 4.11), with 26% and 22% water saved on boths crops, respectively. In the case of potato, the highest yield maximization was obtained at T3 (25%), followed by T2 (21%). Similarly, for wheat, the highest yield maximization was achieved at T3 (34%), followed by T2 (29%).

In addition, yield maximization was also achieved at T1, T4, and T7 in both crops, but the amount was smaller compared with T2 and T3. Prior to optimization, the yields of potato and wheat were reduced by 33% and 37%, respectively, at T3 (Table 4.4), while after optimization, the yields increased by 25% and 34%, respectively. Similarly, at T2, the yields of potato and wheat were reduced by 28% and 32%, respectively, before optimization; however, the yields increased by 21% and 29%, respectively, after optimization. On the other hand, irrigation-scheduling optimizations at T5 and T6 were unable to maximize yield in both crops. In these treatments, the simulated yield was greater than the yield after optimizing the irrigation schedule.

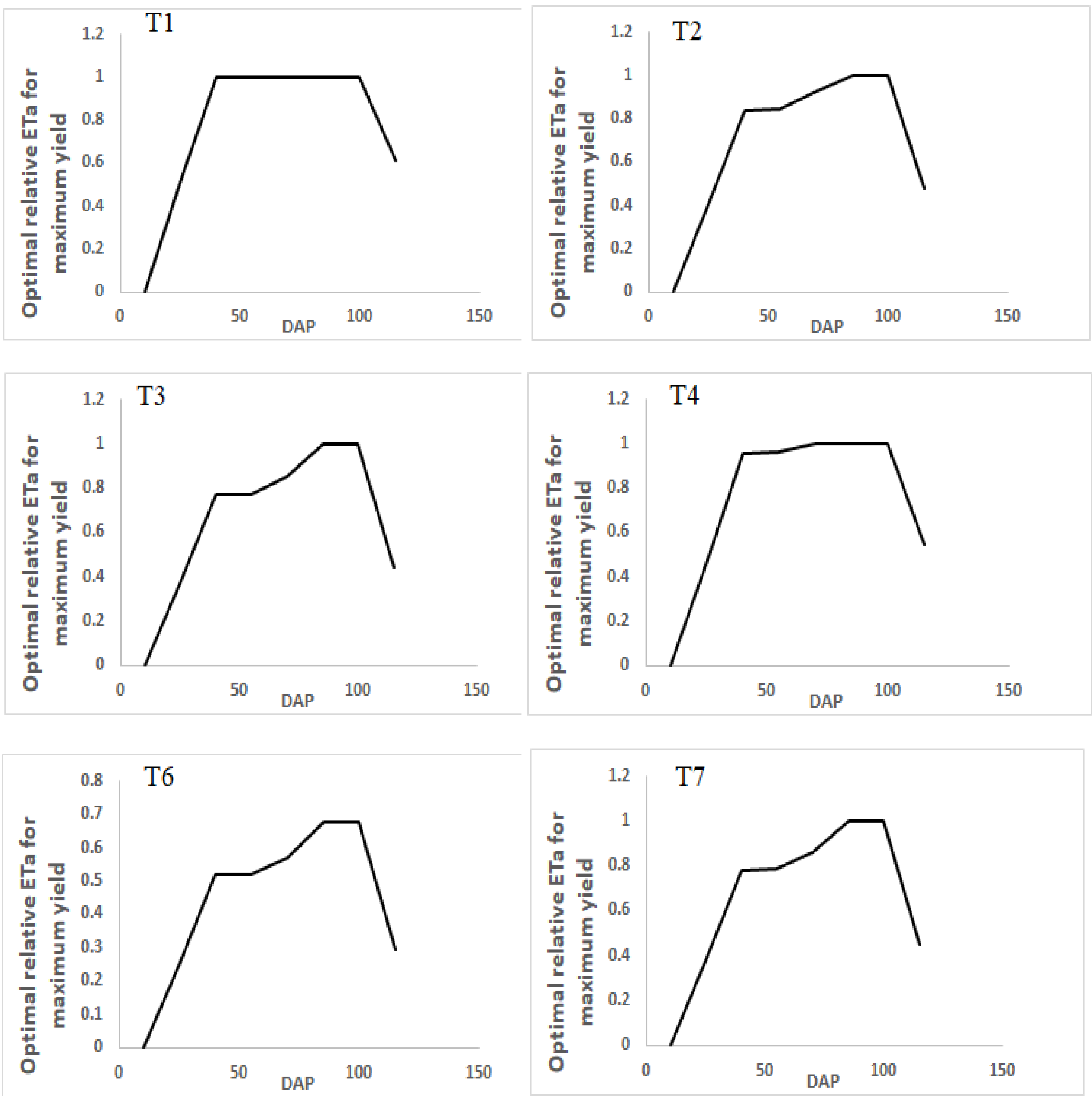

Figure 4.9: Optimal relative ETa for potato under different levels of seasonal-irrigation water

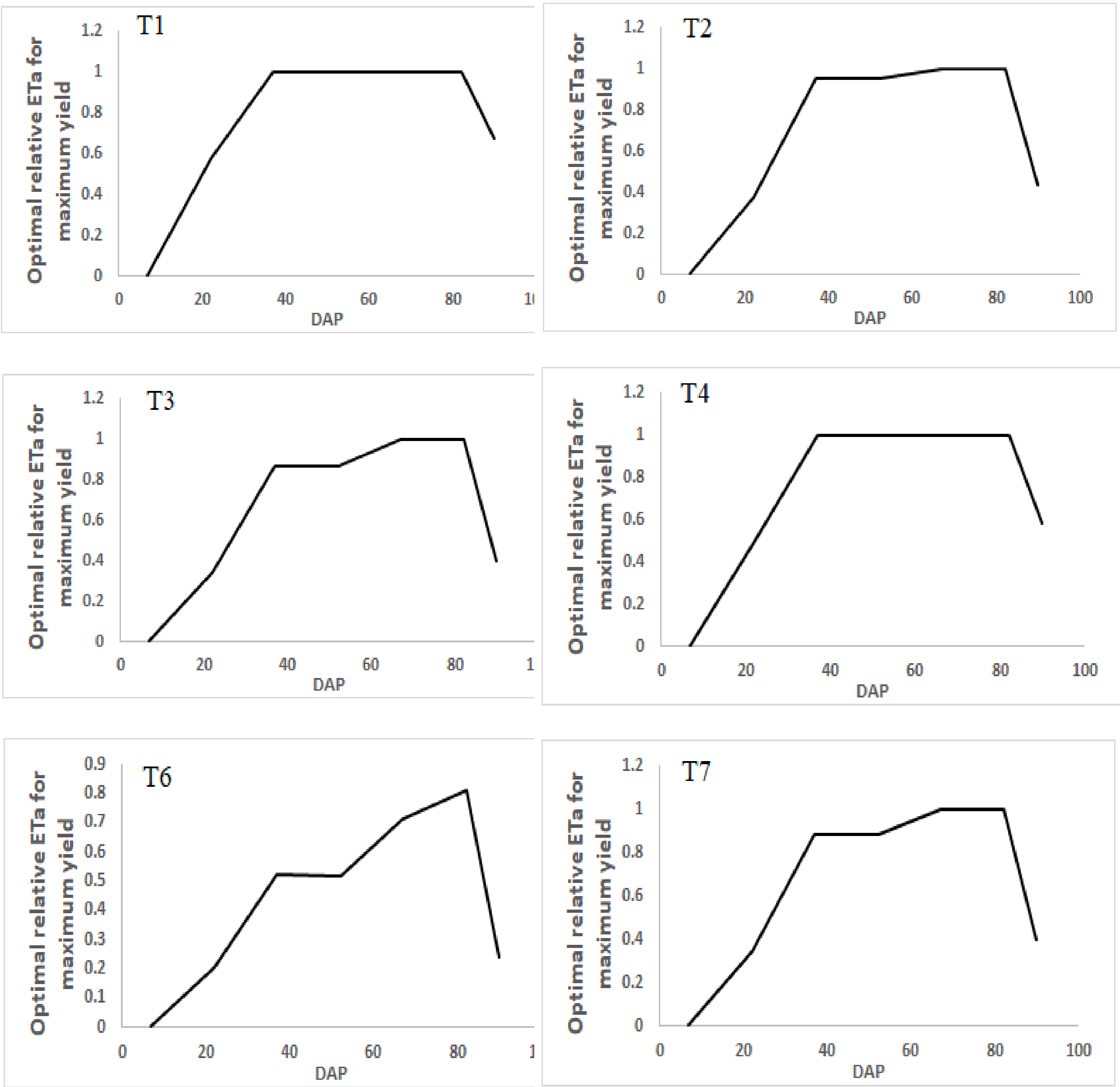

Figure 4.10: Optimal relative ETa for wheat under different levels of seasonal-irrigation water

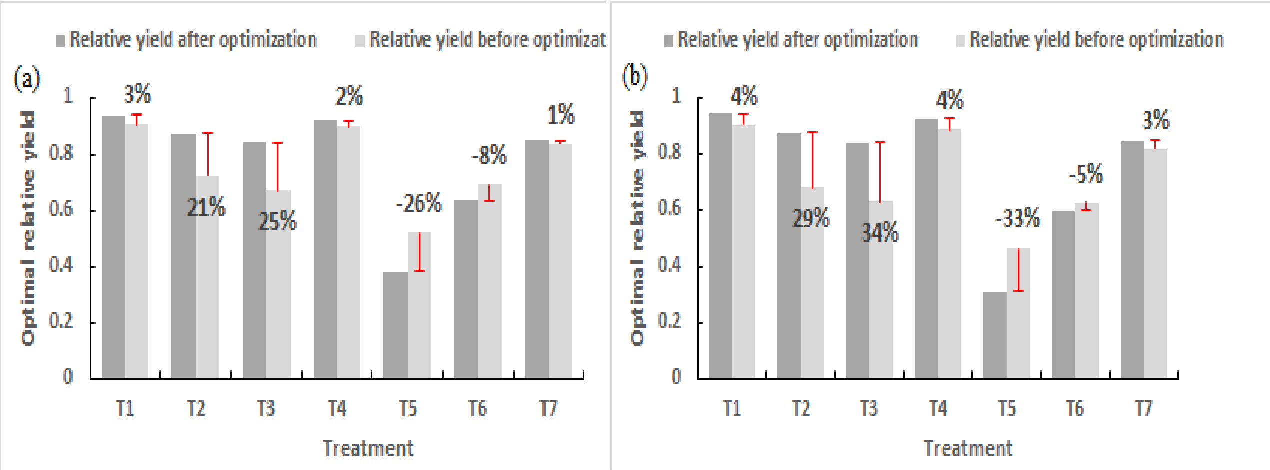

*Figure 4.11: Optimal relative yield before and after optimization: (**a**) potato and (**b**) wheat*

4.5 Discussion

Irrigation-scheduling optimization is an important strategy to cope with climate change impacts and the shortage of agricultural water-resources (Li et al. 2020; Jiang et al. 2021). In this study, full and deficit-irrigation treatments were scheduled in the SWAT model, and yield and evapotranspiration of potato and wheat crops were simulated. The simulated yield and evapotranspiration from each HRU in the selected subbasins were used to compute the Jensen moisture stress-sensitivity index for the two crops. Two groups of deficit-irrigation treatments were used. In the first group, water deficits were scheduled only at a single growth-stage, which allows for distinguishing the most moisture-sensitive growth stages. In the second group, water deficits were triggered at all growth stages based on the ETc of the specific growth-stages, which is also important for examining the water-stress level and its impact on yield. The computed moisture stress-sensitivity indexes were used to establish the Jensen crop-water-production function. Irrigation-scheduling was then optimized using the developed crop-water-production function for seasonal irrigation-intervals.

The findings indicated that water stress at vegetative and starch-accumulation/grain-filling stages lowers production more significantly. These stages of the crop growth cycle are dominated by tillering and reproduction, and this is when crop photosynthetic activity peaks. At this point, water stress will have a more negative impact on vegetative growth and production. Comparable findings from field experiments on wheat by Memon et al. (2021) and on potato by Zhang and Li (2013) and Li et al. (2022) have been reported. The moisture stress-sensitivity index of the two crops was high at the vegetative and starch-accumulation/grain-filling stages and low at the seedling and maturity stages. In fact, at the later stages, the leaf area and canopy size of the crops are relatively small. Therefore, crop water-use during these stages is low and yield reduction due to moisture stress is less significant. As a result, the majority of the water applied at these stages evaporates from the soil. Similar results have been reported in different parts of the world, such as by Li et al. (2022) for potato and Zhang and Oweis (1999) for wheat. However, the magnitude of the moisture stress-sensitivity indexes differs. This variation might be due to differences in local climate conditions and moisture-stress levels. The relative crop yield was estimated using a developed water-production function, which is associated with the moisture-stress-sensitivity index parameter. Compared to the simulated relative yield, the Jensen model accurately predicted the relative yield with negligible errors. This conclusion is supported by the findings of a maize field experiment conducted by (Igbadun et al. 2007).

The optimization of irrigation-scheduling for crops using moisture stress-sensitivity levels is a practical method for saving irrigation water and reducing associated production costs. In this study, the seasonal relative evapotranspiration of different deficit levels of irrigation water was optimized to evaluate yield maximization. Since our goal was to maximize yield with deficit irrigation, all maximized yields following optimization were compared to the yield under full irrigation. The optimization result indicated that in both crops, yield maximization was achieved at T3, T2, T1, T4, and T7 (Figure 4.11). At T3 and T2, the yield was maximized to a greater extent than with other treatments. This was due to the fact that, first, T1 and T4 had lower seasonal deficit-levels than other treatments; second, the deficit at T1 and T4 was scheduled at seedling and maturity growth-stages, respectively. For these reasons, the yield reduction brought on by water stress at T1 and T4 was less significant in comparison with other deficit treatments. Since T1 and T4 were initially close to optimal (the yield of full irrigation), the amount of maximized relative yield after optimization was less than T3 and T2. Increasing irrigation water consumption gradually boosts yield until it reaches the optimum level, after which additional increases in irrigation water would not increase yield but might even slightly reduce it (Li et al. 2020). On the other hand, the seasonal amount of irrigation water level at T3 and T7 was almost equal in both crops. The saved water at T3, T2, and T7 was 26%, 22%, and 25%, respectively, on both crops. The yield of T3 before optimization was far less than T7 (Table 4.4). However, after irrigation scheduling optimization, the relative yield of the two treatments came to be approximately equal. As discussed above, a high yield reduction was observed when moisture stress was scheduled at the vegetative and starch accumulation/grain-filling stages (T3 and T2). After optimizing the relative evapotranspiration between irrigation cycles, significant yield maximization was achieved at T3 with the same amount of seasonal-irrigation water. Generally, the results indicated that scheduling the irrigation water for growing seasons based on the moisture stress-sensitivity level of the crops is valuable for saving irrigation water and maximizing the yield of deficit irrigation. In times of water scarcity, it also enables irrigators to determine how much water they need to maintain for the optimal yield. In addition, such kinds of irrigation-scheduling optimization allow a substantial degree of flexibility in planning the irrigation interval, to consider different soil and climatic conditions (Tsakiris 1982).

This study also revealed that optimizing irrigation-scheduling does not always reflect optimistic results. Optimizing irrigation scheduling in the case of a high irrigation water deficit level may not maximize yield. As it is shown in Figure 4.11, irrigation scheduling optimization at T5 (75% deficit throughout the growing season) and T6 (50% deficit throughout the growing season) was not successful in either crop. This suggests that, for better outcomes, the crop water requirement level should be considered when optimizing irrigation-scheduling.

4.6 Conclusion

To save irrigation water and maximize crop yield, irrigation scheduling optimization was developed using a simulation-optimization model. Following calibration of the sensitive parameters, deficit and full irrigation treatments were scheduled in the SWAT model to examine the moisture-stress-sensitive growth-stages of potato and wheat. The crop water production function of potato and wheat in the study area was calculated using the Jensen moisture stress-sensitivity index. Different seasonal deficit-irrigation levels were optimized between seasonal irrigation-cycles for yield maximization. The general conclusions are:

1. The model can be applied to manage the complicated simulation optimization irrigation-scheduling problems for wheat and potato in the study area.
2. The Jensen moisture stress-sensitivity index indicated that the vegetative and starch-accumulation/grain-filling growth stages of potato and wheat crops are the most moisture stress sensitive stages. Moisture stress at these stages would lower crop yields more significantly.
3. Optimizing irrigation scheduling based on growth stage moisture stress sensitivity levels can save up to approximately 26% of irrigation water in the study area with an insignificant yield reduction. Furthermore, optimizing deficit irrigation-scheduling

based on moisture stress sensitivity levels can maximize the yield of potato and wheat by up to 25% and 34%, respectively.

4. Planning to save irrigation water should be based on the ETc of the crops. This means that irrigation scheduling optimization may not be effective if the seasonal irrigation water is too low compared with ETc.

Furthermore, additional water-stress based optimization experiments are recommended to expand on the current findings in the study area.

CHAPTER V: Water Productivity and Water Balance Assessment in Furfuro Small-Scale Irrigation Scheme Using Agrohydrological Model

In regions where water is the most limited resource, agricultural output should be evaluated based on the amount of water used rather than the amount of land utilized. The value or benefit derived from the use of water is referred to as "water productivity," which covers a wide range of aspects of water management and is important especially in arid and semi-arid countries. This chapter covers water productivity and water balance assessment in the Furfuro SSI scheme using the SWAP agrohydrological model. Field experiments were conducted in the command area of the scheme using the main irrigated crops (wheat, onion, and tomato) to evaluate the water productivity of the traditional and standard irrigation practices. Traditional farmer's irrigation practices are denoted as ‘Farmer plots’ and irrigation practices managed by the researcher are represented as ‘Researcher plots’. Each group contains three plots, one for each crop type. Crop water requirements and irrigation scheduling were determined for researcher plots based on climatic, crop, and soil data for the area. All irrigation practices (amount and timing of application) and field management for farmer plots were carried out by farmers based on their own experiences. However, the depth of irrigation water was measured during each irrigation at all six experimental plots using a 5.08*90 cm Cutthroat flume. The water balance components of the scheme were simulated based on farmers' and researchers' irrigation practices, and water productivity was calculated for both researcher and farmer fields based on seasonal irrigation water applied and yield produced. The result provides insight into how much of the applied water is used by crops and how much of it is lost. Based on this result it is essential to plan strategies for enhancing irrigation water management practices and water productivity. The result has been presented at an international conference to be considered for publication.

5.1 Introduction

In many regions of the world, the need for freshwater by industries, households, agriculture, and nature reserves is higher than the available freshwater, thus signifying the need for improved freshwater management (Van Dam et al. 2006). Along with the growing demand for water, drought, climate change (Ronco et al. 2017), and rapid population growth (Kaur et al. 2010) are causing freshwater availability to decline. In particular, in the Ethiopian Rift Valley, agricultural production has been severely hampered by frequent droughts and declining annual rainfall (Girma and Awulachew 2007; Kassie et al. 2014). The agroecology in the Ethiopian Rift Valley has experienced longer dry spells and low precipitation frequently, affecting crop production (Belay et al. 2017). Due to climate change, the streamflow of the rivers, which are a source of water for irrigation schemes has been projected to decline (Orke & Li, 2022). The main components of the water balance have been projected to decline due to climate change, which is expected to occur in the Central Rift Valley of Ethiopia in the coming decades (Muluneh 2020). Therefore, effective management of the available agricultural water is essential to sustain agricultural production in the region.

Agricultural output needs to be measured in terms of how much water is consumed rather than how much land is used in areas where water is the most limiting factor (Molden 2007). This will aid in improving the output per unit of water consumed, known as water productivity (WP). WP is a term used to describe the value or benefit attained from the use of water, encompassing many different facets of water management and is crucial, particularly in arid and semi-arid regions (Molden and Sakthivadivel 1999; Droogers and Bastiaanssen 2002; Kijne et al. 2003a). Irrigated agriculture is by far the biggest freshwater consumer globally. Effective irrigation water management in this sector is vital to saving water and enhancing WP. WP in agriculture can be improved in several ways under field conditions. The application of deficit irrigation, which aims to reduce the amount of irrigation water, is the most popular and widely applied method (Schneider and Howell 2001; Molden et al. 2010; Nagaz et al. 2012). To reduce soil evaporation and improve water productivity, soil management techniques like film plastic mulching and crop straw mulching can make a significant difference (Chakraborty et al. 2008; Zhao et al. 2012). Agricultural water productivity indicators can provide a clear picture of where and when water can be saved. They are also helpful for examining the potential rise in crop yield brought on by increased access to water (Singh et al. 2006). Therefore, measurable data on water productivity indicators is essential for the planning of effective irrigation water management practices.

Understanding the relationships between soil, crop, water, and atmosphere is important to investigate which farming practices help to produce "more crop per drop." Considering the spatial variability in soil, irrigation water application techniques, crop growth and development, and field management conditions, knowledge of water balance components at the field level can provide information on the WP of individual crops grown. Therefore, it is essential to figure out the associations among water hydrological components such as transpiration, evaporation, and percolation under field conditions to enhance water management and productivity (Singh et al. 2006). However, it is difficult, time-consuming, and expensive to measure all hydrological components under field conditions. In the past few years, several agrohydrological models have been developed to understand various processes occurring in space and time.

Soil-Water-Atmosphere-Plant (SWAP) is a one-dimensional vertically directed model that simulates the transport of water, solutes, and heat in topsoil in interaction with vegetation development (Kroes et al. 2017). The SWAP model describes a domain from the top of the canopy into the groundwater, which may interact with the surface water system. The model allows for learning in-depth details about how the system behaves in space and time, combined with field experiments (Singh et al. 2006), and is used to simulate field-level water balance components such as rainfall, irrigation, transpiration, evaporation, evapotranspiration, and percolation. SWAP (version 4.2.0) incorporates three crop growth modules (one simple module for static crops and two detailed modules for dynamic crops) to simulate irrigation practices, crop growth, and yield (Kroes et al. 2017). The SWAP model has been extensively applied for irrigation water management, forecasting crop yield, and water productivity for various crops in different parts of the world (Singh et al. 2006; Van Dam et al. 2006; Vazifedoust et al. 2008; Jiang et al. 2015; Xue and Ren 2017). Using the SWAP model, the impacts of irrigation water management on groundwater dynamics have also been studied (Qureshi et al. 2013; Ma et al. 2015; Xu et al. 2015). This study aimed to determine the water balance components and analyze the WP of the main crops of the Furfuro irrigation scheme in the Ethiopian Rift Valley using the SWAP agrohydrological model. The WP of the main crops grown in the scheme was analyzed with respect to different water balance components.

5.2 Materials and methods

5.2.1 Description of the study area

The Furfuro irrigation scheme is located in the Wulbareg district of southern Ethiopia (Figure 5.1), in the ranges of 7°39′21″ to 7°40′24″ latitude and 38°10′47″ to 38°11′53″ longitude. The scheme is situated about 25 km southeast of Worabe City, the capital of Siltie Zone, in the western escarpment of the Dijo watershed. The scheme was constructed in 2007 with a command area of 200 ha. Its water source is the Furfuro River, which flows from the northern edge of the upper Dijo catchment to Shala Lake. The study area has humid and sub-humid climatic conditions with a bimodal rainfall pattern (short and main rainy seasons). The short rainy season known as *Belg* typically begins in March and lasts until May, which is used to supplement irrigation. The main cropping season, called *Kiremt*, lasts from June until the end of September. The study area usually experiences dry conditions from November to March, which is the typical irrigation season. Onion, tomato, wheat, and other small vegetable crops are most popularly grown in the scheme. According to the meteorological data, the area's annual mean rainfall varies between 560 and 1300 mm (Figure 5.2). The mean minimum and maximum temperatures in the study area are 9 °C and 26 °C, respectively (Figure 5.3). The dominant soil types in the area are sandy loam and sandy clay loam (Abrar et al. 2023), with an intensively cultivated agriculture system.

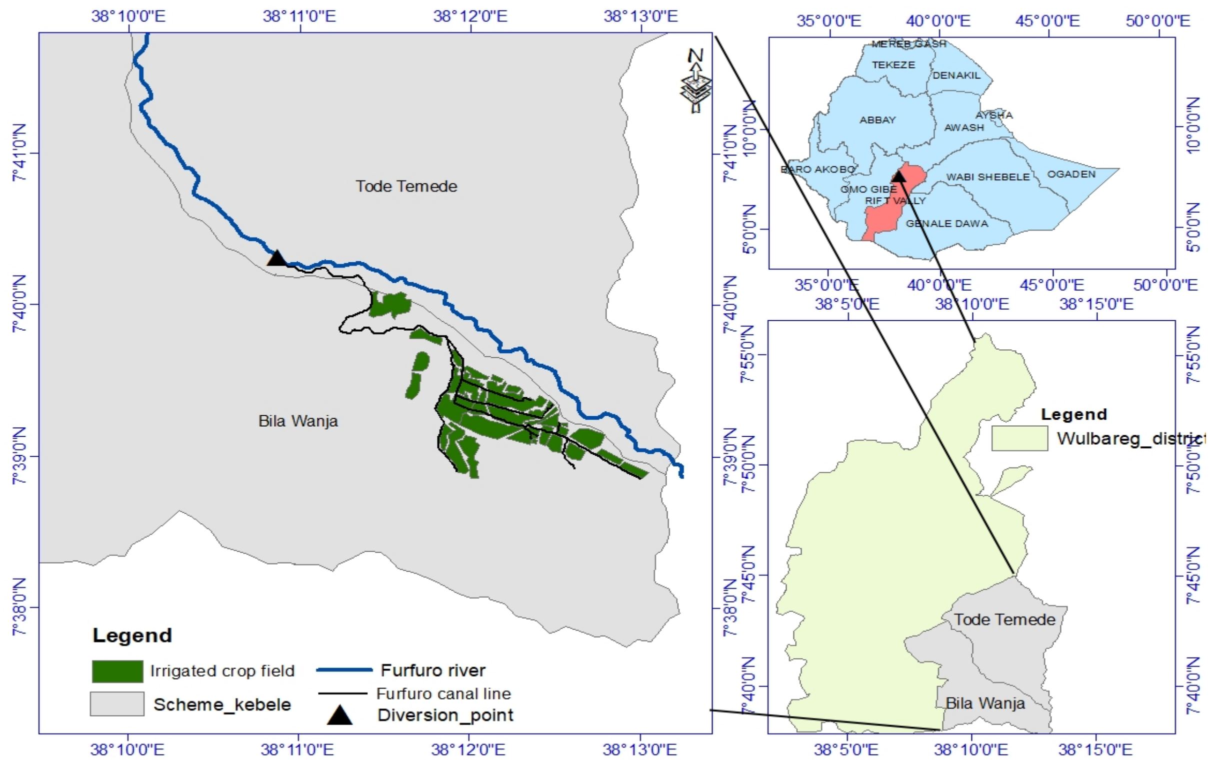

Figure 5.1: Location map of the study area

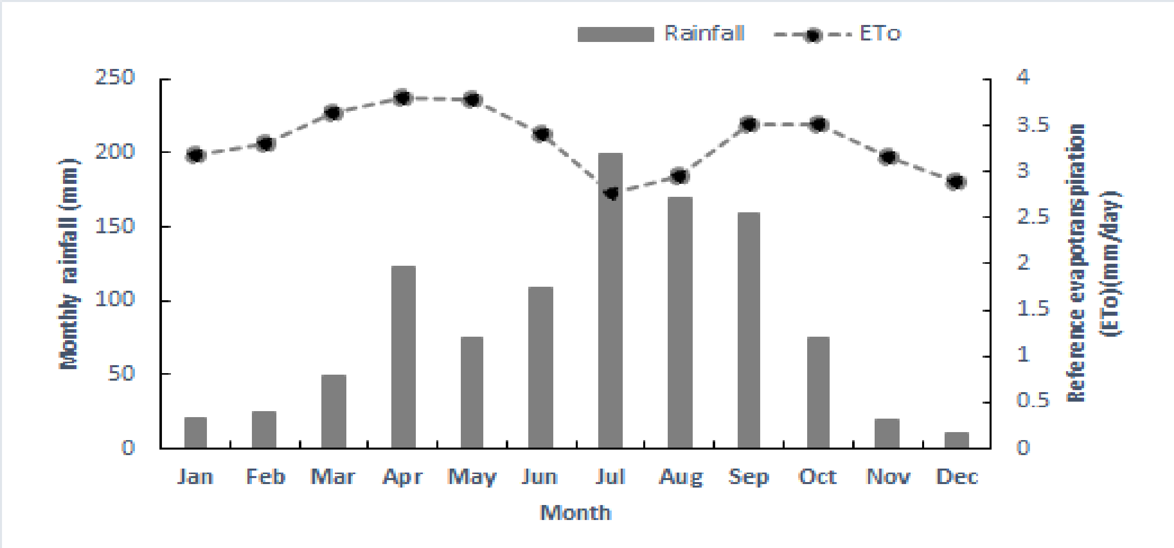

Figure 5.2: Rainfall and Reference evapotranspiration of the study area

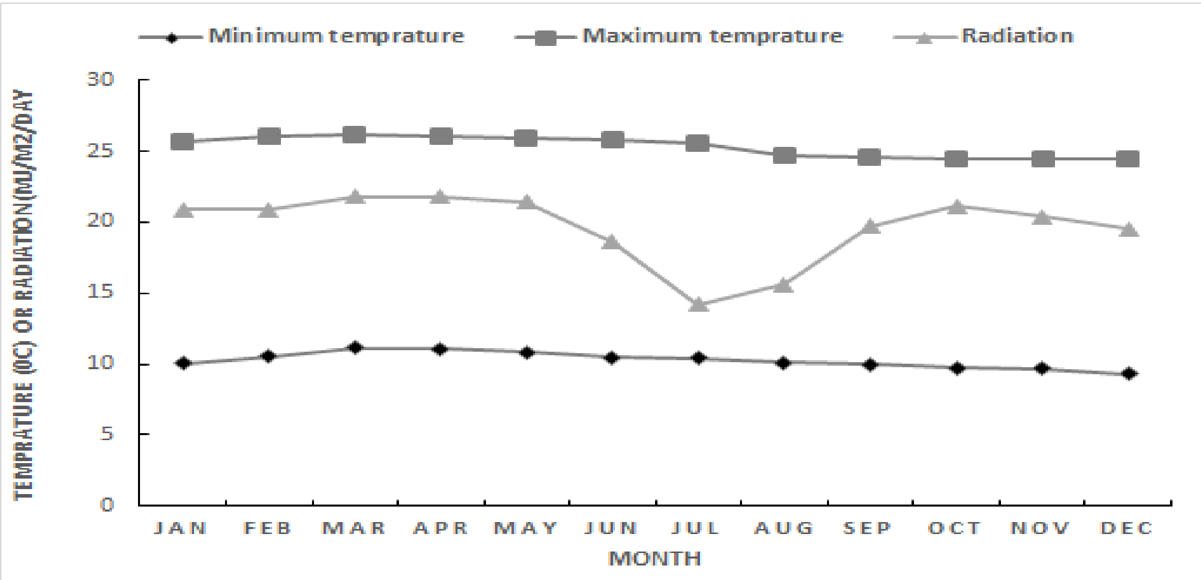

Figure 5.3: Temperature and Radiation of the study area

5.2.2 Data collection

The SWAP model requires meteorological, soil, crop, and irrigation data to simulate water balance and crop growth parameters. The average long-term (1991–2020) meteorological data was used, which was collected from the Ethiopian National Meteorology Service Agency (ENMSA). Field experiments were conducted in the scheme command area in 2022–23 to collect data for the calibration and validation of the SWAP model (Table 5.1). The physical properties of the soil in the experimental area were determined in the soil laboratory. The experiments were conducted on six experimental plots using the main irrigated crops (wheat, onion, and tomato). The six experimental plots were categorized into two groups: Researcher plots and Farmer plots. Each experimental group contains three plots, one plot for each crop type. Researcher plots were irrigated based on predetermined crop water requirements (CWR) and irrigation schedules. The CWR was determined using CROPWAT computer model based on the climatic, soil and crop data of the study area. Before each irrigation, the soil moisture level of researcher plots was checked using Watermark (Figure 5.4). All irrigation practices (amount and timing of water application) and field management for farmer experimental plots were carried out by farmers based on their own experiences. However, the depth of irrigation water was measured during each irrigation event at all six experimental plots using a 5.08*90 cm Cutthroat flume.

Figure: 5.4: Soil moisture level measuring at field using Watermark

The soil moisture content before and after each irrigation (for the wheat plot) was determined at different soil depths using the gravimetric method to calibrate and validate the SWAP model:

$$\theta_m = \frac{\text{Weight of wet soil} - \text{Weight of oven dry soil}}{\text{Weight of oven dry soil}} * 100 \quad 5.1$$

Where, θ_m is the gravimetric soil water content

Gravimetric water content is then converted to volumetric water content (θ_v) using the soil bulk density and density of water.

$$\theta_v = \theta_m * \frac{\text{Soil bulk density}}{\text{Water density}} \quad 5.2$$

Crop data such as leaf area, growth stage-based dry matter, plant height, and yield were collected from each experimental plot. The leaf area index (LAI) was calculated from the collected leaf area (Kang et al. 2003) by:

$$LAI = 0.759 * \mathrm{P} * \sum_{i=1}^{m} \sum_{i=1}^{n} \left(\frac{L_{ij} * W_{ij}}{m}\right) \quad 5.3$$

where, P is plant density per area, n is the number of leaves of the n^{th} sample plant, m is the number of measured plants, L_{ij} is leaf length, W_{ij} is the maximum leaf width

Table 5.1: Collected data for input and calibration and validation of the SWAP model

Data type	Method of collection	Purpose
Climatic data	Meteorological station	Input
Irrigation depth	Filed measurement using Cutthroat flume	Input
Soil water content	Field soil sampling and gravimetric method	Calibration and validation
Soil properties	Laboratory analysis	Input
Crop development stage	Field observation	Input
Plant height	Field measurement	Input
Leaf area	Field measurement	Calibration and validation
Dry matter partitioning	Field measurement	Calibration and validation
Rooting depth	Field measurement	Input
Crop yield	Field measurement	Calibration and validation

5.2.3 SWAP model

The SWAP model determines the field-scale transport process in a physical and deterministic manner. The soil water transport and root water extraction are described by Richards' equation:

$$C_w(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S_a(z) \quad 5.4$$

where C_w is the differential water capacity (cm^{-1}), h is the soil water pressure head (cm), K is the hydraulic conductivity ($cm\ d^{-1}$), S_a is root water extraction rate ($cm^3\ cm^{-3}\ s^{-1}$), and z is soil depth (cm)

To solve equation (5.4), relationships among the soil moisture content θ, soil water pressure head h, and hydraulic conductivity K are required. The soil hydraulic functions of Mualem (1976) and van Genuchten (1980) have been applied to describe the soil moisture retention curve:

$$\theta(h) = \theta_{res} + \frac{\theta_{sat} - \theta_{res}}{[1+|\alpha h|^n]^{\frac{(n-1)}{n}}} \quad 5.5$$

where, θ_{res} is residual water content ($cm^3\ cm^{-3}$), θ_{sat} saturated water content ($cm^3\ cm^{-3}$), and α (cm^{-1}) and n (-) are empirical shape factors.

The hydraulic conductivity curve is given by:

$$K(\theta) = K_{sat}\, S_e^{\lambda}\left[1 - \left(1 - S_e^{\frac{n}{n-1}}\right)^{\frac{(n-1)}{n}}\right]^2 \quad 5.6$$

where, K_{sat} is the saturated hydraulic conductivity ($cm\ d^{-1}$), $S_e = (\theta - \theta_{res})/(\theta_{sat} - \theta_{res})$ relative saturation (-), and λ an empirical coefficient (-).

The precipitation, potential evapotranspiration (ET_P), and irrigation fluxes determine the upper boundary condition. SWAP applies the Penman-Monteith equation to calculate ET_P based on daily weather data (temperature, solar radiation, wind speed, and humidity) and canopy characteristics such as surface albedo, minimum crop resistance, and crop height (Allen et al. 1998). The lower boundary can extend up to the top of the groundwater flow system. Solute transport is modelled by the equation of convection-dispersion. The detailed crop growth module of the SWAP model is based on the WOrld FOod STudies (WOFOST) model. WOFOST simulates photosynthesis, crop growth, and crop production, including potential and actual dry matter yields, and accounts for salt and water stress conditions (Spitters et al. 1989;

Supit et al. 1994). The byproduct of photosynthesis helps crops grow their leaves, stems, roots, and reproductive organs and maintain their respiratory systems. The potential gross assimilation of a crop under ideal conditions can be calculated using the effective incoming radiation to simulate the dry matter growth rate. The produced dry matter is split among roots, stems, leaves, and storage organs using partitioning factors depending on the stage of crop development (Kroes et al. 2017). The 4.2.0 version of SWAP does not account for the effects of nutrient deficiency, pests, weeds, and diseases on crop growth and production. However, the WOFOST module provides feedback for crop growth conditions under different salt and water stress levels.

5.2.4 Calibration and validation of the model

Calibration and validation of the SWAP model were performed using the observed soil moisture contents from the field experimental plot at different depths. The one-at-a-time (OAT) technique was used to identify sensitive parameters and calibrate the model manually. The sensitive parameters were adjusted until the difference between observed and simulated soil moisture content met acceptable values. Irrigation was scheduled in the main input data of the SWAP module for the six experimental plots based on field-obtained data. The seasonal irrigation water consumptions of the six experimental plots were divided into ten-day irrigation intervals based on crop growth stages and then simulated individually. There is no shallow groundwater in the study area, and the water source for irrigation is always canal water; thus, the free drainage option was selected in the bottom boundary condition. Since there is no risk of shallow groundwater in the study area, lateral drainage was not simulated. Similarly, solute transport was not simulated, assuming that the quality of the canal water was good (<2 dS m^{-1}). Root mean square error (RMSE) and Nash-Sutcliffe model efficiency (NSE) were used to evaluate the level of difference between observed and simulated values.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(Q_o - Q_s)^2}{n}} \tag{5.7}$$

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}(Q_o - Q_s)^2}{\sum_{i=1}^{n}(Q_o - Q_{savr})^2}\right] \tag{5.8}$$

where, n represents the number of observed data, Q_o denotes observed soil moisture ($cm^3\ cm^{-3}$), Q_s represents simulated soil moisture ($cm^3\ cm^{-3}$) and Q_{savr} represent the average simulated soil moisture ($cm^3\ cm^{-3}$).

The detailed crop growth module (WOFOST) was used to simulate irrigation and crop growth parameters. After calibrating the model with the soil hydraulic parameters and irrigation depth, the crop growth parameters in the WOFOST sub-module were adjusted manually by running the simulation several times to increase the precision of the output values. An initial value of 70 s m^{-1} was used for the minimum canopy resistance of all crops (Singh et al. 2006; Verma et al. 2012). A green vegetation cover has an albedo of about 0.20-0.25 (Allen et al. 1998); thus, 0.22 was used for onion and tomato, but 0.19 was used for wheat to be accurate with the calibrated model. Plant height, LAI, and dry matter partitioning were adjusted with data collected directly from experimental plots.

5.2.5 Water productivity

WP can be defined in various ways, which offers valuable indicators for assessing water use and determining when and where water savings can be achieved (Singh et al. 2006). The water balance components (rainfall (R), irrigation (I), transpiration (T), evaporation (E), evapotranspiration (ET), and percolation (Q)) of the experimental plots were simulated using the calibrated SWAP model. The WP of the main crops grown in the study area was then calculated using the simulated water balance components and the measured yield from the experimental plots (Singh et al. 2006; Van Dam et al. 2006). The yield obtained from the experimental plots was converted to Kg ha^{-1}, and the simulated water balance components in mm were changed to volume basis (m^3 ha^{-1}). Then, the physical WP with respect to total applied water (I+R) for a specific growing season was calculated as:

$$WP_{I+R} = \frac{\text{Yield (Kg ha}^{-1})}{\text{I+R (m}^3\text{ha}^{-1})} \qquad 5.9$$

When considering only the usable form of water that is T, then the WP is given by:

$$WP_{T} = \frac{\text{Yield (Kg ha}^{-1})}{\text{T (m}^3\text{ha}^{-1})} \qquad 5.10$$

Distinguishing plant transpiration from soil evaporation at field level is difficult. Therefore, the WP considering ET can be calculated as:

$$WP_{ET} = \frac{\text{Yield (Kg ha}^{-1})}{\text{ET (m}^3\text{ha}^{-1})} \qquad 5.11$$

If the percolated water is concerned, then the WP can be calculated as:

$$WP_{ETQ} = \frac{\text{Yield (Kg ha}^{-1})}{\text{ETQ (m}^3\text{ha}^{-1})} \qquad 5.12$$

The economic WP was also calculated using the cost of production and the selling price of the yield. Input cost data such as for seed, fertilizer, and pesticides was collected during the field experiment and through interviews with farmers. All fixed and variable costs specific to each crop type were included in the cost of production. Data on the selling prices of the yield were collected in the local markets. For each crop, the net benefit was calculated by deducting the total production cost from the total price at which the yield was sold. Then, the economic WP of each crop was calculated in the same manner as the physical WP, except the numerator (yield) was changed to USD ($).

5.3 Result and Discussion

5.3.1 Calibration of the SWAP model

The result of model calibration and validation with soil moisture indicated that the simulated soil moisture content is in agreement with observed values (Figure 5.5). The observed and simulated soil moisture contents at the top depth (0–20 cm) were between 0.13 and 0.233 and 0.063 and 0.267 (cm^3 cm^{-3}), respectively (Figure 5.5a). Similarly, the observed and simulated soil moisture contents at the bottom depth (60–80 cm) were between 0.1 and 0.244 and 0.087 and 0.269 (cm^3 cm^{-3}), respectively (Figure 5.5d). The most sensitive parameters were empirical shape factors of α (cm^{-1}) and n (-), and they were adjusted based on the observed soil moisture content. During manual calibration of the model, optimizing the values of empirical shape factors using the OAT technique helps to increase the accuracy of simulated soil moisture. The optimized values of empirical shape factors of α (cm^{-1}) and n (-) were 0.0157 and 1.57 at the top layer and 0.0135 and 1.271 at the sublayer, respectively (Table 5.2). The same values were obtained when the optimization process was repeated with different initial values for α and n, demonstrating the uniqueness of the optimized parameter (Singh et al. 2006; Vazifedoust et al. 2008). The other parameters, such as θ_{res}, θ_{sat}, and λ, were less sensitive, and their influence on simulated output was insignificant. Initial values for less sensitive parameters were set using models and literature of similar soil physical properties. The initial value for saturated hydraulic conductivity K_{sat} was selected from the ‘Soil Water Characteristics’ model for a similar soil textural class. The RMSE between observed and simulated soil moisture data ranges from 0.031 to 0.041 (Table 5.3). Additionally, it was discovered that the average value of the NSE indicator was within the range of good performance.

Table 5.2: Soil hydraulic parameters for the experimental location

Parameter	Top layer	Sub layer
Soil layer (cm)	0-40	>40
Saturated water content, θ_{sat} (cm^{3}cm^{-3})	0.31	0.30
Residual water content, θ_{res} (cm^{3}cm^{-3})	0.01	0.01
Saturated hydraulic conductivity K_{sat} (cm d^{-1})	30.45	28.40
Soil texture	Sandy clay loam	Sandy clay loam
Shape parameter, α (cm^{-1})	0.0157	0.0135
Shape parameter, n	1.570	1.271
Shape parameter, λ	-1.6	-1.00

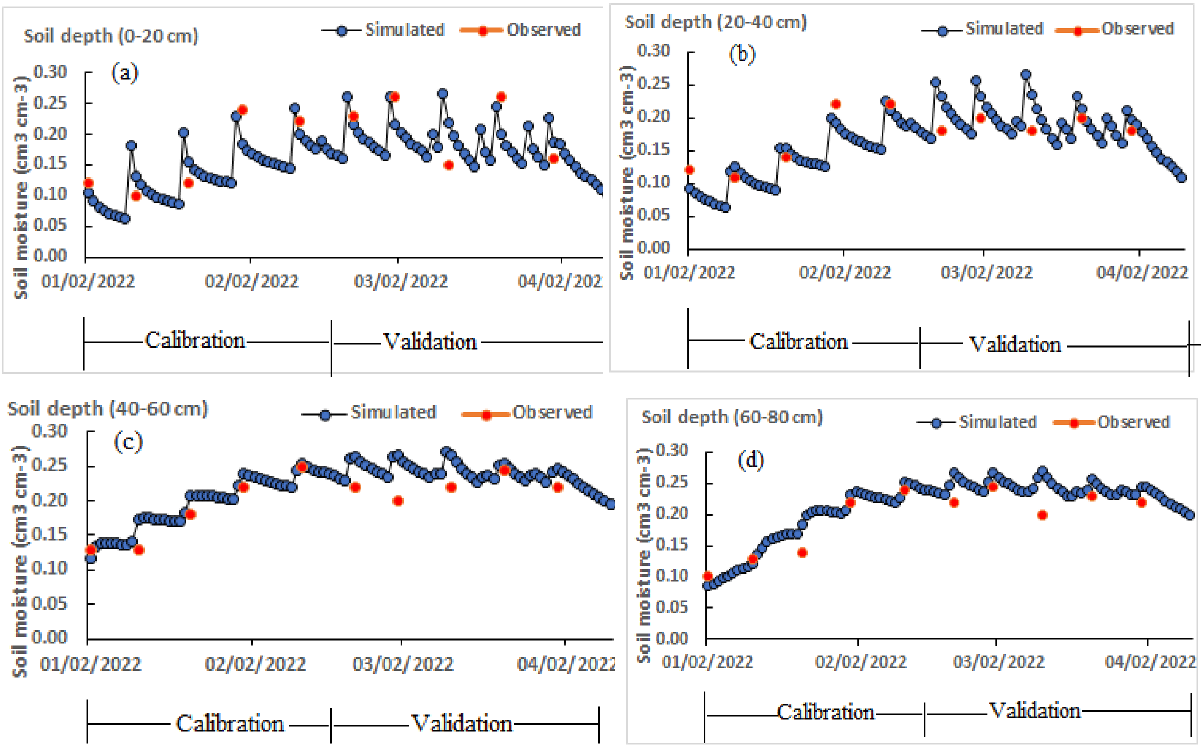

Figure 5.5: Observed and simulated soil moisture content

Table 5.3: RMSE and NSE of the calibration with soil moisture contents

Soil depth (cm)	N	RMSE	NSE
0-20	10	0.041	0.52
20-40	10	0.031	0.40
40-60	10	0.035	0.48
60-80	10	0.033	0.62

Note: N is number of observations

The most important adjusted crop parameters are given in Table 5.4. Simulations of LAI, dry matter, and yield data for both researcher and farmer plots closely followed the field-measured data. The LAI was measured three times in the growing season for each crop. The model simulated the LAI nearly accurate during the initial and development stages. However, relatively significant variations were observed between measured and simulated values at later growth stages. Low accuracy at a later growth stage may be caused by the fact that the leaf area was measured manually at the field level. The simulated yield (dry weight of living storage organ) of wheat and onion was reasonably close to the observed yield; however, the simulated yield of tomato was quite smaller than the observed values. Dry matter production and dry weight of living storage organs were most sensitive to LAI and green vegetation cover (albedo) changes. This is because LAI determines how much light is intercepted and indirectly influences the dry matter accumulation in the plant organs (Vazifedoust et al. 2008). Dry matter production is also moderately sensitive to Minimum canopy resistance, Temperature sum from emergence to anthesis (TSUMEA), and Light use efficiency for real leaf. Generally, the results show that the model simulates the soil moisture content and crop growth practically well; however, future use will need further improvements.

Table 5.4: Main adjusted crop growth parameters in the SWAP-WOFOST detailed module

Parameter	Wheat	Onion	Tomato
Temperature sum from emergence to anthesis, TSUMEA (°C)	1400	1650	1750
Temperature sum from anthesis to maturity, TSUMAM (°C)	850	850	1000
Leaf area index at emergence (m^2/m^2)	0.01	0.01	0.04
Minimum canopy resistance, r_{crop} ($S\ m^{-1}$)	70	70	70
Green vegetation cover (albedo)	0.19	0.22	0.22
Light use efficiency ($kg\ ha^{-1}\ h^{-1}/J\ m^2\ s^{-1}$)	0.45	0.45	1.0

5.3.2 Water balance

Calculating reliable WP indicators requires an accurate simulation of the water balance components. In this study, the water balance components in the Furfuro SSI scheme were simulated using the calibrated model with field experimental data. The simulated water balance components are presented in Table 5.5. The contribution of the rainfall during the period of simulation was low. The simulated irrigation depth was slightly superior to the applied depth at all plots. However, it was directly proportional to the applied depth on researcher and farmer plots, and it represents the field condition. The simulated ET was 318.5 and 320.9 mm for wheat, 439.7 and 436.3 mm for onion, and 483 and 483.3 mm for tomato at the researcher and farmer plots, respectively. The simulated ET of wheat agreed with the mean ET obtained by Mebrie et al. (2023) in northern Ethiopia. The simulated ET of onion was slightly higher than the ET that has been reported by Bossie et al. (2009) in the central rift valley of Ethiopia. On the other hand, the simulated ET of tomato was less than the result of Dirirsa et al. (2017) in the Central Rift Valley of Ethiopia. The ET variation is possibly due to climatic differences across locations in the country.

Table 5.5: SWAP simulated water balance at the researcher and farmer field plot

	Researcher plot			Farmers field		
Water balance components	Wheat	Onion	Tomato	Wheat	Onion	Tomato
Rainfall (mm)	55.9	55.9	55.9	55.9	55.9	55.9
Irrigation (mm)	524	606	693	627	685	780
Transpiration (mm)	223.3	364.3	437.1	227.5	361	437.5
Evaporation (mm)	95.2	75.4	45.9	93.4	75.3	45.8
Evapotranspiration (mm)	318.5	439.7	483	320.9	436.3	483.3
Percolation (mm)	210.9	167.1	169.8	308.5	252.6	253.9
Soil water storage (mm)	30.42	35.2	71.2	33.2	32.6	73.5

For all crop types, the simulated percolated depth of farmer plots was greater than that of researcher plots. As shown in Table 5.5, the percolated depth is 210.9 and 308.5 mm for wheat, 167.1 and 252.6 mm for onion, and 169.8 and 253.9 mm for tomato at the researcher and farmer plots, respectively. The farmer plots in all crop types were always over-irrigated throughout the growing season. Despite the higher irrigation depth at farmer plots, the simulated T and ET in the growing season were closely the same with researcher plots for the same crop type. This implies that there was a substantial amount of unusable water at farmer plots. Van Dam et al. (2006) reported a comparable finding in Sirsa district, India. Over-irrigation increases the percolation amount (Vazifedoust et al. 2008), which is unusable water. A fraction of the over-irrigated water could either evaporate or be stored in the soil. There was no significant difference in soil moisture storage between researcher and farmer plots; however, the storage of tomato plots was greater than that of wheat and onion in both researcher and farmer plots.

5.3.3 Water productivity

Analysis of WP with different water balance components is beneficial for saving irrigation water (Singh et al. 2006). The physical and economic WP in both researcher and farmer plots was calculated using the simulated water balance components and field-measured yield data. Results indicated that the physical WP of all researcher plots was greater than that of farmer plots in all water balance components (Table 5.6). This was due to the fact that farmer plots received higher seasonal water depths than researcher plots for the same crop type. Farmers irrigated their fields, disregarding the crop's water requirement throughout the growth stage. Eshete et al. (2020) have reported excessive irrigation water application in the Ethiopian irrigation system, particularly in vegetable crops. The crop water requirement is based on climatic factors and the metabolic activities of the crop (crop factor) (Allen et al. 1998). Water used for irrigation in excess is non-beneficial, and it could be percolated, evaporated, or stored in the soil. Over-irrigation can reduce the WP in three ways: first, it increases the unusable form of water (evaporation, percolation, etc.) since crops cannot use water beyond their demand. Second, over-irrigation causes the leaching of essential soil nutrients, which are beneficial to increasing crop yield (Barton and Colmer 2006). Third, it reduces root zone aeration (Cui et al. 2020), which affects crop development and yield production.

As shown in Table 5.6, the physical WP of wheat was less than that of onion and tomato in all water balance components. In both researcher and farmer plots, the physical WP of tomato was greater than that of onion and wheat in all water balance components. The physical WP_{ET} of wheat was 0.17 kg m^{-3} at the researcher plot and 0.11 kg m^{-3} at the farmer plot, which is much less than the results reported internationally by Xue and Ren (2017) and Padhiary et al. (2020) and locally by Meskelu et al. (2017). The reason for the low physical WP_{ET} of wheat was a crop disease that severely affected the yield during the grain filling stage. Eshete et al. (2020) stated that crop disease affects the water use efficiency of the Ethiopian irrigation system. This implies that comprehensive disease-control systems are necessary for improving the WP of crops. The physical WP_{ET} of onion was 1.56 kg m^{-3} at the researcher plot and 1.5 kg m^{-3} at the farmer plot. The result falls within the range of 1.36 and 1.65 kgm^{-3}, which has been noted by Kifle et al. (2017) in northern Ethiopia. On the other hand, the physical WP_{ET} of tomato was 2.27 kg m^{-3} at the researcher plot and 2.16 kg m^{-3} at the farmer plot. Gebru et al. (2018) reported 4.2 kg m^{-3} in northern Ethiopia. The reasons for spatial variation of crop WP_{ET} might be due to differences in climatic factors, irrigation water management practices, and crop disease outbreaks.

The physical WP_T of wheat, onion, and tomato were 0.24, 1.89, and 2.50 Kg m^{-3} at researcher plots and 0.15, 1.82, and 2.38 Kg m^{-3} at farmer plots, respectively. Variations in physical WP_T between different crops can be observed due to variances in the chemical composition and harvest index of crops (Vazifedoust et al. 2008). The percolated water reduced the physical WP_{ET} to WP_{ETQ} in both researcher and farmer plots (Table 5.6). In the study area, there is no shallow groundwater, and the source of water for irrigation is canal water. Therefore, the percolated water will not be recycled, and it can be considered non-beneficial. Generally, to improve physical WP, either yield must be increased while maintaining a constant water level or yield must be kept constant while using less water (Hamdy et al. 2003).

Table 5.6: Physical WP of the wheat, onion, and tomato at researcher and farmer plots

Physical WP	Researcher plot			Farmers plot		
	Wheat	Onion	Tomato	Wheat	Onion	Tomato
WP_{I+R} (kg m^{-3})	0.09	1.04	1.46	0.05	0.89	1.25
WP_T (kg m^{-3})	0.24	1.89	2.50	0.15	1.82	2.38
WP_{ET} (kg m^{-3})	0.17	1.56	2.27	0.11	1.50	2.16
WP_{ETQ} (kg m^{-3})	0.10	1.13	1.68	0.06	0.95	1.42

The economic WP was also calculated using the net benefits gained from each plot and the simulated water balance components. The economic WP_T of wheat, onion, and tomato were 0.10, 1.04, and 1.42 \$ m^{-3} at researcher plots and 0.03, 1.00, and 1.34 \$ m^{-3} at farmer plots, respectively (Table 5.7). For wheat, onion, and tomato, the economic WP_{ET} were 0.07, 0.86, and 1.28 \$ m^{-3} at the researcher plots and 0.02, 0.82, and 1.21 \$ m^{-3} at the farmer plots, respectively. Economic WP decreased in all plots by taking into account the percolated water. The result indicated that the economic WP of all researcher plots was greater than that of farmer plots in all water balance components. This is directly associated with water consumption level and production quantity. The applied water volume differences between researcher and farmer plots have brought considerable variation in economic WP. On the other hand, wheat had a lower economic WP than onion and tomato, despite having a higher selling price per kg. In this study, tomato had a higher economic WP than wheat and onion. This was because tomato had a higher production volume, and the selling price per kg was also close to wheat during the data collection time for this study. In order to improve the economic WP, it is therefore clear that the economic viability of crops must be taken into account.

Table 5.7: Economic WP of wheat, onion and tomato at researcher and farmer plot

Economic WP	Researcher plot			Farmers plot		
	Wheat	Onion	Tomato	Wheat	Onion	Tomato
WP_{I+R} (\$ m^{-3})	0.04	0.57	0.83	0.01	0.48	0.70
WP_T (\$ m^{-3})	0.10	1.04	1.42	0.03	1.00	1.34
WP_{ET} (\$ m^{-3})	0.07	0.86	1.28	0.02	0.82	1.21
WP_{ETQ} (\$ m^{-3})	0.04	0.63	0.95	0.01	0.52	0.80

5.4 Conclusion

In this study, SWAP, the agrohydrological model, was used to determine the WP of the main irrigated crops in the Furfuro SSI scheme. The SWAP agrohydrological model can be applied to simulate water balance components such as evapotranspiration, transpiration, and percolation, as well as crop growth parameters such as dry matter and LAI to determine crop WP. The model is effective, enabling the investigation of viable strategies for managing water and crops to address water resource issues. Determination of WP in terms of water balance components provides information about how much water is lost from irrigation. A substantial amount of irrigation water is lost through percolation in the scheme due to over-irrigation in the farmer's practice. A lack of effective irrigation scheduling, excessive irrigation water application, and other issues are end up in poor on-farm water management and water productivity in the study area. Farmers' shortage of knowledge on-farm water management practices, especially when and how much water to irrigate, is a critical problem in the study area. Crop disease is also another factor that affects crop WP. Understanding the relationships between soil, crop, water, and atmosphere is important to investigate which farming practices help to produce "more crop per drop. The application of irrigation water based on crop water demand in the growing season can be used to save irrigation water and enhance the agricultural

WP. On the other hand, tomato demonstrated higher WP in the study area compared with wheat and onion, and wheat achieved the lowest WP due to the incidence of crop disease. Generally, irrigation water application based on crop water demand, crop selection, and crop disease control systems can be applied to enhance the WP.

CHAPTER VI: Summary and general conclusion and recommendations

6.1 General

The need for improved living standards and rapid population growth increased the demand for food production on a global scale. Conversely, erratic rainfall and recurring droughts have a significantly negative impact on agricultural productivity (Lebdi 2016; Kafle et al. 2020). Irrigated agriculture remains the most practical solution for reducing poverty and enhancing food security, especially in developing countries like Sub-Saharan Africa, which heavily depend on agriculture.

The Ethiopian government considers irrigation development a vital approach to mitigate climate change, attain food security, reduce poverty, and promote economic growth in the country. Over the past two decades, more attention has been given to the developing irrigation schemes in the country, particularly SSI. However, several dysfunctional and underperforming SSI schemes exist in various locations of the country due to poor planning, protection, and management systems (Amede 2015; Haileslassie et al. 2016b; Gebul 2021). Major problems of the SSI schemes in the country include poor weir stability and water storage capacity, poor operation and maintenance habits, the absence of strong IWUAs, ineffective irrigation scheduling, and a shortage of high-yielding crop varieties.

Therefore, this study aimed to first assess and understand the irrigation users' observations on technical and IWUAs management performance in the selected SSI schemes in the Ethiopian Rift Valley using household and scheme-level surveys. The study included field experiments to evaluate the on-farm irrigation scheme performance, modeling irrigation scheduling to optimize irrigation water, and scheme-level water balance assessment using an agrohydrological model to improve water productivity.

The general objective of this study is to investigate scheme-level institutional and on-farm irrigation water management practices and propose and develop approaches for effective irrigation water management to enhance water productivity and ensure sustainable production in the SSI schemes in the Ethiopian Rift Valley.

The specific objectives are:

- To assess the farmers' perception of the technical and irrigation water user associations' management performance of four SSI schemes and propose approaches to enhance irrigation water management.
- To evaluate the on-farm performance of two SSI schemes and provide evidence for decision-makers and the local community to take remedial action to enhance the performance of schemes for improved production.
- To develop a simulation optimization model for potato and wheat irrigation scheduling to save irrigation water and maximize yield.
- To analyze water balance components to save irrigation water and improve water productivity of the main crops.

6.2 Farmers' Perception on Technical and Irrigation Water User Associations (IWUAs) Performance of Selected Small-Scale Irrigation Schemes in the Ethiopian Rift Valley

In Ethiopia, irrigated agriculture is a key component of development policies that are intended to ensure food security under the current climate change conditions. The Ethiopian government has placed a high priority on the development of irrigated agriculture, which has mostly been accomplished by expanding SSI. Consequently, significant efforts and investments have been placed into water resource potential studies, irrigation system design, and infrastructure development. Particularly over the past two decades, in the programs "Plan for Accelerated and Sustained Development to End Poverty (PASDEP)" and "Growth and Transformation Plans (GTP)," significant achievements have been recorded in terms of the expansion of SSI (Gebul 2021). However, although it is generally agreed upon that irrigation is the most practical approach for lowering poverty, enhancing food security, and promoting general economic development in developing countries (Inocencio et al. 2007), the poor management of SSI schemes under the current growing competition for scarce water resources and climate change scenarios is a major concern. Due to poor management systems, several SSI schemes are underperforming in Ethiopia (Amede 2015; Agide et al. 2016; Haileslassie et al. 2016b). The problem is more severe in the case of the Ethiopian Rift Valley.

There is a growing need for the investigation of farmers' practices and opinions and adaptation and mitigating approaches to deal with irrigated agriculture challenges at local and regional levels (Deressa et al. 2009; Ricart et al. 2019). Understanding farmers’ perceptions allows the sharing of experiences and aids in the development of efficient adaptation strategies for the sustainability of agricultural systems (Lebel et al. 2015). In the second chapter of this study, farmers' perceptions and level of interest in the technical and IWUA’s management performance were assessed in four selected SSI schemes (Furfuro, Murtute, Bedene, and Sibisto) in the Ethiopian Rift Valley. Household surveys (173 households in the four SSI schemes), FGDs, KIIs, field visits, and performance reports were used for data collection. The survey data mainly focused on the reliability and water delivery performance of the schemes, fairness of irrigation water allocation among farmers, canal protection, operation and maintenance system, irrigation scheduling, and farmer and IWUA training. In addition, data on the strategies taken by farmers during irrigation water scarcity and the major challenges that confronted the farmers in irrigation system production were collected.

Results showed that the reliability and water delivery performance of Furfuro and Sibisto were rated as good by 52% and 41% of respondents, respectively, and poor by 22 and 25%. The survey results pointed out that the canal and diversion site cleaning and assistance with agricultural input supply have been coordinated by IWUA leaders at the Furfuro and Sibisto irrigation schemes. Additionally, illegal water diversion (vandalism) control systems were also implemented to generate inclusive water allocation plans between users. However, several irrigation users complained about the general management approach. In Murtute and Bedene, 73 and 51% of respondents, respectively, said that the reliability and water delivery performance were poor, and 11 and 21% rated them as good. Similarly, in Murtute and Bedene, several irrigation users criticized the fairness of the water allocation system.

All irrigation schemes had problems with water supply; though the severity of the problems varied. The survey participants and FGD members indicated that poor reliability and water delivery performance are mainly caused by poor maintenance and operating habits. During the field visit problems were realized. Water loss from overtopping and deteriorated structures was significant, especially at Murtute and Bedene. Water loss through conveyance and distribution systems indicates the poor management of the schemes by IWUAs (Sultan et al. 2014; Agide et al. 2016; Orojloo et al. 2018). The operation, maintenance, and water allocation systems of all SSI schemes in this study were unsatisfactory. Crops, particularly those at the tail reach of the schemes, experienced water shortage and, in some cases, wilted due to unreliable water flow. All of the irrigation schemes in this study did not have any restrictions on the amount of irrigation land that could be used. This leads to unfairness in water allocation between head and tail reach residents. The survey participants and the FGD members suggested the formulation of comprehensive water allocation plans, controlling water consumption, and imposing restrictions on irrigation land size to improve the water allocation system in the schemes.

The overall remark of participants in surveys showed that the IWUAs were unable to manage the schemes based on the outlined rules and regulations in the FDRE 2014 proclamation. The study results indicated that irrigation production is constrained by a shortage of technical knowledge, the weak performance of the IWUA, and poor irrigation infrastructure for effective management of irrigation at all schemes in this study. Lack of awareness on the guiding principles and financial constraints affected the IWUA's ability to manage the schemes properly. Studies in many countries indicated that farmers must enhance their capacity in technical and institutional domains to improve the performance of irrigation schemes (Kazbekov et al. 2009; Thiruchelvam 2009; Ghazouani 2012; Mutambara et al. 2016). Fees from irrigation water users must be collected, according to the FDRE 2014 IWUAs proclamation, in order to maintain and operate irrigation schemes. However, none of the IWUAs in this study were used to collect fees from water users. They therefore face financial limitations in executing their responsibilities. Several irrigation schemes in Ethiopia are managed without a cost-recovery system (Lebdi 2016). The majority of them cannot pay for their operating expenses. The implementation of water pricing may encourage sustainable financial management and more effective water resource management (Davidson et al. 2019).

In addition, survey participants indicated that poor market access, high input costs, and crop diseases are affecting their income in the study area. Poor value chain systems and dealers' misleading information affect the farmer's decisions on the market. Therefore, the government and stakeholders need to intervene by strengthening local irrigation institutions such as IWUAs, in order to succeed in irrigation development. The development of market value chains is another important issue that requires government intervention.

6.3 On-farm Performance Evaluation of Small-Scale Irrigation Schemes in the Ethiopian Rift Valley: Internal and External Performance Process Approach

Irrigated agriculture is the largest consumer of freshwater on a global scale, using 70% of all freshwater withdrawals. The Ethiopian economy is largely based on agriculture, which accounts for 43% of the gross domestic product, and 85% of employment, and is the source of input materials for industries. Nevertheless, the production is vulnerable to climate change and recurrent droughts. Irrigated agriculture has expanded across the country using primary SSI schemes in order to improve food security and lessen the effects of climate change. However, SSI schemes in Ethiopia are commonly characterized by poor on-farm irrigation water management and, consequently, poor performance (Derib et al. 2011; Eguavoen et al. 2012). Non-uniform on-farm water distribution, poor irrigation scheduling, and inappropriate duration of irrigation are some causes contributing to poor on-farm irrigation water management and low water productivity (Haileslassie et al. 2016a). Practices that include timely and optimal irrigation water application as well as those that improve plant water uptake are referred to as on-farm water management practices, which are used to reduce yield gaps (Rockström and Barron 2007). Improving irrigation system performance requires determining some relevant performance criteria and locating indicators that can provide information on the status of the schemes.

Chapter Three of this research describes the on-farm performance evaluation of Furfuro and Bedene SSI schemes using internal and external performance indicators. Climate, soil, water, and crop data were among the most important data collected for this study. Evaluating the on-farm performance of SSI schemes is an important step in determining the underlying causes of problems and looking at management options that can enhance production and revitalize failing irrigation projects. In this study, field experiments were conducted within the command area of the two schemes in the 2021/22 and 2022/23 irrigation seasons. Three crop fields (wheat, onion, and tomato) at the Furfuro and three crop fields (wheat, onion, and potato) at the Bedene were used to measure the irrigation water application depth. The irrigation water to the fields was measured using a 5.08*90 cm Cutthroat flume. Yield data, irrigated area, and incomes generated from irrigation users were collected from the respective district agricultural offices. Yield selling price data was collected from local markets. Scheme design and performance reports were assessed to gather the necessary information. Internal performance indicators, which include conveyance, irrigation, application, and distribution efficiencies, were analyzed, and external performance indicators, which include agricultural, water use, and physical sustainability indicators, were determined.

Results showed that Furfuro had average conveyance, application, and distribution efficiencies of 84%, 59%, and 50%, respectively, while Bedene had 79%, 63%, and 55%, respectively. The conveyance efficiencies in the two schemes were below the recommended values. Poor operation and maintenance practices and inadequate canal protection led to low conveyance efficiency. For the two irrigation schemes, the average irrigation application efficiency values were within the recommended ranges. However, across command areas within a scheme, application efficiencies varied. This indicated that the on-farm irrigation water management was not directed by a scheme-level irrigation water management system. The distribution efficiencies in the two schemes indicated that there was poor water application uniformity in the schemes. Low water distribution efficiency in surface irrigation systems will result in drainage losses, possibly leading to extremely inefficient water use. The study showed that the overall efficiencies of the schemes were 49.56% and 49.77% for Furfuro and Bedene, respectively. The minimum acceptable overall efficiency of irrigation schemes is 60%. This indicated that the two SSIs have low performance.

The study indicated that the OCA was less than the OIA in the two schemes. The yield per command area of the two schemes was less than the yield per irrigated area, implying that the irrigation intensity in the two schemes was less than one. Data on the irrigated area indicated that in Furfuro, 72%, and in Bedene only 27% of the total command area was covered by irrigation during the data collection season for this study. This was due to a shortage and improper management of irrigation water. The yield per irrigated area provides insight into how well scheme-level agronomic and irrigation water management practices were implemented.

On the other hand, based on the data analysis for this study, the OIS was less than the OCW at Furfuro and they were equal at Bedene. In Furfuro, the supplied irrigation water was greater than the demand in the specific season. The study found that in Furfuro, there was excess water in the command area. However, crops grown at the tail reach of the scheme experienced a water shortage. This implies a lack of a scheme-level compressive water management system. In Bedene, the amount of irrigation supply was less than the requirement in the specific season. Thus, the supplied and consumed amounts were equal, resulting in equal production values per cubic meter of supplied and consumed water. Strengthening local water institutions, such as irrigation water user associations, is important to improve on-farm water management performances.

6.4 Optimization of Irrigation Scheduling for Improved Irrigation Water Management in Bilate Watershed, Rift Valley, Ethiopia

Irrigation scheduling is making decisions on when and how much to irrigate. In Ethiopia, one of the major factors in the poor performance of irrigation schemes is improper irrigation scheduling (Alemayehu et al. 2006; Ayenew 2007). The need for water abstraction is rising due to ongoing irrigation expansion; during the last two decades, there has been a notable increase in the amount of land under irrigation in the country. Continuous water scarcity and increased emphasis on environmental issues have already driven regulatory countries to reconsider their water allocation procedures (Brown et al. 2010). To cope with the scarcity of irrigation water in the current climate change scenario, practicing efficient irrigation water management techniques such as irrigation-scheduling optimization is important. Agro-hydrological simulation models are capable of illuminating the dynamics of crop growth under different irrigation schedules and climatic conditions. The simulation models can be used to conduct scenario analysis in order to look for the most effective management approaches. Appropriate irrigation scheduling techniques are an important approach for saving irrigation water, improving the productivity of water, and enhancing the benefits to farmers (Koech and Langat 2018). Furthermore, irrigation-scheduling optimization is very helpful in achieving a fair distribution of irrigation water among users at the basin level, and it can also improve irrigation scheme performance. Knowledge of the yield response of crops to water conditions is important for effective irrigation scheduling optimization. In this study, the crop-water production function of potato and wheat was used to describe the relationship between crop water use and yield produced.

Chapter four of this thesis presents the irrigation scheduling optimization results for potato and wheat crops in the Bilate watershed, Ethiopian Rift Valley. The optimization process was started by scheduling different deficit irrigation treatments in the SWAT model based on the crop water requirement of the two crops, and yield and evapotranspiration were simulated. The Jensen crop water production function was then developed for the two crops (potato and wheat) using the simulated yield and evapotranspiration. Crop water production function is beneficial in irrigation water management systems (Igbadun et al. 2007). It is also helpful in determining irrigation strategies in situations where water supply is scarce and in assessing the economic implications of various crop water use levels (English 1990). In this study, the Jensen moisture stress sensitivity index was determined using the Python/Jupyter Notebook packages based on a multiple nonlinear regression analysis. The optimization of the irrigation scheduling was carried out based on the moisture stress sensitivity level of the crops. The optimal relative evapotranspiration for maximum relative yield was calculated using the genetic algorism (GA) on the platform of MATLAB (R2020a, MathWorks Inc., Natick, MA, USA).

The crop water production function and moisture stress sensitivity level were used to optimize the irrigation water in the growth stages. The comprehensive analysis of different deficit irrigation level simulations for potato and wheat crops indicated that deficit irrigation treatments are beneficial to identifying the most moisture stress growth stages of the crops. The result of the deficit irrigation simulation showed that the moisture stress sensitivity is higher at vegetative and starch-accumulation/grain-filling stages than at seedling and maturity stages. This means that at vegetative and starch-accumulation/grain-filling stages water deficit can reduce yield significantly. The finding shows that there is a strong correlation between the moisture sensitivity index and the growth stages of crops. During the seedling stages, the transpiration of the crops is low, and higher evaporation is expected. When crops grow higher, the transpiration increases until it reaches its maximum level and comes down after maturity. It is strongly recommended to carefully determine the actual growth stage-based crop water requirement before scheduling the deficit irrigation since it affects the crop water production function.

This study pointed out that effective deficit irrigation optimization based on the moisture sensitivity level is useful for saving irrigation water and improving crop yield. Comparisons of the yield of crops after and before optimization of the irrigation water showed that significant crop yield increment can be achieved in a reduced amount of irrigation water after optimization. Before optimization of the deficit irrigation, the simulated yield was significantly reduced compared with the full irrigation, particularly at T2 and T3 (the details are in Chapter 3). However, after optimization of the same amount of irrigation water based on the moisture stress sensitivity level of crops in the growing period, the yield increased. The result suggests that irrigation scheduling based on crop moisture stress sensitivity levels can be achievable at the scheme or basin level. The irrigation scheduling optimization method can be applied to irrigation system design and operation. It also allows for a great deal of flexibility in determining the irrigation interval in order to account for different soil and climate conditions. Irrigation scheduling optimization can be applied in conditions where the quantity of irrigation water available for the season is limited, and it can be applied to maximize the seasonal irrigation water distribution for a single crop (Tsakiris 1982).

6.5 Water Productivity and Water Balance Assessment in Furfuro Small-Scale Irrigation Scheme Using Agrohydrological Model

Water productivity articulates the value or benefit obtained from the use of water. Enhancing water productivity can significantly improve food production globally and alleviate poverty (Al-Said et al. 2012). Water scarcity issues can be mitigated by understanding water productivity scientifically to make more efficient use of limited water resources and increase the socioeconomic benefits of available water. Agricultural water productivity is directly related to rural poverty (Hanjra et al. 2009; Molden et al. 2010), and its improvement makes more people able to take advantage of the scarce shared water resources (Cook et al. 2009). The Ethiopian irrigation systems are dominated by SSI schemes, which are typically characterized by low water productivity (Derib et al. 2011). Lack of effective irrigation scheduling, uneven distribution of water on the farm, excessive or insufficient irrigation water application, and other issues can end up in poor on-farm water management and water productivity. Farmers' shortage of knowledge on farm water management practices, especially when and how much water to irrigate, is a critical problem (Haileslassie et al. 2016a). Understanding the relationships between soil, crop, water, and atmosphere is important to investigate which farming practices help to produce "more crop per drop. It is essential to assess the associations among irrigation water hydrological components such as transpiration, evaporation, and percolation on the farm level under various ecohydrological situations to enhance water management and productivity.

In Chapter Five of this study, the irrigation water balance and the water productivity of the Furfuro SSI scheme were assessed using the SWAP agrohydrological simulation model. Simulation models are effective in scenario analyses, enabling the investigation of viable strategies for managing water and crops to address water resource issues (Ines and Droogers 2002). They provide information at unlimited spatial and temporal resolution, making them useful tools for understanding the actual process. SWAP simulates the movement of water in the soil by taking into account the spatial and temporal variances of the water potentials within the soil profile (Ines and Droogers 2002). The SWAP model uses the soil cover fraction (SC) or LAI to determine soil evaporation and potential plant transpiration. It can also provide strong information about water balance components such as capillary rise, crop transpiration, soil evaporation, and percolation which are difficult to measure in the field.

Information about the water balance components of irrigation water is useful to improve water management and crop water productivity. The on-farm irrigation water management practices significantly affect crop water productivity. In Chapter five of this study, the crop water productivity of the farmers' irrigation practice and standard irrigation practice (based on the crop water requirement and standard irrigation scheduling) is demonstrated. The result indicated that the farmer's field received irrigation water regardless of the crop water demand and proper irrigation scheduling. Irrigation intervals are mutually decided upon and fixed among growers in many developing countries, such as Ethiopia (FAO 2016). Inadequate field irrigation techniques and poor water conveyance and distribution systems are the main causes of excessive water diversion. The irrigation water requirement of crops depends on the growth stages and climatic conditions. Over-irrigation increases the percolation and the runoff amount, which is unusable water. A fraction of the over-irrigated water could either evaporate or be stored in the soil which is significantly reduces the water productivity. Optimizing crop production per unit of water requires knowledge about irrigation application, which includes understanding when to irrigate, how much water to apply, and what level of stress at different growth stages (Tolossa 2021). In regions where water is the scarcest resource, it might be more advantageous for farmers to maximize water productivity rather than crop yield (Tolossa 2021). This is due to the fact that since the latter is not constrained, the water saved can be used to irrigate more land.

Over-irrigation can reduce crop water productivity in three ways: first, it increases the unusable form of water (evaporation, percolation, etc.) since crops cannot use water beyond their requirement. Second, over-irrigation causes the leaching of essential soil nutrients, which are beneficial to increasing crop yield. Third, it reduces root zone aeration and it might create favorable conditions for crop disease incidence which affects crop development and yield production. Excessive irrigation water application also affects the scheme-level crop water productivity. In several irrigation schemes in Ethiopia, usually, farmers at the head of the scheme have more advantages of irrigation water accessibility than those at the tail reach of the schemes. Crops grown at the tail reach of the schemes experience water shortages. These situations affect the overall scheme-level crop water productivity. The other result discussed in Chapter Five is the comparison of the crop water productivity of the major crop grown at the Furforo Irrigation Scheme. Wheat had lower physical and economic water productivity than onion and tomato in the study area. This was particularly due to the incidence of crop disease. Therefore, farmers should take care during crop selection and field management after planting.

6.6 Limitations of the study

Although I am confident that this research was well planned and achieved, there are always things that might have been better, thus resulting in some limitations to this work. The farmers perceptions on the technical and water management performance of SSI schemes (Chapter 2) would have been more beneficial if the influence of design and construction on management were analyzed. However, information on the primary design and construction of SSI schemes in Ethiopia is hardly available. This might limit the conclusions drawn based on questionnaires, reports, and observation. The irrigation supply data used for the analysis of on-farm performance evaluation at Furfuro and Bedene (Chapter 3) was the monthly average measured at the diversion site at different times of the day. However, due to unplanned water allocation at basin level, the discharge data might be affected, particularly at Bedene. The results would have been more convincing if discharge was measured throughout the day.

The precision of model simulations depends on the accessibility of various crop, soil, and water data. The result of the optimization of irrigation scheduling in Chapter 4 would have been more interesting if the crop water stress sensitivity level per growth stage were obtained from field experimental yield data. The crop water stress sensitivity level obtained from simulated data might deviate from the field obtained sensitivity level. In addition, the assessment of water productivity at different water balance components (Chapter 5) could have been at the watershed or basin level if experiments were conducted at all schemes considered in Chapter 1. This is also due to a financial and time shortage for conducting the experiments

6.7 General conclusions and recommendations

This study identified that due to a lack of training, guidance, and financial resources, the IWUAs were unable to manage the SSI schemes based on the outlined rules and regulations. In all irrigation schemes in this study, there was a problem with inconsistent water flow and unfair water allocation between users. Inconsistent water flows in the schemes were caused by poor maintenance and operating systems. Though the FDRE 2014 IWUAs proclamation has declared fee collection for irrigation water, none of the IWUAs in this study collect fees from irrigation users. Because of their financial limitations, they were therefore unable to maintain the deteriorating canals on time. Water distribution among users was unfair due to a lack of inclusive irrigation water allocation plans. Water scarcity affected crops, especially those at the tail reach of the schemes, as a result of uneven water allocation and irregular flow. While the severity of problems differs among the irrigation schemes in this study, all schemes had poor institutional management systems. Furthermore, a lack of value chain and market access and a high cost of inputs impacted the livelihood of the farmers.

The overall internal performance indicator of the Furfuro and Bedene SSI schemes indicated that the schemes were underperforming due to a lack of effective on-farm water management practices. The result implies that there is significant water loss in the schemes, and it reflects the findings of the survey on farmers' perceptions (Chapter Two of this research). Inadequate canal protection, poor operation and maintenance habits, and a shortage of awareness of on-farm irrigation water management skills affected the efficacy of the schemes. The relative irrigation and water supply of the Furfuro scheme demonstrated that, despite some parts of the scheme experiencing water shortages, the command area had a surplus water supply. Low river flow potential and an increasing need for irrigation water upstream of the Bilate River contributed to water stress in the Bedene SSI scheme. Generally, due to a shortage and mismanagement of irrigation water, the actual irrigated area of the schemes was less than the design command area, thus the total irrigation yield and output were less than expected.

Irrigation scheduling optimization based on crop water stress level can be helpful to save irrigation water and enhance water productivity. Particularly, in water shortage areas effective irrigation water optimization technique is useful to save water and increase the irrigated lands. The optimization method can also be applied in water-sufficient regions to enhance crop yield through the application of optimum water to the crops. Determination of crop water productivity in terms of water balance components provides information about how much water is lost from irrigation. This can be used to take appropriate measures to save irrigation water and enhance water productivity. The study also showed that irrigation water application based on crop water demand and crop selection significantly determines the scheme-level crop water productivity. Crop disease significantly affects the crop water productivity in the study area.

Therefore, by strengthening their interventions in various scenarios, the government and other stakeholders can enhance the effectiveness of SSI schemes. To be successful in irrigation development, local irrigation institutions (IWUAs) need to be strengthened. They need training on scheme management principles, and they need to have sustainable financial resources. In order to achieve irrigation scheme sustainability in the current difficult contexts, a sufficient budget must be allocated to support long-term capacity building at the national and local levels.

Fee collection from the irrigation water users should be implemented, which helps maintain deteriorated canals. Institutions at the district and zonal levels must also provide the IWUAs with strong supervision. In order to enhance the water allocation system in the schemes, it is also crucial to make sure that comprehensive plans for water allocation, water consumption control systems, and limitations on the size of irrigation land are implemented. The other important issue that needs government intervention is market value chain development. This could be done by strengthening market connections by promoting high-value and off-season crops, providing farmers with up-to-date market information, and connecting farmers to particular markets. In addition, updating farmers with regional and national market information could assist them in adjusting planting times following market demand. The planning, development, and management of irrigation schemes should include farmers.

Encouraging irrigation water management and irrigation agronomy research can be used to advance the farmer's indigenous knowledge. Training farmers in improved on-farm water management practices such as irrigation scheduling methods, irrigation water optimization systems, and agronomic practices can be useful. The application of simple and practical irrigation scheduling technologies should be encouraged to improve sustainable management practices. Enhancing crop disease-controlling techniques is most important for improved crop water productivity. Furthermore, it is pertinent to support the exchange of experiences between farmers (farmer-to-farmer learning) and experts from district and zonal levels and in other regions of the country. Negotiation between zonal and district-level institutions upstream and downstream of the rivers, particularly the Bilate River, is crucial. This can help in arranging comprehensive water turns and reduce the unreliability of water flow to the schemes.

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ANNEXES

A. List of Publications

Wabela, K., Hammani, A., Tekleab, S. et al. Farmers' perception on technical and irrigation water user associations (IWUAs) performance of selected small-scale irrigation schemes in the Ethiopian Rift Valley. Sustain. Water Resour. Manag. 10, 9 (2024). https://doi.org/10.1007/s40899-023-00989-x

Wabela, K., Hammani, A., Taky, A. & Tekleab, S. (2024) On-farm performance evaluation of small-scale irrigation schemes in the Ethiopian Rift Valley: Internal and external performance process approach. Irrigation and Drainage, 1–13. Available from: https://doi.org/10.1002/ird.2960

Wabela, K.; Hammani, A.; Abdelilah, T.; Tekleab, S.; El-Ayachi, M. Optimization of Irrigation Scheduling for Improved Irrigation Water Management in Bilate Watershed, Rift Valley, Ethiopia. Water 2022, 14, 3960. https://doi.org/10.3390/w14233960

B. Meteorological data for the irrigation scheme sites

B1. Meteorological data for Furfuro scheme

Month	Mean rainfall(mm)	Mean Min T (°C)	Mean Max T (°C)	RH (%)	Wind speed(m/s)	Sunshine (hrs)
Jan	20.3	10.1	25.7	52.4	1.2	8.5
Feb	25.3	10.6	25.9	48.0	1.3	8.4
Mar	49.0	11.1	26.1	53.9	1.3	7.8
Apr	123.0	11.0	25.9	62.7	1.3	6.9
May	75.8	10.8	25.9	70.4	1.1	6.8
Jun	109.4	10.6	25.8	79.9	1.2	5.1
Jul	199.6	10.5	25.6	85.3	1.3	3.5
Aug	169.5	10.5	25.5	85.3	1.1	3.9
Sep	159.8	10.5	25.5	80.7	0.8	5.4
Oct	75.7	10.3	25.5	63.5	1.3	8.2
Nov	19.1	10.2	25.5	52.4	1.3	8.8
Dec	11.0	9.9	25.5	48.5	1.3	9.3

B2. Meteorological data for Bedene scheme

Month	Mean rainfall(mm)	Mean Min T (°C)	Mean Max T (°C)	RH (%)	Wind speed(m/s)	Sunshine (hrs)
Jan	18.5	13.1	30.0	52.4	1.2	8.5
Feb	22.1	13.7	31.1	48.0	1.3	8.4
Mar	47.7	14.4	30.7	53.9	1.3	7.8
Apr	118.8	14.8	29.3	62.7	1.3	6.9
May	71.0	14.7	28.2	70.4	1.1	6.8
Jun	100.6	14.6	26.3	79.9	1.2	5.1
Jul	125.1	14.6	24.7	85.3	1.3	3.5
Aug	121.3	14.5	25.3	85.3	1.1	3.9
Sep	111.2	14.5	27.1	80.7	0.8	5.4
Oct	66.4	12.8	28.6	63.5	1.3	8.2
Nov	34.6	12.1	29.6	52.4	1.3	8.8
Dec	17.7	12.3	29.6	48.5	1.3	9.3

C. Survey questionnaires

C1. Household questionnaires

Personal information of respondent:

Name: ------------------------------- Age: -------- Sex: ------------ Occupation: ----------

Literate or illiterate --------------------------------- family size----------------------------

1. Role in the community

A. Kebele leader B. IWUA head C. IWUA member D. Kebele member E. other

2. Do you use irrigation for agricultural production? If yes,

Experience in years? ------------------------the amount of irrigated land (in ha): -------------

major irrigated crops: ---

3. Water source: A. modern scheme B. traditional scheme C. wells D. other
4. How do you know the next irrigation day?

A. based on the wilting sign of plants B. I will check the soil is dry or not

C. I have defined irrigation time D. based on the availability of water

E. other methods (write) --

5. How do you know how much to irrigate? ---
6. Is there IWUA in your scheme? A. yes B. no C. I don’t know

   If yes, describe its strength A. strong B. medium. C. weak

   If your answer is strong mention major tasks,---

If your answer is weak, mention major problems,--

7. Do the IWUA in your scheme has documented rules and regulations?
   A. yes B. no C. I don't know
   If yes, mention some rules ---
8. Is there a water management problem in your scheme? A. yes B. no
   If yes, mention problems---
   What do you think to solve the problem? ---
9. How often does the IWUA meet and discuss on management issues?
   A. Once in a month B. twice in a month
   C. no meeting D. Another: -------------------------------
10. How the water allocates to users?
    A. based on scheduled program B. based on water manager's personal interest
    C. based on users' request D. another way: ---------------------
11. How do you rate the water reliability and delivery performance of your scheme?
    A. poor B. moderate C. good
    If A or B, what are the reasons for the problems? ---
12. Is there a problem with the fair distribution of water?
    A. serious problem B. sometimes problem C. no problem
    If your answer is A or B, mention the problems: --
13. Any restrictions on the amount of irrigated land?
    A. yes, the amount of irrigated land defined by local administration
    B. No, there is no restriction
14. How do you observe general management system of your scheme? e.g canal protection, on-farm training, rules for controlling water consumption and water thefts, and maintenance. A. poor, B. moderate c. good
15. What measurements do you apply to solve irrigation water shortage?
16. Are there any conflicts between water users? A. yes B. no
    If yes, mention major reasons ---
17. Are there any conflicts between water users and IWUA? A. yes B. no
    If yes, mention major reasons ---
18. How do you solve conflicts? A. through IWAU B. through local administration C. local elders D. through courts E. in other ways
19. Did you get training on irrigation? A. yes B. no

If yes, mention the type of training---

20. Did you get any support from woreda or zone? A. yes B. no
    If yes, mention type of supports: ---
21. How much do you produce /season/ area?
    Vegetable------------------------------------ cereals --
    Pulse-- other crops ------------------------------------
22. What are the major problems do you think about in your irrigation production?
    A. water shortage B. water distribution problem
    C. water not available on time D. others (write)-------------------------------------
    How do you solve these problems? ---
    ----
23. What do you do to improve your irrigation production? ------------------------------------
24. Do you pay for irrigation water? A. yes B. no
    If yes, how do you pay? A. per hectare B. per m^3 C. per hour
25. Are you happy with the payment process? A. yes B. no
    If no, mention problems,---

C2. KII Questionaries

1. What is your responsibility in irrigation management?
   A. water manager B. IWUA head C. expert
   D. woreda office expert E. zone office expert F. Farmer
2. Do you think the irrigation management process is going well? A. yes B. no
   If no, what are major problems?--
   What do you think to solve the problems? --
3. Do you think the full irrigation potential of the kebele/woreda/zone is underuse?
   A. yes B. no
   If no, what are the problems for not using the full potential? -------------------------------
   ----
4. Is there IWUA? A. Yes B. No.
   If no, why you don't organized the IWAU?--
   If yes, what is its responsibility?--
5. Do you think the IWUA performing well? A. yes B. no
   If no, mention major problems,--
6. Do you support the farmers in any way (for zone and woreda)? A. yes B. no
   If yes, mention the type of support--
7. Do you suppevise the IWAU (for zone and woreda)? --------------------------------------
   ----
8. How do you allocate water for users (For IWUAs leaders)?
   A. based on scheduled program B. based on the water manager's personal interest C. based on users' interest
9. Is there a water management problem? A. yes B. no
   If yes, mention problems--
10. Do you have monitoring techniques for fair distribution of water b/n water users?
    A. yes B. no C. I don't know

If yes, mention some ---

11. How do you manage the field water application of the farmers (for zone and woreda)?
12. What do you think major problems in irrigation management
13. How do you manage the operation and maintenance? ---------------------------------------

C3. FGD Questionaries

1. Do you think the irrigation management process is going well?
   If no, what are major problems?--
   What do you think to solve the problems? ---
2. Is there IWUA? If yes, describe its strength
   If your answer is strong mention major tasks,--

   If your answer is weak, mention major problems,--

3. Do IWUA has documented rule and regulations?
   If yes, mention some rules ---
4. How often does the IWUA meet and discuss on management issues? ---------------------
   ----
5. How the water allocates to users? ---
6. Do you face a shortage of water in your scheme?
   If yes, how do you solve the problem? ---
7. Do you have monitoring techniques for fair distribution of water b/n water users?

   If yes, mention some techniques --

8. Who maintains the water distribution system? ---
9. Is there a problem with the fair distribution of water?
   If yes, mention the problems: ---
   Who led the water distribution? ---
10. Are there any conflicts between water users?

    If yes, mention major reasons --

11. How do you rate women's participation in irrigation production? -------------------------
12. Is there any budget source for the scheme?
    If yes, mention the sources---
    Who manage it? --
    Is there a management problem? If yes mention problems---------------------------------