Innovative irrigation water management: a strategy to increase yield and reduce salinity hazard of small scale irrigation in Ethiopia

Degol Fissahaye Yohannes

Propositions

1. Construction of water harvesting structures is not a guarantee for improving production and productivity in irrigation schemes unless proper irrigation water management is realized.
   (this thesis)

2. Easy and non-sophisticated approaches to on-farm irrigation water management are a good option to sustain small-scale irrigation schemes in Ethiopia.
   (this thesis)

3. Gender inequality in agriculture makes it hard to attain food security.

4. Building upon local innovations with the community is crucial for sustainable and successful transfer of technologies.

5. To become a wise agricultural scientist, one needs to know how to live and work with farmers.

6. A PhD degree opens new windows on societal challenges.

Propositions belonging to the thesis, entitled

Innovative irrigation water management: a strategy to increase yield and reduce salinity hazard of small scale irrigation in Ethiopia

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Chapter

1. General introduction

1.1 Irrigation in sub-Saharan Africa

Agriculture is the major social and economic sector in Africa, providing about two thirds of the employment in the continent (APR, 2015). In sub-Saharan Africa (SSA), the livelihood of about 85% of the inhabitants depends on agriculture (World Bank, 2008a).

Most of the agricultural land in Africa is rain-fed and subject to erratic rainfall and recurrent droughts, often leading to low performance (Lebdi, 2016; CTA, 2003; African Development Bank, 2018). As a result, food insecurity, poverty and low resilience to climatic effects are quite immense particularly in rural areas of SSA, including Ethiopia. Thus, increasing agricultural productivity is absolutely essential in Africa to address the challenges of food insecurity and climatic variability. Irrigation in this regard can be the most viable option for boosting agricultural productivity (Inocencio et al., 2007; Lebdi, 2016; Molden, 2007).

The successful economic growth, poverty alleviation and food security improvement achieved by Asian countries such as Hong Kong, Singapore, South Korea, Taiwan, Indonesia, Malaysia, Thailand and Vietnam has been largely attributed to expansion of irrigated agriculture, coupled with the use of high-yielding varieties and fertilizers (FAO, 2006; Hussain and Hanjra, 2004). According to Lebdi (2016), irrigation in SSA has contributed to the improvement in food security of the rural livelihood though it is still insufficient to eradicate hunger and secure food.

Many of the SSA countries, including Ethiopia, have not yet developed their full potential in irrigated agriculture. The total irrigated land in Africa is about 13 million ha, which makes up only 6 percent of the total cultivated area, as compared to 37 percent in Asia and 14 percent in Latin America (Scheumann et al., 2017). Looking at SSA, only 4 percent of the area in production is under irrigation (Svendsen et al., 2009). Moreover, for various reasons that include lack of capacity, irrigation management skill and market (Scheumann et al., 2017), poor governance and environmental impacts (World Bank, 2007), poor performance of most existing irrigation schemes is a major challenge for the sector throughout the continent and especially in SSA.

Considerable attention has been given by many developing countries, including Ethiopia, to the development of Small Scale Irrigation (SSI) for reducing poverty and achieving food security (Commission for Africa, 2005; Bhattarai et al., 2002; Hussain & Hanjra, 2004). In addition, it is expected that SSI provides sustained agricultural growth, employment for the landless and contributes to overall economic growth by boosting agro-industry (Molden, 2007).

Lagging growth pace of agricultural production in SSA countries in contrast to their relative population growth is another major challenge. According to the United Nations (2019), the current world population of 7.7 billion is expected to increase to around 9.7 billion in 2050. The sub-Saharan Africa countries could account for more than half (double their current population size) of that projected population growth (United Nations, 2017). To meet the food requirement of a growing global population by 2050, agricultural production needs to increase by 60% from its current level (Alexandratos and Bruinsma, 2012) and about 90% in developing countries alone (FAO, 2017).

At the same time, irrigation water withdrawals account for about 70% of global fresh water (Thenkabail et al., 2011). On top of this, water for irrigated agriculture will be limited due to rising competition from rapidly growing industrial sectors and urban populations (UNDP, 2007). Of the total global population, about 40% lives in international river basins (United Nations, 2008) while 62% of Africa’s total land is covered by transboundary river basins (Wolf et al., 1999). The increasing competition for fresh water in transboundary river basins will further intensify, particularly in Africa.

The climate is also changing at an alarming rate, which can be observed in terms of increases in temperature and changes in precipitation patterns. These changes can exacerbate the pressure on water availability, as well as access to and demand for water in Africa (IPCC, 2007; Molden, 2007; WWAP, 2015). As a major user of global freshwater withdrawal, the irrigation sector will be heavily impacted by climate change (IPCC, 2007).

Finally, proper management of irrigated agriculture is vital to providing successful and sustainable production. Inappropriate irrigation practices are likely to result in low production and productivity, water losses and adverse environmental impacts. According to Vörösmarty et al. (2005), the current performance of irrigated agriculture has been confirmed to be unsustainable. In particular, the threat of increasing irrigation-induced soil salinization has been a serious issue especially in arid and semi-arid regions (Tanji and Kielen, 2002; Wang et al., 2008). About 20% (45 Mha) of the irrigated land in the world is affected by salinity (Shrivastava and Kumar, 2015) with an annual loss of about 0.5 Mha land due to salinity and related water logging problems (Smedema, 2000).

Over-irrigation, rise of groundwater level and use of saline water for irrigation are the major causes of soil salinization in arid and semi-arid regions. The effect of salinity on soil and plants depends on the magnitude and nature of the salts, soil texture, and type of irrigation methods practiced at field and stage of plant growth. Generally, higher soil-water salinity (total concentration of soluble salts) causes physiological drought in plants due to high osmotic potential (Richards, 1954) whereas higher proportion of sodium ions relative to calcium and magnesium ions disperses soil aggregates and affects soil permeability. In addition, salt stress decreases plant growth owing to specific ion toxicity and nutritional disorder or a combination both factors (Läuchli and Epstein, 1990; Munns and Tester, 2008).

Thus, development and adoption of appropriate irrigation management practices is a matter of urgency in order to address the food security and environmental challenges facing the rural communities of SSA through increased production, water conservation and protection of the environment.

The aim of this study is to assess, understand and evaluate the current irrigation water management practices in relation to crop yield and soil salinization in the Tigray region of northern Ethiopia, and then come-up with practical and sustainable irrigation water management solutions that can increase productivity and enable farmers to cope with the problem of water scarcity and soil salinity.

1.2 Problem definition

Ethiopia in general and the Tigray region in particular are characterized by chronic food insecurity due to irregular rain and recurrent droughts (CIA, 2018; FAO, 2014; World Bank, 2007). Soil moisture stress is the major constraint to agricultural productivity in the Tigray region. Even in periods of relatively good rainfall, soil moisture is insufficient during the crop growing period, resulting in very low crop yields in the region (Berhe, 2011; Eyasu, 2005).

To address the problem of water scarcity and achieve food self-sufficiency, agricultural development through promotion of small scale irrigation (SSI) has been a priority for the Ethiopian government. Accordingly, huge efforts and investments have been made in Ethiopia since 1991 to increase the irrigated area and, with that, food production. As the main strategy of Ethiopia's Growth and Transformation Program, SSI has grown rapidly from 853,100 ha in 2009/10 to 1,853,100 ha in 2012/13 (MoFED, 2014). In line with the government’s policy in the Tigray region, about 92 micro-dams were constructed between 1992 and 2012, and several were under construction or in study and design phases (Berhane et al., 2016).

Despite these expanding ventures and immense endeavors, the performance of many SSI schemes is very poor (Amede, 2015; Awulachew and Ayana, 2011; Carter and Danert, 2006; Cofie and Amede, 2015; IFAD, 2005; MoA, 2011a). There are several unsuccessful and failing SSI that exist in Ethiopia (Awulachew et al., 2005; Carter and Danert, 2006) due to poor planning and management of the irrigation schemes. This reality in turn is threatening the livelihood of the rural community in Ethiopia.

As indicated by various reports and research results, poor irrigation water management is one of the major issues threatening the success and sustainability of the SSI schemes in the country (Dejen et al., 2011; Fonteh, 2017; IFAD, 2005; MoA, 2011b; MoFED, 2012). Little attention has been given to this failure of irrigation water management in the country (Dejen et al., 2011; Etissa et al., 2014; Kifle and Gebretsadikan, 2016; Van Halsema et al., 2011). To change this situation, research is needed to identify solutions that can lead to effective farmer adaptation, especially for irrigation water management when dealing with water scarcity in the face of climate change.

Many studies have identified irrigation water management as a problem in Ethiopia and recommended the need to improve irrigation efficiency and water productivity. However, there is insufficient detailed information about current irrigation water management; information which is needed for effective rehabilitation of the failing schemes and enhancement of farmers' adaptation capacity. Moreover, innovative approaches that consider the available local resources and capacity and knowledge of the beneficiaries are lacking. Local assessment of scheme and plot level irrigation water management practices, challenges, perceptions and adaptation strategies is vital to help researchers, policy makers and development actors design appropriate measures for the rehabilitation and sustainable management of the irrigation schemes.

Among the various irrigation water management practices, improper irrigation scheduling is one of the major factors, responsible for low production and productivity in most SSI in the county (Etissa et al., 2014; MoA, 2011b), and particularly in the Tigray region (Eyasu, 2005; Libseka et al., 2015; MoA, 2011b). As a consequence of poor irrigation scheduling, huge amounts of water losses, low crop yields and environmental impacts (such as waterlogging and secondary soil salinization) have become major concerns in most SSI schemes (CRS, 1999; Etissa et al., 2014; Eyasu, 2005; Mintesinot et al., 1999; Mintesinot, 2002; Teshome, 2003). According to various studies (CRS, 1999; Dejen et al., 2011, Etissa et al., 2014; Eyasu, 2005; MoA, 2011b), lack of simple approaches for scheduling, and low technical knowledge and practical skill levels of farmers on the fundamentals of irrigation are the major reasons contributing to poor irrigation scheduling practices in Ethiopia.

Although weather-based irrigation scheduling is the most common and practical approach, it continues to be a challenge in Ethiopia due to lack and/or limited availability and poor quality of meteorological data (Ayenew, 2003; Dinku et al., 2016; World Bank, 2006a).

Furthermore, lack of locally trained professionals and access to computers make it more complicated. Innovations on irrigation management and practices are, thus, greatly needed to bridge these gaps (Pereira et al., 2002) while there is also a need to develop simple monitoring tools and conceptual frameworks that enable structured learning (Annandale et al., 2011).

Irrigation scheduling practices in SSI must be simple, useable and understandable by farmers in order to be adopted (Hill and Allen, 1996; Hargreaves and Samani, 1987). Experience shows that a locally based approach has the potential to be highly effective and successful (Shortt et al., 2004). It is therefore important to identify, develop and evaluate simple and practical approaches for irrigation scheduling that consider local conditions and which can be easily practiced by local extension agents as well as understood and applied by farmers.

Compared to other SSI in Ethiopia, the success and sustainability of irrigated agriculture in the Tigray region has been facing more challenges (Awulachew et al., 2005; Eyasu, 2005; MoA, 2011b; Mitiku et al., 2001). In the Tigray region, the water harvested in micro-dams is being used for complementary irrigation after the harvest of the rain-fed crops, in order to enable double cropping. The complementary irrigation season generally starts around mid-December and extends till May. Most of the micro-dams in the region are found in areas dominated by sedimentary rock and, as a result, 53% to 60% of them are encountering serious seepage problems (Berhane et al., 2016; Haregeweyn et al. 2006). The high seepage losses in turn reduce the availability of irrigation water. The scarcity of water for irrigation is further complicated by previously mentioned poor irrigation water management practices. Consequently, low production and productivity, loss of water, waterlogging, soil salinization, rise in water table and decrease in the size of irrigated area have been reported in many SSI irrigation schemes in the Tigray region (Eyasu, 2005; Mintesinot etal., 1999; Mintesinot, 2002).

As a counter measure to the existing acute water scarcity in the Tigray region, using seepage water for irrigation in most SSI schemes is becoming common practice although seepage water from micro-dams is known to be saline (Eyasu, 2005, Mitiku et al., 2002). The seepage water is used as the sole source for irrigation or in conjunction with fresh canal water. Using saline water as a source for irrigation without appropriate management can result in the accumulation of salts in the root zone and adversely affect crop productivity (Bezborodov, 2010; Minhas and Bajwa, 2001; Rhoades, 1984). This is likely among the major factors aggravating soil salinization and crop yield decline in the region (Eyasu, 2005; Teshome, 2003). The problem is expected to be more exacerbated in vegetable crops such as onion, which is the major irrigated crop and sensitive to salinity.

Thus, improved management practices for sustainable use of poor quality water in irrigation are required (Crescimanno, 2007; FAO, 2012; Rhoades et al., 1992).

If we identify, test and evaluate simple and practical, site specific techniques for improving the conjunctive management of the scarce water resources, it will be more possible to increase water management efficiency and productivity as well as mitigate soil salinity and crop yield decline. As the long term effects of saline water on soil health and crop yield are gradual, it is also essential to evaluate the long term impacts of promising innovations using field experiments to reach sound conclusions and assure sustainability of irrigated agriculture in Tigray and elsewhere in Ethiopia. In view of these crucial problems and research needs, this PhD research project intends to accomplish the following research objectives.

1.3 The research objectives

The general objective of the study is to investigate, in a participatory manner, the impact of innovative water management practices on crop yield and soil salinity in small scale irrigated agriculture in Tigray, Northern Ethiopia, as a contribution to sustainability in irrigation development.

The specific objectives are:

- to assess the current irrigation water management practices, challenges, and farmers' perceptions and adaptation,
- to identify, develop and evaluate appropriate and practical irrigation scheduling on maize yield and salinity hazard in a participatory manner,
- to identify a sustainable way of using both fresh and moderately saline water resources for the production of onion, through cyclic irrigation strategy, and
- to simulate and predict the long-term impact of conjunctive irrigation strategies on crop yield and soil quality.

1.4 Research approach

We applied irrigation scheme level as well as field level approaches to meet our research objectives. The current status of the irrigation scheme was analysed through scheme as well as field level assessments. Data from field experiments were used to evaluate alternative irrigation scheduling and conjunctive irrigation strategies on crop yield and soil salinization, as well as on farmers and local extension agents' opinions. Further, as a decision support tool, the SWAP model was used to evaluate the long term impacts of the conjunctive irrigation strategies on crop yield and soil health.

1.5 The study site/area

The Tigray National Regional State is located in northern Ethiopia (between latitudes of 12° 15' N and 14° 57' N and longitudes of 36° 27' E and 39° 59' E) with a total area of 53,638 km^2 and stretching from the Sudan border in the West to Eritrea in the North. The Ethiopian regions of Amhara and Afar border it in the South and East, respectively. The total population of Tigray in 2018 is estimated at 5.44 million (CSA, 2013), and the majority (more than 80%) are agriculturalists, contributing about 40% (2010/11) of the regional gross domestic product (BPF, 2010). There are 47 Woredas (districts) in the Tigray region.

The study site, Gumselassa watershed, is located in Hintalo-Wojerat Woreda (12° 65' N and 13° 27' N and 39° 15' E and 39° 55' E) in the southern zone of the Tigray region (Figure 1.1). Similar to many other parts of the region, the Woreda is characterized by low and erratic rainfall with high temporal and spatial fluctuation, which is typically semi-arid. The average annual rainfall recorded at the Adigudom meteorological station (the nearest station to the study site) is about 500 mm that tends to be unimodal, with more than 89% of the rain falling within the period of four months from June to September (Figure 1.2). Gumselassa has a catchment size of 24.6 km^2. The SSI was constructed in 1995 by the Regional Government. The dam has a water holding capacity of 1.92 million m^3 and is designed to irrigate 110 ha of land. The major irrigated crops in the area are maize, onion, tomato, vetch, pepper, garlic, green pea, chickpea, potato, teff, and barley. Clay is the most dominant soil type.

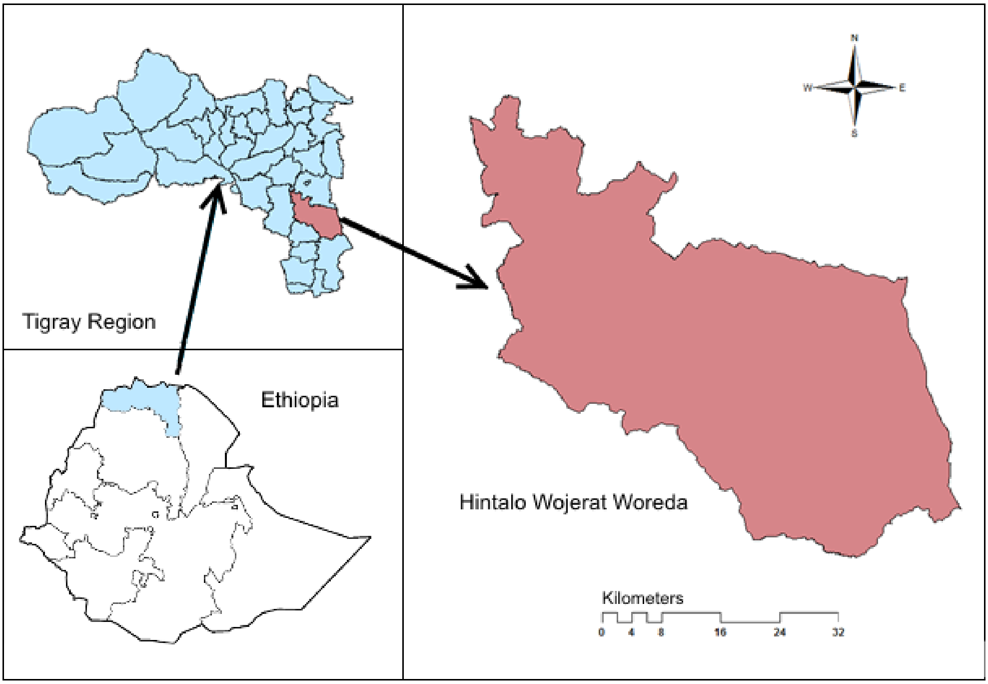

Figure 1.1 *Location map of Hintalo-Wojerat Woreda (District).*

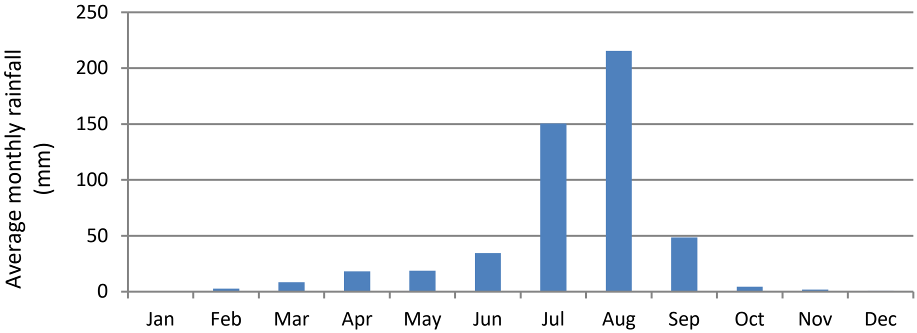

Figure 1.2 *Average monthly rainfall of 43 years (1975-2017) at Adigudom station.*

1.6 Thesis outline

Chapter 2 contains the findings regarding the farmers’ practices, perceptions, problems, challenges and adaptation strategies related to irrigation water management. In this chapter irrigation scheme and plot level data were combined to reach sound conclusions. In Chapter 3 the results of the evaluation of alternative irrigation scheduling methods are presented based on two year field experiments. This chapter also includes suggestion for the best irrigation scheduling method based on the field performances of the alternative strategies and the farmers' opinions. Chapter 4 covers the evaluation of cyclic irrigation strategies based on field experiments. Similar to Chapter 3, this chapter also includes suggestions for the best cyclic irrigation strategies based on the observed yield, the salt build-up in the root zone and farmers' and local extension agents' opinions. In Chapter 5 the outcomes of the simulation of the long-term impacts of existing and suggested cyclic irrigation strategies on relative yield and salinity build-up using the SWAP model are presented. Lastly, in Chapter 6, a synthesis of the main findings and implications of the study are presented.

2. Irrigation water management: farmers' practices, perceptions and adaptations at Gumselassa irrigation scheme, North Ethiopia

Poor irrigation water management associated with water scarcity is the major reason for underperformance of most small-scale irrigation schemes in Ethiopia. In order to devise appropriate measures for rehabilitation of the failing schemes and to enhance farmers' adaptation capacity to water scarcity, it is important to assess site specific plot and scheme level water management practices, challenges, farmers' perceptions and adaptation strategies. So far, there is no such study in the context of Tigray, Ethiopia. A survey was conducted on 109 farmers in three groups based on the source of irrigation water, which included canal, seepage and both canal and seepage water users. Focus group discussions with elders, water users association (WUA) committee and women headed households were also made. Furthermore, random field measurements on conveyance loss, groundwater depth and quality (EC) were also taken to verify the farmers' perception. The respondents' perception of severe water scarcity at scheme level and poor on-farm and scheme level water management practices are among the major causes for aggravating water scarcity, crops yield decline and soil salinization were in line with field observations. Despite several adaptation strategies of the farmers at plot and at scheme level, yield is still declining. The only adaptation strategy that has been enforced by the local government authority was reduction of the irrigated land. However, in the 2016 irrigation season the farmers were allowed to make their own decisions that resulted in innovative water scarcity adaptation strategies and that doubled the irrigated land as compared to the local authority plan. This showed the significance of allowing the beneficiaries to make their own decisions. To rehabilitate Gumselassa irrigation scheme as well as to enhance the adaptation capacity of the farmers to water scarcity capacity building and empowerment of the WUA and improvement on the existing water structure is required.

Based on:

D.F. Yohannes, C.J. Ritsema, H. Solomon, J. Froebrich, J.C. van Dam, 2017. Irrigation water management: Farmers' practices, perceptions and adaptations at Gumselassa irrigation scheme, North Ethiopia. Agricultural Water Management. 191, 16–28.

2.1 Introduction

The Ethiopian economy does depend on Agriculture which is heavily hindered by climate change. Many literatures testified that Ethiopia is prone to recurrent drought and food insecurity as a result of highly erratic rainfall (Awulachew, 2006; FAO, 2011; MoA, 2012; Namara et al., 2006; World Bank, 2006a). The country has been experiencing devastating impacts of drought which resulted in poverty (MoA, 2012), famine (JGHPD, 2016), migration, loss of life and property (World Bank, 2008b).

Irrigation development is an important means for achieving food self-sufficiency in many arid and semi-arid countries, including Ethiopia, in order to address the main challenge caused by food insecurity and water scarcity. Many literatures also agree that development of irrigation can be taken as a strategy for reducing poverty and ensuring food security in the world poorest regions (Hussain & Hanjra, 2004; Keller & Roberts, 2004; Magistro et al., 2007; Polak & Yoder, 2006; World Bank, 2007).

Agricultural development through irrigation has been a priority for the Ethiopian government since 1991 (NRST, 1997). To mitigate impact of climate change (FDRE, 2007), to address the main challenge caused by food insecurity and water scarcity, to stimulate economy (MoFED, 2006; MoFED, 2010;MoWR, 2002), as well as to reach the level of middle-income country economically as of 2020-2023, promotion of small scale irrigation (SSI) is identified as one of the priority policies for Ethiopia (MoFED, 2006; MoFED, 2010).

Accordingly, huge efforts and investments have been done in Ethiopia to increase the irrigated area so as to increase food production and achieve food self-sufficiency. Recently SSI as major strategy of the Growth and Transformation Plan of Ethiopia, the development increased rapidly from 853,100 ha in 2009/10 to 1,853,100 ha in 2012/13 (MoFED, 2014) which shows the government’s effort and commitment.

Despite these increasing investments and huge efforts the performance of many small scale irrigation schemes is far from satisfactory (Amede, 2015; Awulachew and Ayana, 2011; Carter and Danert, 2006; Cofie and Amede, 2015; IFAD, 2005; MoA, 2011a; Teshome, 2003). According to Peden et al. (2002), sometimes no difference in food security status is observed between rain fed and small scale irrigation users. There are many already failed and failing SSI that exist throughout Ethiopia (Carter and Danert, 2006).

According to different reports and research results, the major reasons jeopardizing the sustainability of irrigation schemes are poor water management and institutional arrangements (IFAD, 2005), excessive siltation, poor agronomic and water management practices and the failure of local institutions to sustainably manage the SSI schemes (MoFED, 2012). This has resulted in water and yield loss, and undesirable environmental impacts.

Tigray region is one of the most degraded and drought prone regions of Ethiopia. As a result the region has been engaged in massive irrigation development activities within the framework of the national strategies since 1994 (NRST, 1997). By the end of 2003, 54 micro-dams have been constructed (Haregeweyn et al., 2006). The total irrigated land increased from 4,000 ha in 2004 to 83,000 ha in 2009 (BPF, 2010). However, poor irrigation water management has been one of the major factors challenging the success and the sustainability of these efforts in the region (Eyasu, 2005; Mitiku et al., 2001).

Even though Ethiopia is one of the fastest growing economies in sub-Saharan Africa, poverty still remains to be a major challenge making the country highly vulnerable to a wide range of climate change (MoA, 2012; MoARD, 2015), particularly in the agricultural sector (Jones et al., 2013; MoA, 2012). In the recent year (2016) about 10.2 million people need food assistance in Ethiopia due to the occurrence of severe drought, of which over 1.2 million were from Tigray region (JGHPD, 2016).

Though, the Ethiopian government is addressing water scarcity through constructing various water harvesting structures, the issue of sustainability is given little attention. According to WWAP (2015), the current performance of the irrigation sector is environmentally unsustainable. Little attention is given to the already existing schemes in the country and particularly in the region irrespective of their problems and challenges. Worldwide, the sustainability of agriculture is a major concern for researchers, farmers, and policy makers (Foley et al., 2005). Through revamping of the existing schemes there is still great opportunity to enhance productivity (World Bank, 2007).

In order to devise appropriate measures for rehabilitation of the failing schemes and to enhance farmers’ adaptation capacity especially to water scarcity in the face of climate change, it is important to assess site specific irrigation water management practices, challenges, farmers’ perceptions and their adaptation strategies. So far there is no irrigation water management study that combines plot and scheme level challenges, farmers’ practices and perception and adaptation strategies of the failing schemes in the context of Tigray region. Using data from a survey, field observations and measurements, this study addressed the above stated gapes with special attention to irrigation water management in Gumselassa irrigation scheme, Tigray region, North Ethiopia. This paper is organized as follows: Section 2 describes the study area and the data collection methodology. Section 3 presents the results and discussion. This section explores the farmers' irrigation practices, their perceptions, major problems and impacts of existing irrigation water management practices and adaptation strategies. Section 4 draws conclusions and policy implications.

It is believed that this study will help local and regional decision makers and researchers in developing site specific appropriate strategies for rehabilitating the failing irrigation schemes and enhancing the farmers' adaptation capacity.

2.2 Methodology

2.2.1 Study site description

The study was conducted at Gumselassa irrigation scheme, Tigray region, Northern Ethiopia specifically located between $13^013'$ to $13^015'$ N and $39^030'$ to $39^033'$ E (Figure 2.1). The Gumselassa irrigation system was constructed in 1995 by the Regional Government to initiate complementary irrigation in the area, which usually starts around in January and extends to June. The irrigation practice at this scheme was started about two decades ago depending on an earthen dam with a reservoir capacity of 1.9 M m^3 of water. The planned command area was 110 ha of land to benefit more than 550 households. However, the maximum total irrigated land reduced to about 86 ha in 2003 (Teshome, 2003). Since 2004, the maximum area (active command area) that received water from the canal was restricted to about 60 ha of land due to mainly design problem and water shortage. This study mainly focuses on the active command area.

The climate in the study area is characterized by low and erratic rainfall. The average annual rainfall and reference evapotranspiration are 500 mm and 1577 mm, respectively which indicate that the area is typically semi-arid.

Review of secondary sources and discussions with the regional Bureau of Agriculture and Rural Development and *Woreda*[1]level office leaders and experts as well as EAU4Food (European Union and African Union cooperative research to increase Food production in irrigated farming systems in Africa) project members confirmed that the Gumselassa irrigation scheme can be representative for other irrigation schemes in Tigray region as most of the problems have been manifested in this site. Therefore, it is an appropriate site for research in water management.

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[1] District or an administrative hierarchy below Zonal administration.

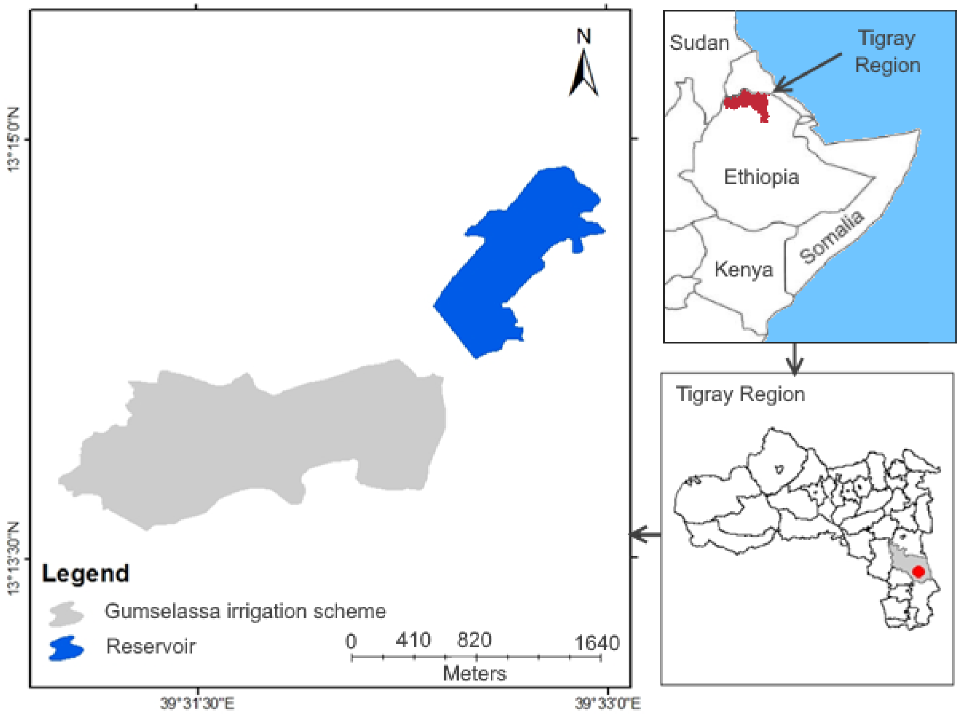

Figure 2.1 *Location of Gumselassa irrigation scheme.*

2.2.2 Method of data collection

2.2.2.1 Field visits

Frequent field visits and observations on the command area, canals, and drainage and farmers' irrigation activities were made in 2015/16. During the field visits, discussions were held with local experts, local administrators, irrigation scheme farmers’ committee and individual farmers. The discussion focused on the general set up of the irrigation scheme, major problems and constraints, Water User Association (WUA) and irrigation water management.

2.2.2.2 Group formation and sampling procedure

For the purpose of water supply, the command area is divided into left and right banks. The primary canal branches out into two secondary canals. Each canal supplies water to one bank. The active irrigation scheme was clustered into 5 zones namely left upper, left middle, right upper and right middle and tail end. Although, it was not possible to get the same respondents number in each zone, stratified random sampling was considered as much as possible to homogenize the distribution.

The sample survey was grouped into three categories based on the source of water they utilize for irrigation. The first group was the majority who use canal water for irrigation, the second group those who use seepage water for irrigation and third group comprised those who utilize frequently both seepage and canal water conjunctively for irrigation.

2.2.2.3 Interviews

Semi-structured questionnaires were prepared each group. After pre-testing the questionnaires, 75 farmers from the first group, 25 farmers from the second group and 9 farmers from the third group were interviewed. The interview was conducted during the irrigation season from December 2015 to April 2016. The data were analyzed with descriptive statistics using SPSS 22 software.

2.2.2.4 Focus group discussions

After the interview, focus group discussions with elders, irrigation committee, water distributors and with local leaders were held to verify ambiguous issues related to irrigation water management. To assess any issues related to irrigation water management and women headed households (WH HH) interviews and discussions with 15 WH HH were conducted.

2.2.2.5 Quantitative measurement

To relate the qualitative result obtained from the survey with quantitative data, random measurements were done on canal conveyance loss, water quality (EC) of canal water, seepage water and groundwater and the groundwater level. For conveyance loss measurement six irrigators, three each from the left as well as the right bank of the command area were selected and the discharges at the quaternary and farm inlet were measured using Parshall flumes.

2.3 Results and discussion

2.3.1 Socio-economic characteristics of farmers

From the total of 109 farmers interviewed, the majorities (56%) were older than 50 years and more than 52% farmers have an experience of irrigation for more than 15 years. Of the interviewed respondents, 69.7% were owners of irrigated lands and 32.1% were *sharecroppers*[2](Table 2.1).

Table 2.1. *Distribution and characteristics of sample respondents.*

Age	Irrigation Experience (year)	Water Source for irrigation								
		Canal			Seepage			Both		
		Ownership			Ownership			Ownership		
		Own	Share-cropper	Total	Own	Share-cropper	Total	Own	Share-cropper	Total
>60	>15	9	2	11	8	1	9	1		1
	10-15	3	0	3	1	1	2			
	<10	0	2	2	2	0	2			
50-60	>15	11	5	16	1	1	2	2		2
	10-15	4	3	7	0	1	1	1		1
	<10							2		2
40-50	>15	10	4	14	1	0	1			
	10-15	6	3	9						
	<10	3	6	9	0	3	3	2		2
30-40	>15	0	1	1						
	10-15							1		1
	<10	2	1	3	4	1	5			
Total		48	27	75	17	8	25	9	0	9

2.3.2 Woman headed households (WH HH) involvement in irrigation

Though the number of women headed households (WH HH) having irrigation plots in the active command area were 69 (23%), contrary to our expectation none of them were actively involved in irrigation practice. They rather arrange sharecropping and get one third or half of harvest in every season. The presence of many WH HH with ownership of irrigated lands during our survey in 2015/16 were thus in the form of sharecroppers. A discussion with irrigation committee and a separate interview and discussion with 15 WH HH revealed that there was only one WH HH named Amete Etay, who had been actively engaged in irrigating her plot for three years from 2000-2002 and then onwards she offered it to sharecroppers. From the interview and discussion made with her, the major reasons for offering her plot to sharecroppers are summarized below as a case study in Box 2.1.

A study conducted in Nicaragua by Blaauw (1992) also indicated that women prefer to irrigate late due to similar reasons. According to IFAD (2012), gender inequity has resulted in failure of irrigation schemes.

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[2] Sharecropper- a tenant farmer who pays a share of crop harvest as land rent to land owner

Moreover, the interview and discussion with the other WH HH with irrigation plots in the study area revealed that their reasons for offering their plots to sharecroppers were similar to Amete's reason though they don't have practical experience in irrigated agriculture.

Box 2.1 *Case study of Amete Etay (WH HH)*

The difficulty to manage both household and irrigation activities simultaneously, lack of family labour, lack of oxen for ploughing and lack of money to purchase fertilizer were her major reasons for quitting irrigation. She had to perform her household duties (fetching water, cooking etc.) and yet usually arrives late to request irrigation water. However, the rule of the WUA states that "first come first serve" and she often wouldn't get water at the right time. Her three years practical experience revealed that irrigated agriculture was challenging, drudgery and discouraging for WH HH. Then she had no choice other than offering it to sharecroppers.

Empowerment of women especially in Sub-Saharan Africa countries has been cited as indispensable for poverty reduction, human development and economic growth. To achieve these goals, the Ethiopian government has taken many steps to empower women and they are entitled to affirmative measures in political, social and economic life (FDRE, 1995). Despite the impressive progress for example in enrolment to higher education, health, recruitment, positions and involvement in politics, agricultural land redistribution etc., involvement of woman in irrigation is still unsatisfactory.

In order to engage woman irrigators equally as men in community managed irrigation schemes, it is necessary to enhance women decision-making in irrigation management through local level policies and efforts and involvement and representation in WUA. Many studies also advocate the need for participation and empowerment of women in water related issues (Awulachew, 2010; ICWE, 1992; IFAD, 2012; World Bank, 2007; Xie, 2006).

2.3.3 Farmers' irrigation practices

2.3.3.1 Irrigation water source, allocation and distribution

Scheme wise, the majority of the farmers use canal water from the dam for irrigation. On the other side, there is a significant amount of water that seeps few meters downstream from the embankment of the dam. Though, various studies reported that this seepage water is saline (Eyasu, 2005; Mitiku et al., 2002), it is being diverted and used for irrigation mainly due to canal water scarcity. Similarly, due to the increasing demand and unreliability of canal water for irrigation especially in arid and semiarid regions of the world, farmers are forced to use poor quality water alone or along with canal water (Amer, 2010; Kaledhonkara et al., 2012; Kazmi et al., 2012; Minhas et al., 2007; Qureshi et al., 2004).

In the study area, most of the farmers at the tail end use this saline seepage water for irrigation. According to Eyasu (2005), a maximum of 25 ha (125 farmers) and an average of 18 ha (90 farmers) irrigated using this seepage water. However, from the current study (Table 2.2), the average irrigated land irrigated during 2010-2016 using seepage water was about 12 ha (60 farmers). Though more than 20 farmers at the upper and middle position of the command area use both canal and seepage waters interchangeably for irrigation, the frequent conjunctive users of both waters were 9 farmers.

Table 2.2 *Irrigated area and number of beneficiaries in Gumselassa irrigation scheme from 2010-2016.*

Year	Total irrigated area (Ha)	Canal water users		Seepage water users		Both water users	
		Irrigated area (Ha)	No. of Beneficiary	Irrigated area (Ha)	No. of Beneficiary	Irrigated area (Ha)	No. of Beneficiary
2016	22.6	15.4	77	2.6	13	4.6	23
2015	34.1	24.8	124	7.5	37	1.8	9
2014	39	27*	135*	12	60		
2013	46	34*	170*	12	60		
2012	52	34*	170*	18	90		
2011	60	43*	215*	17	85		
2010	54						
Average		29.7		11.5			

* Represents canal and both (canal and seepage) water users

The irrigation water is open every day early morning at 5 to 6 AM and the closing time may extend up to 5PM from Monday to Saturday except in public and religious holidays. The water allocation system is based on first come first serve rule. The "*Abo Mai*[3]" (Father of water) is responsible for allocating the water. It is common to observe farmers queuing gathered near the embankment of the dam early in the morning. Those who come late may not get water that day.

The farmers within the group irrigate their plot based on their queue irrespective of the distance of their plots from the water source. One or two farmers may irrigate at a time depending on the discharge. The worst scenario was, one or two farmer/s located on the middle position of command area may irrigate first then, a second farmer/s located on the upper position command area may continue and so on. And it has been observed that this type of canal water distribution results in conveyance water wastage. Seepage loss in unlined conveyance system is the major portion of water loss in the irrigation system (Ali, 2011). In this way huge amounts of water are being wasted through canal seepage and runoff.

According to Eyasu (2005), the irrigated area in Gumselassa in earlier time was divided into irrigation units consisting of a group of farmers with their group leader. The water was

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[3] Person responsible for water allocation and distribution (within the sized portion of the scheme for irrigation)

distributed in a rotational manner. The group leaders were responsible for water management and maintenance within their unit. Similarly, Van Halsema et al., (2011) reported a rotational manner of water distribution to blocks in Haleku irrigation scheme in Ethiopian rift valley.

However, the recent study in Gumselassa confirmed that there were no irrigation units and group leaders, but individual farmers were responsible for requesting water to the Abo Mai. This showed that the WUA has been weakened and the water distribution and allocation system in Gumselassa SSI has been deteriorated. And yet the efficiency of irrigated agriculture greatly depends on the manner of allocation and distribution of water within the scheme. In surface irrigation rotational system of water distribution is proved to be efficient from the operational point of view and social fairness since it gives an equal chance to everyone. In line with this the introduction of a rotational water distribution system to the WUAs in Osh Province, Kyrgyzstan (Abdullaev et al., 2006; Kazbekov et al., 2009) and Mahi-Kadana Irrigation Project, India (Jayaraman, 1981), resulted in more equitable water distribution and allowed farmers to be always aware of their irrigation turn including when and for how long to irrigate their fields. Moreover, increase in production was observed. However, especially in water scarce schemes ensuring adequacy and equity will be difficult without coordinating the users and enforcing rotations and rules (Ghazouani et al., 2012). This demands organizational and management skill of the WUA. Farmers organization/WUA needs capacity building in technical and institutional issues to sustain the irrigation systems (Thiruchelvam, 2010). Urgent action is thus required to improve scheme level water allocation and distribution through technical support and strengthening of WUA.

2.3.3.2 Irrigation method

The dominant irrigation method in Ethiopia is surface irrigation. Uncontrolled flooding, controlled flooding and to a limited extent low-cost gravity fed and pressurized irrigation systems are practiced (MoA, 2011b).

The irrigation method commonly practiced in Gumselassa irrigation scheme is surface irrigation. We have assessed the frequently practiced surface irrigation methods separately for those who use canal water and seepage water and both canal and seepage water for irrigation. From our sample survey those who use only canal water were 68.8%. Among these (Figure 2.2), 18.7% practice furrow irrigation, 21.3% farmers practice flooding irrigation and the majority (60%) practice both irrigation methods interchangeably depending on the crop type and labour availability. In the areas irrigated by seepage water, the majority (76%) of the farmers practices both flooding and furrow irrigation and the rest (24%) practice only flooding irrigation.

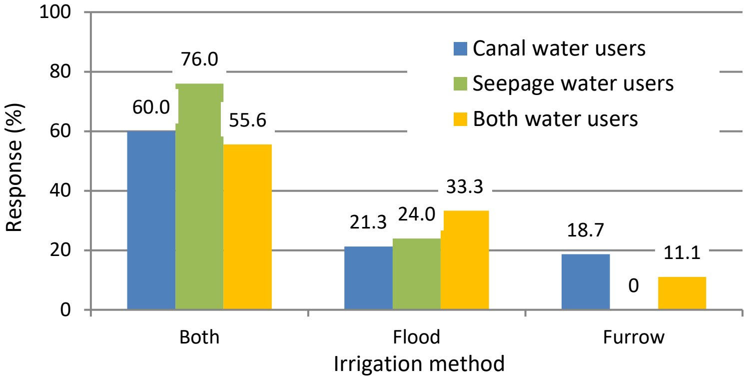

Figure 2.2 *Irrigation methods practiced in Gumselassa irrigation scheme.*

In the rift valley of Ethiopia furrow and basin irrigation methods are common (Ayenew, 2007; Haile and Kasa, 2015). However, in Gumselassa irrigation scheme uncontrolled (wild) flooding is the most practiced irrigation method. While flooding their plots the water is not distributed as desired. The farmers guide and distribute the water by forming irregular temporary channels using hoe.

The furrows are made using the traditional plough pulled by animals, which has shallow depth and narrow width. The irrigation water in most cases overtops and destroys the furrow and practically changes to flooding. Both irrigation methods (flooding and furrow) were highly affected by the poor flow control, poor land levelling and grading practices and lack of appropriate drainage in the study area. Land grading in combination with flow control practice can highly affect surface irrigation efficiency (Bos et al., 2008). MoA (2011b) also mentioned inappropriate irrigation methods are among the major causes for poor irrigation water management of SSI in Ethiopia.

Water scarcity for irrigation is a global issue. SSI were mainly constructed with the objective of addressing the problem of water scarcity and hence to achieve food security. However, the farmers' water application practice in the study area can be considered as poor and susceptible to huge water loss and undesirable environmental impacts. Improving water productivity and water usage efficiency should be given priority in dry areas in order to sustain agricultural production and it may be achieved through land levelling and drainage (World Bank, 2007), improved irrigation methods (Ali, 2010).

2.3.3.3 Irrigation scheduling

On average the irrigation interval practiced for the common irrigated crops (maize and onion) by the farmers ranged from 2 to 3 weeks. For cereals (barely, sorghum, teff) and legumes (vetch and chickpea) the irrigation interval ranged from 3 up to 4 weeks. The amount of applied water in each irrigation depends on the personal judgment of individual farmer. In other words, the irrigation intervals and the amount of water application practiced by the farmers were not based on crop water requirement (CWR). As a result of these combined with poor land levelling, it is common to observe ponded water in many farmers plots after irrigation for a considerable time and runoff to adjacent plots because of over irrigation. Poor irrigation water management has been a universal problem especially in sub-Saharan Africa and in other developing countries. Many researchers also agree (Alemayehu et al., 2006; Ayenew, 2007; Eyasu, 2005; Fanadzo et al., 2010; Haile and Kasa, 2015; MoA, 2011b) that inappropriate irrigation scheduling, which is not based on the CWR and soil type has been one of the major cause for poor performance of many irrigation schemes.

Besides, other factors that include lack of a locally adopted manual for crops and scheduling (Awulachew, 2010), limited knowledge and insufficient skill of farmers as well as development agents (Awulachew, 2010; Haile and Kasa, 2015; MoA, 2011b) were reported as the major problems in irrigated crop production of Ethiopia. It has been learnt during this survey that training on irrigation water management has never been provided to the farmers and they have been irrigating their plot intuitively irrespective of the soil and crop water requirement. So far, the *Woreda* (local) office of Agriculture and Rural Development (WoARD) Extension department has been restricted to mostly supply of fertilizer and sometimes seeds and chemicals (pesticides and fungicides). From the focus group discussion, it was concluded that as a rule of the local WoARD, farmers are expected to purchase fertilizer in order to get irrigation water. The local extension service towards water management is poor and it can be regarded as non-existent.

2.3.4 Farmers' perceptions on major problems and consequences

2.3.4.1 Crop yield

The irrigated crops include maize, onion, tomato, pepper, garlic, vetch, cabbage, green pea, chickpea, potato, teff, barley. The trend of coverage of irrigated crops are shifting from diversity of several crops to maize (major) and onion dominated cultivation, although in very dry years’ vetch and chickpea are also preferred.

Low yield and yield decline of most crops have been among the major problems frustrating farmers in the study area. As indicated in Figure 2.3, 93.3%, 72% and 77.8% of the respondents from the canal, seepage and both water users, respectively perceived a reduction trend in yield of most irrigated crops. The yields of most crops are by far lower than the national average.

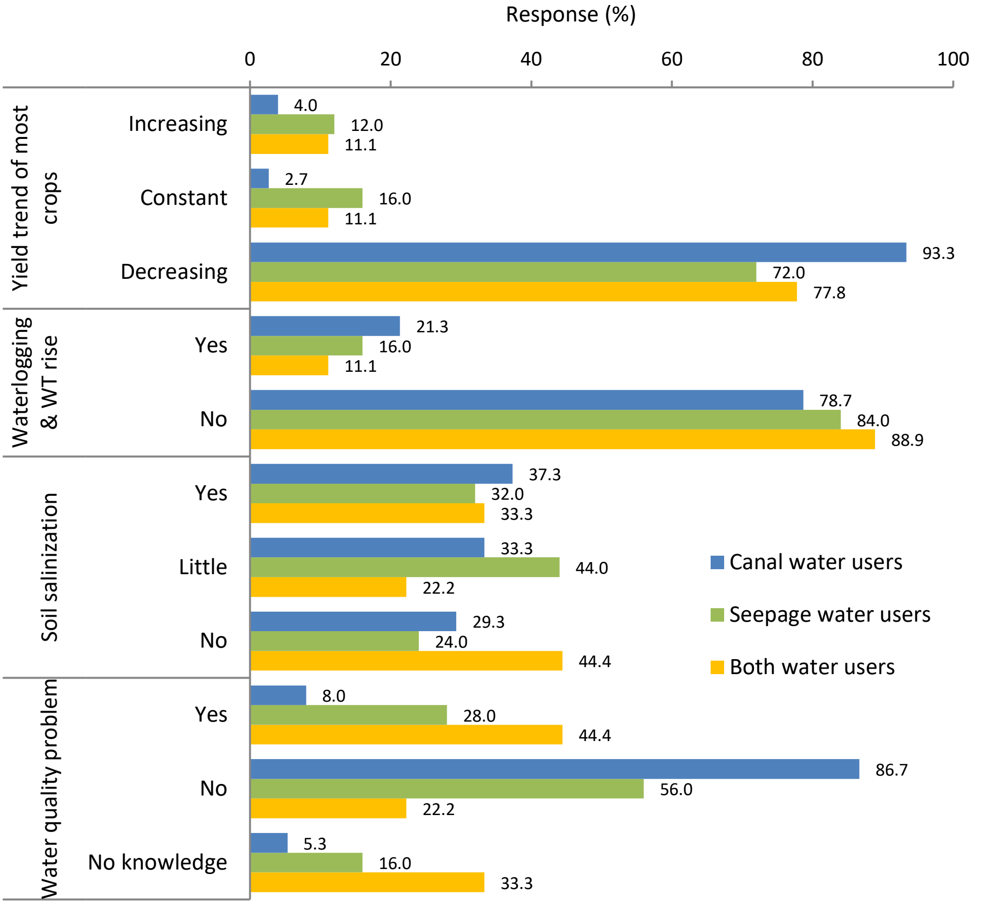

Figure 2.3 *Farmers' perception of major problems related to irrigation water management at farm level.*

From the total interviewed 109 respondents, 75 (68.8%) and 51(46.8%) have good experiences of growing maize and onion as a priority irrigated crops, respectively. Thus, to get a deeper insight of yield, special focus was given to these crops. Of the major growers of maize and onion, the perceived earlier (5-10 years ago) and recent (up to 5 years) yield trend of maize and onion are presented in Figure 2.4. Furthermore, from the major growers (of maize and onion) responses, the earlier (5-10 years ago) and recent (up to 5 years) yields of maize and onion are depicted in Table 2.3. As shown in Figure 2.4, more than 61% and 96% of the farmers perceived a reducing yield trend for maize and onion, respectively. Results of the interview (Table 2.3) reveals that the average earlier and current yields of maize were about 3 t ha^{-1} and 2.25 t ha^{-1}, respectively. Similarly, the average earlier and recent yield of onion were 8.85 t ha^{-1} and 4.25 t ha^{-1}, respectively. The difference of yield from earlier to current irrigation years were 25% and about 50% for maize and onion, respectively.

Yet, the global and national productivity of maize is 5.57 t ha^{-1} and 3.42 t ha^{-1}, respectively (FAO, 2016). The comparison of the current maize yield in the study area with global and national productivity reveals that there is 59.6% and 32.2% yield reductions, respectively. Similarly, the national and global productivities of onion are 10.47 t ha^{-1} and 19.33 t ha^{-1}, respectively (FAO, 2016). The current onion yield in the study area is, however, substantially lower (59.4%) than the national productivity. Awulachew and Ayana (2011) also indicated a substantial yield difference between the actual and potential yield of several irrigated crops. Generally, the productivity of agriculture in Sub-Saharan Africa is below yield potential (Chauvin et al., 2012). Some studies agreed that the growth in agricultural production in Ethiopia (Amede et al., 2008) as well as in sub-Saharan Africa (Chauvin et al., 2012) is mainly due to expansion of agricultural land. Improved agricultural practices are required to reduce the large yield gap of the existing schemes (FAO, 2012).

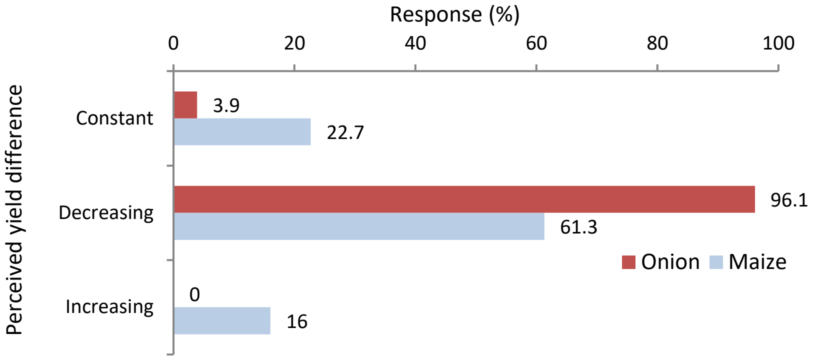

***Figure* 2.4** *Perceived differences between earlier (5-10 years ago) and recent (up to 5 years) yields of maize and onions.*

Though the reasons for the poor performance of SSI in the country and especially in the study area have been many, complex and interlinked (as discussed in section 2.3.3), it can be concluded that the farmers' poor practices of irrigation water management at scheme as well as at farm level were among the major reasons for low and declining crop production and undesirable environmental impacts in Gumselassa irrigation scheme. Other studies conducted in South Africa (Fanadzo et al., 2010) and in Zimbabwe (Samakande et al., 2004) also concluded that poor water management was the major cause for low productivity in the irrigation schemes. The other factors identified during focus group discussion that contribute to low and declining productivity in the scheme were soil salinization, poor soil fertility, disease and pest.

***Table 2.3** Farmers' responses of earlier (5-10 years ago) and recent (up to 5years) yields of maize and onions.*

Maize				Onion			
Earlier (5-10 years)		Recent (up to 5 years)		Earlier (5-10 years)		Recent (up to 5 years)	
Yield (t ha^{-1})	Frequency	Yield (t ha^{-1})	Frequency	Yield (t ha^{-1})	Frequency	Yield (t ha^{-1})	Frequency
1.25	1	1	4	3.5	1	2	6
1.5	4	1.5	8	4	1	2.5	5
1.75	2	2	25	4.5	2	3	5
2	9	2.25	2	5	3	3.5	6
2.25	2	2.5	23	6	2	4	10
2.5	8	3	9	7	3	5	8
2.75	1	3.25	1	7.5	3	6	4
3	12	3.5	3	8	7	7	3
3.5	17			9	9	7.5	2
3.75	11			10	11	8	2
4	8			12.5	7		
				15	2		
Total	75		75		51		51
Average yield (t ha^{-1})							
2.997		2.250		8.853		4.245	

2.3.4.2 Water shortage

Shortage of water is one of the major factor affecting production and productivity of the irrigated crops. From the interviews, all of the farmers (100%) perceived that there is a shortage of irrigation water at command level. According to this study (Figure 2.5), the major causes for water shortage perceived by the respondents were insufficient and reducing trend of rainfall (100%), siltation of the dam (79.8%), poor on-farm water management (76.1%) and poor allocation and distribution system (63.2%).

According to other studies conducted in the Nile valley by Bryan et al., (2009) and Deressa et al., (2009), 65% and 53% of the respondents, respectively, perceived a decrease in precipitation. The result in this study is thus in line with these studies, which are entirely attributed to their basin level aggregated data. Similarly, to the same study of the former authors, about 79% of the respondents perceived a decrease in precipitation in South Africa.

Though siltation of the reservoir was among the major problems quoted by the respondents, it is already covered by other studies (for example Haregeweyn et al., 2005; Tamene et al., 2006; Tamene et al., 2011) whereas the current study focused mainly on the command area. The majority of the farmers' perception on poor on farm and scheme level water management was in line with the findings of this study (section 3.3).

The Gumselassa irrigation scheme as well as most SSI schemes in Ethiopia are performing below their design capacity (Amede, 2015; Awulachew, 2010). The size of the command area in the study scheme has been shrinking over time (Table 2.2) as a result of low reservoir water and this has been aggravated by the poor water management practices at command and at plot levels (section 3.3).

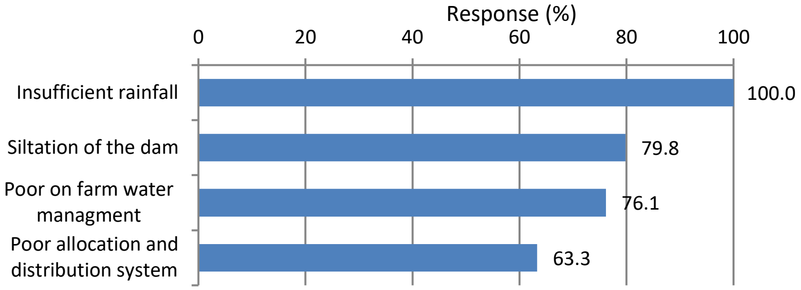

Figure 2.5 *Farmers' perception on the major causes of irrigation water shortage at command level.*

According to Eyasu (2005) the average scheme performance (1999-2002) for canal irrigated area was 40% (67 ha) below the design capacity. From our findings the current performance for the years 2011-2016 was 70% (30 ha) below the design capacity and had shown a reducing trend. Similarly, the average seepage water irrigated area in the same years was 18 ha (Eyasu, 2005) whereas the average value for the years from 2011 to 2016 according to this study was 12 ha. This huge performance difference of the scheme within the last decade was mainly attributed to insufficient rainfall that resulted in reduced filling of the reservoir volume and poor water management practices. Although nothing can be done to the natural cause (precipitation), there is still a big room for improving the performance of the scheme in the context of water management. In case of interventions to improve the performance of Gumselassa and other similar SSI schemes suffering of water scarcity, priority should be given to improvement of water efficiency at farm as well as at scheme level.

Farmers responses to the indirect questions on rating the amount of irrigation water applied at a time by most of the farmers reveals that, about 76% and 23.8% replied too much and reasonable, respectively. Most of the respondents perceived over irrigation at plot level despite their perception of water scarcity at scheme level.

We have also witnessed that the amount of water applied is not measured and over irrigation is common to the extent that much water overtops to an adjacent farmer's plot. It is a paradox that such over irrigation is happening in the same year that Ethiopia in general and the study area in particular had faced the worst drought in 30 years (JGHPD, 2016).

From the focus group discussions, the identified major reasons for over application of irrigation water include low awareness, selfishness, difficulty in distributing water uniformly under flooding irrigation method and lack of guarantee on water availability in their next turn, as it might be finished especially when the reservoir water level becomes lower near the end of the irrigation season.

In order to relate farmers' perceptions of the distribution system to measured values, we have randomly quantified the conveyance loss of six irrigators (Table 2.4) by measuring the discharge from quaternary canal to the farm inlet using two Parshall flumes. The measurement was recorded after the discharge becomes constant to exclude huge initial losses by infiltration. Accordingly, more than 50% conveyance losses was recorded. From our field observation most of the canals were either covered by vegetation or partially filled by silt. In addition to the poor allocation and distribution practices of the *Abo Mai* that result into water loss especially by seepage while allocating water to a single farmer having plot located far away from the embankment, poorly maintained canals and unregulated water flow have been among the major reasons for the huge conveyance losses. This poor conveyance efficiency indicates that there is an agreement with the farmers' perception and confirms that much water is lost through seepage and runoff. And this is one of the major reasons contributing to water shortage, water table rise and soil salinization in the farms. And this in turn is linked with weak WUA, lack of technical knowledge and lack of follow-up by the farmers' irrigation committee.

Table 2.4 *Conveyance losses between quaternary canals and farm inlet (measured in 2015).*

Water course no.	1	2	3	4	5	6
Measured average discharged at Quaternary canal (l/sec)	8.5	4.94	3.5	6.35	7	9
Measured average discharged at farm inlet (l/sec)	5.3	2.4	2.5	5.2	6.3	7.4
Distance between Quaternary canal and farm inlet (m)	130	270	160	210	117	200
Water losses percentage	37.6	51.4	28.6	18.1	10	17.8
Water losses percentage per 100 meters	29	19	17.9	8.6	8.5	8.9

A study conducted in Pakistan by Saeed and Khan (2014) indicated that 56% yield decline of maize and wheat at the tail end was due to conveyance and seepage losses, where the conveyance loss was reported at 24%. To enhance the performance and effective utilization of water, canal conveyance and distribution losses need to be minimized. According to Meijer et al. (2006), concrete lining of irrigation canals were estimated to reduce 50% of the groundwater recharge in Uda Walawe irrigation scheme (Sri Lanka) and concluded as an appropriate measure for reallocation of water in the irrigation scheme and creating social equity. Yet, due to cost reason, concrete or any hard-surface lining can be considered only for the major primary and secondary canals. Compaction of soil (clay material) on the canal bed and banks is an alternative cheaper method to reduce canal water losses. Many studies (Kahlown and Kemper, 2004; Yao, et al., 2012) confirmed that by compacting the soil around the canal, seepage losses can be reduced significantly. For effective seepage control and long life of the canals, a regular inspection and routine maintenance programme should be carried out (Van den Bosch et al., 1992). Through improving the distribution plan and conveyance system of Gumselassa irrigation scheme, there is a great opportunity for saving water that could irrigate larger size of the command area.

2.3.4.3 Environmental impacts

Soil salinization has been a serious problem in the study area. As depicted in Figure 2.3, most of the respondents perceived that salinity problem is evident in this specific irrigation scheme. Among the respondents, 37.3%, 32% and 33.3% of them from canal, seepage and both water users, respectively believed that they have salinity problem in their plot. Similarly, 33.3%, 44% and 22.2% from the canal, seepage and both water users, respectively perceived little salinity problem. Earlier *Woreda* report (unpublished) indicated that about 60 plots were affected by salinity and from the current investigation in 2016, 12 and 23 farmers had abandoned their plots due to severe soil salinization and they faced total crop failure and very low yield, respectively.

The abandonment of parts of large irrigation schemes as a result of salinity and waterlogging were reported in Ethiopian rift valley (Awulachew, 2010; Girma and Awulachew, 2007). However, except progressive accumulation of salts and the potential danger and effect (Carter and Danert, 2006; Etissa et al., 2014; Eyasu, 2005; MoA, 2011b; Ulsido et al., 2013), limited information was found about land abandoned particularly as a result of salinity and waterlogging in SSI. Yield reduction may be acceptable to some degree, though land abandonment by poor farmer where he/she entirely depends on should be unconceivable. The current study identified salinity as a major and accelerated problem at Gumselassa SSI scheme in contrary to earlier studies, which indicated salinity as a creeping problem (Eyasu, 2005; Teshome, 2003).

From the sample survey majority (>85%) of the respondents believed that the cause of salinity in most farms have been over irrigation as most of the farmers are irrigating intuitively in the absence of crop water requirement based scheduling. Poor drainage, seepage from canals and water table rise have been the other factors attributing to soil salinization. As depicted in Figure 2.3, higher response (more than 20%) of the canal water users perceived a problem of water logging and water table rise. The main reason that contributes for these problems is that their plots are located within the proximity to the embankment in addition to their easier access to irrigation water. From our random measurements, groundwater levels as shallow as 80 cm were recorded in farmers' fields located in the upper command area. The electrical conductivities (EC) of the ground water ranged from 1.1 dS m^{-1} to 6.5 dS m^{-1}. This confirms that saline and shallow water table was among the major reasons for soil salinization in the study area. Other studies also confirm that the major causes for secondary salinization in arid and semi-arid areas are over irrigation and shallow water table (Ghassemi, et al., 1995; Ritzema, et al., 1996). Based on this research in Gumselassa SSI, it can be indicated that the adverse environmental impact is reaching at unacceptable levels and revitalization of the scheme through appropriate salinity management is required.

Respondents were also asked on water quality problem (Figure 2.3). Among the canal water users, 8%, 87.7% and 5.3% replied yes, no and no knowledge, respectively. From the respondents that have been using only seepage water, 56% of them perceived it as a good quality water and from both water users, more than 44%, 22% and 33% perceived yes, no and no knowledge, respectively. From the field measurements in 20015/16 irrigation season the EC (salinity) ranged from 0.4 to 0.6 dS m^{-1} and 0.8 to 1.9 dS m^{-1} for the reservoir and seepage water, respectively. According to Ayres and Westcot’s (1985) these results are categorized under none and slight to moderate salinity hazard for reservoir and seepage water, respectively. Moreover, in line with this reference, it can be implied that most of the respondents have a good perception of the qualities of the available irrigation waters.

2.3.5 Adaptation/mitigation strategies

2.3.5.1 Mitigation measures at farm and household levels

To sustain crop yields, the farmers have already adopted different strategies. Most of them have been applying inorganic fertilizer, animal manure and compost to replenish the fertility of the soil. However, from the focus group discussions, the amount of applied fertilizer, animal manure and compost is very low and it is not based on research. The major reasons were high cost of fertilizer and low availability of animal manure and crop residue since animal manure and crop residues are the major sources of energy in Ethiopia (World Bank, 2006a).

The other major strategies adopted to sustain their yield have been crop shifting from a large diversity of crops to a few tolerant crops. In their attempt to sustain crop yields, the farmers’ mitigation measures to water scarcity may have a positive or negative effect on the adverse impact of salinity problem or vice versa. Table 2.5 reveals farmer’s responses to adaptation measures practiced for the problems of water scarcity and soil salinization separately. Accordingly, 32.6%, 52% and 33% of the respondents from canal, seepage and both water users, respectively perceived that they adopted crop shifting from diversity of several crops to drought tolerant crops to counter act to water shortage problems. Regarding crop shifting respondents from the seepage water users as compared to the others have higher percentage. This shows that they face severe water scarcity as compared to the other users. Although, all (100%) of the seepage water users have been using this water due to water shortage, the severity is worsened because others (who have access to canal water) at the upstream also use seepage water. Most (77.8%) of the respondents from both water users adopted seepage water for irrigation during shortage of canal water, and the rest uses seepage water to avoid long queue for canal water. This sometimes causes conflict between the upstream and downstream farmers. Eyasu (2005) also indicated that seepage water has been used for irrigation in most of the earthen dams of the Tigray region mainly due to water scarcity.

Table 2.5 *Household mitigation measures for water scarcity and soil salinization.*

		Percent response		
Description	Response	Canal water users	Seepage water users	Both water users
Water scarcity mitigation	Crop shifting (drought tolerant crop: maize, vetch, chickpea, barley).	32.6	52	33.3
	Use of seepage water for irrigation		100	77.8
Soil salinization mitigation*	Crop selection (salt tolerant crop: maize, vetch)	43.4	36.8	40.0
	Agronomic (animal manure, compost)	58.5	52.6	60.0
	Drainage	5.7		
	Reduction of the amount of applied water at once	7.5		
	No action taken	20.8	12.0	

* Respondents that replied the existence of salinity problem “yes” or “little”

In response to irrigation water scarcity, utilization of alternative water sources (drainage water, ground water etc.) have been major farmers’ adaptation strategies in many arid and semiarid regions of the world. For example, reuse of drainage water was reported as farmers’ adaptation strategy at the tail end of branching canals in Egypt due to long period shortages of fresh water (Ghazouani et al., 2014). Minhas et al. (2007) mentioned that farmers withdraw saline/alkali groundwater in response to unreliable canal water supply in semiarid parts of South Asia. Similarly, in response to limited canal water supply, farmers have been using both surface and groundwater for irrigation in Haryana, India (Kaledhonkara et al., 2012) and Lagar, Pakistan (Kazmi et al., 2012).

Although the farmers’ adaptation measures in utilizing seepage water contributes to securing irrigation water availability, it could be one of the reasons for aggravating soil salinization in the study area. There are global experiences that reveal even irrigating with good quality water had caused land salinization and waterlogging in many irrigation schemes, due to poor management practices (Rhoades et al., 1992). Yet, more careful management practices are required to effectively utilize poor quality water (a potential source for irrigation) especially in water scarce areas as compared to good quality water (FAO, 2012; Rhoades et al., 1992).

The respondents that reported the existence of salinity problem 'yes' and 'little' were asked if they take any measure to counteract the adverse effect of salinization. The results of the interview (Table 2.5) revealed that the major strategies adopted have been agronomic (use of animal manure and compost) and similar to water scarcity mitigation, shifting of crop from diversity of several irrigated crops to salinity tolerant crops (maize, vetch). The percentage of respondents that adopted crop shifting to water scarcity problems were higher for seepage water users as compared to canal and both (canal and seepage) water users however the percentage of respondents that adopted the same strategy for the problem of soil salinization were lower for seepage water users. This indicates water scarcity had been a larger problem than salinization for seepage water users. Few (5.7%) and (7.5%) of the respondents from canal water users adopted drainage and reduction in the amount of water applied, respectively. Whereas about 21% and 12% had taken no action to mitigate salinity problem from the canal and seepage water users, respectively.

Despite the different adaptation strategies, the productivity of most crops has been declining and the adaptation strategies practiced by farmers could not solve the problem significantly. In line with this. World Bank (2007) stated that, farmers in poor countries may not be able to adapt to climatic change without additional support. Thus, there is a need to build farmers awareness, knowledge and adapting capacity to the fundamental challenges in irrigated agriculture.

2.3.5.2 Mitigation measure taken at command level

i) Local government authority adaptation strategy

During low rainfall years, reduction of the size of the command area, to be irrigated area has been the major strategy adopted for a long time. Earlier during the establishment of the scheme, the size of the command area to be irrigated used to be decided by regional and local experts from the *Woreda* office of Agriculture and Rural Development (WoARD) and office of Water Resources. Currently, a local expert from WoARD decides on the size of area to be irrigated based on simple observation of the water availability in the reservoir, and then the irrigation committee (representative farmers) of the command area equally distributes the share to both the left and right banks of the command area. As shown in Table 2.2 above, the command area has been shrinking over time as a result of water scarcity. Farmers with plots near the dam always benefited, since the seasonally decided size of the command area to be irrigated includes the top of command area (near the embankment) and stretches to downstream direction. Many scientific studies also agree that tail end deprivation is a universal problem.

Although, the government has generally responding to the problem of irrigation water scarcity by building water harvesting structures, its involvements and responses to water scarcity/shortage of schemes aggravated due to climatic problems is poor. Usually food aid has been the major government support in extreme drought events. However, to sustainably minimize the adverse impacts of drought, the Government could have given due attention to build the farmers' local adaptation capacity to climatic variability. There are many opportunities to enhance productivity especially in sub-Saharan countries, e.g. through improving irrigation efficiency (Bekele, 2014; FAO, 2012; Hillel, 1997; Juana et al., 2013) or the revitalization of existing irrigation schemes (Juana et al., 2013; Kadigi et al., 2012; World Bank, 2007). In irrigation schemes facing water scarcity like Gumselassa, regional and local government policies should give priority to support research, extension service and development endeavors that focus on water scarcity adaptation strategies.

ii) Farmer's irrigation committee adaptation strategies

Most of the time, the farmers are free to choose any crop they like to grow. However, during very dry years the irrigation committee decides on the crops to be grown (Table 2.6). In order to accommodate more farmers, the commonly chosen crops are vetch (manly) and chickpea, which are drought tolerant. Though the amount of yield is not quantified, from the focus group discussion, these crops can be harvested with two irrigations. Regardless of the decision to grow tolerant crops, some farmers grow onion and maize.

***Table 2.6** Mitigation measures taken at command level.*

S/N	Action taken	Frequency	Responsible	Enforcement
1	Reduction of the size of the irrigated area	Frequently practiced	Local Office of Agriculture and Rural Development	Strict
2	Crop selection	Sometimes	Irrigation committee (farmers)	Moderately strong
3	Long irrigation interval	Sometimes	Irrigation committee (farmers)	Moderate
4	Purchasing fertilizer to get water	Frequently practiced	Local Office of Agriculture and Rural Development	Mostly strong
5	Changing of irrigated cropping calendar	In 2015/16	Farmers' irrigation committee	Strict
6	Absence of pre-plant irrigation	In 2015/16	Farmers' irrigation committee	Strict

In the recent (2016) irrigation season, the water harvested in the reservoir was very low due to severe drought. The decision of the local office of Agriculture and Rural Development (LoARD) on the size of the command area was only 10 ha (50 beneficiaries) irrigating using canal water in obligation with purchasing fertilizer. The farmers were of the opinion that it was not justifiable to purchase fertilizer for fear of crop failure due to water shortage. Considering the risk, then the local office of Agriculture and Rural Development gave the mandate to the farmers' irrigation committee to decide on the size of land to be irrigated irrespective of fertilizer for the first time. Then, the committee made decisions: first, on the absence of pre-plant irrigation: second, "every farmer must grow vetch"; third, shifting the start of irrigation to from January (the usual calendar) to December. As a result, they managed to increase the size of the command area irrigated area from 10 ha to 20 ha (100 beneficiaries) with equal share to water in both banks. The enforcements of the decisions made were strict for the first time and all of the irrigators successfully harvested their crops.

Though, there has been many water management problems in Gumselassa irrigation scheme, the decision on the absence of pre-plant irrigation to share or allocate the limited water to as much as many farmers was an innovative breakthrough. This innovative decision combined with tolerant crop choice and shifting sowing date had doubled the beneficiaries as compared to the LoARD decision. Though some studies (Bekele and Tilahun, 2007; Demelash, 2013; Kifle and Gebretsadikan, 2016) indicated some measures to mitigate water scarcity, no such practical experience has been documented in irrigated schemes in Ethiopia.

Pre-plant irrigation in Gumselassa irrigation scheme is a common practice to soften the soil for ploughing. Huge amounts of water is lost during pre-plant irrigation through the cracks formed during the dry season, as the majority of the soil is vertisol. On the other hand absence of pre-plant irrigation may have a negative impact on leaching of salts, weed control and land preparation. According to Glantz et al. (2009), an effective adaptation to local climate change may not be appropriate when the circumstance changes. This simple practical innovation of omitting pre-plant irrigation has a great potential to disseminate to other SSI especially during the occurrence of drought. One important lesson learnt from this study was the practical importance of allowing farmers to make their own decisions. Appropriate innovations relative to irrigation management and practice are required to address the problem of water scarcity (Pereira et al., 2002). Local communities have the potential for creating and developing innovative problem solving approaches when enabled (Darko et al., 2016; Gorjestani, 2004) and a locally based approach has the potential to be highly effective and successful (Shortt et al., 2004). The farmers' irrigation committee in the study area when enabled, at least assured fair sharing of water within the scheme although they lack the capacity for overall efficient and effective management of the scarce water resource. Despite the instrumental role of the WUAs in Kyrgyzstan in addressing the problem of water distribution and allocation among large farmers, Kazbekov et al., (2009) concluded further training of farmers and managers to build their capacity to share water and ensure equity especially during periods of water scarcity.

According to the information obtained from the focus group discussion, although the enforcement was not strict, a long irrigation interval has also been used as a strategy to save water. The *Abo Mai* may announce that the canal water may not be released for a considerable time (for instance a week). However, some farmers argue that their crop will fail and after three or four days the water should be released. This is entirely linked with the poor planning calendar of the scheme, in such a way that the land preparation of the farmers varies and consequently the planting time does. However, in the current (2016) irrigation year the enforcement was so strong due to severe drought.

Despite its paramount importance Eyasu (2005) earlier revealed that less attention was given to the institutional capacity to manage the irrigation scheme in the region (including in the study area) and in many irrigation schemes in Ethiopia (Yami, 2013) and in other countries (Fanadzo, 2012). On the other hand, in the strategic direction of Small-scale Irrigation Capacity Building Strategy of the country, ensuring community participation and establishing/or strengthening of water users associations' capacity in organizational and scheme management aspects are among the identified key elements to effectively and efficiently manage the irrigation schemes (MoA, 2011a).

The local government authorities should thus revisit the strategies and should allow, advise and/or give more room for WUAs participation in decision processes concerning the irrigation scheme management rather than their top-dawn interferences. Moreover, direct participation of farmers in irrigation management is widely accepted as an effective means of enhancing their knowledge of irrigation and efficiency of water use (Qiao et al., 2009). A study conducted in three regions of Ethiopia by Yami (2013) also confirmed that the WAUs were unable to ensure rule enforcements as a result of interferences of external authorities without their consent.

To enhance coping strategies of the WUA and resilience of the irrigation scheme to water scarcity, the local and regional authorities' interventions should focus on developing and strengthening the technical, institutional, legal and regulatory issues of the WUAs in participatory manner. Moreover, the governmental and nongovernmental organizations support should focus on solving the existing problems, which are beyond the technical and economic capacity of the farmers, such as maintenance and lining of major irrigation canals and construction of drainage structures.

The prerequisite for farmers access to irrigation water, which is “purchase of fertilizer to get water” as mentioned in section 2.3.3, indirectly affects the size of irrigated area as some farmers who could not afford or were not willing to buy fertilizer left their land fallow or offered it to sharecroppers.

2.4 Conclusions

Despite the poor performance of most small-scale irrigation, less attention is given by the responsible stakeholders. This study contributes to the knowledge and practices of sustaining the existing SSI to water scarcity by appraising farmers’ irrigation practices, perceptions and adaptation strategies and drawing conclusions from Gumselassa irrigation scheme, North Ethiopia.

In spite of the good perception of the farmers’ on poor irrigation water management practices as the major causes for aggravating water scarcity, low crop yields and decline of crop productivity, undesirable environmental impacts, their overall plot and scheme level adaptation strategies were not good enough. The farmers are constrained by lack of technical knowledge, weak enforcement capability of the Water Users Association (WUA) and poor irrigation infrastructures to manage the irrigation water properly at plot as well as at scheme level.

Overall, lack of government support and the top-down approach practiced by local government authority in imposing decisions have been also constraining the farmers’ adaptation strategies. In the 2016 irrigation season, the farmers declined the local government authority decision to irrigate 10 ha (50 beneficiaries) and the farmers were given the mandate for the first time to decide through their WUA committee (their representatives). An innovative adaptation strategy of the WUA committee that included omitting water for pre-plant irrigation, shifting the irrigation calendar, growing drought tolerant crops and strict enforcement enabled in doubling the irrigated area to 20 ha (100 beneficiaries). This practical outcome provides useful information for government authorities on the efficacy of allowing farmers to make their own decision and its great potential for other irrigation schemes with similar challenges.

The finding of this study points out that, the local government authorities should revisit their approach and should advise, allow and ensure WUA participation in decision processes concerning the irrigation scheme rather than top-dawn interference. Moreover, researchers should build on and rectify such innovative practices of the farmers’ to enhance their resilience efficacy to water scarcity and for wider use.

Involvement of local government authorities on sustainability of irrigation schemes is poor and thus, there must be readiness to learning from past mistakes. In order to revitalize Gumselassa irrigation scheme and to enhance the adaptation capacity of the farmers to increasing water scarcity, the government should support the farmers through: i) building self-managed WUA, with strong leadership and enforcement capability. These include, interventions to develop the technical, institutional, legal and regulatory issues of the WUA, ii) improvement on the existing water infrastructure, including canal control structures, drainage, conveyance and distribution systems, iii) continuous capacity building through training of farmers on the basics of irrigation and irrigation system iv) facilitating and supporting research institutes to develop irrigation agronomy manuals that can be easily understood by the beneficiaries.

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3. A participatory and practical irrigation scheduling in semiarid areas: the case of Gumselassa irrigation scheme in Northern Ethiopia

Poor irrigation scheduling practices have been quoted as the major challenges for sustainability of small-scale irrigation schemes in Ethiopia due to complexity of techniques, cost and inaccessibility of soil-water monitoring tools, lack of various local climatic data and soil-water parameters. For local experts to easily schedule irrigation and to promote adoption by farmers, a method that considers local resources and opinions, cheap and simple computation procedure of irrigation schedule is needed. So far, there is no such study in the context of Ethiopia. A simple irrigation scheduling method (Practical) was developed based on the FAO procedure (Brouwer et al., 1989), employing Hargreaves ET_0 *equation and the opinions of local farmers and extension agents. Then, the method was validated on-farm through participatory and close observation of farmers by comparing with CropWat simulated (Complex) and local (Traditional) scheduling practices for 2014/15 and 2015/16 irrigation seasons considering maize as indicator crop. The design was RCBD with three replications. Data on irrigation depths, yield and yield components and soil salinity were collected and analysed. Furthermore, a farmers' day was arranged to collect opinions on the crop stand and scheduling techniques. In both irrigation seasons, the Practical irrigation schedule method resulted in higher grain yield while saving substantial amount of water and in significantly higher water productivity compared to the other methods. Maximum (0.68 kg* m^{-3} *in 2014/15) and minimum (0.47 kg* m^{-3} *in 2015/16) water productiy were found in the Practical and Complex approaches, respectively. The average root zone salinities among the alterative irrigation scheduling methods were not significant, in both irrigation seasons. Farmers' and experts' opinions were in favour of the Practical scheduling method. The Practical irrigation scheduling method is thus recommended for maize, around Gumselassa area. Further, the presented procedure can be adopted for preparation of irrigation calendars of other crops and in other regions.*

Based on:

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3.1 Introduction

With unreliable and highly erratic rainfall, Ethiopia is characterized by food insecurity due to high risk of annual droughts as well as intraseasonal dry spells (CIA, 2018; FAO, 2014; WFP, 2016). In order to address the problem of water scarcity and food insecurity, promotion and development of small scale irrigation (SSI) has been a priority policy for the Ethiopian Government (FDRE, 2007; MoFED, 2006; MoFED, 2010;MoWR, 2002). In effect of this the irrigated area of SSI increased from 853,100 ha in 2009/10 to 1,853,100 ha in 2012/13 (MoFED, 2014).

Despite the huge expansion, the performance of most SSI schemes in the country is far from satisfactory (Amede, 2015; Awulachew and Ayana, 2011; Carter and Danert, 2006; Cofie and Amede, 2015; IFAD, 2005; MoA, 2011a; Teshome, 2003; Yohannes et al., 2017). Poor irrigation water management has been among the major reasons quoted for underperformance of the schemes.

Tigray is one of the most degraded and drought prone regions of Ethiopia. Similar to the other schemes in the country, poor water management practices, particularly improper irrigation scheduling is one of the factors for underperformances of most SSI schemes in the region (Eyasu, 2005; Libseka et al., 2015; Yohannes et al., 2017).

Lack of simple and practical scheduling techniques, limited knowledge and inadequate practical skills of farmers and local extension agents on crop water needs, soil types and climatic condition, in the country (Awulachew, 2010; Etissa et al., 2014; Haile and Kasa, 2015;MoA, 2011a), and particularly in Tigray region (Eyasu, 2005; Yohannes et al., 2017) as well in many other countries (Hill and Allen, 1996; ICID/FAO, 1996; Maheshwari et al., 2003), have been the major reason for poor on-farm water management practices.

In Tigray region, irrigation scheduling is being decided by a local water committee and/or based on the farmer’s intuition, irrespective of soil, plant and weather conditions (Eyasu, 2005; Mintesinot, 2002; Mitiku et al., 2002). As a result, over or under irrigation of fields is common in the region (Eyasu, 2005) as well as in many irrigation schemes in the country (MoA, 2011a).

These have resulted in low production and water productivity, waterlogging, soil salinization, rise in groundwater levels and decrease in command area (Eyasu, 2005; Mintesinot, 2002). Many studies (Alemayehu et al., 2006; Ayenew, 2007; Fanadzo et al., 2010; Haile and Kasa, 2015) also confirmed that inappropriate irrigation scheduling as among the major factors for poor performance of many irrigation schemes.

Many advanced and novel scientific irrigation scheduling techniques have been developed in the past three decades. However, the adoption by farmers is low, especially in developing countries (Annandale et al., 2011, Fanadzo et al., 2010). The major reasons for low adoption are reported to be lack of soil water parameters and diverse climatic information (Torres, 1998), complexity of the techniques that farmers are confused by choice and do not understand the difference between the different scheduling techniques (Stirzaker, 2006), failure of the scientist to understand the situation of farmers and extension agents and the constraints under which they operate (Pleban and Israeli, 1989;Vanclay, 2003). Much of the studies are focused on the exact science of irrigation scheduling rather than simple and practical measures that would affect farmers decision (Maheshwari et al., 2003).

Although few researches and attempts were conducted on irrigation scheduling (Demelash, 2013; Kifle, et al., 2017; Kifle and Gebretsadikan, 2016; Mintesinot et al., 2004; Muktar and Yigezu, 2016) using the CropWat model in Ethiopia, none of these participated farmers and consequently the outputs didn’t serve the end users. Besides, the Complex/conventional approach applied by researchers cannot be practiced by the local extension agents. Unavailability of climatic data and absence of simple implementation manuals for farmers were also among the major reasons for failure of the attempts.

In addition to the need of diverse and reliable climatic data, the Complex method of irrigation scheduling requires computer access, trained professionals and soil-water monitoring tools where all are rarely available in most parts of Ethiopia.The choice of the irrigation scheduling method should consider the technology level of the farm (ICID/FAO, 1996).

Past research and practical experience emphasized that irrigation scheduling practices must be simple, useable and understandable by farmers in order for them to be adopted (Hargreaves and Samani, 1987;Hill and Allen, 1996). Though few simple methods of scheduling has been developed (Torres, 1998), the practicality and adoption is still low for several reasons. For example, simple irrigation scheduling calendars (Hill and Allen, 1996) were developed which demand professional and sufficient weather data to apply.

To secure food security in drought-prone regions like Tigray, concrete efforts to improve on-farm water management is required (Hillel, 1997). Thus, improving irrigation scheduling by individual farmers in the region should be a matter of urgency.

Not much has been done on development of simple and practical irrigation scheduling techniques that can be exercised by local extension agents and easily adopted by farmers.

Innovations are required relative to irrigation management and practice (Pereira et al., 2002) and there is a need to develop simple monitoring tools and conceptual frameworks that enable structured learning (Annandale et al., 2011).

Considering the poor socioeconomic status of the farmers, very low technology level of the farms, inaccessibility of tools and lack of local climatic data and trained professional in Tigray as well as in most rural parts of the country, there is a heightened need to develop by far simpler and easier irrigation scheduling techniques. The aim of the study is thus to identify, test and validate practical irrigation scheduling that considers the local conditions, which can be easily practiced by the local extension agents and easily understood and applied by the farmers.

A participatory procedure that included local farmers' and extension agents' opinions in combination with the method published by FAO (Brouwer et al., 1989) and Hargreaves equation (Hargreaves and Samani, 1985) were used for this study. The FAO approach requires limited data and the procedures to be followed are easy for local extension agents. Hargreaves equation is a worldwide accepted simple and reliable method of estimating evapotranspiration that requires only temperature data (Allen, 1993; Hargreaves, 1994;Hargreaves and Allen, 2003; Jensen et al., 1990). In most rural parts of Ethiopia, where computers are not accessible, the other advantage of the Hargreaves approach is, the ET_0 computation can be done manually using ordinary simple calculating machine.

Local extension agents can benefit from the simple procedures in developing irrigation calendars for other irrigated crops. Finally, this study gives important lesson for local and regional decision makers, on their endeavour to increase the productivity of small scale irrigated agriculture.

This paper is organized as follows: Section 2 describes the study area, practical irrigation schedule development method, alternative irrigation schedules and data collection and analysis methods. Section 3 presents the results. In this section results of the alternative irrigation schedules which included depth of the applied water, yield and yield components, soil salinity and local opinions are presented. Section 4 discusses the results. Section 5 draws conclusions on the main findings of the study and presents policy implications.

3.2 Methodology

3.2.1 Study area description

On-farm experiments were conducted in Hintalo-Wojerat *Woreda (district)*, Tigray region, Ethiopia, in 2015 and 2015/16 irrigation seasons, at the Gumselassa SSI scheme located between $13^0$13'to $13^0$15' N and $39^0$30' to $39^0$33' E (Figure 3.1). More than 60 % of the study area is covered with black clayey soil (Mintesinot et al., 1999). Some physical properties of the soil in the study area are shown in Table 3.1. The rainfall in the study area is unimodal, and highly erratic in space and time. The annual average rainfall is 500 mm and agro-ecologically, the area is classified as typical semi-arid (Yohannes et al., 2017).

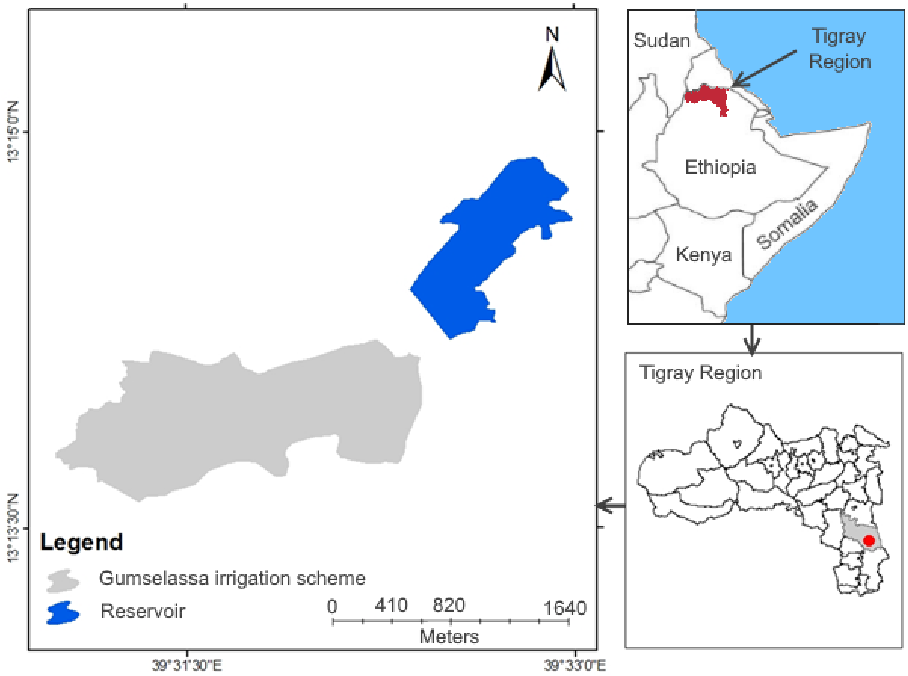

Figure 3.1 *Location of Gumselassa irrigation scheme (adopted from Yohannes et al., 2017).*

The water source for Gumselassa irrigation scheme is an earthen micro-dam designed to irrigate 110 ha. Review of secondary (past studies) sources and discussions with the local office of Agriculture and Rural Development indicated, poor on-farm water management practices as among the major causes for overall poor performance of the irrigation scheme, that resulted in low crop yields and development of soil salinization.

***Table 3.1** Soil physico-chemical properties of the soil at the experimental plot.*

Soil depth (cm)	Particle size distribution (%)			Texture (USDA)	pH	Organic matter (%)	Bulk density (gm/cm^3)	FC Wt. (%)	PWP Wt. (%)	TAW (mm)
	Sand	Silt	Clay							
0-20	17	32	51	Clay	8.31	2.46	1.25	35.1	20.5	36.5
20-40	15	31	54	Clay	8.44	2.63	1.32	35.4	22.8	33.3
40-60	15	29	56	Clay	8.41	2.20	1.27	37.2	24.2	33.0
60-80	14	28	58	Clay	8.37	2.14	1.33	35.5	24.0	30.6
80-100	13	29	58	Clay	8.29	2.21	1.34	35.6	25.5	27.1
Total										160.5

FC- field capacity, PWP- permanent wilting point and TAW- total available water

3.2.2 Farmers' and extension agents' participation

3.2.2.1 Participation during pre-implementation

A two-step discussions, in the first-step discussions with local extension agents, local leaders, irrigation committee (farmers' representatives) and elder farmers were done individually, regarding irrigation water management related problems, particularly on irrigation scheduling. Then, in the second-step, a meeting was arranged where 25 farmers including the irrigation committee and the *Abomays* (water distribution leaders) and 3 local extension agents were present. Intensive discussion was made on the problem and challenges of irrigation scheduling in the study area.

In the second-step, further discussion was carried out on different techniques of irrigation scheduling. Then we proposed our initiatives on the development of simple and practical irrigation technique, on-farm test and comparison against their scheduling practices and Complex scheduling technique (using CropWat). Then intensive discussions were done on the participants' concern, suggestion and comment, regarding the alternative scheduling techniques.

To suit local conditions and to facilitate further adoption, adjustments were done to our first proposed irrigation calendars, based on the vital inputs of the participants. The opinions and suggestions forwarded were based on their local practices and experience, which focused on adjustments for easier understanding, follow up and comparisons of the new scheduling techniques by the majority farmers. Beyond on-farm scheduling, they also shared the need of creating convenience for water allocators/distributors at scheme level. Moreover, the crop characteristics and the selection of the experiment plot (which could represent the majority of plots) in the irrigation scheme were determined based on their suggestion. To avoid repetition and for the purpose of clarity, the local inputs are described in relevant steps of the study.

3.2.2.2 Participation during the experimental period

During the experiment period, more efforts were done to involve farmers from the inception till the end since they are the ultimate beneficiaries. They were participating in installation of Parshall flumes, diversion and distribution of water, cultivation, weeding, harvesting activities and guarding of the experimental plot. Moreover, informal field visits and discussions were common among the vicinity farmers during several irrigation events.The premise was through participation and frequent field observation by which farmers' would acquire practical knowledge on the performance and constraints of the alternative irrigation scheduling approaches. Besides facilitating and improving information feedback (between farmers and researchers), the farmers would be in a position to judge the different irrigation scheduling techniques from their own perspectives.

3.2.3 Development of irrigation schedule

3.2.3.1 Practical irrigation schedule

The development of the Practical irrigation schedule were based on procedures of the "*Simple Calculation Method*" in FAO training manual no. 4 (Brouwer, et. al, 1989) in combination with the Hargreaves equation (Hargreaves & Samani, 1985) and local farmers' and extension agents' inputs. The FAO approach requires limited data and the procedures to be followed are easy. To suite the local conditions and to facilitate adoption, the local farmers' and extension agents' inputs were also used in the development process. The Hargreaves equation was used for estimation of the potential evapotranspiration (ET_0). The Hargreaves equation is a worldwide accepted simple method for estimating evapotranspiration that requires only temperature data (Allen, 1993; Hargreaves, 1994; Hargreaves and Allen, 2003; Jensen et al., 1990). Then a predefined irrigation calendar was prepared following the steps indicated below.

Step I. Estimation of Reference Evapotranspiration (ET_0)

The Hargreaves equation (Hargreaves and Samani, 1985) shown below was used to estimate ET_0.

$$ET_0 = 0.0023 \times RA \times (T^0C + 17.8) \times TD^{0.5} \tag{3.1}$$

Where:

ET_0= reference evapotranspiration, in mm/day,

RA= extraterrestrial radiation, in equivalent mm of water evaporation

T^0C = is mean monthly temperature $[(T_{mx} + T_{mi})/2]$, in degree Celsius

TD= mean maximum minus mean minimum temperatures in degree Celsius

The monthly mean maximum and mean minimum temperatures were computed (Table 3.2) from a 35 years temperature data of the nearest (about 43 km far) meteorological station. RA values were used from Doorenbos and Pruitt (1977).

***Table 3.2** Long term climatic data and estimated potential evapotranspiration.*

Month	Rainfall of Adigudom town (mm)	Long term climatic data of Quiha station					RA (mm/day)	Hargreaves ET_0(mm/day)	CropWat ET_0 (mm/day)
		Min Temp (°C)	Max Temp (°C)	Humidity (%)	Wind (m/s)	Sun (hours)			
Jan	0.7	9.0	23.3	42	3.6	9.6	12.6	3.71	5.04
Feb	2.5	9.9	24.6	39	4.3	9.8	13.7	4.24	6.00
Mar	8.6	11.6	25.4	39	4.2	9.1	15.0	4.64	6.29
Apr	19.6	13.3	26.0	39	4.0	9.3	15.7	4.81	6.53
May	18.6	13.5	27.1	35	3.0	9.8	15.8	5.09	6.33
Jun	36.7	13.3	27.5	36	2.1	7.4	15.6	5.16	5.39
Jul	155.3	12.6	23.5	66	2.0	5.2	15.6	4.25	3.84
Aug	208.4	12.5	22.6	71	1.7	5.1	15.7	4.03	3.52
Sep	45.5	11.4	24.7	49	1.7	7.5	15.1	4.55	4.45
Oct	3.5	10.7	23.8	41	2.9	9.5	14.2	4.14	5.25
Nov	1.9	9.9	22.8	42	3.5	9.8	13.0	3.67	5.09
Dec	0.8	8.8	22.6	42	3.7	9.9	12.2	3.50	4.94
Average		11.4	24.5	45	3.0	8.5	14.5	4.32	5.22

Step II. Estimation of crop water need (ET_C)

Approximate durations of growth stages 20, 40, 40 and 35 days (Table 3.3) for the initial, development, mid and late seasons stages, respectively were used for maize from the local farmers and extension agents suggestion. Since there is no location specific crop factor (K_C) in the country, the growth stages' based K_C values for maize were adopted from Brouwer and Heibloem (1986). As ET_C had to be determined on a monthly basis, for months that do not correspond with the growth stages, the average weighted K_C values were computed to change the growth stages' based K_C to monthly based K_C (Table 3.3) as indicated in Brouwer and Heibloem (1986). For ease of computation, 30 numbers of days were considered for all months for the computations of the average monthly K_C. Then, the monthly ET_C (mm/day) was computed using Eq. (3.2).

$$ET_C = ET_0 \times K_C \tag{3.2}$$

Where:

ET_C= crop evapotranspiration or crop water need (mm/day)

Then the monthly crop water need ET_C (mm/month) was obtained, by multiplying the monthly ET_C (mm/day) by the respective number of days in each month, as shown in Table 3.3.

Table 3.3 *Estimated potential and crop evapotranspiration in 2014/15 and 2015/16 irrigation seasons using the Practical approach.*

Year	Growth stages	Days	Dates	Mon	No. of days	K_C per Gr. St.	K_C per month	ET_0 (mm/day)	ET_C (mm/day)	ET_C (mm/month)
2014/15*	Initial	20	Jan 10- 30, 2015	Jan	20	0.4	0.40	3.71	1.49	30
	Crop dev.	40	Feb 1-Mar 10, 2015	Feb	30	0.8	0.80	4.25	3.40	102
				Mar	10		1.03	4.64	4.78	143
	Mid-season	40	Mar 11-Apr 20, 2015	Mar	20	1.15				
				Apr	20		1.00	4.81	4.81	144
	Late season	35	Apr 21-May 25, 2015	Apr	10	0.7				
				May	25		0.70	5.09	3.56	89
	Total	135			135					508
2015/16	Initial	20	Nov 28-Dec 17, 2015	Nov	3	0.4	0.40	3.67	1.47	4
				Dec	17		0.57	3.50	2.01	60
	Crop dev.	40	Dec 18-Jan 27, 2016	Dec	13	0.8				
				Jan	27		0.84	3.71	3.10	93
	Mid-season	40	Jan 28-Mar 7, 2016	Jan	3	1.15				
				Feb	30		1.15	4.24	4.88	146
				Mar	7		0.81	4.64	3.74	112
	Late season	35	Mar 8-Apr 12, 2016	Mar	23	0.7				
				Apr	12		0.70	4.81	3.37	40
	Total	135			135					456

LGS-length of growing seasons, in days

***** Since land preparation was done in December 2014, it is named as 2014/15 irrigation season.

Step III. Estimation of net and gross irrigation application depths

The net irrigation depth (d_{net}) was adapted from Brouwer et al. (1989), and estimated using soil type (texture) and crop root depth as inputs. The maize crop (deep rooted) under clayey soil (in the case of the study area) requires d_{net} of 70 mm. Considering short (10m), well graded and closed furrows (no runoff) and controlled discharge, 75% field application efficiency was considered. Then, using Eq. (3.3) the gross applied depth (d_{gross}) of 93.3 mm was computed and rounded to the nearest 5 mm, i.e. 95 mm.

$$d_{gross} = \frac{d_{net}}{ae} \times 100 \tag{3.3}$$

Where:

d_{net} and d_{goss} in mm

ae= field application efficiency, in percent

Step IV. Computation of irrigation water need (IN) over the total growing season.

The irrigation water need **(**in mm**)** is calculated as(Table 3.4):

$$\mathrm{IN} = \mathrm{ET_c} - \mathrm{P_e} \tag{3.4}$$

Where

P_e = effective rainfall, in mm month^{-1} (always equal to or larger than zero) and calculated as,

$P_e = 0.6P - 10$, for P <= 70 mm month^{-1}

$P_e = 0.8P - 24$, for P > 70 mm month^{-1}

P = Total rainfall, in mm month^{-1}

The monthly average rainfall was taken from 39 years (1975-2014) data in Adigudom town rainfall station located about 3 km from the Gumselassa irrigation scheme.

Step V. Computation of number of irrigation applications and irrigation interval

The number of irrigation applications (I_{na}) (Table 3.5) was computed as:

$$\mathrm{I_{na}} = \frac{\mathrm{IN}}{\mathrm{d_{net}}} \tag{3.5}$$

Where:

IN = irrigation water need, in mm

Then, the irrigation interval (I_{int}) was calculated as:

$$\mathrm{I_{int}} = \frac{\mathrm{LGS}}{\mathrm{I_{na}}} \tag{3.6}$$

Where:

I_{int}= irrigation interval, in days

LGS = length of growing season, in days

Step VI. Computation of monthly net irrigation depth (dm_{net})

The monthly net irrigation depths (dm_{net}) in the growing season of maize (Table 3.6) were calculated using Eq. (3.7).

$$\mathrm{dm_{net}} = \frac{\mathrm{ND}}{\mathrm{I_{int}}} \times \mathrm{d_{net}} \tag{3.7}$$

Where:

dm_{net}= monthly net irrigation depth, in mm

ND = number of days per month

Step VII. Checking and adjusting for deficit in the months of peak season

The monthly calculated dm_{net} values were deducted from the estimated monthly IN as shown in Table 3.6. Positive and negative values of the differences indicate excess and deficit of water, respectively. To avoid crop water stress especially in the months of peak irrigation water need, it is important to refine the scheduling method. Based on the recalculated irrigation interval for the months of peak irrigation water need (Table 3.7), the dm_{net} values for the entire irrigation season were refined (Table 3.6) following the procedure indicated by Brouwer et al. (1989) through reiterations to avoid deficits especially in the peak months.

Based on the planting dates and determined irrigation interval, a predefined irrigation calendar was prepared. Considering the shallow crop root depth (early stage) and the farmers' and *Woreda* extension agents' suggestions and local practices the net irrigation depths (d_{net}) for the first three irrigation events were reduced to 50 mm, to avoid excess water loss.

Step VIII. Calendar validation

The Practical (Hargreaves' based) calendar was tested and validated on-farm against Complex (Penman-Monteith based), described below (3.2.3.2), and Traditional (farmers' practices) scheduling techniques for 2014/15 and 2015/16 irrigation seasons as shown in Table 3.9 and Table 3.10. In the second irrigation season in 2015/16, due to insufficient rainfall the harvested water in the reservoir was very low. The size of irrigated area in the irrigation scheme is usually decided based on the amount of harvested water. Besides the low amount of harvested water, considering the amount of water that can be saved which otherwise would have been lost by seepage and evaporation from the reservoir, the irrigation committee shifted the irrigation calendar by more than a month earlier from January (2016) to the end of November (2015), so that more farmers can be accommodated. Thus, the Practical and Complex irrigation calendars for the second season were updated accordingly.

3.2.3.2 Complex (CropWat simulated) irrigation scheduling

The CropWat 8 computer software developed by FAO (Swennenhuis, 2009) was used for determination of the crop and irrigation water requirement (Table 3.8) and irrigation scheduling (table 3.9). This program helps to calculate the potential evapotranspiration (ET_0) using various climatic data (temperature, humidity, wind speed and sunshine hours), based on Penman-Monteith method. Long term climatic data (Table 3.2) from the nearby (about 43 km far) station were used. The crop factor, length of growing season used was the same as the Practical approach.

Using the CropWat model, several options such as variable irrigation interval and amount (irrigating at critical or fixed depletion), fixed interval per growing stage and variable depth were consulted with the farmers and extension agents. However, for ease of understanding and comparisons of the new scheduling techniques (Practical and Complex) by the majority farmers, fixed irrigation interval for these two scheduling techniques were suggested by the group. The soil input data for CropWat considered were:

- Texture: clay
- Total available soil moisture: 160 mm (Table 3.1)
- Maximum rain infiltration rate: 30 mm/day (adapted from CropWat for clay soil)
- Initial moisture depletion: 80%. The amounts of applied water for all treatments were accounted starting on the first irrigation event (day one) which was done immediately after sowing. 80% depletion was considered based on a feel and appearance approach
- Maximum rooting depth: 2 m

Then, based on "the fixed irrigation interval" and "refilling to field capacity" option the irrigation schedule was calculated.

3.2.3.3 Traditional irrigation schedule

The Traditional method of irrigation schedule represented the farmer’s existing scheduling practice and was considered the control. The farmer was allowed to irrigate all the replications of the traditional treatment based on his experience without any interference of the researcher for the entire growth period. Yet, the amount of applied water during each irrigation event was simply recorded using a Partial flume.

3.2.4 Experimental design

Nationally developed maize variety “Melkassa-II” (*Zea mays* L.), which is popular in the study area, was used as indicator crop in this study. Three treatments (irrigation scheduling methods) namely “Traditional”, “Practical” and “Complex (CropWat simulated)” were replicated three times in randomized block design (RCBD) on-farm in 2014/15 and 2015/16 irrigation seasons.

3.2.5 Data collection and analysis

3.2.5.1 Soil samples

Before the set-up of the treatments on the experimental field, composite and undisturbed soil samples at 20 cm layer up to 1 were collected from three random locations in 2015.The soil texture, pH and organic matter were analysed from the composite soil samples in a laboratory following the standard procedures. Soil bulk density (BD), field capacity (FC) and permanent wilting point (PWP) were analysed from the undisturbed soil samples. Further at planting and at harvest in both irrigation seasons, soil samples were collected at 20 cm interval across the profile up to 1 meter from all replications of each treatment and soil salinity of saturated extracts (EC_e) were measured at laboratory following validated procedure.

3.2.5.2 Irrigation water

Pre-plant irrigation is common practice in the study area to soften the soil for ploughing. Since it was done for the entire farm before the experimental lay out, the amount was not included in our study. The irrigation water applied to each plots was monitored onwards from sowing date. For the traditional scheduling treatment the farmer's irrigation intervals were recorded and the amount of applied water was monitored using Parshall flume in each irrigation event. For the Practical and Complex treatments, simple data sheets (displaying instant calculations of the depths of applied water) were prepared and the determined amounts of water were applied using Parshall flumes, at each irrigation events. The salinity (electrical conductivities; EC_W) and pH of the irrigation water were monitored using portable and calibrated EC and pH meters.

3.2.5.3 Yield and yield components

Grain yield and yield components (total fresh biomass, plant height, number of ears per plant, ear length, number of kernels per ear and 1000 kernels weight) were measured at harvest (physiological maturity).

3.2.5.4 Water productivity (WP)

The ratio of crop yield to the amount of water applied was calculated using Eq. (3.8).

$$\mathrm{WP} = \frac{\mathrm{Y}}{\mathrm{I}} \tag{3.8}$$

Where:
WP = water productivity, in kg m^{-3}
Y =grain yield of maize, kg ha^{-1}
I – total irrigation water applied, in m^3 ha^{-1}

3.2.5.5 Farmers' and local experts' opinion

Farmers' day was arranged at harvest of the maize crop in both irrigation seasons. In the farmers' day four groups were formed. The three groups were "farmers' group" consisting of six farmers each and the fourth group was "expert group" formed from four staff members of the *Woreda* (local) office of Agriculture and Rural Development, which constituted experts from extension, irrigation, crop and natural resources. Then, each group was allowed to rank the crop stand of the three treatments, freely upon the group's consensus. Moreover, the farmers' and the local experts' opinions and suggestions regarding the conveniences and appropriateness of the different scheduling methods were collected through open discussions.

3.2.5.6 Statistical analysis

The data were checked for the assumptions of normality and homogeneity of variances using Shapiro-Wilk and Levene's tests, respectively. Then, mean comparison on the effect of irrigation treatments on yield and yield components as well as the soil salinity were analysed by one-way ANOVA (F-Test) using SPSS-20 statistical software, separately for each irrigation season. The variance components (within and between groups) were estimated using general linear model. The results are presented in the form of graphs and tables. The farmers and expert groups treatment mean rank comparison of the crop stand is also presented in a Table.

3.3 Results

3.3.1. Potential evapotranspiration (ET_0) and crop evapotranspiration (ET_C)

As depicted in Table3.2, the estimated monthly ET_0 for the irrigation season of the study area were higher for Penman-Monteith as compared to the Hargeaves method, except in those three months from July to September, although the climatic data used for both methods were collected from the same station at about 43 km distance.

In both irrigation seasons, lower crop water needs (ET_C) were found in the Practical method as compared to the Complex method. The determined ET_C using the Practical scheduling method were 508 mm and 456 mm in the 1st (2014/15) and 2nd (2015/16) irrigation seasons, respectively (Table 3.3). In the Complex method, these values were 756.8 mm and 708.9 mm for the former and latter irrigation seasons, respectively (Table 3.8).

3.3.2 Irrigation amount and interval

Following the Practical method the first calculated number of irrigation events (7) and the irrigation intervals (19 days) were the same for both irrigation seasons (Table 3.5). However, for the 1st season experiment, the calculated dm_{net} (using 19 days interval) showed 33 mm and 32 mm water deficit in the months of March and April, respectively (Table 3.6). Similarly, for the 2nd season a deficit of about 36 mm and 2 mm were shown in the months of February and March, respectively. To avoid crop losses, refinement were done for the entire growing season based on the calculated deficit months I_{int} (15 days) as shown in Table 3.7. For clarity the refined (recalculated) dm_{net} is placed in Table 3.6 below 19 days interval column.

Table 3.4 *Irrigation water need (IN) of maize crop for 2014/15 and 2015/16 irrigation seasons.*

Irrigation season	2014/15					
Month	Jan	Feb	Mar	Apr	May	Total
Rainfall (mm/month)	0.7	2.5	8.6	19.6	18.6	50.0
Effective rainfall (mm/month)	0.0	0.0	0.0	1.8	1.2	2.9
ET crop (mm/month)	29.7	101.8	143.4	144.3	89.0	508.2
IN (mm/month)	29.7	101.8	143.4	142.5	87.9	505.3

Irrigation season	2015/16						
Month	Nov	Dec	Jan	Feb	Mar	Apr	Total
Rainfall (mm/month)	1.9	0.8	0.7	2.5	8.6	19.6	34.1
Effective rainfall (mm/month)	0.0	0.0	0.0	0.0	0.0	1.8	1.8
ET crop (mm/month)	4.4	60.2	93.0	146.3	112.1	40.4	456.3
IN (mm/month)	4.4	60.2	93.0	146.3	112.1	38.6	454.6

Table 3.5 *Number of irrigation events and irrigation interval (I_{int}).*

Irrigation season	IN (mm/growth season)	No. of irrigation events (I_{na})	I_{int} (days)
2014/15	505.3	7.2 (7)*	19.3 (19)*
2015/16	454.6	6.5 (7)*	19.3 (19)*

* Rounded to the nearest whole number

Table 3.6 *Monthly irrigation requirements, net application depths and deficits (under different irrigation intervals) in 2014/15 and 2015/16 irrigation seasons.*

Irrigation interval	Irrigation season	2014/15					
	Month	Jan	Feb	Mar	Apr	May	Total
19 days	IN	30	102	143	143	88	505
	dm_{net}	74	111	111	111	92	497
	dm_{net}-IN	44	9	-33	-32	4	-8
15 day (based on Table 3.7)	IN	30	102	143	143	88	505
	dm_{net}	67*	100*	140	140	117	563
	dm_{net}-IN	37	-2	-3	-3	29	58

Irrigation interval	Irrigation season	2015/16						
	Month	Nov	Dec	Jan	Feb	Mar	Apr	Total
19 days	IN	4	60	93	146	112	39	455
	dm_{net}	11	111	111	111	111	44	497
	dm_{net}-IN	7	50	18	-35.8	-1.5	6	43
15 day (based on Table 3.7)	IN	4	60	93	146	112	39	455
	dm_{net}	10*	100*	140	140	140	56	586
	dm_{net}-IN	6	40	47	-6	28	17	131

*****dm_{net} for 1st two months reduced from 70 mm to 50 mm

Despite the difference in the planting dates of the irrigation seasons, the adjusted irrigation interval was appeared to be the same for both irrigation seasons. In our calculation as shown in Table 3.6, both deficit months (Feb & Mar) were considered. Still, for both irrigation seasons, a small amount of monthly deficits are shown. These deficits would be smaller when partitioned in the two irrigation events; moreover, considering the higher application depth (95 mm) than the determined (93.3 mm), while the rounding, the deficits were ignored.

Table 3.7 *Recalculation of irrigation interval and No. of irrigations based on months of crop water deficits.*

Irrigation season	Deficit months	IN (mm/month)	Sum (mm) (a)	NID (b=a/dnet) (b)	I_{int} (days) (c=NDD/b) (c)	Total I_{na} (d= LGS/c) (d)
2014/15	Mar	143	286	4.1 (4)*	15	9
	Apr	143				
2015/16	Feb	146	258	3.7 (4)*	15	9
	Mar	112				

IN= irigation water need, NID= no. of irrigation events in the deficit months, NDD= total number of days in the deficit months, *Rounded to the nearest whole number

Table 3.8 *Crop water requirement (ET_C) and irrigation requirements of maize in 2014/15 and 2015/16 irrigation seasons using Penman-Monteith (CropWat simulated).*

Irrigation season													
2014/15 (planting date: 10 Jan 2015)							2015/16 (planting date: 28 Nov 2015)						
Month	Dec	Stage	Kc	ETc (mm/ dec)	Eff rain (mm / dec)	Irr. Req. (mm/ dec)	Month	Dec	Stage	Kc	ETc (mm/ dec)	Eff rain (mm/ dec)	Irr. Req. (mm/ dec)
Jan	1	Init	0.4	2	0	2	Nov	3	Init	0.4	6	0	6
Jan	2	Init	0.4	20.1	0	20.1	Dec	1	Init	0.4	20	0	20
Jan	3	Deve	0.41	23.9	0	23.9	Dec	2	Deve	0.41	20.4	0	20.4
Feb	1	Deve	0.56	31.5	0	31.5	Dec	3	Deve	0.59	32.3	0	32.3
Feb	2	Deve	0.76	45.7	0	45.7	Jan	1	Deve	0.81	40.6	0	40.6
Feb	3	Deve	0.95	46.3	0	46.3	Jan	2	Deve	1.02	51.5	0	51.5
Mar	1	Deve	1.14	70.3	0	70.3	Jan	3	Mid	1.22	71.7	0	71.7
Mar	2	Mid	1.23	77.3	0	77.3	Feb	1	Mid	1.25	70.7	0	70.7
Mar	3	Mid	1.23	86.1	0.1	86	Feb	2	Mid	1.25	74.7	0	74.7
Apr	1	Mid	1.23	79.3	0.4	78.8	Feb	3	Mid	1.25	60.7	0	60.7
Apr	2	Late	1.23	80.1	0.6	79.5	Mar	1	Late	1.23	76.5	0	76.5
Apr	3	Late	1.11	71.9	0.6	71.3	Mar	2	Late	1.1	69	0	69
May	1	Late	0.93	59.6	0.2	59.5	Mar	3	Late	0.91	63.9	0.1	63.8
May	2	Late	0.75	47.7	0	47.7	Apr	1	Late	0.73	47	0.4	46.5
May	3	Late	0.63	15.1	0.4	14.5	Apr	2	Late	0.63	4.1	0.1	4.1
Total				756.8	2.3	754.4	Total				708.9	0.6	708.3

For the Complex method discussed in section 3.2, the irrigation interval considered (15 days) was the same as the Practical methods and similarly the determined irrigation events (9 times) were the same, too.

The farmer's (Traditional) irrigation interval ranged from 13 to 17 days and from 14 to 21 days for the 1st and 2nd season experiments, respectively (Table 3.10). The minimum intervals were recorded in the 2nd and the maximum in the 3rd, 4th and around the last irrigation events for both irrigation seasons. The same numbers of irrigation events (8) were recorded for the Traditional method for both irrigation seasons, which were lower than the other approaches (9).

The total water applied by the Practical approach was 756 mm, which was the same for both irrigation seasons. However, the total applied water in the 1st season experiment was 898.4 mm and 983.8 mm for the Traditional and Complex methods, respectively, and during the 2nd season 873.1 mm and 960.9 mm was applied by the former and later approaches, respectively. Higher depths of water were applied by the Complex followed by the Traditional and then by the Practical methods in both irrigation seasons.

Table 3.9 *Maize irrigation schedule calendar, net and gross irrigation depths (mm) by the Practical and Complex methods in both irrigation seasons.*

Irrigation event	Date	Days after planting	Practical method		Complex method	
			d_{net}	d_{gross}	d_{net}	d_{gross}
			Irrigation season 2014/15**			
1st	10/Jan/15	1	50	65	9.3	12.4
2nd	24/Jan/15	15	50	65	42.2	56.3
3rd	07/Feb/15*	29	50	65	65.2	86.9
4th	23/Feb/15	45	70	95	92.3	123
5th	10/Mar/15	60	70	95	118	157.2
6th	25/Mar/15	75	70	95	109	145.6
7th	09/Apr/15	90	70	95	108	144.5
8th	24/Apr/15	105	70	95	106	141
9th	09/May/15	120	70	95	87.7	116.9
Total			570	765	738	983.8
			Irrigation season 2015/16			
1st	28/Nov/15	1	50	65	9.3	12.5
2nd	12/Dec/15	15	50	65	42.1	56.2
3rd	27/Dec/15	30	50	65	63.3	84.4
4th	11/Jan/16	45	70	95	85.4	113.8
5th	26/Jan/16	60	70	95	110	147.2
6th	10/Feb/16	75	70	95	102	135.9
7th	25/Feb/16	90	70	95	109	145
8th	11/Mar/16*	104	70	95	109	145.2
9th	27/Mar/16	120	70	95	90.6	120.7
Total			570	765	721	960.9

* Irrigated one day earlier because water gates are not operational on Sunday

****** Since land preparation was done in December 2014, it is named as 2014/15 irrigation season.

The amount of water applied by the Traditional approach depends upon the farmer's experience. In the first two irrigations the applied water was lower as compared to the rest of the irrigation events and showed almost an increasing trend except for the last irrigation cycle in both irrigation seasons.

In the Traditional scheduling, maximum depth (>120 mm) per applications were recorded in the 5th, 6th and 7th irrigation events. For the Complex approach, higher application depths (>130 mm) were recorded during the 5th to 8th irrigation events. In both treatments, starting the 3rd (for Traditional) and the 4th (for Complex) up to the last irrigation events, there was frequent ponding of water on the plots for a considerable time (3-8 hrs.) after irrigation. During these irrigation events, wet soil surface for a couple of days was also observed especially in the Complex treated plots.

Table 3.10 *Irrigation interval and applied irrigation depth by Traditional irrigation schedule.*

Irrigation event	Date	Irrigation interval	d_{gross} (mm) R-I*	R-II	R-III	Average
			Irrigation season 2014/15			
1st	10/Jan/15	1	92.6	98.7	87.7	93
2nd	23/Jan/15	13	74.1	79.3	85.3	79.6
3rd	11/Feb/15	19	122.4	120.7	129.6	124.2
4th	28/Feb/15	17	109.5	118.5	113.7	113.9
5th	14/Mar/15	14	127.8	130.6	125.5	128
6th	30/Mar/15	16	126.9	117.8	132.8	125.8
7th	14/Apr/15	15	125.2	125.6	128.5	126.4
8th	01/May/15	17	105.4	107.2	109.7	107.4
Total			883.9	898.4	912.8	898.4
			Irrigation season 2015/16			
1st	28/Nov/15	1	97.6	92.2	87.9	92.6
2nd	11/Dec/15	14	77.3	86.1	77.6	80.3
3rd	01/Jan/16	21	110.5	114.1	124.9	116.5
4th	19/Jan/16	17	104.2	109.5	116.4	110
5th	02/Feb/16	14	120.3	124.2	125.4	123.3
6th	17/Feb/16	15	128.6	125.6	133.6	129.3
7th	05/Mar/16	17	124.7	117.6	122.2	121.5
8th	23/Mar/16	18	91.1	99.6	108.1	99.6
Total			854.3	868.9	896.1	873.1

*R-replication

3.3.3 Soil salinization

The salinity (electrical conductivity) of the irrigation water varied across the growing seasons from 0.45 dS m^{-1} (pH-7.45) at the beginning of irrigation seasons to 0.68 dS m^{-1} (pH-7.6) at the end.

The distribution of salts (EC_e) in the soil profile up to 100 cm at planting and at harvest for both irrigation seasons is depicted in Table 3.11.

In the 1st season (2014/15) experiment, the average root zone (100 cm) salinity (EC_e) at planting were 1.69, 1.94 and 1.83 dS $m^{-1}$for the Complex, Traditional and Practical treatments, respectively. Statistically, all were similar. In the same season, at harvest, higher surface (0-20 cm) salinity was found in the I_2 (2.43 dS m^{-1}) followed by I_1 (2.34 dS m^{-1}), and lower value was found in the I_3 (2.03 dS m^{-1}) treatment. On the contrary, the EC_e in the preceding profile (20-40 cm) was higher in I_3 (1.88 dS m^{-1}) as compared to the other treatments. Lower soil salinity below 50 cm depth was found in the I_1 compared to the other treatments. In all treatments EC_e showed an increasing trend towards deeper soil regions at planting time,but at harvest the salinity the salinity in the 0-20 cm surface layer appeared to be higher than at the start of the growing season.

Table 3.11 *Effects of irrigation schedule on distribution of salts (dSm^{-1}) in the soil profile.*

Sampling time	Treatment	Sample depth (cm) 0-20	20-40	40-60	60-80	80-100	Ave
		Irrigation season 2014/15					
Planting	I_1=Complex	1.44	1.62	1.5	2	1.89	1.69
	I_2=Traditional	1.5	1.56	2.06	2.36	2.24	1.94
	I_3=Practical	1.45	1.38	1.62	2.28	2.43	1.83
Harvest	I_1=Complex	2.34ab	1.8	2.63	2.53	2.77	2.41
	I_2=Traditional	2.43a	1.61	2.91	2.99	2.93	2.57
	I_3=Practical	2.03b	1.88	2.51	2.82	3.04	2.45
		Irrigation season 2015/2016					
Planting	I_1=Complex	1.32	1.34	1.62	2.01	2.09	1.67
	I_2=Traditional	1.43	1.41	1.88	1.98	2.19	1.78
	I_3=Practical	1.46	1.37	1.98	2.08	2.04	1.79
Harvest	I_1=Complex	2.22	1.69	2.01	2.12a	2.14	2.04
	I_2=Traditional	1.96	1.9	2.32	2.21a	2.54	2.19
	I_3=Practical	1.76	1.95	2.46	2.68b	2.63	2.29

***** Note: Means followed by the same letters in column are not statistically different at P<0.05.

In the same season the average EC_e at harvest was 2.41, 2.57 and 2.46 dS m^{-1} for the I_1, I_2 and I_3, respectively. Although a significant increment in soil salinities were observed at harvest as compared to planting in all treatment, the variation in average root zone salinities at harvest among all the treatments was not significant.

In 2015/16 at harvest, the EC_e of $I_1$was higher (2.22 dS m^{-1}) at the surface (0-20 cm) and lower at the preceding profiles as compared to the other treatments. In contrast, except in the surface (0-20 cm), higher EC_e was found in all layers in I_3 compared to the other treatments. The average EC_e across the entire profile were 2.04 dS m^{-1}, 2.19 dS m^{-1} and 2.3 dS m^{-1} in the I_1, I_2 and I_3treatments, respectively. At harvest, the soil salinity in the 60-80 cm depth was significantly ($P<0.05$) higher in I_3 (2.68 dS m^{-1}) as compared to I_1 (2.12 dS m^{-1}) and I_2 (2.21 dS m^{-1}). However, the average root zone salinity between all treatments was not significant.

In both irrigation seasons, a white efflorescence appeared on the surfaces of all treatments after the soil dried, although the severity varied between irrigation events. At harvest, in both irrigation seasons, lowest surface EC_e values were found in the Practical treatment and the lowest average root zone EC_e was found in the Complex treatment.

3.3.4 Yield and yield components

The results of variance components are depicted in Table 3.12. In both irrigation seasons the proportion of treatment (between groups) variances of most parameters were higher as compared to replication (within group) variances.

The effect of different irrigation scheduling treatments showed significant results of maize biomass in both irrigation seasons (Table 3.13). In 2014/15, the I_3 (Practical) treatment significantly increased (at $P<0.05$) the biomass as compared to other treatments (I_1 and I_2). However, in 2015/16 the results showed non-significant differences in biomass between the I_3 and other treatments. Maximum and minimum biomass of 25.8 t ha^{-1} (2014/15) and 20.4 t ha^{-1} (2015/16) were recorded in I_3 and I_1 treatments, respectively. In 2014/15 the biomass in both the I_1 and I_2 treatments showed non-significant results, although significant differences were found in 2015/16.

As shown in Table 3.13, the effect of different irrigation scheduling treatments showed non-significant results in grain yield among all treatments in 2014/15. However in 2015/16, the I_3 treatment gave significantly higher grain yield than all treatments. In both irrigation seasons, the I_2 and I_3 treatments were, however, statistically not significant in grain yield. In 2015, average grain yield results were 4.78, 4.83 and 5.22 t ha^{-1} in I_1, I_2 and I_3 treatments, respectively. The corresponding grain yield in 2015/16 was 4.5, 4.41 and 5.05 t ha^{-1}, respectively.

The plant height was significantly higher for I_3 as compared to I_1 in 2014/15. However, no significant differences on plant height were observed in 2015/16. The effect of irrigation scheduling on ear length showed no significant differences among all treatments in both irrigation seasons. The number of ears per plant and the number of kernels per ear in 2015/16 were significantly higher for I_3 as compared to I_1, though all the treatments failed to show any significant differences in 2014/15 in the number of ears per plant and the number of kernels per ear. In both years, the I_3 treatment significantly enhanced 1000-kernel weight as compared to other treatments, though no significant differences in 1000-kernels weights were found between the I_1 and I_2 treatments in both years.

Table 3.12 *Variance components of onion yield and yield components.*

Irrigation season	Source	Biomass (t ha-1)	Grain yield (t ha-1)	Plant height (cm)	Number of ears per plant	Ear length (cm)	Number of kernel per ear	1000 kernel wt. (gm)	WP (kg m-3)
2014/15	Treatment	2.32 (60.0%)	0.05 (45.0)%	3.49 (51.8%)	0.005 (45.4%)	0.24 (28.4%)	152.75 (44.4%)	1367.4 (86.7%)	0.01029 (92.8%)
	Replication	0.08 (2.1%)	0.035 (32.1%)	0.46 (6.9%)	0.002 (20.7%)	0.42 (49.5)	40.05 (11.6%)	93.2 (5.9%)	0.00034 (3.1%)
	Error	1.46 (37.9%)	0.025 (37.9%)	2.78 (41.3%)	0.004 (33.7%)	0.19 (22.1%)	151.65 (44%)	116.8 (7.4%)	0.00046 (4.2%)
2015/16	Treatment	4.07 (54.3%)	0.118 (81.6%)	2.75 (21.6 %)	0.006 (54.1%)	0.34 (40.6%)	966.12 (64.2%)	1370.4 (62.3%)	0.01031 (97.3%)
	Replication	0.46 (6.1%)	0.022 (15.5%)	5.51 (43.2%)	0.001 (8.3%)	0.12 (13.9%)	246.82 (16.4%)	608.2 (27.7%)	0.00025 (2.4%)
	Error	2.97 (39.7%)	0.004 (2.9%)	4.5 (35.3%)	0.004 (37.6%)	0.38 (45.5%)	291.43 (19.4%)	221.2 (10.1%)	0.00003 (0.3%)

Note: Numbers within parenthesis represents the proportion (percentage) of variation of the total variation.

Table 3.13 *Effect of irrigation schedule on yield and yield components and water productivity of maize.*

Irrigation season	Treatments	Biomass (t ha-1)	Grain yield (t ha-1)	Plant height (cm)	Number of ears per plant	Ear length (cm)	Number of kernel per ear	1000 kernel wt. (gm)	WP (kg m-3)
2014/15	I1=Complex	22.9(1.56)a	4.78(0.35)a	170.7(2.82)a	1.04(0.08)a	15.9(0.8)a	373.3 (12.5)a	285.3(10.9)a	0.49(0.04)a
	I2=Traditional	23.0(1.35)a	4.83(0.07)a	172.6(1.5)ab	1.05(0.04)a	15.7(0.9)a	371.9(3.97)a	309.8(10.3)a	0.54(0.04)a
	I3=Practical	25.8(0.75)b	5.22(0.23)a	174.9(1.14)b	1.18(0.1)a	16.7(1.49)a	397.2(20)a	359(20)b	0.68(0.03)b
2015/16	I1=Complex	20.4(2)a	4.5(1.9)a	169.7(1.2)a	1.07(0.06)ab	15.5(1.2)a	364(8.5)a	294.8(25)a	0.47(0.02)a
	I2=Traditional	24.4(1.46)b	4.41(0.2)a	171.2(7.7)a	1.04(0.08)a	15.8(1.17)a	373.7(27)a	300(42)a	0.50(0.02)b
	I3=Practical	24.1(2.02)ab	5.05(0.08)b	173.6(7.29)a	1.2(0.07)b	16.7(1.9)a	424.7(28)b	363(23)b	0.66(0.01)c

Note: Means followed by the same letters in column are not statistically different at $P<0.05$; Numbers within parenthesis represents the standard deviation.

3.3.5 Water productivity (WP)

The average water productivity of the different irrigation scheduling treatments is presented in Table 3.13. The WP was significantly influenced by the different irrigation schedules in both irrigation seasons. Maximum WP (0.68 kg m^{-3} in 2014/15 and 0.66 kg m^{-3} in 2015/16) was found in I_3 in both irrigation seasons. The I_1 treatment resulted in lower WP (0.49 kg m^{-3} in 2014/15 and 0.47 kg m^{-3} in 2015/16) in both irrigation seasons. The I_3 treatment significantly increased the WP as compared to the other (I_1 and I_2) treatments, in both irrigation seasons. The WP for both I_1 and I_2 were not statistically significant in 2014/15, though the WP for I_2 in 2015/16 was significantly higher than I_1. The simple linear regression between WP and yield (Figure 3.2) showed that an increase in WP with yield increment and water decrement.

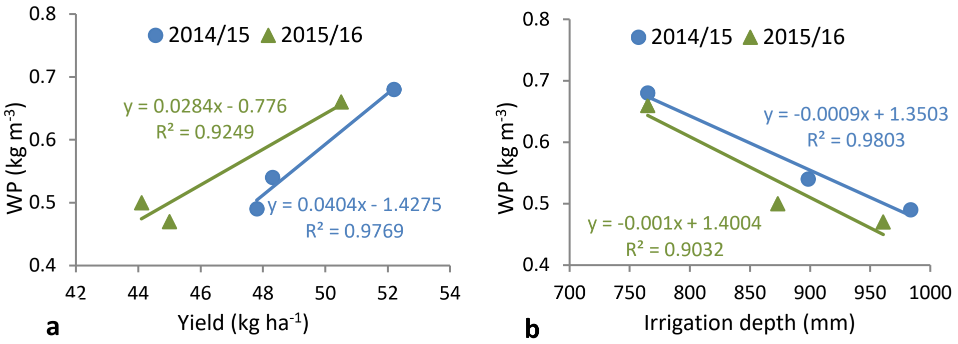

Figure 3.2 *Relationships of water productivity (WP) with grain yield and irrigation depth for 2014/15 and 2015/16 irrigation seasons.*

3.3.6 Farmers' and local experts'(extension agents') opinion

3.3.6.1 Ranking of crop stand

The farmers' and extension agents' groups mean rank (according to their own criteria) of the treatments are depicted in Table 3.14. Each group was invited to present their ranking results as well as major justifications.

In 2014/15, the I_3 treatment was ranked the best by all of the groups, although statistically similar as compared to I_2 in the farmer group II. The treatment mean rank in I_1 and I_2 were the same for farmers' group I and III. Although, the mean rank of I_1 was the least for the experts and the farmers group-II, compared to I_2, it was significant only for the latter group.

In the second season (2015/16), similarly the I_3 treatment was given the best rank by all farmers groups, although farmers group-II gave the gave same rank to the I_2 treatment. The mean rank variation between I_1 and $I_2$was significant for farmers group I and group II.

Table 3.14 *Farmers and expert group mean rank of crop stand.*

Irrigation season	Treatment	Farmer groups				Expert group
		G-I	G-II	G-III	Mean	
2014/15	I_1=Complex	2.33a	2.67a	2.33a	2.44a	2.33a
	I_2=Traditional	2.33a	1.67b	2.33a	2.11a	2a
	I_3=Practical	1b	1b	1b	1b	1b
2015/16	I_1=Complex	2a	2.33a	2.67a	2.33a	2.67a
	I_2=Traditional	2.67b	1b	2.33a	2a	2.33a
	I_3=Practical	1c	1b	1b	1b	1b

Note: Means followed by the same letters in column are not statistically different at $P<0.05$. The smaller the number, the best the rank

In both irrigation seasons, the farmer groups' overall mean rank variation for I_3 was significantly different (best) compared to I_1 and I_2. However, the overall mean rank between I_1 and I_2 was statistically similar for both irrigation seasons. From the groups' presentation, the farmers major critera of ranking the crop stand were the expected grain yield and total biomass, which were judged from observation of the plant height, stem thickness (diameter) and number of ears.

3.3.6.2 Scheduling technique opinions

All the participants appreciated the water saved by the I_3 (Practical technique). While comparing the irrigation intervals, most of the participants were in favor of the fixed irrigation interval (I_1 and I_3). The major reasons raised were its convenience and easiness for individual farmers and scheme water distributors in such a way that they both will know ahead whose turn is next. Important concern raised by the farmers was the capacity and skill of the Water Users Association, on providing fixed interval-based irrigation scheduling at scheme level.

The second major point raised by the experts was on the technical feasibility of measuring water by an individual farmer. Water is not metered on-farm in most irrigation scheme in Ethiopia. However, during the experimental seasons the farmers were surprisingly able to classify the irrigation scheduling techniques qualitatively in their own local language, based on their observation of the applied water to each treatment. "*Ablek leck*" means too much water for I_1, "*Limud*" means usual for I_2 and "*Chebreck-chebreck*" means little by little for I_3.

3.4 Discussions

3.4.1 *Effect of irrigation scheduling on potential evapotranspiration (ET_0) and irrigation amount*

The determined crop water needs (ETC) using the Practical scheduling method were, about 33% and 36% lower than that of the Complex method for the 1st(2014/15) and 2nd (2015/16) irrigation seasons, respectively. The obtained results also showed that the gross amount of applied water by the Complex method was higher by 28.6% (2014/15) and 25.6% (2015/16) than the Practical method. Similarly, the gross applied depths by the Traditional method were higher by 17.4 % and 14.1 % as compared to the Practical method, for the corresponding irrigation seasons.

The big difference between the Practical and Complex methods irrigation could be attributed to many factors such as the approach followed, unreliability of climatic data and the crop factor. For example the daily estimated ET_0 by the Hargreaves method were lower by 19.6 to 29.3% compared to the Penman-Monteith method for the months corresponding to the irrigation season (Table 3.2). That is from January 10 to May 25, 2015 and from November 27, 2015 to April 12, 2016, for the 1st and 2nd irrigation seasons, respectively. Although, the station where the climatic data were collected (about 43 km distance) and the study area have similar elevation, Ethiopia in general and the region in particular are characterized with a complex variation in local topography. As a result large errors in predicting and interpolating of climatic data was reported in the country (Boke, 2017).

Further, CropWat distributes the Kc values for the development and late season stages by interpolation in the form of a smooth curve (Table 3.8). However in the Practical method a single K_c value or weighted average K_c value for overlapping months of growth stages are used. This might have also contributed to the difference in amount of irrigation determined between the Practical and Complex methods.

Frequent field observations confirmed surface water-ponding and saturated soil for a significant time after irrigation, in both the Complex and Traditional treatments. Regarding the Traditional practices, this is in line with the finding of Yohannes et al. (2017) reporting qualitatively over-watering practices of the farmers in the same irrigation scheme based on a scheme level survey conducted in 2015/16, side by side with this study.

Nevertheless, the findings of this research indicates that the Practical irrigation scheduling approach resulted in relatively better performance in estimating the irrigation amount, although, further robust research on local climate and ET_0 is required.

The higher ETC values in the 1st irrigation season as compared to the 2nd irrigation season were due to a change in the irrigation calendar (start of irrigation) of the later irrigation season, associated with cooler weather.

3.4.2 Effect of irrigation scheduling on crop performance and water productivity

Higher grain yields were recorded in the Practical method in both irrigation seasons, although, it was significant only in 2015/16. A significant biomass increase was also obtained in 2014/15 for the Practical as compared to the other treatments. Over all, the Practical method resulted in better crop performance as compared to the other treatments. Since land preparation, fertilizer application and other agronomic practices were the same for all treatments, it can be concluded that the combined effect of the applied amount of irrigation water and interval created a favorable soil water environment for production of a greater amount of grain yield, and overall better crop performance.

The gross amount of applied water particularly from the 4th to the 8th irrigations events for the Complex and Traditional approaches range from 123 to 157 mm and 114 to 129 mm, respectively. As shown in Table 3.1, the total plant available water (PAW) of the soil in the study area is 160.5 mm. For the sake of comparison, the applied irrigation for the Complex approach in terms of PAW depletion ranges from more than 70% to about 100%. The surface water ponding and prolonged soil wetness indicates that the applied water was much in excess of the depleted water from the root zone by evapotranspiration.

Nitrogen available for plant uptake is susceptible to leaching and denitrification losses due to excess water and prolonged wetness (IPNI, 2019; Kanwar et al., 1988). Thus, the higher amounts of applied water (especially in I_1 treatment) was likely to be responsible for lower performance of the crop by creating deficiency of nitrogen due either leaching and/or denitrification. In a research conducted to quantify the impact of over-irrigation on maize yield at University of Neberaska-Lincolon, United States (Irmak, 2008), over-irrigation of maize to 125 percent of ET_C resulted in a yield reduction as compared with fully irrigated (100 percent ET_C). Another study conducted in Limpopo, South Africa reported excessive irrigation water is among the factors for poor maize yields on farmer’s fields (Machethe et al., 2004).

Besides to lower grain yields, the Complex and Traditional methods resulted in applying more water than the Practical method. Especially in the Complex method, about 218 mm (in 2014/15) and 196 mm (in 2015/16) in excess of the Practical method was applied. The Practical method significantly increased the water productivity in both irrigation seasons compared to the other methods (Table 3.13). The finding of this study showed that, higher water productivities are associated with higher grain yields (Figure 3.2a) as well as lower total irrigation depths (Figure 3.2b) in both irrigation seasons. These also confirm that over-irrigation in both the Complex and Traditional methods occurred.

3.4.3 Effect of irrigation schedules on soil salinization

In both irrigation seasons at harvest (Table 3.11), lower surface (0-20 cm) soil salinity was observed in the Practical compared to the other treatments. The salinity values presented in Table 3.11 at harvest indicate the effect of upward capillary salinization.

As discussed in section 3, surface water ponds were common in both the Complex and Ttraditional treatments due to the higher application depths (in most of the irrigation events) and poor internal drainage of the clayey soil (Table 3.1).Thus, evaporative concentration of salts at the surface and capillary movement from the succeeding soil profile are among the likely major reasons for relatively higher surface salt concentration in both the Complex and Traditional treatments. Due to similar reasons, Akhand and Al Araj (2013) found higher salts in the upper (0-25 cm) relative to lower (25-50 cm) depth, which is in line with the finding of this research. According to a survey conducted in 2015/16 (in similar seasons) in the study area, Yohannes et al. (2017) also revealed that farmers believed over-irrigation is the major cause for soil salinization in the irrigation scheme. On the other hand, in both irrigation seasons, the average root zone salinity was slightly lower in the Complex treatment. This indicates that despite the clayey textured soil, leaching seems to be relatively better in the Complex treatment.

At planting of both irrigation seasons, the salt concentrations were lower in all treatments, due to leaching during the rainy season. Difference in salt concentration was also found between the irrigation seasons, which was over all lower in the 2nd season. This is attributed to the change in the planting date of the 2nd (a month earlier) experiment, which reduced the capillary movement of soluble salts, as a result relatively colder conditions.

A wide salinity tolerance exist among different maize cultivars (genotypes), as a general indication the yield potential under increasing salinity of water (EC_i) and soil (EC_e) is: 100%

at EC_i= 1.1 dS m^{-1} and EC_e= 1.7 dS m^{-1}, 90% at EC_i= 1.7 dS m^{-1} and EC_e= 2.5 dS m^{-1}, and so on. During harvest the average root zone salinity found in all treatments was lower than 2.5 dS m^{-1} (the threshold for 90% yield potential), and slightly higher (2.57 dS m^{-1}) in 2014/15 inTraditional treatment. According to various researchers (Farooq et al., 2015; Maas et al., 1983;Maas and Hoffman, 1976), maize is more sensitive to salinity at early stage (emergence and vegetative) than at later growth stages (development of grain yield and yield components).

Considering the good quality (0.45-0.67 dS m^{-1}) of the irrigation water applied and the observed average root zone salinities at planting and harvest, this may not pose significant effects on the yield of maize, as shown in this study.

3.4.4 Farmers' and experts' opinion

While conducting the field experiments, many farmers had followed the entire progress cautiously in both irrigation seasons. Allowing farmers participation in on-farm research encourages information feedback between farmers and researches. It helps in identification of the limitations and requirements by the farmers in the selection of appropriate irrigation scheduling methods.

The local farmers and extension agents were in favor of the Practical approach. This result is more or less in agreement with the obtained results in section 3. In addition to water saving and better crop performance advantages, the major reason for selection of the Practical approach was its convenience for farmers and water distributors due to the fixed interval and constant application. Local extension agents need easy scheduling methodology while farmers also demand for simple, Practical and convenient calendars to achieve improved irrigation management at farm level (Clyma, 1996). Under low technology situations ICID/FAO (1996), simple and operational rules with fixed interval and constant water application are recommended.

Other main concerns raised by the farmers were skill and capacity of the WUA to provide such schedule. This is also true worldwide that WUAs in many countries need capacity building in technical and institutional issues to improve the performance of irrigation schemes (Ghazouani et al., 2012; Kazbekov et al., 2009; Mutambara et al., 2016; Thiruchelvam, 2010; World Bank, 2006b).Thus, building institutional capacity and technical skill of WUA should be considered to arrange and enforce predetermined scheduling calendars.

3.5 Conclusions

Despite the availability of various scientific irrigation scheduling techniques, the adoption by farmers is poor, mainly due the complexity of techniques, inaccessibility of soil-water monitoring tools, lack of local climatic and soil water data and absence of stakeholders' participation. Using Hargreaves equation (which requires only temperature data for estimation of ET_0) and based on the simple procedures for irrigation scheduling in Brouwer et al. (1989) as well as the local farmers' and extension agents' inputs, a simple scheduling calendar (Practical) for maize was tested and validated on-farm against CropWat (Complex) simulated and farmers (Traditional) scheduling methods for two years (2014/15 and 2015/16) at Gumselassa irrigation scheme, North Ethiopia.

The result of the study showed that, the Practical approach resulted in higher grain yield, substantial saving in irrigation water amount and subsequently in significant improvement in water productivity as compared to the other approaches in both years.

Although most of the farmers in the study area are illiterate or completed an elementary school level, they were surprisingly able to classify the alternative irrigation scheduling approaches based on the amount of applied water, qualitatively in their own local language. This leads to the conclusion that, if allowed/participated in scheduling practices, farmers are more or less capable of applying the desired amount of water roughly based on their observations and experiences. Overall, from results of the crop-stand ranking and opinions of the alternative approaches, the local farmers and experts were in favor of the Practical approach. This also gives important information that beneficiaries can be equipped with Practical facts to judge alternative technologies from their own perspectives.

For successful implementation of such a simple irrigation calendar in a community managed irrigation scheme like Gumselassa, technical support and capacity building of the Water Users Associations and concerned governmental and non-government organization is required, especially on arranging and synchronizing schedules at scheme level.

In most rural areas of Ethiopia as well as in other similar countries, where climatic data are lacking or unreliable and the technology level of the farm is low, this technique can significantly improve the irrigation water management practices. Furthermore, local extension agents can practice and easily prepare irrigation calendars for different crops and planting dates following the procedure developed in this study. Moreover, researchers should build on and further improve such simple procedures in other agro-ecological zones, for wider uptake and use. This study also recommends the need for local meteorological studies and observation facilities in the vicinity of irrigation schemes to further optimize irrigation scheduling.

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4. Effect of cyclic irrigation using moderately saline and non-saline water on onion (*Allium Cepa* L.) yield and soil salinization in semi-arid areas of Northern Ethiopia

Due to scarcity and/or unreliability of canal water supply, seepage water is regularly used either for sole irrigation or in conjunction with canal water in most small-scale irrigation schemes in northern Ethiopia. This has been a major cause for low crop yield and aggravating soil salinization. The problem is more exacerbated on onion cultivation as it is sensitive to salinity while it is the major irrigated vegetable crop in the area. Thus, it is essential, to assess a sustainable way to use both water resources conjunctively for the production of onion. A new study was conducted to evaluate the effect of cyclic irrigation using non-saline and moderately saline water on onion yield and soil salinization for two seasons (2014/15 and 2015/16) in the Gumselassa irrigation scheme, Tigray, Ethiopia. Fresh water (EC, 0.41-0.78 dSm^{-1}*) from a micro-dam and moderately saline seepage water (EC, 0.82-2.19 dSm*$^{-1}$*); two main sources of irrigation water in the scheme, were used for the study. Four irrigation water treatments were applied with three replications consisting of: C (canal water alone), S (seepage water alone), 2CS (two times canal water and one time seepage water in cycle) and CS (one time canal water and one time seepage water in cycle) replicated trice. The study was conducted on-farm under close observation and involvement of farmers and extension agents. Data on onion yield and yield components, soil salinity and opinions of the local farmers' and extension agents' were collected and analysed. Maximum (24.8 t ha*$^{-1}$* in 2015/16) and minimum (20.36 t ha*$^{-1}$* in 2015) bulb yield were found in treatments C and S, respectively. In both irrigation seasons, the onion bulb yield variations among the treatments C, 2CS and CS were not significantly different, however the treatment S reduced the onion yield significantly as compared to all but CS in 2015/16.The treatment S resulted in significant salt accumulation, especially in the upper soil profile (0-20 cm). The farmers' and experts' treatment evaluation were the least and significant for S. The cyclic irrigation options are thus recommended to alleviate the problem of fresh water scarcity, without undue onion yield reduction and soil salinization in Gumselassa, and similar irrigation schemes.*

Based on:

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4.1 Introduction

Scarcity of fresh water especially in arid and semi-arid regions of the world has been a major challenge in irrigated agriculture. In response to the increasing scarcity of good quality water for irrigation, farmers are forced to use poor quality water such as brackish, saline or sodic ground water, drainage water and wastewater (Elamin and Al-Wehaibi, 2005;Feigin et al., 1991;Qureshi, 2014).For this reason, vast irrigation areas are threatened by salinization, yield reduction and land abandonment (Crescimanno, 2007; Crescimanno et al., 2004; Qureshi, 2014; Rhoades et al., 1992; Szabolcs, 1994).

Good-quality water resources are diminishing, and saline water must be utilized at best without causing detrimental yield loss and environmental impact (Rhoades, 1984; Shay, 1990; Smith et al., 1996). Even irrigation with good quality water under poor management can create salinization. Thus, adequate management practices are urgently needed for sustainable use of poor quality waters (Crescimanno, 2007).

The use of poor quality water for irrigation has been widely documented (for example Feigin et al., 1991; Elamin and Al-Wehaibi, 2005; Minhas et al., 2007). Conjunctive use of water for irrigation has been one strategy to utilize water resource where good and poor quality waters coexist and can be applied by blending or applying a cyclic method (Grattan and Rhoades, 1990). Blending involves mixing saline with fresh water and a cyclic method means alternate application of saline and fresh water.

Many researchers agree the superiority of cyclic over blending (Minhas et al., 2007; Sharma and Minhas, 2005; Singh, 2014) that it is easier to apply, it does not need reservoir for blending while soil salinity can also be reduced at critical time of physiological growth allowing room for salt sensitive crops (Chanduvi, 1997; Grattan and Rhoades, 1990; Rhoades et al., 1992).

In Tigray region of the northern Ethiopia, likewise in other countries, seepage water from micro-dams has been diverted and directly used for irrigation in many community managed small-scale irrigation schemes, mainly due to scarcity and/or unreliability of fresh canal water (Eyasu, 2005; Teshome, 2003; Yohannes, 2017). Depending on the local situation the seepage water is either used continuously for the entire growing season or in conjunctive (in cyclic manner) with fresh canal water with no predetermined sequences (Yohannes et al., 2017).

Some studies quoted that the use of the seepage water is one of the major causes for aggravating soil salinization and crops yield decline, especially in the Tigray region (Eyasu, 2005; Yohannes et al., 2017). The problem is more pronounced as the seepage water is being utilized for growing salt sensitive crops, particularly onion (*Allium Cepa* L.).

Onion is one of the major high value irrigated vegetable crops for small holders with a wide coverage in Ethiopia. As an integral part of the Ethiopian diet it is the most locally consumed vegetable crop and the main source of cash income for small holder in the country and particularly in Tigray region. Onion is a shallow rooted crop and sensitive to salinity. Soil salinity (EC_e) above 1.2 dS m^{-1}(Allen et al., 1998; Doorenbos and Kassam, 1979;Maas and Hoffman, 1977) and water salinity (EC) above 0.8 dSm^{-1}(Ayers and Westcot, 1985) generally result in onion yield reduction.

Most of the studies conducted on onion crop in the country mainly focused on fertilizer response, the effects of intra-row spacing or the effect of both on yield and/or yield or growth components of onion (Abdissa et al., 2011; Assefa, et al., 2015; Awas et al., 2010; Belay et al., 2015; Gessesew et al., 2015a; Gessesew et al., 2015b).Despite the existing practices of using poor quality water for irrigating particularly salt sensitive crops with great importance in yield and sustainability, less attention is given by the scientific community in the country and particularly in the Tigray region. Farmers in the region are constrained by lack of knowledge and skill of improved irrigation water management practices, which resulted in productivity decline and intensification of land degradation (Eyasu, 2005; Gebremeskel et al., 2018; MoA, 2011b; Yohannes et al., 2017).

Generally, most of the studies conducted in the country are on-station with little or no involvement of the extension works, and with farmers using low technology in the field of irrigation water management (MoA, 2011b).For sustainable agricultural productivity of the irrigation schemes, appropriate management strategies that involve farmers' participation are required (Gebremeskel et al., 2018; Yohannes et al., 2017),particularly in Tigray region.

Worldwide several studies on cyclic irrigation strategy have been conducted on different crops (Bradford and Letey, 1992; Choudhary et al., 2006; Murtaza et al., 2006; Qadir and Drechsel, 2010, Schaan et al., 2003). Studies on cyclic irrigation strategy of cotton, rice, wheat, sugar beet, tomato, cantaloupe, pistachio have shown positive effects upon production (Qadir and Drechsel, 2010). However, there is insufficient information on cyclic irrigation of onion in semi-arid areas, while onions are one of the major irrigated cash crops.

Moreover, most of the studies conducted worldwide are related to green houses using artificially salinized water with the aim to establishrelationships between salinity and crop yield (e.g. Gandahi et al., 2017; Katerji et al., 2001; Van Genuchten and Hoffman, 1984).As a result the outputs didn’t directly serve thewider community of end users.Evans et al. (2012), earlier also reported poor achievement in conjunctive use management and its widespread implementation.Thus, practical on-farm studies involving the local farmers that could influence their decisions are essential to address the twin challenges of sustainability and water scarcity of the irrigated agriculture.

A study on conjunctive use of water for irrigation (new in its kind in the context of Ethiopia) was conducted with the aim to assess a sustainable way of using both fresh and moderately saline water resources for the production of onion, through a cyclic irrigation strategy. Prime attention was given to yield and salinity hazard, and a participatory approach was employed to collect farmers' opinions for further facilitation of adoption.

It is believed that this study will directly help local farmers to increase their production and in improving equitable water allocation. It also gives important lessons for local and regional decision makers on their endeavour to address the sustainability of small scale irrigated agriculture. Finally, this study on conjunctive irrigation can be regarded as a new breakthrough in the context of Ethiopia, and researchers in the subject matter can benefit as starting and guiding information in their further investigations.

The paper is organized as follows. Section 2 describes the study area, the experimental set-up and methods of data collection and analysis. In section 3, the results of the alternative irrigation treatments upon the soil salinity, onion yield and yield components and local opinions are presented. Section 4 discusses the results, while section 5 presents the main findings and policy implications.

4.2 Methodology

4.2.1 Study site description

The experiment was conducted at the Gumselassa irrigation scheme in Hintalo Wojerat Woreda, Southern Zone of Tigray region, Northern Ethiopia. The irrigation scheme is located between $13^0$13′ to $13^0$15′ N and $39^0$30′ to $39^0$33′ E (Figure 4.1) with an average altitude of 2000 m a.s.l.

The major water source for irrigation is a micro-dam with a reservoir design capacity of 1.9 M m^3 of water. The second source is seepage water that comes from the reservoir (through the bed and earthen dam body), which is diverted to a canal and used for irrigation. Depending on the harvested water in the dam reservoir, the size of the total irrigated area varies across years. According to Yohannes et al. (2017), based on six years data (2011-2016) analysis, about 12-35% percent of the total irrigated area was covered by seepage water. The major soil of the scheme is clay (Table 4.1) with poor infiltration characteristics (Eyasu, 2005). Most of the irrigation schemes in the region, including the study area are characterized by poor drainage systems (Eyasu, 2005; Gebremeskel et al., 2018; Yohannes et al., 2017). The irrigated crops include maize, onion, vetch, chickpea, green pea, teff, tomato, garlic, sorghum, lentil, barley, pepper, cabbage and potato.

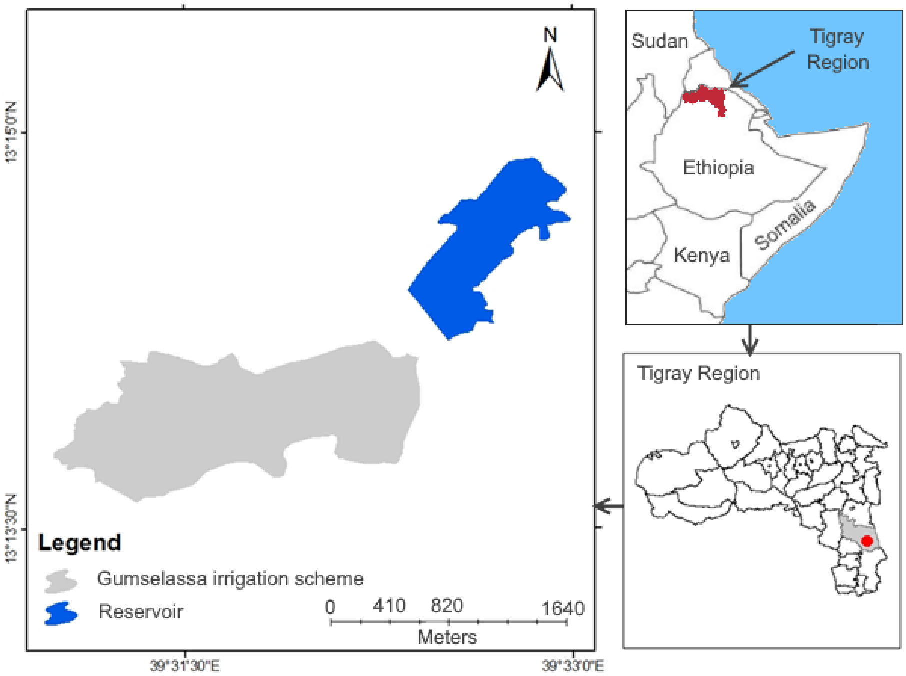

Figure 4.1 *Location of Gumselassa irrigation scheme (adopted from Yohannes et al., 2017).*

Table 4.1 *Soil properties of the experimental plot.*

Soil depth (cm)	Particle size distribution (%)			Texture (USDA)	OM (%)	FC Wt. (%)	PWP Wt. (%)	BD (gmcm^{-3})	TAW (mmm^{-1})
	Sand	Silt	Clay						
0-20	17	28	55	clay	2.31	37.9	23.1	1.29	190.9
20-40	15	27	58	clay	2.00	36.0	21.0	1.30	195.0
40-60	15	25	60	clay	1.84	37.0	22.8	1.33	188.9

Note: OM- organic matter content, FC- field capacity, PWP- permanent wilting point, BD- bulk density, TAW- total available water(the water held in the soil between field capacity and permanent wilting point)

The average annual rainfall and reference evapotranspiration are 500 mm and 1577 mm, respectively, which indicate that the area is typically semi-arid.

4.2.2 Methods of data collection

4.2.2.1 Experimental design

The experiment was conducted for two consecutive irrigation seasons (2014/15 and 2015/16) irrigation seasons from December to April.

From the farmers' fields that could be irrigated by both canal and seepage water through gravity irrigation, a fairly representative and appropriate field for the experiment was selected. The experiment was set in Randomized Complete Block design (RCBD) with treatments replicated thrice. Four water treatments were applied comprised of: C= irrigation by canal water throughout the growing period, S= irrigation by seepage water throughout the growing season, CS= irrigation by canal and seepage water in alternate cycle, 2CS= irrigation twice by canal water and third by seepage water in cyclic manner.

Each treatment had 10.5 m^2 (5 m * 2.1 m) plot size, containing 7 rows/furrows. The border between treatments within a block was 2 m and between blocks it was 1.5 m. The Adama Red onion (*Allium Cepa L.*) variety, which is popular in the country and most preferred by the farmers in the study area, was selected for the experiment. The onion seedlings were transplanted with a spacing of 10 cm between plants and 30 cm between rows/furrows, which is the usual practice of the farmers' in the study area.

4.2.2.2 Irrigation schedule

Before set-up of the experimental plots, the field was irrigated using fresh canal water. The irrigation treatments were initiated at transplanting. The irrigation schedule (amount and interval) was based on the national recommendations for the soils in the study area, with some adjustment to suit local conditions (GIA, 2011). Accordingly, 30 mm net depth at a time was applied, based on the peak demand of onion assuming little or no rainfall occurs during the growing season (GIA, 2011). Taking into consideration short (5 m) well graded and closed furrows (no runoff) and regulated discharge, a 75% application efficiency was used. Then, the gross applied depth was 40 mm. For the first three weeks a five days irrigation interval was deployed, then extended to seven days until three weeks to harvest. Considering the shallow crop root depth (early stage), the local practices and the farmers' and the local extension agents' suggestions to avoid huge initial water loss, the gross irrigation depth applied was reduced to 30 mm for the first four irrigations, and then increased to 40 mm for the rest of the irrigation events. The crop was irrigated 17 times during the growing season and the total applied irrigation depth was 640 mm. The applied amount of water was measured using a Parshall flume.

4.2.2.3 Farmers participation

As major stakeholders, farmers were invited and participated in most activities, starting from the onset up to the end of the experiment in both irrigation seasons. Selection of onion variety and adjustment of irrigation schedule to the local circumstances were done in consultation with the local farmers and extension agents. Many farmers had served in preparation of nursery and raising of onion seedling, ploughing, diversion of irrigation water, guarding, cultivation, weeding and harvesting activities in consultation with the researchers. Two trained farmers were involved in flow measurement using the Parshall flume. During the experimental period, formal and informal field visits and discussions with local farmers and extension workers were commonly noticed.

4.2.2.4 Crop agronomy and management

Adama Red variety onion seeds were sown in a nursery prepared in the study area. After 50 days intensive care, the seedlings were transplanted to the experimental plots. Based on the national recommendation rates, 100 kg ha^{-1} Urea and 200 kg ha^{-1} Diammonium Phosphate (DAP) were applied. Urea was applied two times, half at transplanting and the rest half one month after transplanting. DAP was applied at planting only.Similarly, weeding and cultivation were done as per the practices of the farmers.

4.2.3 Data collection and Analysis

4.2.3.1 Water and soil data

The electrical conductivities (EC) and pH of the canal and seepage water were monitored using portable EC and pH meters. Soil sample profiles with 20 cm depth interval up to 60 cm were collected from each treatment at harvest and planting in both irrigation seasons. Then the samples were air-dried, crushed and sieved (2 mm sieve) in the laboratory. The electrical conductivity of the saturated paste (EC_e) of each sample was analyzed in a laboratory.

4.2.3.2 Yield and yield components

The plant height and the numbers of leaves per plant of the onion stands were quantified by selecting 15 plants randomly, from the central three rows of each treatment. After 75% of the leaves dried, the onion crop was harvested and cured.Fresh bulb yields were measured from the central three rows of the treatments. Bulb weight, diameter and length were measured by randomly selecting 15 onion bulbs from the harvest of the central three rows.

4.2.3.3 Farmers and experts opinion

From the major onion growers in the irrigation scheme, fifteen farmers (that utilize canal, seepage and both water sources for irrigation, water users association committees/their representatives) and three local experts from the *Woreda* Office of Agriculture and Natural Resources were invited during harvest.

They were provided with four types of cards labeled with numbers from one (1) up to four (4). The labeled cards were prepared with different colours to let illiterate farmers easily understand what each card stands for. The value of each card and representations were: “1” or “Green” the best, “2” or “Blue” the second best, “3” or “Yellow” third and “4” or “Red” the least. A short tutorial was delivered to all participants on the value of the cards and on how to use it. Then after careful observation of each block every participant was allowed to rank the replications of the treatments in each block, freely upon his/her observations. Then, a discussion was made with all the participants regarding the performance of the different treatments and their major reasons or criteria for ranking. Moreover their concern, comments and suggestion on the conjunctive (cyclic) irrigation strategy were collected.

4.2.3.4 Analysis of data

The Normality distribution and homogeneity of variance were tested by Shapiro-Wilk and Levene’s tests, respectively. One-way (F-Test) analysis of variance was performed to evaluate the effect of irrigation treatments on onion yield and yield components per year (total bulb yield, bulb weight, bulb diameter and length, plant height and number of leaves) using SPSS 20 statistical software. The proportion of within and between variance components were estimated using general linear model. The mean difference was estimated using the least significant difference (LSD) comparison. Similarly, mean comparison of the farmers' and extension agents' ranking on the different treatments for both irrigation seasons was also analyzed using SPSS.

4.3 Results

4.3.1 Water quality

The water sources used for irrigation and their qualities are depicted in Table 4.2. The electrical conductivity (EC) of the water sources for irrigation varied from planting to harvest. The EC and pH for canal water ranged from 0.41-0.78 dSm^{-1} and from 7.4-7.9 at planting and harvest, respectively. The corresponding values for seepage water were 0.82-

2.19 dS m^{-1} and 7.8-7.9. Similarly, Eyasu (2005) also reported high spatial and temporal EC variation of the water sources within the same cropping season in the same study area.

Table 4.2 *The qualities of irrigation water sources at Gumselassa irrigation scheme.*

Irrigation season			2014/15		2015/16	
Water source			Canal	Seepage	Canal	Seepage
Sampling time	Planting	EC	0.44	1.12	0.41	0.82
		pH	7.5	7.8	7.6	7.9
	Harvest	EC	0.78	2.19	0.65	1.96
		pH	7.4	7.9	7.9	7.9

Note: samples are measured at the head of farm gate

4.3.2 Soil salinity

The profile salt distribution of 20 cm soil layers (EC_e) including standard deviation's error bars are depicted in Figure 4.2 for the different irrigation treatments at planting and harvest of the onion crop for both irrigation seasons.

At planting, a surface (0-20 cm) salinity (EC_e) of 1.70, 1.68, 1.75 and 1.72 dS m^{-1} was found for treatments C, 2CS, CS and S in the 2014/15 irrigation season, respectively. The corresponding values for 2015/16 were 1.63, 1.72, 1.64 and 1.69 dS m^{-1}, respectively.

The effect of different irrigation treatments at harvest resulted in significant variation on the average soil salinities, in both irrigation seasons. At harvest the EC_e of all treatments increased, especially at relatively higher magnitude in the upper root zone, in both irrigation seasons. Although the severity varied between irrigation events and treatments, after the soil dried, appearance of white efflorescence on the soil surfaces were common. At the end of the growing season, lower (1.95 dS m^{-1} in 2014/15 and 1.83 dS m^{-1} in 2015/16) and higher (2.96 dS m^{-1} in 2014/15 and 2.94 dS m^{-1} in 2015/16) surface (0-20 cm) EC_e values were found in C and S treatments, respectively.

In the 2014/15 irrigation season, at harvest an average (0-60 cm) ECe of 1.78, 1.97, 2.28 and 2.77 dS m^{-1} was recorded in C, 2CS, CS and S treatments, respectively. For 2015/16, the EC_e values for the corresponding treatments were 1.74, 1.85, 1.98 and 2.15 dS m^{-1}, respectively. A clear salinity build-up in an increasing order was observed from canal to combinations of canal and seepage and seepage water, as shown in Figure 4.2. The soil salinity (EC_e) increased with increasing salinity (concentration) of the irrigation water and the application frequency of saline water.

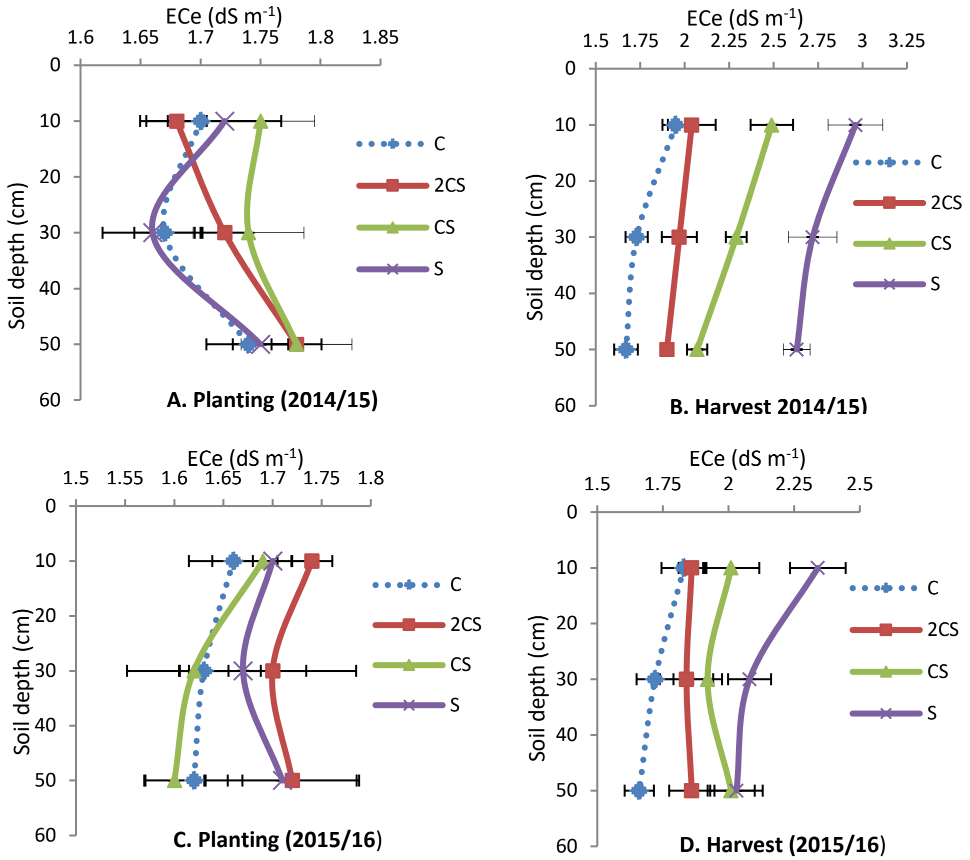

***Figure 4.2** Profile distribution of salinity (EC_e) of different irrigation treatments at planting and harvest of onion crop.*

4.3.3 Onion bulb yield

As depicted in Table 4.4 the effect of different irrigation water treatments resulted in significant variations for onion bulb yield. The highest bulb yield was found in continuous canal water use whereas the lowest was in continuous seepage water use.

In both irrigation seasons maximum (23.21 t ha^{-1} in 2014/15 and 24.77 t ha^{-1} in 2015/16) and minimum (20.36 t ha^{-1} in 2014/15 and 22.97 t ha^{-1} in 2015/16) onion bulb yields were found in C and S treatments, respectively. In both irrigation seasons, both treatments C and 2CS significantly ($P<0.05$) increased the bulb yield as compared to S, though not statistically different from CS. Although, the treatment S showed the lowest yield in both irrigation seasons, the bulb yield difference was statistically similar as compared to CS in 2015/16.

Table 4.3 *Variance components of maize yield and yield components*

Irrigation season	Source	TBY (t ha^{-1})	BW (gm)	PH (cm)	LN	BD (cm)	BL (cm)
2014/15	Treatment	1.757	74.79	10.65	0.305	0.196	0.315
		(91.3%)	(84.1%)	(63.2%)	(35.9%)	(79.7%)	(71.4%)
	Replication	0.132	9.33	1.86	0.337	0.03	0.056
		(6.9%)	(10.5%)	(11%)	(39.7%)	(12.1%)	(12.7%)
	Error	0.036	4.84	4.34	0.207	0.02	0.070
		(1.9%)	(5.5%)	(25.8%)	(24.4%)	(8.3%)	(15.9%)
2015/16	Treatment	0.681	31.92	3.6	0.138	0.465	0.374
		(69.9%)	(71.2%)	(34.4%)	(27.6%)	(64.9%)	(80.2%)
	Replication	0.215	1.23	3.79	0.091	0.121	0.022
		(22%)	(2.8%)	(36.3%)	(18.1%)	(16.9%)	(4.6%)
	Error	0.079	11.68	3.07	0.273	0.130	0.071
		(8.1%)	(26%)	(29.3%)	(54.3%)	(18.2%)	(15.2%)

Note: TBY-total bulb yield, BW-bulb weight, PH-plant height, LN-leaf number, BD-bulb diameter, BL-bulb length; Numbers within parenthesis represents the proportion (percentage) of variation of the total variation.

Table 4.4 *Effects of irrigation water treatments on onion yield and yield components.*

Irrigation season	Treatment	TBY (tha^{-1})	BW (gm)	PH (cm)	LN	BD (cm)	BL (cm)
2014/15	C	23.21(0.43)a	92.27(3.8)a	53.95(2.54)a	12.2(1.11)a	5.71(0.19)a	6.33(0.4)a
	2CS	23.14(0.37)a	90.57(4)a	51.89(1.91)a	11.7(0.26)a	5.69(0.15)a	5.88(0.46)ab
	CS	22.41(0.44)a	85.17(3.29)a	49.28(1.94)ab	11.27(0.5)a	5.08(0.34)b	5.47(0.06)bc
	S	20.36(0.4)b	72.93(3.9)b	45.9(3.31)b	10.77(0.85)a	4.81(0.18)b	4.97(0.35)c
2015/16	C	24.77(0.44)a	99.63(2.9)a	56.84(3.3)a	12.87(0.75)a	6.6(0.65)a	6.57(0.3)a
	2CS	24.72(0.4)a	97.03(3.3)ab	55.71(3.19)a	12.83(0.85)a	6.53(0.35)a	6.47(0.25)a
	CS	23.99(1.1)ab	92.17(4.2)bc	54.86(3.2)a	12.13(0.25)a	5.73(0.6)ab	5.87(0.45)b
	S	22.97(1.07)b	86.03(3.8)c	51.82(0.87)a	11.93(0.32)a	5.1(0.1)b	5.2(0.1)c

Note: Means followed by the same letters in column are not statistically different at $P<0.05$; Numbers within parenthesis represents the standard deviation

4.3.4 Onion growth and yield components

The proportion of the treatment (between groups) variances of most onion parameters were higher as compared to the replication (within group) variances in both irrigation seasons (Table 4.3). Further, the effect of different irrigation water treatments showed significant results for onion bulb weight, plant height and bulb diameter and height and insignificant result for the number of leaves as shown in Table 4.4.

4.3.5 Bulb weight (BW)

In both irrigation seasons higher bulb weight (92.27 gm in 2014/15 and 99.63 gm in 2015/16) were recorded in treatment C. However, these values were not significantly different from 2CS and CS in both irrigation seasons. The lowest average BW (72.93 gm in 2014/15 and 86.03 gm in 2015/16) was found in treatment S and the variation was statistically significant as compared to all treatments and to treatments C and 2CS in 2014/15 and 2015/16, respectively.

4.3.6 Plant Height (PH)

The effect of different irrigation water treatments resulted in significant variations on the plant heights in 2014/15 but statistically similar in 2015/16. The tallest plants were recorded in C (53.95 cm) followed by 2CS (51.98 cm) in 2014/15, and the variation in PH of both were significant as compared to S. In the same season, the shortest plants were found in S (45.9 cm), although, these lengths were statistically similar as compared to CS (49.28 cm). In the second irrigation season (2015/16), the tallest PH (56.84 cm) was recorded in treatment C, which was statistically different from all treatments.

4.3.7 Leaf number (LN)

Maximum (12.2 in 2014/15 and 12.87 in 2015/16) and minimum (10.77 in 2014/15 and 11.93 in 2015/16) number of leaves were recorded in treatments C and S, respectively. However, the variations of LN among all the treatments were statistically similar in both irrigation seasons.

4.3.8 Bulb diameter (BD)

The effect of different irrigation treatments on the average BD was significant in both irrigation seasons. Maximum BD was found in C (5.71 cm in 2014/15 and 6.6 cm in 2015/16) followed by 2CS (5.69 cm in 2014/15 and 6.53 cm in 2015/16). The BD variations between C and 2CS and between CS and S in 2014/15 were statistically similar, though, the former treatments resulted in significantly higher BD as compared to the latter treatments. In 2015/16 the treatment S resulted in significantly lower BD as compared to C and 2CS, however, it was statistically similar compared to CS.

4.3.9 Bulb length (BL)

The variations of bulb length were significantly affected by the application of different irrigation treatments in both irrigation seasons. Maximum average bulb length (6.57 cm in 2015/16) was found in C and minimum (4.97 cm in 2014/15) was found in S. In both irrigation seasons significantly higher BL was found in C as compared to CS and S, however, BL in C was not significantly different from 2CS. The BL in 2CS was statistically similar as compared to CS in 2014/15, however they were significantly different in 2015/16. In both irrigation seasons, the lowest BL was recorded in treatment S, which was significantly different compared to all treatments in 2015/16 and only to C and 2CS in 2014/15.

4.3.10 Farmers' and extension agents' opinion

The farmers' and extension agents' mean ranks of the crop stand at harvest are presented in Table 4.5. Results of the farmers’ evaluation of treatments were significant and similar in both irrigation seasons. The best (1.42 in 2015/16) and least (4 in both irrigation seasons) ranking were found in C and S, respectively. Ranking of C was significantly better as compared to CS and S in both irrigation seasons. However, it was statistically similar as compared to 2CS for both irrigation seasons. The mean ranking for treatment S was the least and it was significant as compared to all treatments, but CS in 2015/16.

Based on the average mean ranking of the local experts’, the treatments were prioritized in deceasing order of: C, 2CS, CS and S for both irrigation seasons (Table 4.5). The mean ranking variation between 2CS and CS was statistically similar, however significantly higher as compared to both CS and S in both irrigation seasons. The mean ranking for treatment S was the least, and significant as compared to all treatments in both irrigation seasons.

From the open discussions, their major criterion for ranking the treatments was majorly the bulb size by judging the anticipated total bulb yield. The second criterion was the difference in the magnitude of visible surface salt efflorescence from their personal observations.

Table 4.5 *Farmers and experts mean rank of the treatments crop-stand for 2014/15 and 2015/16 irrigation seasons.*

Irrigation season	Treatment	Farmers rank	Experts Rank
2014/15	C	1.47a	1.33a
	2CS	1.58a	1.67a
	CS	3.07b	3b
	S	3.89c	4c
2015/16	C	1.6a	1.57a
	2CS	2ab	1.67a
	CS	2.49b	2.78b
	S	3.91c	4c

Note: small rank number represents the best
Means followed by the same letters in column are not statistically different at $P<0.05$.

The other point raised by farmers and local experts was the capacity of the irrigation committee on planning and fair allocation of the different water sources among the farmers as well as the issue of rules and regulations for effective implementation of cyclic irrigation.

4.4 Discussion

Continuous application of canal and seepage water resulted in lowest and highest salt accumulation at the end of both irrigation seasons, respectively. The 2CS treatment resulted in the second lower salt accumulation followed by the CS treatment. Since the amount of applied irrigation water was the same for all treatments, the difference in the magnitude of salt accumulation is attributed majorly to the quality of the irrigation waters utilized and the application frequency (for the cyclic treatments) of the seepage water. Similar results were reported by Chauhan et al. (2005). The highest salt accumulation in treatment S is also in agreement with the finding of Eyasu (2005), who reported higher salt accumulation in the part of the command area irrigated solely by seepage as compared to the area irrigated by fresh canal water in his study area.

Lower salt concentration was found at planting in both irrigation seasons. This indicates leaching of salts during the rainy season and to some extent due to pre-plant irrigation. The drop in soil salinity in the irrigation scheme after the raining season is also in agreement with the finding of Eyasu (2005).

The overall performance of the crop was better in 2015/16 for all treatments. This is attributed to the lower initial soil salinity. Due to the same reason, similar results were reported by Nagaz et al., (2012).The relatively lower EC_e in 2015/16 as compared to 2014/15 is majorly attributed to the earlier planting time.

Overall the initial soil salinities (EC_e) were higher than the threshold (1.2 dS m^{-1}) where onion yield starts to decline. This may have a negative effect on crop performance across all the treatments. However, sole utilization of the seepage water for irrigation would exacerbate the root zone salinity and subsequently have impact on yield.

The highest bulb yield was found in treatments with continuous use of canal water while the lowest were observed in treatments with continuous use of seepage water. The bulb yield found in 2CS was similar (0.3-0.2% difference) compared to C.

Although, the magnitude varies, highest soil salinities were found in the upper profile of all the treatments. This could be due to evaporative concentration of salts at the surface attributed to the poor internal drainage of the soil (clay) and capillary rise from the lower soil profiles.Especially the increase in surface salinity for treatment S, compared to the initial condition ranged from about 38% in 2015/16 to 72% in 2014/15. This indicates that continuous use of seepage water for irrigation has been among the major factors for decline of onion yields and soil salinization in the study area.

Salinity decreased bulb weight, bulb diameter, plant height and number of leaves per plant. However, from the mean comparison (Table 4.4), insignificant variation in the growth components (number of leaves per plant in both irrigation season and the plant height in 2015/16) were observed as compared to the yield components (bulb weight, diameter and length) across the treatments. These indicated that, the yield components relatively seem more affected by the irrigation treatments as compared to the growth components. This could be mainly due to the relatively lower salt concentration of the seepage water (1.12 dS m^{-1} in 2014/15 and 0.82 dS m^{-1} in 2015/16) at establishment and earlier vegetative growth stage of the crop. Then, the rising EC of the water may have affected more the bulb enlargement due to osmotic problems and associated nutritional effects, particularly in the S treatment. Compared to S the higher bulb yield in CS is mainly due to the dilution effect of the canal water which consequently lowers the adverse effect of salt on the crop.

In a study conducted in the same irrigation scheme, Yohannes et al. (2017) reported different perceptions on the quality of irrigation water sources between and within a group of farmers that utilize canal, seepage and both sources of water for irrigation.

However, from this study, the local farmers and extension agents rank different water sources more or less similar, with their finding depicted in section 4.3 of this thesis. The study indicated that the farmers directly understood the effect of the treatments on onion yield, and thus the difference in quality of the irrigation water sources.Moreover, the farmers' involvement and continuous observations facilitate and enhance their practical knowledge on how to utilize conjunctively the existing irrigation water sources for production of onion. Participating farmers in irrigation management is widely accepted as an effective means of enhancing their knowledge of irrigation (Qiao et al., 2009), and facilitates further adoption of promising technologies locally.

The limited capacity of the irrigation committee on arranging planned conjunctive (cyclic) irrigationappropriately and institutional aspects were the major concerns raised by the farmers and local experts. The irrigation committee and farmers need capacity building in technical and institutional issues to improve the performance of irrigation schemes (Ghazouani et al., 2012; Kazbekov et al., 2009; MoA, 2011b; Mutambara et al., 2016;World Bank, 2006a).Thus,building institutional capacity and technical skills on planning and fair allocation of the different water sources among the farmers should be considered for more effective implementation of planned cyclic irrigation.

4.5 Conclusions

Direct use of seepage water for irrigation has been among one of the major causes for crop yield decline and expansion of soil salinization problem in Ethiopia. Utilizing the seepage water for irrigating salt sensitive crops (eg. Onion) makes the problem even more worse.

Two years (2014/15 and 20115/16) on-farm study was conducted to evaluate the effect of cyclic irrigation using moderately saline (seepage, 0.82-2.19 dS m^{-1})and none-saline (canal, 0.41-0.78 dS m^{-1}) water on onion yield and soil salinization, under surface irrigation in the Gumselassa irrigation scheme, northern Ethiopia. Four irrigation treatments were applied comprising: C= sole irrigation using fresh canal water, S= sole irrigation using seepage water, CS= irrigation using canal and seepage water in alternate cycle, 2CS= irrigation twice by canal water and third by seepage water in cyclic manner.

Continuous irrigation with canal water resulted in lower root zone salt accumulation and highest bulb yield, while sole irrigation with seepage water resulted in significant onion yield reduction and higher surface (0-20 cm) salt accumulation.The yields obtained using the cyclic irrigations (2CS and CS) were not significantly different as compared to entirely canal irrigation water use. Result of the study showed that root-zone salinity increased with increasing salinity of the water sources and frequency of application of the seepage water. The treatment yield declines did correspond with increasing soil salinity. The local farmers' and extension agents' overall opinions of the treatments performance also revealed the least preference for treatment S.

Alternate (1:1) cyclic application of canal and seepage irrigation water could therefore be considered a practical way for onion cultivation in Gumselassa irrigation scheme, and other schemes with similar challenges. Further, it could also be a promising option for improving the equity of canal water between the head reach and tail-end farmers in the irrigation scheme.

The nature of the study, which was on-farm with the involvement of local farmers and extension agents, helps in enhancing their knowledge and practical skills on conjunctive use of water for irrigation and facilitation of further adoptions.

Regional and local leaders should focus on capacity building of the farmers, specifically in planning and scheme level water allocation, supported by rules and regulations for successful implementation of cyclic irrigation. Finally, the study is a major breakthrough for further assessment and study of the unrecognized but promising conjunctive irrigation practices in Ethiopia.

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5. Modelling of soil salinity and crop response to cyclic irrigation strategies: A decision support tool for sustainable irrigation production in Tigray, North Ethiopia

Research recommendations on irrigation water management strategies are usually limited to one or two years of field experiment and ignore the gradual and long-term impacts on soil health and crop yield. The SWAP (Soil-Water-Atmosphere-Plant) model ver. 3.2 was used to evaluate the long-term impact of cyclic irrigation strategies using fresh (0.44-0.78 dS m^{-1}) canal water and moderately-saline (1.12-2.19 dS m^{-1}) seepage water on the relative yield of onion and soil salinization in semi-arid regions of Tigray, North Ethiopia. The collected data from 4 irrigation treatments of fresh canal water, moderately-saline seepage water and two cyclic (conjunctive) applications of both waters were used to calibrate and validate the SWAP model. Using the validated SWAP, long-term (2005-2014) simulations were carried out considering two scenarios, i.e., 60 mm pre-plant irrigation (PPI) for the 1st case and 70 mm PPI plus 20% leaching fraction for the 2nd case. Result of the simulation revealed that, irrigating using seepage water resulted in lower onion yield and higher salt accumulation (>4 dSm^{-1}) in the root-zone, for both scenarios. The cyclic irrigation strategies however, kept the soil salinity below 4 dS m^{-1}, except in very dry years. Scenario II, significantly reduced the salt accumulation in all treatment, however, the increase in the relative yield of onion was substantial only in dry years (2009-2012). Considering the long term soil salinization, the conjunctive irrigation strategies can, thus, be used safely, under scenario II. Yet, due to elevated salinity in dry years, salt sensitive crops shouldn't be a choice to avoid significant yield decline from their potential.

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5.1 Introduction

Development of small scale irrigation (SSI) has been among the priority policy for the Ethiopian government to address the main challenge caused by food insecurity and water scarcity since the last three decades (MoWR, 2002; MoFED, 2006; MoFED, 2010; NRST, 1997). However, the performance of many small scale irrigation schemes is far from satisfactory (Amede, 2015; Awulachew and Ayana, 2011; Carter and Danert, 2006; Cofie and Amede, 2015; IFAD, 2005; MoA, 2011a; Teshome, 2003).

Similar to many arid and semi-arid regions of the world (Amer, 2010; Crescimanno and De Santis, 2004; Kaledhonkara et al., 2012; Kazmi et al., 2012; Minhas et al., 2007; Qureshi et al., 2004), scarcity of fresh irrigation water supply has been a major challenge in most SSI in the country. In response to the increasing scarcity of good quality water for irrigation farmers are forced to use poor quality/seepage water from micro-dams particularly in Tigray region, North Ethiopia. For this and other reasons, many irrigation schemes are threatened by soil salinization and yield reduction (Eyasu, 2005; Gebremeskel et al., 2018; Yohannes et al., 2017).

To address the interrelated challenges of sustainability and water scarcity of irrigated agriculture in Ethiopia and in other regions of the world, appropriate innovations are required to irrigation management and practice (Jhorar et al., 2009; Pereira et al., 2002; Yohannes et al., 2017).

Most of the recommendations related to the management of irrigated agriculture in Ethiopia are derived from results of one or two year field experiments. The long-term impact of irrigation water management practices on the environment and food security should be evaluated to assure sustainability of irrigated agriculture.

The use of field experiments is the most reliable approach for studying different scenarios related to the use of saline water for irrigation. However, the field experiments are usually conducted over one or two years while effects of the use of saline water for irrigation are gradual and take 10 or more years (Droogers et al., 2000).

To overcome such restrictions models can be used to simulate the long-term salt dynamics and crop yields based on limited data of short-term field experiments. Reliable advanced models are available that can describe long-term status of salt, water and/or crop conditions (Bastiaanssen et al., 2007; Lamsal et al., 1999; Singh and Singh, 1996). The detailed agro-hydrological Soil-Water-Atmosphere-Plant (SWAP) model (Kroes et al., 2017) has the advantage that it can simulate long term physical, biological and chemical processes at field level, and it has been successfully applied in different agro-climatic conditions to address different management practices on crops and the environment (Droogers and Bastiaanssen, 2002; Sarwar and Feddes, 2000; Van Dam, 2000).

Despite the great potential of the SWAP model it has been applied to a limited extent in arid and semi-arid climatic conditions (Mostafazadeh-Fard et al., 2008a; Singh, 2004; Verma et al., 2010). Moreover, there is no practical application of the SWAP model documented so far in the context of Ethiopian irrigated agriculture.

Thus considering the problems and gaps stated above, the SWAP model was used to predict the long term effects of cyclic irrigation of fresh and moderately saline seepage water on salt dynamics and relative yield of onion crop, based on field experiments conducted in a semi-arid region of Ethiopia.

5.2 Brief description of the SWAP model

SWAP (Soil-Water-Atmosphere-Plant) is a physically based vertical agro-hydrological model developed by Wageningen University and Research centre to simulate transport of water, solute, heat and plant growth in a Soil-Water-Atmosphere-Plant environment (Kroes et al., 2017; Van Dam et al., 2008).

In the model, soil water flow is described by the Richards’ equation, which is a combination of Darcy’s law and the continuity equation. Solute transport in the SWAP model is governed by convection, dispersion and diffusion (Beltman et al., 2008; van Genuchten and Cleary, 1979). The crop growth can be computed based on simple (Doorenbos and Kassam, 1979) or detailed crop growth algorithms (Van Ittersum et al., 2003).

The SWAP model provides a wide range of upper and lower boundary conditions. The upper boundary conditions of the model are described by potential evapotranspiration, rainfall and irrigation. The model requires daily meteorological data for computation of the potential evapotranspiration using the Penman-Monteith equation or reference evapotranspiration computed by other methods. The bottom boundary can be described by the groundwater level as a function of time, fluxes from a deep aquifer, fluxes to or from open surface drains, and other conditions. Irrigation inputs to the model can be prescribed at fixed time, depth and quality or it can be scheduled according to crop demand. A more detailed description of the model and all its components can be found in

Van Dam et al. (1997). For this study the SWAP model version 3.2 is used as described by Kroes et al. (2008).

5.3 Material and methods

5.3.1 Site description

The Gumselassa irrigation scheme (study site) is located in the Tigray region, belonging to the Hintalo-Wojerat district near Adigudom in northern Ethiopia. The irrigation scheme is located between $13^0$13′ to $13^0$15′ N and $39^0$30′ to $39^0$33′ E with an average altitude of 2000 m a.s.l. The major soil in the irrigation scheme is clay (Table 5.1) with poor infiltration characteristics (Eyasu, 2005).

Table 5.1 *Soil physical characteristics of the study soil.*

Soil depth (cm)	Particle size distribution (%)			Texture	BD
	Sand	Silt	Clay	(USDA)	(gm/cm^3)
0-20	17	28	55	Clay	1.29
20-40	15	27	58	Clay	1.3
40-60	15	25	60	Clay	1.33
60-80	16	28	56	Clay	1.28
80-100	19	29	52	Clay	1.28
100-130	18	28	54	Clay	1.32
130-160	22	28	50	Clay	1.32
>160	25	27	48	Clay	1.35

Fresh water collected in a micro-dam during the rainy season (June-September) is the major source of irrigation. Seepage water and/or in conjunction with fresh water is also used for irrigating a substantial part of area.

5.3.2 Detail of experimental work

In 2014/15 and 2015/16 irrigation seasons, a field experiment was conducted to evaluate the impact of cyclic irrigation of fresh and moderately saline water on onion yield and soil salinization. For this purpose, four treatments were imposed consisting of sole irrigation with canal water (C), sole irrigation with seepage water (S), two irrigation applications with C and third with S in cyclic manner (2CS), and irrigating by canal and seepage water in alternate cycle (CS). The depth and water quality in each treatment and details of the experimental work are presented in Table 5.2 and Table 5.3.

This research is an extension of the field experiment aimed to evaluate the long term effect of cyclic irrigation on yield and soil quality. Part of the data collected in 2014/15 and additional data collected during the same season were used for model calibration and validation.

Table 5.2 *Irrigation scheduling and water quality (EC) under different treatments.*

No. of irrigation	Irrigation depth (mm)	Water quality, EC (dS m^{-1}) of Treatments			
		C	2CS	CS	S
1	30	0.44	0.44	0.44	1.12
2	30	0.44	0.44	1.11	1.11
3	30	0.46	1.16	0.46	1.16
4	30	0.48	0.48	1.19	1.19
5	40	0.49	0.49	0.49	1.21
6	40	0.53	1.27	1.27	1.27
7	40	0.56	0.56	0.56	1.33
8	40	0.61	0.61	1.38	1.38
9	40	0.63	1.45	0.63	1.45
10	40	0.65	0.65	1.54	1.54
11	40	0.67	0.67	0.67	1.65
12	40	0.68	1.66	1.66	1.66
13	40	0.71	0.71	0.71	1.74
14	40	0.73	0.73	1.85	1.85
15	40	0.75	2.01	0.75	2.01
16	40	0.77	0.77	2.10	2.10
17	40	0.78	0.78	0.78	2.19

Table 5.3 *Detail of experimental work in 2014/15 irrigation season.*

Crop and variety	Onion (Adama red)	Date of transplanting: 10/01/2015 Date of harvesting: 14/05/2015
Irrigation	Source and quality	Canal, 0.44-0.78 dS m^{-1} Seepage, 1.12-2.19 dS m^{-1}
	Depth	30 mm in the first four irrigations and 40 mm in the rest
	Interval	Every 5 day in the first three weeks and 7 days in the rest
Ground water	Depth	1.07-3 meter
	Quality	4.25 dS m^{-1}

5.3.3 Model Input data

5.3.3.1 Upper boundary conditions

One of the main advantages of the SWAP model is the availability of a wide range of upper and lower boundary conditions. For this study reference evapotranspiration (ET_0) calculated by the Hargreaves equation (Hargreaves and Samani, 1985), which is recommended (Yohannes et al., forthcoming) for the study area, was directly used as input. The Hargreaves method requires only maximum and minimum temperatures and extra-terrestrial solar radiation. Daily temperature data were obtained from Mekelle

Airport meteorology station which is located about 40 km far from the study site. The daily Hargreaves ET_0 estimate might be subjected to error due to large variation indaily weather (Hargreaves and Allen, 2003), and therefore to ensure better ET_0 estimate the recommended five-days’ time step was applied. In addition, daily rainfall data were collected from the Adigudom town rainfall-station located about 3 km from the study site.

5.3.3.2 Soil water

The dominant soil in the study area is black clay with deep horizon covering more than 60% area (Mintesinot et al., 1999). As depicted in Table 5.1 the bulk density gets denser below 1.6 m. Thus for our simulation purpose, the profile is divided in two soil layers of 0-1.6 m (upper layer) and 1.6-3m (bottom layer).

Using the texture and bulk density data, pedotransfer functions were used to assess the related Mualem Van Genuchten parameters (Van Genuchten, 1980). These parameters are the residual water content (θ_{res}), saturated water content (θ_{sat}), shape parameters (α, n, λ) and the saturated hydraulic conductivity (K_{sat})(Table 5.4).

The soil salinity (EC_e) of each treatment before transplanting was taken as model input from 0-20, 30-40, 40-60, 60-80 and 80-100 cm soil layers. Data on initial soil moisture contents were not available but estimated by running SWAP for one year in advance with the same inputs and the final soil moisture were used as initial condition.

Table 5.4 *Mualem van Genuchten soil hydraulic parameters.*

Soil	Top soil	Subsoil
Depth of layer (m)	0-1.6	1.6-3
Soil texture (USDA)	clay	clay
Residual water content, θ_{res} ($cm^3\ cm^{-3}$)	0.10	0.10
Saturated water content, θ_{sat} ($cm^3\ cm^{-3}$)	0.51	0.48
Shape parameter, α (cm^{-1})	0.0181	0.0169
Shape parameter, n	1.2979	1.3241
Saturated hydraulic conductivity, K_{sat} ($cm\ d^{-1}$)	17.08	15.76
Shape parameter, λ	0.5	0.5

5.3.3.3 Crop and irrigation data

Depending on the data availability, the SWAP model gives the option to compute crop yields based on a simple or detailed crop growth algorithm. In this study the simple growth model was used due to a limited amount of crop data. Adama red onion (*Allium Cepa* L.) variety, which is the most preferred irrigated vegetable crop, was selected for this study. The potential bulb yield for this onion variety in Ethiopia is about 3000-3500 kg ha^{-1} (EIAR, 2007), however, the actual yields reported in the study area were very low.

The irrigation water amount (mm) and the quality (EC) were monitored in every irrigation application for all treatments (Table 5.2). The irrigation water in the study area became more saline from the start to the end of irrigation season. The actual irrigation amount, quality and interval of each irrigation event were used for simulation purpose. For crop salinity stress the response function of Maas and Hoffman (1977) was used (Table 5.5).

Table 5.5 *Crop property data.*

Simulation period		10 Jan 2015-14 May 2015
Crop		Onion
Length of growing season (day)		125
Maximum rooting depth (cm)		60
Crop factor, K_C (-)		Initial: 0.7, Development: 0.88, Mid-season: 1.05 and Harvest: 0.75
Leaf area index, LAI (−)		Initial: 0.41, Development: 1.76, Mid-season: 2.36, and Harvest: 2
Critical pressure head for root water extraction (cm)	Early growing	h3h:450, h31:550
	Bulbing time	h3h:550, h31:650
Yield response factor, Ky (-)		Initial: 0.45, Development: 1.1, Mid-season: 0.8 and Harvest: 0.4
Salt stress	Threshold EC_e (dS m^{-1})	1.2
	Slope (% per dS m^{-1})	16

Table 5.6 *Parameters for the calculation of solute transport.*

Initial soil salinity, EC_e (dS m^{-1})	1.71, 1.7, 1.76, 1.68 and 1.74 dS m^{-1} for 0-20, 20-40, 40-60, 60-80 and 80-100 cm depths, respectively
Initial groundwater salinity, EC (dS m^{-1})	4.25
Diffusion coefficient in water, D_w (cm^2 d^{-1})	0
Dispersion length, L (cm)	20

5.3.3.4 Bottom boundary condition

The groundwater levels were monitored at each irrigation events and used as bottom boundary condition.

5.3.4 Model calibration and validation

Since SWAP is a well-tested simulation model for crop growth, water and salt transport at field scale, the one year field data (2014/15) were assumed sufficient for calibration and validation of the model. Thus, the data collected before transplanting in 2014/15 irrigation seasons were used for calibrating the model and the data collected at harvest were used for model validation.

5.3.5 Model performance evaluation

The performance of the model was evaluated by comparing the measured onion yield and soil profile salinity with the simulated results of the SWAP model. The root mean squared error (RMSE) and mean absolute error (MAE) were used to quantify the agreement between the measured and simulated values. The RMSE and MAE were calculated by applying eq. (5.1) and eq. (5.2), respectively.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2} \tag{5.1}$$

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|O_i - P_i| \tag{5.2}$$

Where
N = Total number of observations,
O_i= Observed values, and
P_i= Predicted value

5.3.6 Scenario building and model application

Use of seepage water for irrigation has been among the major factors aggravating soil salinization in the Gumselassa region. Since our interest was to evaluate the long term effects of alterative management strategies on crop yield and soil quality, a scenario was constructed and simulated over a period of ten years from 2005 to 2014. The annual rainfall for the simulation period ranged from 276 mm (2008) to 639 mm (2012) with an average of 459 mm. The high variability of the rainfall within the simulation period allows evaluating the alternative irrigation strategies under more extreme conditions.

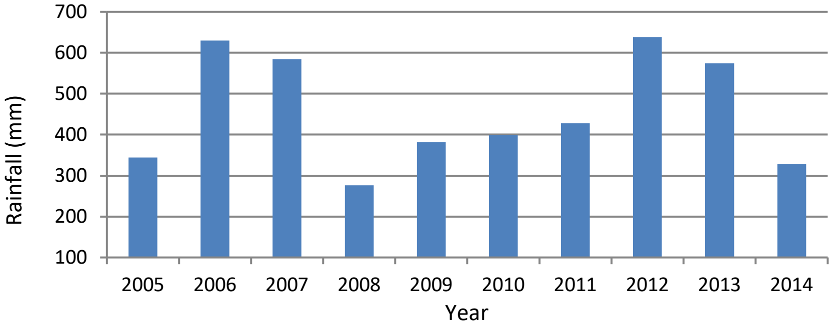

Figure 5.1 *Annual rainfall of Adigudom rainfall-station for the period 2005 - 2014.*

Onion relative yields and salt build-up were the major criteria considered for evaluating the performance of the different irrigation treatments. The relative yield was determined as the ratio of the obtained yield from field experiments to the potential yield. A potential bulb yield of 30 t ha^{-1} for the Adama Red onion variety (EIAR, 2007) was considered. During the rainy season several crops such as vetch, barley, teff and others are grown by the farmers. Due to its wide coverage, it was assumed that vetch (*Lathyrus sativus* L.) is grown in sequence with onion although its yield was not monitored. The average planting and harvest dates of vetch were supplied by the local farmers.

The actual daily meteorological data for the simulation period (2005-2014) and calculated Hargreaves ET_{ref} were used as model input. Surface and profile salinity data measured in a few locations of the command area of the study site are available for 2004 (Eyasu, 2005). The data shows low to high salinity levels. The lower salinity levels ranged from 0.35 dS m^{-1} for the surface (30 cm) to 0.56 dS m^{-1} at 180 cm depth. Thus, for our long term simulation an initial soil salinity of 0.4 dS m^{-1} was considered for the entire soil profile. Other inputs (crop, soil hydraulic parameters and irrigation scheduling) were kept constant for all years.

5.3.6.1 Scenario I (reflection of the current practices)

In this scenario for all simulations a depth of 60 mm (pre-plant) irrigation with fresh canal water three weeks before transplanting were considered, in line with the local practices. The farmers in the study area may practice sole irrigation using fresh canal water, sole irrigation using seepage water or both conjunctively (with no predetermined sequences), depending on the location of their plot and/or existing local situation. Majority of the farmers use fresh canal water for irrigation and sole irrigation using seepage is usually practiced in farms located particularly at the tail end of the irrigation command area. Conjunctive irrigation is practiced at the top and middle positions of the command area mostly in farms located near the natural drain. Since the amount of applied irrigation water and frequency varies across individual farmers in the command area, it is assumed that, sole irrigation using canal (C) and seepage (S) in this scenario can more or less represent the majority canal users and the tail-end seepage water users, respectively.

5.3.6.2 Scenario II (Increasing pre-plant irrigation and introducing 20% LF)

In an attempt to reduce soil salinization, additional simulations were performed by increasing the amount of pre-plant irrigation by 10 mm plus including a leaching fraction of 20% in each irrigation event.

5.4 Results and discussion

5.4.1 Model validation

5.4.1.1 Comparison of measured and simulated relative yield

The performance of the model was evaluated by comparing the measured relative onion yield and soil profile salinity with the simulated results of the SWAP model. The results depicted in Figure 5.2 revealed a close agreement between the simulated and measured values for the relative yield of the different treatments. The calculated root mean square error and mean absolute error for the relative yields (Figure 5.3) are 0.049 and 0.04, respectively. These values are within the acceptable range reported by Kumar et al. (2015), Verma et al. (2010, 2012), and Wahba et al. (2002). Moreover, the coefficient of determination (R^2) value of 0.96 indicated a good agreement between the measured and simulated values.

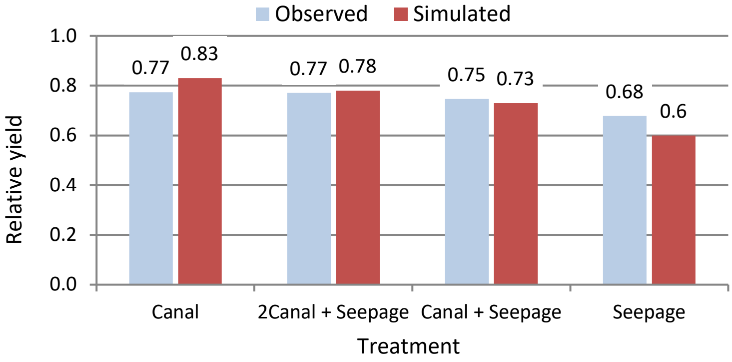

Figure 5.2 *Measured and simulative relative yields of onion crop for all treatments.*

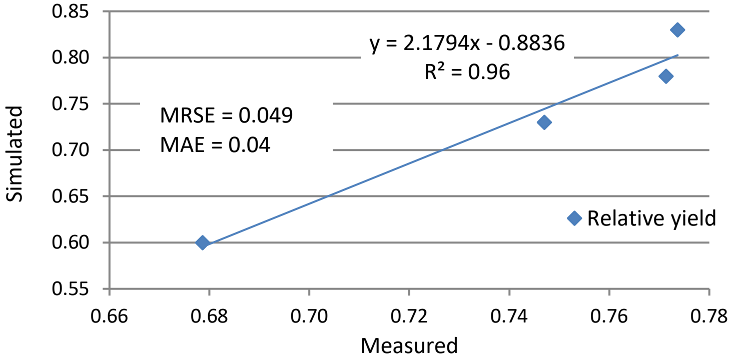

Figure 5.3 *Relationship between measured and simulatedonion relative yield.*

5.4.1.2 Comparison of measured and simulated soil salinity

The results depicted in Figure 5.4 and Figure 5.5 reveal a close match between the measured and simulated profiles salinity. The calculated RMSE (0.29 dS m^{-1}) and MAE (0.22 dS m^{-1}) of the treatments were on the lower side of the range as reported by Verma et al. (2012), Hirekhan et al. (2007), and Kumar et al. (2015). The value of coefficient of determination for salinity was 0.79 (Figure 5.5). Overall the observed statistical value indicated good performance of the model for simulating soil salinity.

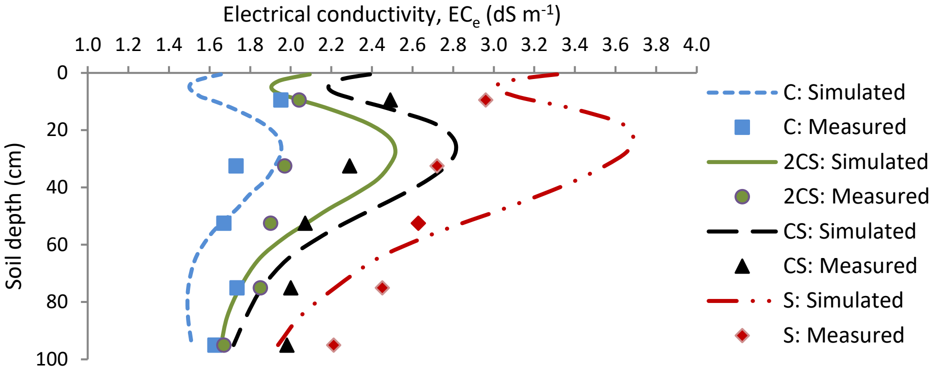

***Figure 5.4**. Measured and simulated salinity profile of different treatments at harvest.*

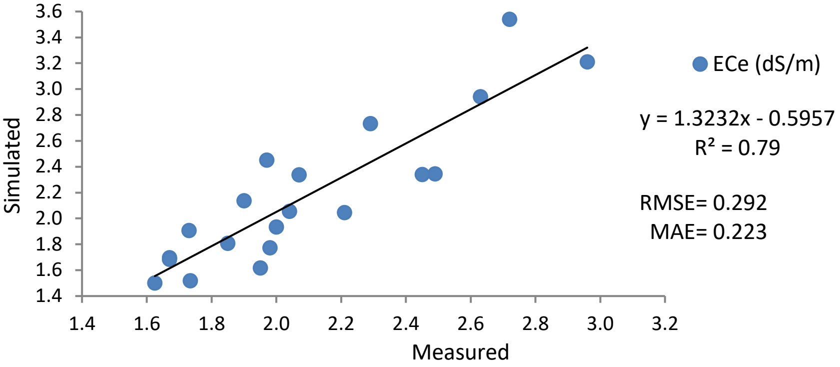

***Figure 5.5** Relation between measured and simulated soil salinity under different treatments at harvest.*

5.4.2 Long-term simulations and evaluation of irrigation management strategies

5.4.2.1 Relative yield under different treatments

The long-term (ten years period) simulation revealed that the relative yield varied from 73 to 84% and from 37 to 67% for treatments with irrigation using fresh water only and moderately-saline seepage water, respectively (Table 5.7). The relative yield for the cyclic modes varied from 59 to 82% and from 52 to 79% for the 2CS and CS treatments, respectively. The lowest relative yield in treatment S was attributed to increased salt accumulation in the root zone, which was observed in other dry years as well.

Table 5.7 *SWAP simulated relative yield for different treatments.*

Year	Treatment			
	C	2CS	CS	S
2005	0.84	0.82	0.79	0.67
2006	0.82	0.76	0.71	0.55
2007	0.84	0.77	0.72	0.56
2008	0.83	0.72	0.66	0.47
2009	0.78	0.65	0.58	0.42
2010	0.78	0.65	0.59	0.43
2011	0.78	0.66	0.59	0.44
2012	0.73	0.59	0.52	0.37
2013	0.82	0.71	0.65	0.5
2014	0.82	0.74	0.69	0.54

5.4.2.2 Long-term salinity build-up

At the time of harvest, the average salinity of the top (100 cm) soil profile for C, 2CS, CS and S treatments varied between 1.15-2.36, 1.56–2.99, 1.79-3.32 and 2.47-4.23 dS m^{-1}, respectively (Figure 5.6). A clear salinity build-up in an increasing order was for all treatments. The soil salinity (EC_e) increased with increasing salinity of the irrigation water and the application frequency of saline water, and similar trends of salinity build-up were also reported by Verma et al. (2014).

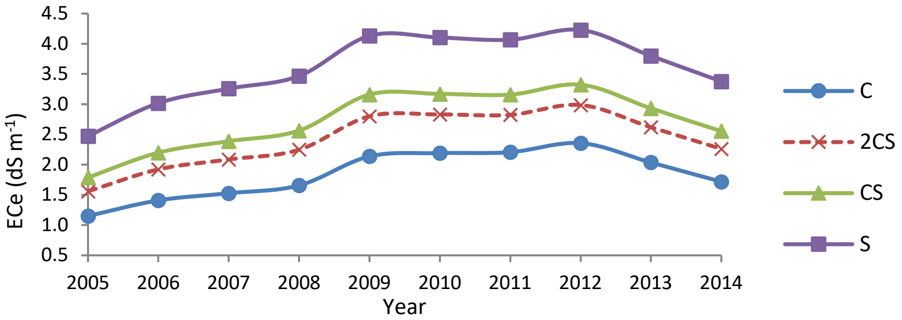

Figure 5.6 *Profile (100 cm) soil salinity (EC_e) for different treatments at time of harvest.*

The average salt build-up in the top soil (0-100 cm) before transplanting showed high variability between the simulation years (Figure 5.7). Starting from the second year of simulation the salinity value varied between 1.13 - 2.94 dS m^{-1} and 2.47 - 5.21 dS m^{-1} in C and S treatments, respectively. The salinity (1.58 - 4.13 dS m^{-1}) for the cyclic modes ranged between the values predicted for C and S treatments. The long-term simulation results also revealed that the soil salinity before transplanting or before the start of irrigation (December-January) was highly influenced by the amount of rainfall in the rainy season (June-September) in all treatments.

Before transplanting in dry years (2009-2012), the average (100 cm) soil salinity for the treatment S (sole application of seepage water) ranged between 4.68 to 5.21 dS m^{-1}, above the threshold value (4 dS m^{-1}) for salt affected soils (USSL Staff, 1954). This might cause crop stress and decline in yields of most irrigated crops in the locality. The problem might be more pronounced at sowing and early establishment of most irrigated crops as the salt accumulation is higher in the top (0-30 cm) soil profile as depicted in Figure 5.8. Thus, irrigation with moderately saline seepage waters does not guarantee the long term sustainability as the soil salinity rises above 4 dS m^{-1} in years of below average rainfall.

On the other hand sole application of fresh canal water and application of both the cyclic modes (2CS and CS) can keep the soil salinity below the threshold value of 4 dS m^{-1}, except in the occurrence of successive dry years (2009-2012) that the salinity for CS might elevate to 4 dS m^{-1} as shown in 2012 (Figure 5.7). However, still in very dry years, the cyclic irrigation strategies might not be a guarantee for cultivation of salt sensitive crops, due to enhanced surface (0-30 cm) soil salinity as shown in the years 2009-2012 (Figure 5.8).

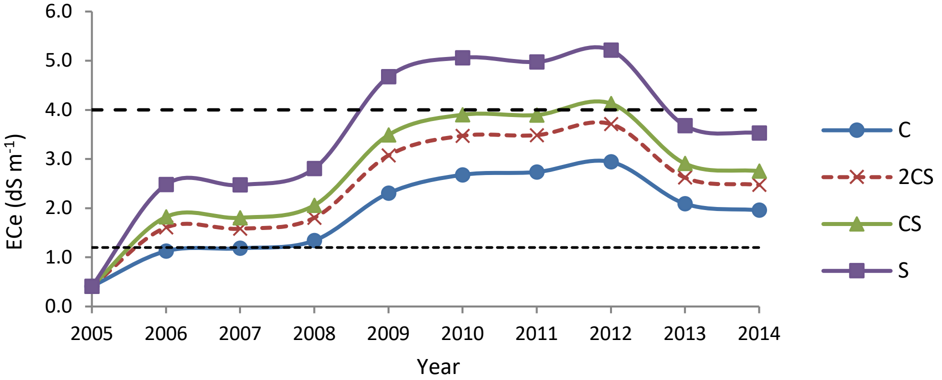

***Figure 5.7** Average soil salinity of the top 100 cm depth under the different treatments before transplanting.*

In early January (before planting), the ten years simulation also revealed that the accumulation of salt under all treatments was highest in the top soil to 30 cm depth and lower deeper in the profile (Figure 5.8). This is manly attributed to poor leaching capacity of the soil and salinization due to capillarity, and the results are similar with the salinity trends reported by Yohannes et al. (forthcoming). Gebremeskel et al. (2018) also reported an average surface (0-30 cm) soil salinity level of 3.5 dS m^{-1} from scheme level salinity assessment conducted in 2005 in the same irrigation scheme.

Taking salt sensitive crops like onion into consideration, use of fresh canal water is not still a guarantee for sustainable onion production as in very dry years the top accumulation of salts may adversely affect germination and crop establishment. This might be one of the major reason for low yield of onion as reported by Eyasu (2005) and Yohannes et al. (2017).

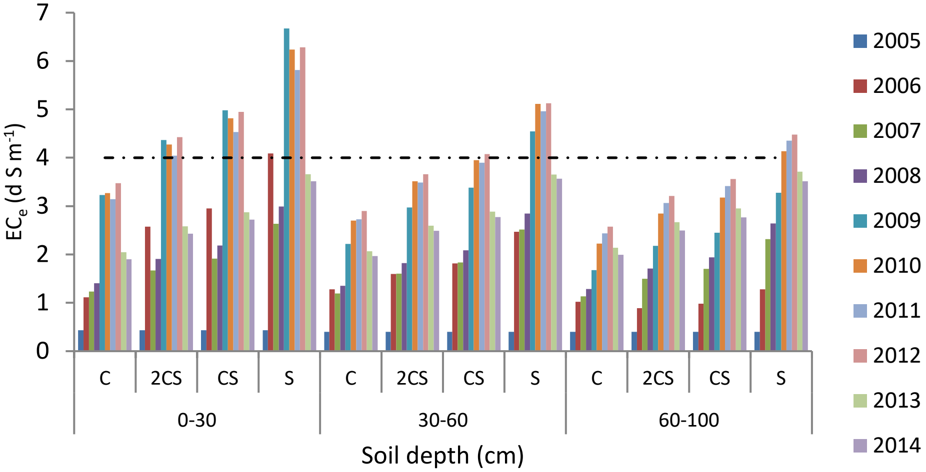

Figure 5.8 *Average soil salinity (EC_e) at different depths as influenced by application of canal, seepage and cyclic modes for irrigation.*

5.4.3 Long-term simulations and evaluation of irrigation management strategies under scenario II

5.4.3.1 Relative yield under different treatments

The long-term simulation showed (Table 5.8) that, the RY under scenario II were quite higher in dry years (2009-2011) and lower in wet years (2005-2008) for most of the treatments as compared to Scenario I. This indicates that the increased 10 mm pre-plant irrigation and additional LF (20%) reduced the yields mainly due to excessive soil water condition during the wet years (2005-2008). In contrast, the higher observed RY in dry years in the 2nd scenario, indicates that, the applied amount of water in the 1st scenario was not sufficient to leach salts and/or satisfy the crop demand satisfy the crop demand.

Table 5.8 SWAP simulated relative yield for different treatments under scenario II.

Year	Treatment			
	C	2CS	CS	S
2005	0.79	0.77	0.74	0.62
2006	0.79	0.76	0.72	0.57
2007	0.79	0.75	0.71	0.57
2008	0.79	0.7	0.63	0.42
2009	0.79	0.71	0.65	0.48
2010	0.79	0.72	0.66	0.5
2011	0.79	0.72	0.67	0.51
2012	0.78	0.66	0.58	0.38
2013	0.78	0.73	0.69	0.53
2014	0.79	0.75	0.71	0.57

5.4.3.2 Long-term salinity build-up

From results of the long term simulation (Figure 5.9), the average soil salinity (100 cm) at harvest varied between 1.14 - 1.62 dS m^{-1} and 2.43 – 3.21 dS m^{-1} in C and S treatments, respectively. Similar to the formers scenario, the salinity (1.57 - 2.55 dS m-1) for the cyclic modes ranged between the values predicted for C and S treatments. In early January before transplanting, salinity value ranging from 1.03 - 1.93 dS m^{-1} and 2.22 – 3.99 dS m^{-1} for the treatments C and S were observed, respectively (Figure 5.10). This value revealed that, the additional 10 mm pre-plant irrigation plus the introduction of LF (20%) resulted in significant reduction of soil salinity in all treatments (Figure 5.9, 5.10) as compared to the first scenario.

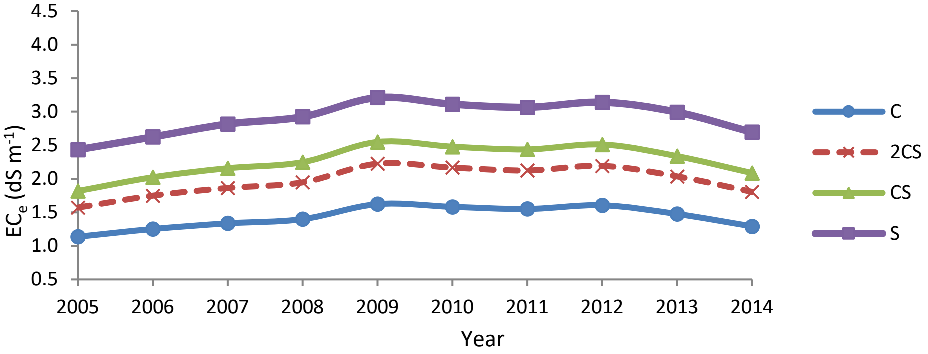

Figure 5.9 Profile (100 cm) soil salinity (EC$_e$) for different treatments at time of harvest for under scenario II.

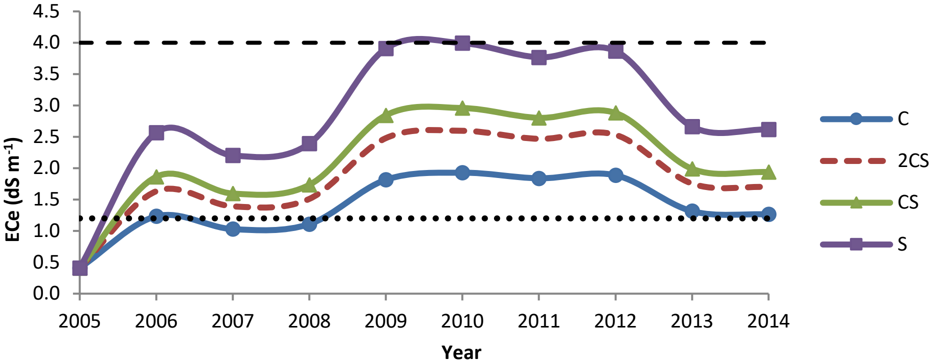

Figure 5.10 Average soil salinity of the top 100 cm depth under the different treatments before transplanting under scenario II.

During dry years (2009-2012), at harvest, the simulated average soil salinity (100 cm) particularly for treatment S, ranged between 3.07-3.21 dS m^{-1}, as shown in Figure 5.9. The corresponding value at planting ranged between 3.77-3.99 dS m^{-1} (Figure 5.10). Compared to the 1st scenario, the reduction in salinity ranged from 22.3 to 25.7 and 16.5 to 25.7% at harvest and planting, respectively. Increasing the pre-plant irrigation and introducing LF (20%) can lower the soil salinity below 4 dS m^{-1}, unlike the 1st scenario.

In dry years, the long term simulation in Scenario II also lowered the salinity in the top (0-30 cm) soil layer, for the cyclic modes, unlike in the first scenario. Still, the salinity level (0-30 cm) in the cyclic modes that varied between 2.39-3.2 dS m^{-1} (Figure 5.11), in the dry years could be inappropriate for growing salt sensitive crops.

Results of the simulation indicated that increasing pre-plant irrigation by 10 mm and introduction of 20% LF for the cyclic modes, can meet the agronomic criterion in the context of salt affected soils (EC$_e$ below 4 dS m^{-1}), even in dry years. On the other hand it was unable to bring down the surface (0-30 cm) and the succeeding (30-60 cm) soil profiles' salinity below 4 dS m^{-1}, for the treatment S, in dry years (Figure 5.11).

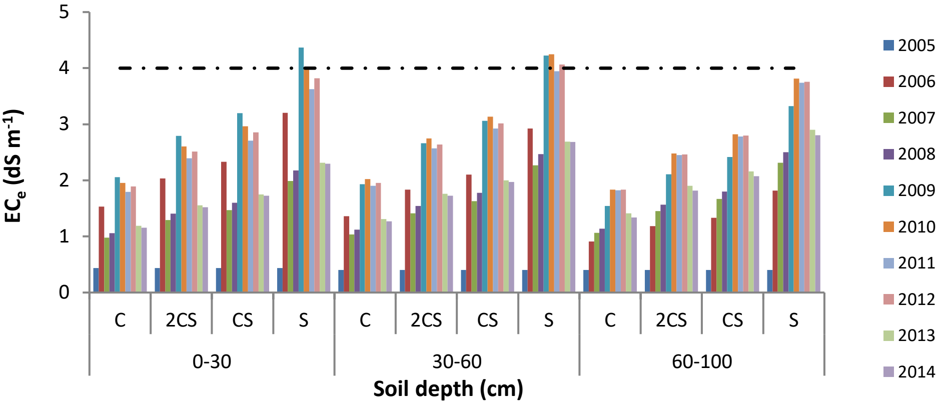

Figure 5.11 Average soil salinity (EC$_e$) at different depths as influenced by application of canal, seepage and cyclic modes for irrigation under scenario II.

5.5 Conclusions

Use of seepage water for irrigation has been one of the major factors contributing to low crop yields and aggravating soil salinization in small scale irrigation schemes in the Tigray region, Northern Ethiopia. The long term (10 years) effect of cyclic irrigation strategies using fresh canal and moderately-saline seepage water on onion relative yield and soil quality were evaluated using the SWAP model. The irrigation strategies were comprised of C (canal water alone), S (seepage water alone), 2CS (two times canal water and one time seepage water in cycle) and CS (one time canal water and one time seepage water in cycle). The model was calibrated and validated using data from a field experiment conducted in 2014/15 in Gumselassa irrigation scheme. Considering the four irrigation strategies, two scenarios (below) were evaluated for their long-term effects (2005 to 2014) on relative yield of onion and soil salinization.

- Scenario I (reflecting existing practices) - 60 mm pre-plant irrigation using fresh canal water, and
- Scenario II – 70 mm pre-plant irrigation (PPI) using fresh canal water and introduction of 20% leaching fraction (LF)

.

Results of the ten years period of simulation revealed a clear effect of the different irrigation water qualities and the application frequencies on salinity build up in the soil profile. Result of the modelling also showed that the salinity build-up is critically affected by the amount of annual rainfall.

Irrigation using seepage water resulted in significant decline in the potential yield of onion in both scenarios. The results of long-term simulations reveal that increasing PPI to 70 mm and introduction of 20% LF scenario increased the yield of onion in dry years. This indicates that, in dry years the applied water in the 1st scenario was not sufficient to leach salts from the root zone and/or satisfy the crop demand.

The long term simulation also revealed that sole irrigation using seepage water (1.12-2.19 dS m^{-1}) under the existing 60 mm PPI, will result in saline soils (EC_e> 4 dS m^{-1}) in dry years, in particular in the root zone, accommodating most irrigated crops. Even during the occurrence of wet years, salinity will reach to a level (2.63 - 4 dS m^{-1}) in the top soil, affecting germination and establishment of most crops. Considering the current irrigation scheme condition, poor leaching characteristics of the soil (clay) and management practices, sole irrigation using seepage water is really risky, and should be avoided.

Increasing PPI to 70 mm and introduction of 20% LF significantly lowered the salt accumulation in the root zone, under all irrigation strategies. Unlike the 1st scenario, this strategy also has the potential to lower the average soil salinity (100 cm) below 4 dS m^{-1} (the threshold for saline soils), while utilizing sole irrigation using seepage water. However, full irrigation with seepage water in the dry years is still unsafe, due to high accumulation of salts in the shallow depths (0-30 cm) of the root zone.

Although, most of the deposited salts in dry years will be leached down by the excess monsoon rainfall in the wet years, overall the long-term simulation shows a gradual build-up of salinity in the soil profile under all irrigation strategies in both scenarios. Therefore, it is of utmost importance to deploy clever irrigation strategies aiming at optimizing irrigation amount and scheduling in dependence of weather forecast and crop requirements. In addition, proper soil management might be able to improve soil hydraulic properties, e.g. through incorporation of organic matter or deploying deep tillage.

6. Synthesis

6.1 General discussion

In African developing countries with their high dependency on agriculture, irrigated agriculture remains the most viable option for reducing poverty and improving food insecurity. In line with this, many countries of sub-Saharan Africa (SSA), including Ethiopia, have been expanding small-scale irrigation (SSI) for the last decades as a priority policy. However, the issue of sustainability is given little attention. Poor irrigation water management practice has been one of the major challenges jeopardizing the success and sustainability of most of the irrigation schemes. Acute irrigation water scarcity, declining crop yields, irrigation-induced soil salinization and waterlogging are serious issues threatening food security and environmental well-being. Moreover, simple and practical irrigation water management innovations that can influence farmers' decisions are lacking.

Therefore, the aim of this thesis was to first assess, understand and evaluate the factual irrigation water management practices in relation to crop yield and soil salinization, and come-up with simple and practical irrigation water management strategies capable of influencing farmers' decisions and enabling them to cope with the problems of water scarcity and soil salinity. The study combined household and scheme level assessments, field experiments and long term modelling to determine the potential for sustainable production of the irrigation schemes.

The general objective of this PhD research was to evaluate the impact of innovative water management practices on yield and soil salinity in small scale irrigated agriculture in Tigray, Northern Ethiopia, as a contribution to sustainability in irrigation development.

The specific objectives of the PhD research were:

1. to assess the irrigation water management practices, challenges, and farmers' perceptions and adaptation,
2. to identify, develop and evaluate appropriate and practical irrigation scheduling on maize yield and salinity hazard in a participatory manner,
3. to identify a sustainable way of using both fresh and moderately saline water resources for the production of onion, through cyclic irrigation strategy, and
4. to simulate and predict the long-term impacts of conjunctive irrigation strategies on crop yield and soil quality.

6.1.1 Irrigation water management practices, challenges, and farmers' perceptions and adaptation

Although irrigated agriculture is the most viable option globally agreed for reducing poverty, improving food security and overall economic development, particularly in SSA countries (World Bank, 2008a; Inocencio et al., 2007), poor performance of the current irrigation sector, under the challenges of growing competition for the scarce fresh-water and climatic impact, is a major concern. Consequently, there is increasing interest in analysing farmers' practices, perceptions, adaptation and mitigation strategies to face the challenges of irrigated agriculture at local and regional scales (Ricart et al., 2019; Deressa et al., 2009). Understanding farmers' perceptions enables sharing of local experiences, and helps to devise effective adaptation measures for sustainable utilization of agricultural systems (Lebel et al., 2015).

The farmers' practices, their perceptions of major problems, impacts, and plot and scheme level adaptation strategies particularly related to irrigation water management in the study area were analyzed based on a field survey conducted with 109 farmers and field observations. The detailed results and discussions are presented in Chapter 2 of the thesis. The results showed that farmers are aware of irrigation water scarcity due to climatic variability. Further, they also were well aware that poor scheme and farm-level water management practices are the major causes aggravating water scarcity, crops yield decline and soil salinization. In spite of their clear perception of the major causes, farmers' overall plot and scheme level adaptation strategies were not robust. Our findings are also confirmed by vast evidence from other developing countries, showing that good perception by farmers of existing problems and climatic challenges do not assure sustainable adaptation strategies (Adhikary et al., 2013; Alam, 2015; Alam et al., 2017; Dey et al., 2011; Elum et al., 2017; Udmale et al., 2014; World Bank, 2008a; Zahid and Ahmed, 2006).

Yet, appropriate adaptation strategies are vital to assist local communities to cope with extreme weather and climatic variations (Adger et al., 2003; Alam, 2016; Gandure et al., 2013; Niles et al., 2015; Rosenzweig et al., 2013). This study pointed out that the farmers are constrained by lack of technical knowledge, weak capacity of the WUA and poor irrigation infrastructure to manage the irrigation water properly at both scheme and plot levels. Studies show that farmers in many countries need capacity building in technical and institutional issues to improve the performance of irrigation schemes (Ghazouani et al., 2012; International Finance Corporation, 2019; Kazbekov et al., 2009; Mutambara et al., 2016; Thiruchelvam, 2010; World Bank, 2007). Particularly, farmers in nations with serious resource constraints, i.e. SSA in many regions, will not be able to adapt to climate change without external assistance (World Bank, 2007). Thus to enable farmers to create more efficient adaptation strategies, African governments need to help farmers by providing the necessary resources, information and training on adaptation strategies and techniques (Juana et al., 2013).

This study indicated that more focus has been given to expansion of SSI schemes for the last decades, regardless of the poor performances of the existing ones. Underinvesting on managerial aspects can lead to significantly higher costs and lower performance as both managerial and physical aspects of irrigation systems are vital (Inocencio et al., 2007). The low focus given to managerial aspects has been observed in many irrigation schemes (Suhardiman and Giordano, 2014). Yet, the success of green revolution in Asia was not only attributed to irrigation facilities, but also to proper management (FAO, 2006).

Strong Water Users Associations (WUAs) are crucial for the sustainable management of irrigation systems in community-managed irrigation systems (Yami, 2013). They can encourage collective action, contribute to fair conflict resolution, better equity, infrastructure management and maintenance, and improve the financial sustainability of the irrigation system, thereby making more sustainable use of scarce water (World Bank, 2004).

The findings of this study also showed that the performance and sustainability of irrigation schemes are highly constrained by the poor overall performance of the WUA. Irrigation management transfer to WUAs without building their management skill and financial capacities has been a major cause of deterioration of irrigation schemes in several countries, including SSA (Douglas and Juan, 1999; Eyasu, 2005; Fanadzo, 2012; Shah et al., 2002; Vermillion, D.L., 1997; Yami, 2013). Among other technical problems resulting from weaknesses within WUAs, water loss through conveyance and distributary system has been a major concern in many countries (Agide et al., 2017; Orojloo et al., 2018; Sultan et al., 2014) including in the study area. According to Abu-Khashaba (2013), irrigation canal loss can range from 30% to 50% of the total volume of water transported, and seepage loss in unlined conveyance systems in particular can be extremely large (Ali, 2011). In Chapter 2 of this study, it is shown that more than 50% conveyance loss was recorded from quaternary (farm) canals to the field inlet. This has significant implications for dealing with water scarcity, equity, environmental and overall performance of the irrigation system. In addition, such situation can lead to social conflict. For instance Fundi and Kinemo (2018) stated that poor water conveyance infrastructure was the main factor aggravating water user conflicts in Tanzania.

This study made clear that lack of sound irrigation scheduling, lack of knowledge about crop water requirements, absence of incentive for saving water, use of poor quality seepage water for irrigation and absence of technical support from stakeholders are some of the main factors contributing to wastage of water and environmental degradation. Most of these conclusions are also supported by other studies on vast irrigation schemes in SSA (for example, Alemayehu et al., 2006; Ayenew, 2007; Fanadzo et al., 2010; Haile and Kasa, 2015).

This study also pointed out that, in addition to enormous water loss, soil salinization is a major and accelerating problem that requires serious attention. Poor water management in many arid and semi-arid areas also leads to land degradation in irrigated areas through salinisation and waterlogging (Ghassemi et al., 1995; Ritzema et al., 1996; Tenalem, 2007). The outcomes include decreased productivity and loss of agricultural land as observed in the study area as well as many irrigation schemes in developing countries worldwide. Thus, improved water management and investment in farming, such as field leveling and drainage, are essential to address the issues (World Bank, 2007).

Water scarcity for irrigation is expected to increase over time in developing nations owing to increased competition from other industries (UNDP, 2007). Therefore, as the main consumer of fresh water resources, agricultural irrigation must be focussed on moving towards higher water productivity in order to meet the increased demands for fresh water. The rehabilitation and modernisation of current irrigation schemes in SSA is expected to lead to increased water availability and productivity (Lebdi, 2016; Molden, 2007; World Bank, 2007).

Our research also revealed that the absence of public assistance and the top-down approach of local government authorities in enforcing choices, restrict adaptation strategies of farmers. Lack of user involvement in the development and management of irrigation is a major cause of failure in many of the irrigation schemes in Africa (Playán et al., 2018).

A participatory approach can enable local stakeholders to create and develop problem solving innovations and/or rules (Darko et al., 2016; Gorjestani, 2004). A locally based approach has a higher potential to be effective, efficient, and equitable than externally imposed rules (Ostrom, 1990; Shortt et al., 2004). In line with these concepts, this study showed that enabling farmers to make their own decisions resulted in innovative approaches to mitigate water scarcity as described in Chapter 2. The result of this study is in agreement with evidences from other developing countries. Lidon et al. (2018) reported a participatory approach that resulted in actual reform of the water sharing rules of the

Kapilaler irrigated area in Indonesia. Muchara et al. (2014) concluded that farmer participation was a key factor for the success or failure of smallholder irrigation schemes in Mooi River communal irrigation scheme in South Africa. Further, participatory approaches can lead to better infrastructure management and maintenance, leading to more effective water use (FAO, 2017).

The practical outcome from this study provides useful information for decision making government bodies to promote participatory irrigation management, and to consider farmers' decisions for other irrigation schemes with similar challenges.

With regard to water scarcity, water use competition and low water use efficiency, the irrigation sector needs to achieve better water management performance, water use efficiency, and farm-level irrigation monitoring. Physical improvement (revamping and modernizing, land leveling, selective canal lining and introduction of pressurized irrigation) of the existing irrigation systems in SSA can lead to more availability of water, increased water productivity and larger irrigated area (Molden, 2007; World Bank, 2006b; World Bank, 2007). Government support for improvement of irrigation infrastructure in Australia has led to improved water use efficiency and to water savings (Koech and Langat, 2018). Furthermore, where circumstances are favourable, irrigation systems should take advantage of the performance-enhancing impacts of a suitable combination of alternative water resources to ensure a reliable supply of water (Inocencio et al., 2007).

Other institutional changes and management incentives to reduce on-farm water wastage, such as water pricing and deficit irrigation, can further improve irrigation efficiency (World Bank, 2006b). Many irrigated areas in Africa, including Ethiopia, are managed without cost recovery mechanisms (Lebdi, 2016). Let alone construction costs, most of them are unable to cover even their running costs (Molden, 2007). Depending on the irrigation system and water availability, introduction of appropriate water pricing (non-volumetric, volumetric and tradable water rights) may promote sustainable financial management and more efficient water resource management (Davidson et al., 2019), and the reallocation of water to higher priority uses (Cornish et al., 2004). For effective implementation of water pricing in developing countries, government support for the legal, institutional and administrative aspects, as well as rehabilitation of water infrastructure for the control and measurement of flow, is required (Cornish et al., 2004; Davidson et al., 2019).

The plot and scheme level scale as applied in this study was relevant for identification of the interconnected challenges of the software and hardware components of irrigation schemes in SSA countries. Further, these scales make it possible to devise appropriate measures to fit the local biophysical, social and economic aspects of SSI for sustainable management of the scarce water resources.

6.1.2 Simple and practical irrigation scheduling approach

Inappropriate irrigation scheduling has been a major factor for poor performance of many irrigation schemes (Alemayehu et al., 2006; Annandale et al., 2011; Ayenew, 2007; Fanadzo et al., 2010; Haile and Kasa, 2015) particularly in developing countries. To ensure food security in drought-prone regions like Ethiopia and SSA in general, practical efforts to improve on-farm water management are required.

Considering the importance of proper irrigation scheduling, Chapter 3 describes the development of practical irrigation scheduling for maize using the Hargreaves equation, (which requires only temperature data for estimation of ET_0 as described by Brouwer et al. (1989) and simple scheduling procedures, and the local farmers' and extension agents' inputs). The performance was evaluated by comparing this practical approach with both the more complex CropWat simulated and local (Traditional) scheduling practices based on two years field experimentations. Hereafter,the applied approaches and the implications of the results for the larger SSA countries are described.

Worldwide, many scientific approaches to irrigation scheduling are available in the literature. However, these approaches have not yet been widely adopted (Jones, 2004; Lamm and Rogers, 2015; Stirzaker et al., 2004). The methods of scientific irrigation scheduling are commonly based on a combination of weather, soil and/or plant approaches. The major reasons for low adoption of scientific scheduling approaches by farmers include complexity of techniques, unavailability of required weather and soil water data and lack of participation by stakeholders.

Therefore, developing an irrigation scheduling method that would be readily transferable and acceptable to farmers is a principal challenge (Maheshwari et al., 2003). Worldwide much emphasis is given to technology and sophisticated science, and not how these can affect the decision-making process of the farmers (Stirzaker and Wilkie, 2002). Shearer and Vomocil (1981) surveyed the technology transfer efforts for irrigation scheduling over a 25 years period in Oregon (USA) and concluded that successful technology transfer was more dependent on human behaviour and attitude than having a sophisticated irrigation scheduling method.

Participatory approaches involving farmers and communities are important for adoption of sustainable natural resources management practices (World Bank, 2007). Combining traditional knowledge with formal knowledge can tackle challenges to on-farm management (IAASTD, 2008). The participatory method facilitates a working relationship in which the end-users' priorities and values become fully expressed in the production of new technologies (Chambers, 2008).

In line with this, Prasad et al. (2015) studied the role of participatory on-farm technology demonstration in addressing climatic uncertainties in several vulnerable districts of India. They found about 20-40% crop yield increase due to adoption of improved water management technologies. Kerr et al. (2019) conducted a four year survey on the impact of participatory agroecological research on food security in Malawi. They showed that household food security and dietary diversity significantly increased over a two year period. Virk et al. (2003) evaluated a participatory plant breeding (PPB) programme in rice for the rainfed uplands of eastern India, and reported that the farmers were in favour of the improved varieties rather than the national check variety. Consequently, the farmers produced large quantities of seed that have already spread widely through informal means, ahead of certified seed production.

Farmers' dissatisfaction with the existing irrigation practices, and their perceptions for new technology in relation to their current knowledge are important first steps for any adoption to occur (Stirzaker et al., 2004). In chapter 2, we described that, the farmers perceived over irrigation as a major cause for water shortage, water logging and soil salinization problems. In this line, our approach for development of an irrigation schedule (as described in Chapter 3) that integrates local participation and existing resources, can be used as a potential method for facilitating adoption of promising irrigation management technologies in Ethiopia and generally in SSA.

Poor irrigation water management has contributed to, among other things, the growing scarcity of water and land degradation through salinization and waterlogging (World Bank, 2007). Appropriate irrigation scheduling may thus lead to better crop performance, water savings (FAO, 2012; Koech and Langet, 2018) and progress in mitigating land degradation (Shahid et al., 2013).

The results of this study (detailed in Chapter 3) demonstrated that the simple (Practical) irrigation approach resulted in better crop performance, water savings and significant improvement in water productivity as compared to the Traditional and Complex approaches. The grain yield increment using the Practical approach varied from 8.1 to 14.5% and 9.2 to 12.2% compared to the Traditional and Complex approaches, respectively. Moreover, the Practical approach resulted in savings of 108.1-133.4 mm (14.1-17.4%) and 195.9-218.8 mm (25.6-28.6%) in irrigation water depth compared to the other approaches, respectively.

The findings of this part of the larger study also have several macro and regional level policy implications for improving food security in the rural communities of both Ethiopia and other SSA countries that are facing similar issues. First, this practical approach has great potential for improving equity in irrigating a larger portion of the command area. Second, in most rural areas of the SSA countries, where weather data are lacking or unreliable and the farm technology level is low, this simple technique can significantly improve the overall irrigation water management practices. Similarly, good performance of a simple irrigation calendar was reported by Fessehazion et al. (2014).

For successful implementation of such a simple irrigation calendar in community managed irrigation schemes like the one in Gumselassa (study site), technical support and capacity building of the WUA is required, especially for arranging and synchronizing schedules at scheme level. Moreover, for wider use, researchers need to build on and amend such simple procedures as needed for similar as well as diverse agro-ecologies.

The innovative approach of this research is that we demonstrated the effectiveness of participatory development of a simple, inexpensive and Practical irrigation scheduling approach that considers the local socio-economic conditions and technology of the farm. Moreover, minimum, locally available inputs were utilized and the necessary computations can be easily exercised by the local extension agents without the aid of advanced technologies, such as computers.

6.1.3 The effect of a cyclic irrigation strategy on onion yield and soil salinity

In response to the increasing scarcity of good quality water for irrigation, farmers all over the globe are forced to use poor quality water such as brackish, saline or sodic groundwater, drainage water and wastewater (Elamin and Al-Wehaibi, 2005; Feigin et al., 1991; Qureshi, 2014). For this reason, vast irrigation areas are threatened by salinization, yield reduction and land abandonment (Crescimanno, 2007; Crescimanno, et al., 2004; Qureshi, 2014; Rhoades et al., 1992; Szabolcs, 1994). Similarly, irrigation practiced by pumping or diverting seepage water from micro-dams has been a major cause for low (especially onion) crop yield and aggravation of soil salinization in Ethiopia. Thus, finding a sustainable way to use seepage water in conjunction with fresh canal water is an important strategy for mitigating onion yield decline and soil salinization. Our efforts in this regard are described in Chapter 4.

Water availability is a decisive factor for agricultural production and, thus, ensuring food security (Brown and Funk, 2008; WWAP, 2015). Nowadays, many areas of the world are affected by water scarcity (Alcamo et al., 1997; Assouline et al., 2015; Fedoroff et al., 2010; Sharma and Tyagi, 2004; Singh, 2014). The consequentces of agricultural water shortage are reduced output and earning, making families more insecure and susceptible to poverty (Hanjra et al., 2010; Rahut et al., 2016).

Owing to fresh water scarcity, millions of small-scale farmers around the world are compelled to irrigate with marginal-quality (saline or sodic) water (Molden, 2007; Qadir et al., 2007). However, use of poor quality water for irrigation, especially inappropriately managed, can lead to secondary soil salinization and reduction in crop yield (Bouwer, 2000; Fernández-Cirelli et al., 2009; Minhas and Bajwa, 2001). Yet, for previously mentioned reasons, the need to use poor quality water is expected to rise (Assouline et al., 2015; Sharma and Tyagi, 2004) posing further potential challenges.

Developing strategies for proper utilization of poor quality water for irrigation may contribute to more sustainable production (Marcum, 2004; Qadir et al., 2007; Sharma and Tyagi, 2004). In this regard, conjunctive irrigation of fresh and marginal quality water can be a good option for coping with the increasing scarcity of fresh water (Datta and Jong, 2002; Kaur et al., 2007; Rhoades, 1987; Sharma and Rao, 1998; Yadav et al., 2004). Appropriate conjunctive strategies can thus improve both water use efficiency and the regional environment of irrigated areas (Cheng et al., 2009; Liu et al., 2013; Singh, 2014).

Conjunctive use of surface and ground water in several areas of the world enables farmers to meet crop water demand during the critical stages of crop growth, ensuring food productivity and subsequent scheme benefit in irrigation districts (Karamouz et al., 2004). According to Molden (2007), 80% of vegetables in Hanoi (Viet Nam) are irrigated through conjunctive use of fresh and wastewater and 12,000 hectares in Kumasi (Ghana) are irrigated with wastewater.

Our study in Chapter 2 indicated that spontaneous irrigation using poor quality seepage water is one of the the major causes for crop yield decline and aggravation of soil salinization. Unplanned conjunctive use of poor and good quality water for irrigation can have detrimental environmental and social complications. What is needed is reliable planned conjunctive use to achieve effective and more sustainable goals for crop produciton and resource use.

In Chapter 4 we described our field experiments on the use of seepage (EC: 0.82-2.19 dS m^{-1}) and canal (EC: 0.41-0.78 dS m^{-1}) waters conjunctively (on cyclic basis) aiming for sustainable production of onion. The results of this study showed that cyclic irrigation using fresh water and moderately-saline seepage water (Canal: Seepage, 2:1 and 1:1) resulted in onion yield and soil salinization levels that were not significanlty different compared to irrigation using solely canal water. By contrast, irrigation with solely seepage water resulted in significant onion yield reduction and higher salt accumulation near the soil surface (0-20 cm). These results are in agreement with the on-farm experimental evidence on conjunctive use of fresh and saline water conducted by various other researchers (Ahmadi and Ardekani, 2006; Kaledhonkar et al., 2012; Malash et al., 2008; Mandare et al., 2008; Murtaza et al. 2006; Oster and Grattan, 2002).

The results of these experiments have great local and regional implications for increasing crop production, particularly for SSA countries, where irrigation expansion on the one hand is highly demanded, and water availability on the other hand is expected to further decline owing to increased competition from other sectors (Assouline et al., 2015). In addition, these findings too could be a promising option in an irrigation scheme for improving the equity of canal water use amounts between head-reach and tail-end farmers.

Many studies have recommended use of fresh water during sensitive cop growth stages while use of poor quality water should be restricted to non-sensitive stages (Abdelgawad et al., 2005; Malash et al., 2005). However, this is only possible under the condition of full control of the water sources by individual farmers. For community managed irrigation schemes, the simple predetermined cyclic sequence as described in this study can be applicable and replicable to other irrigation schemes in Ethiopia and elsewhere in SSA countries.

However, organisational planning and management might be more difficult in the case of a conjunctive irrigation strategy (Coe, 1990). Therefore, efforts on collaborating and coordinating water users (Blomquist et al., 2004), capacity building, and WUAs institutional support, underpinned by practical laws and regulations, are critical to the success of conjunctive irrigation strategies.

In many irrigation systems, farmers exploit alternative water sources for irrigation (Scott and Garces-Restrepo, 2001) due to scarcity or unreliability of the principal source. The conjunctive irrigation strategy in this research is based on reservoir and seepage water sources. None the less, the methodology applied along with the outcomes of this study can be adapted and adopted in different regions/localities, where other alternative saline-water sources, such as groundwater and drainage water, are being utilized for irrigation in conjunction with fresh water.

6.1.4 SWAP model based simulation of the long-term impact of conjunctive irrigation strategies

Water resource sustainability relies mainly on proper management and effective use of agricultural water (Fasakhodi et al., 2010). The use of saline water as an option for irrigation presents challenges. As previously mentioned, if used inappropriately, the use of saline water can pose severe threats to agricultural sustainability and food security by creating salt build up salt in the root zone (Tyagi, 2003). The reality of increasing use of marginal-quality water for irrigation worldwide (Assouline et al., 2015; Sharma and Tyagi, 2004), calls for the use of simulation models to investigate long-term impacts and develop sustainable management strategies. This is the subject of Chapter 5 of this thesis.

The agrohydrological model SWAP was calibrated and validated using climatic data and data from field experiments with 4 irrigation treatments consisting of only fresh canal water, only moderately-saline seepage water, and two conjunctive applications of both water types. Then considering a pre-plant irrigation (PPI) of 60 mm, which is the usual practice, the long term impact of the four irrigation strategies on relative yield of onion crop and soil salinization were simulated for a period of ten years (2005-2014; Scenario I). Further, in an attempt to reduce the salinity impact, additional simulations were performed by increasing the amount of PPI to 70 mm plus introducing a 20% leaching fraction (LF) at each irrigation application (Scenario II).

Results of Scenario I revealed a clear effect of the different irrigation water qualities and the application frequencies on relative yield and salinity build-up in the soil profile. The model also anticipated that the quantity of annual rainfall would critically affect the annual salinity build-up. These findings are consistent with the findings of Rasouli et al. (2013) and Verma et al. (2010).

The long-term simulation showed that irrigation using solely seepage water resulted in significantly lower onion yields ranging from 37 to 67% of its potential, in the 1st scenario. The model also predicted that irrigation using solely seepage water in dry years will result in high salinity levels (EC_e> 4 dS m^{-1}) in the 0-100 cm soil profile, where the roots of most irrigated crops grow. This higher accumulation of salts is in agreement with the findings of Eyasu (2005). In addition, irrigation using solely seepage water in wet years showed higher top (0-30 cm) soil salinity ranging from 2.62 to 4 dS m^{-1}, which affects germination and establishment of most irrigated crops. These results confirm that use of solely seepage water for irrigation should be avoided.

Cyclic use of saline and non-saline water can reduce the adverse effects of saline water such as reducing crop yields and building salts in the root zone (Hassanli et al., 2016). Results of the long-term simulation also showed that the conjunctive (cyclic) irrigation strategies in Scenario I, maintained the root zone salinity below the saline soil limit (4 dS m^{-1}). Yet, during dry years, the increased build-up of root zone salinity will affect the growth of more salt-sensitive crops. Hence, during dry years, the usual PPI (Scenario I) should also be avoided.

The long-term simulation showed that the effect of Scenario II on yield was only substantial in the dry years (2009-2011). During these dry periods, Scenario II considerably improved the yield of onion in all instances. However, the yield obtained for seepage water alone was still far below potential, ranging from 38 to 51%.

Compared to Scenario I, increasing PPI and introduction of 20% LF in Scenario II significantly decreased the salt accumulation in all simulation years, under all treatments. Reported studies also indicate that flushing of salts and/or leaching are a main tool for controlling soil salinization (Crescimanno and Garofalo, 2006; Kara and Willardson, 2006; Mansouri et al., 2014; Mostafazadeh-Fard, 2008b). However, leaching of salts may lead to deterioration of groundwater quality which could reduce availability of freshwater at a regional scale (Assouline and Shavit, 2004; Shani et al., 2005; Qadir et al., 2003). Therefore, frequent monitoring of groundwater quality is also necessary (Qadir and Drechsel, 2010).

Results of the simulation also indicated that, in most cases, Scenario II can meet the agronomic criterion in the context of salt affected soils (EC_e below 4 dS m^{-1}), even in dry years. Still, Scenario II was unable to keep the salinity of the upper soil profile (0-60 cm) below 4 dS m^{-1} in dry years, when only seepage water is used. High salinity levels in the upper portion of the root zone are more harmful to plant growth than salinity levels in the lower portion (Bingham and Garber, 1970; Minhas and Gupta, 1993). Thus, full irrigation using only seepage water should be avoided in dry years, even in case of Scenario II.

This study indicated that, by increasing the PPI and introducing 20% LF, the conjunctive strategies can be used for sustainable production of onion in average (500 mm) and above average rainfall years. However, in years with below average rainfall, conjunctive irrigation may reduce yield of salt sensitive crops, including onion, due to elevated surface salinity (2.39-3.28 dS m^{-1}). Thus, extension agents need to provide information and advice to farmers on crop choice and better management practices based on rainfall amounts of preceding years. Experience in Mali has shown that timely weather information did help farmers to better handle climate risks (IRI, 2007).

Our findings indicate that in irrigation schemes with scarce water, as in the case of the Tigray region, cyclic irrigation can be a strategy to alleviate the problem of fresh water scarcity, without undue yield reduction and soil salinization. The exception to this is during the occurrence of successive dry years, when yield decline of sensitive crops is expected due to elevated surface soil salinity.

To assure the long-term sustainability of conjunctive irrigation strategies, we recommend improving the infiltration characteristic of the soil though incorporation of organic matter and deep tillage, as well as improving the existing surface drainage system, in order to facilitate leaching of salts through the soil profile. Further, improved agronomic (Singh, 2005) and crop management practices (Jangir and Yadav, 2011) can substantially reduce the adverse effects of saline irrigation water on crops and soil.

This thesis shows that applying long-term simulation with an agrohydrological model like SWAP is useful in predicting the long-term impacts of conjunctive uses of available water resources on crop yield and soil salinization. Finally, the methodology followed in this thesis, that started by assessing the major problems and current practices (Chapter 2), and continued with field experiments on irrigation schedule and conjunctive irrigation (Chapters 3 and 4), and subsequent simulation of long-term effects (Chapter 5), can be helpful for appropriately addressing the challenges of crop yield decline and salinity hazard in other irrigation schemes that face similar challenges. The modeling approach can be valuable to local and regional decision makers, as a decision support tool for sustainable management of irrigated agriculture.

6.2 Limitations of the study

While confident that this study was well designed and executed, there are always things that might have been better, thus resulting in some limitations to this work. Farmers' practices perceptions and adaptation strategies in Chapter 2 would have been better explained if more locations had been included. The analysis of farmers' perception on different issues (yield trend, soil salinity, water quality etc.) would have benefited if present and past quantitative time series data were available for comparison. However, past quantitative time series are hardly available.

Moreover, from the interviewed farmers 32.1% were sharecroppers. Depending on the existing situation, the land irrigated by sharecroppers might change from year to year due to a change in their tenancy agreement. This might consequently have affected our data on the farmers perceived yield trends, yield differences (between earlier and recent yield crop of maize and onion) and other information on water quality, soil salinity and waterlogging problems.

Similarly the analysis of the field experiments in Chapters 3 and 4 were done based on the data collected from one irrigation scheme dominated by clay soil. The results would have been more convincing if more diverse agro-ecologies and soil types had been included.

The accuracy of model simulations depends on the availability of diverse soil, water and crop data. In Chapter 5 the soil hydraulic functions are obtained using a soil pedo-transfer function, which might deviate from actual field conditions. The simulation results would have been more interesting if a detailed crop growth model (Van Ittersum et al., 2003) had been used. However, the simple crop growth model (Doorenbos and Kassam, 1979) used was due to lack of required input data for the more detailed crop growth model. Further, the simulation performed in this study was at field scale. If additional simulations at various locations in the irrigation scheme had been performed, information on the effects of scheme level water management on the distribution of salts would be gained.

The applied fertilizer rates for the field experiments were based on the common national recommendation. Specific fertilization based on soil testing might have increased the absolute crop yields. However, the effects of the different treatments on the relative crop yields are expected to be similar.

The cyclic irrigation experiment in Chapter 3 was focused on fresh canal and moderately saline seepage water sources. The findings would have been more comprehensive if alternative available water sources (e.g. shallow ground water source) had been included. Furthermore, the irrigation depth applied for all treatments was constant. If variable irrigation depths and leaching fractions were included, there would have been even more convincing management options.

In this study, the salinity analysis was based on the electrical conductivities of the water and/or soil-water, which reflects only the total amount of soluble salts. However, if analysis of the type of salts had been included, it would give a clearer picture of the salts and their specific effects on the soil and plant.

6.3 Recommendations for extension and policy

This study identified poor irrigation water management as the major cause for water scarcity, yield decline and soil salinization in the Gumselassa SSI scheme. Most of the problems are due to lack of knowledge, weak enforcement capability of the Water Users Association (WUA) and poor irrigation infrastructures to manage the irrigation water properly at plot as well as at scheme level. The following recommendations are made to improve irrigation water management for sustainable production and productivity of the scheme.

In community managed irrigation systems, a surface rotational system of water distribution has proven to be efficient from the operational point of view and social fairness. In order to encourage rotational system practice, we recommend support by training, capacity building and technical assistance of the WUA, particularly in planning, scheme level water allocation and distribution and in harmonizing schedules to sustain the irrigation systems.

Conveyance water wastage through canal seepage and runoff (Yohannes et al., 2017) has been identified as a major problem. Hence, it is recommended that government intervention should focus on maintenance and lining of major irrigation canals and improvement of existing water infrastructures, which are beyond the technical and economic capacity of the farmers.

Allowing the farmers to make their own decisions resulted in innovative and effective drought mitigation strategies (Yohannes, et al., 2017) which has great potential for application in other irrigation schemes. Therefore, it is recommended that government authorities advise and stimulate participation of WUAs in decision processes concerning the irrigation scheme management, rather than exerting top-down interventions.

In irrigation schemes where water is scarce, like in Gumselassa, regional and local government policies should give priority to supporting research, extension and development endeavours that focus on water scarcity adaptation strategies. Further, researchers, water managers and extension workers should give due attention to development of simple manuals for irrigation of agriculture fields that can be easily understood and applied by the beneficiaries. To enhance coping strategies of the WUA and resilience of the irrigation scheme to water scarcity, the local and regional authorities' interventions should focus on developing and strengthening the technical, institutional, legal and regulatory issues of the WUAs in a participatory manner.

The process of choosing an appropriate schedule for an irrigation system must take into account the socio-economic status of the farmers, the technology level of the farm and the resources available locally. In most rural areas of Ethiopia, where climatic data are lacking or unreliable and the technology level of the farm is low, simple and practical irrigation scheduling would significantly improve the sustainable management practices with the scarce irrigation water. Hence, it is recommended that such strategies would help the farmers to improve crop productivity and mitigate the problem of soil salinity.

For successful implementation of simple irrigation calendars in community managed irrigation schemes such as Gumselassa, it is recommended that the government build the institutional capacity and technical skill of the WUAs, particularly for arranging and enforcing predetermined irrigation calendars.

Irrigation using poor quality water is one of the most important water scarcity adaptation strategies. Under the current irrigation scheme conditions, irrigation using soley moderately-saline water is discouraged because of the elevated soil salinity. It is vital that the farmers are encouraged to use a predetermined conjunctive (cyclic) irrigation strategy. Finally, to assure the long-term sustainability of conjunctive irrigation strategies, leaching of salts to greater soil depths is recommended through agronomic measures, deep tillage and improving the infiltration characteristic of the soils.

6.4 The need for further scientific study

The government of Ethiopia has been promoting small-scale irrigation schemes and building water harvesting structures to address the problem of water scarcity and food insecurity. However, the performance of many small-scale irrigation schemes in Ethiopia is generally far from satisfactory. For rehabilitation and sustainability measures of the deteriorating irrigation schemes, detailed assessments are lacking. Therefore it is urgent to assess and evaluate site specific practices, problems and challenges.

Our study showed the efficacy of farmers' innovations for water scarcity adaptation. Researchers should assess, build-on and adapt innovative farmer practices to enhance their efficacy and resilience to water scarcity and for wider use.

The meteorological data adopted from distant stations, and the methods used for the evapotranspiration estimation, could be the causes for the large performance differences between the irrigation scheduling techniques. Hence, it is also further recommended that due attention be given to local climate studies.

The field experiment on irrigation scheduling and consequent analysis was done in one location and it was limited to a maize crop only. Based on the results of the study, it would be worthwhile to continue this research at different agro-hydrological sites using the simple approach developed in this thesis.

Soil salinity has been generally identified as a major problem. To devise appropriate salinity management strategies, more in-depth studies of the nature and dynamics of salts is recommended.

Our results from the field experiment on cyclic irrigation strategies demonstrated a sustainable approach for cultivation of onion. For more comprehensive results of cyclic irrigation strategies, further in-depth studies that include cultural, agronomic and tillage practices are recommended.

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Summary

To address the problem of water scarcity and to achieve food self-sufficiency, huge efforts and massive irrigation developments have been made in the last twenty-five years by the Ethiopian Government. However, the performance of many small-scale irrigation (SSI) schemes is still very poor. Deficient irrigation water management is one of the major factors challenging the success and the sustainability of the SSI. Farmers are constrained by inappropriate irrigation management strategies, which result in irrigation water scarcity, yield loss and undesirable environmental impacts in most SSI. The issue of sustainability is given hardly attention.

This thesis tries to assess, understand and evaluate the current irrigation water management practices in relation to crop yield and soil salinization and then come-up with simple and innovative irrigation water management strategies that can influence the farmers' decision and enable them to cope with the problem of water scarcity and soil salinity.

In Chapter 2 farmers' irrigation water management practices, challenges, perceptions and adaptation were studied. We evaluated farmers survey data, field observations and measurements and found that the farmers' perception of the major causes for aggravating water scarcity, crop yield decline and soil salinization were in line with field observations. The overall plot level and scheme level adaptation strategies of the farmers were not good enough. The farmers are constrained by lack of technical knowledge, weak enforcement capability of the Water Users Association (WUA) and poor irrigation infrastructures to manage the irrigation water properly at plot as well as at scheme level.

The government involvement on sustainability of irrigation schemes is poor. Also, the top-down approach by local government authorities has been constraining the farmers' adaptation strategies. The study showed that allowing beneficiaries to make their own decision resulted in innovative drought adaptation strategies. For sustainable utilization of the irrigation scheme, priority should be given to interventions focused on improvement of water efficiency at farm as well as at scheme level.

In Chapter 3 we developed a simple irrigation scheduling method based on an FAO procedure (Brouwer et al., 1989), the Hargreaves ET_0 equation and the opinions of local farmers and extension agents. Then, under participation and close observation of farmers

the method was compared to CropWat simulated and local (Traditional) scheduling practices, using maize as indicator crop.

We found that the simple irrigation schedule method resulted in higher grain yield, substantial irrigation water saving and subsequently in significant improvement of water productivity as compared to the other approaches. Farmers' and experts' opinions were in favour of the Practical scheduling method. The practical irrigation scheduling method is thus recommended for maize in the Gumselassa area. The presented procedure can be adopted for preparation of irrigation calendars of other crops, and in other regions.

In Chapter 4 we presented a sustainable utilization of the scarce irrigation water resources using cyclic (conjunctive) irrigation strategies for the production of onion. The effects of irrigation strategies using fresh water, moderately-saline water and cyclic combinations of both waters on onion yield and soil salinization were evaluated based on two years experimental data. The study was conducted under close observation and involvement of farmers and extension agents. The results indicated that the cyclic irrigation strategies are promising options for the production of onion without undue onion yield reduction and soil salinization as compared to irrigation using fresh water.

In Chapter 5 the long-term (ten years) impact of cyclic irrigation strategies on relative onion yield and soil health were evaluated. Climatic data, and data collected from the irrigation scheme and the field experiment (Chapter 4) were used to calibrate and validate the Soil-Water-Atmosphere-Plant (SWAP) model. Two scenarios, i.e. 60 mm pre-plant irrigation (PPI) for the 1st case and 70 mm PPI plus 20 percent leaching fraction (LF) for the 2nd case, were used for long-term simulations.

Results of the simulation revealed that salinity build-up is critically affected by irrigation water qualities and the application frequencies and the amount of annual rainfall. Irrigating using seepage water resulted in lower onion yield and higher salt accumulation in the root-zone, for both scenarios. Considering soil salinization, results of the long-term simulation indicated that, the cyclic irrigation strategies can be used safely through increasing the PPT to 70 mm and introducing 20% LF.

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Degol Fissahaye Yohannes was born on the 24th of February 1976 in Addis Abeba, Ethiopia. After completing high school in 1993 he studied Agricultural Engineering for five years in Alemaya at the then existing Haromaya University. After his graduation he worked in the Tigray Agricultural Research Institute as a researcher for two years. He pursued his postgraduate studies in the same University and he has obtained his MSc. degree in Irrigation Engineering in 2005. After he obtained his MSc., he continued working as a researcher and head of the Natural Resources Department, in the Tigray Agricultural Research Institute. In 2008, he was employed in Mekelle University and served as a lecturer in the College of Dryland Agriculture and Natural Resources and team leader of the Business Enterprise and Consultancy office of the University. In 2013 he was awarded a scholarship from the EAU4Food project and admitted as a PhD candidate in the Soil Physics and Land Management Group (SLM) of Wageningen University, the Netherlands. Degol is married and has three daughters. Email: degolfs@yahoo.com

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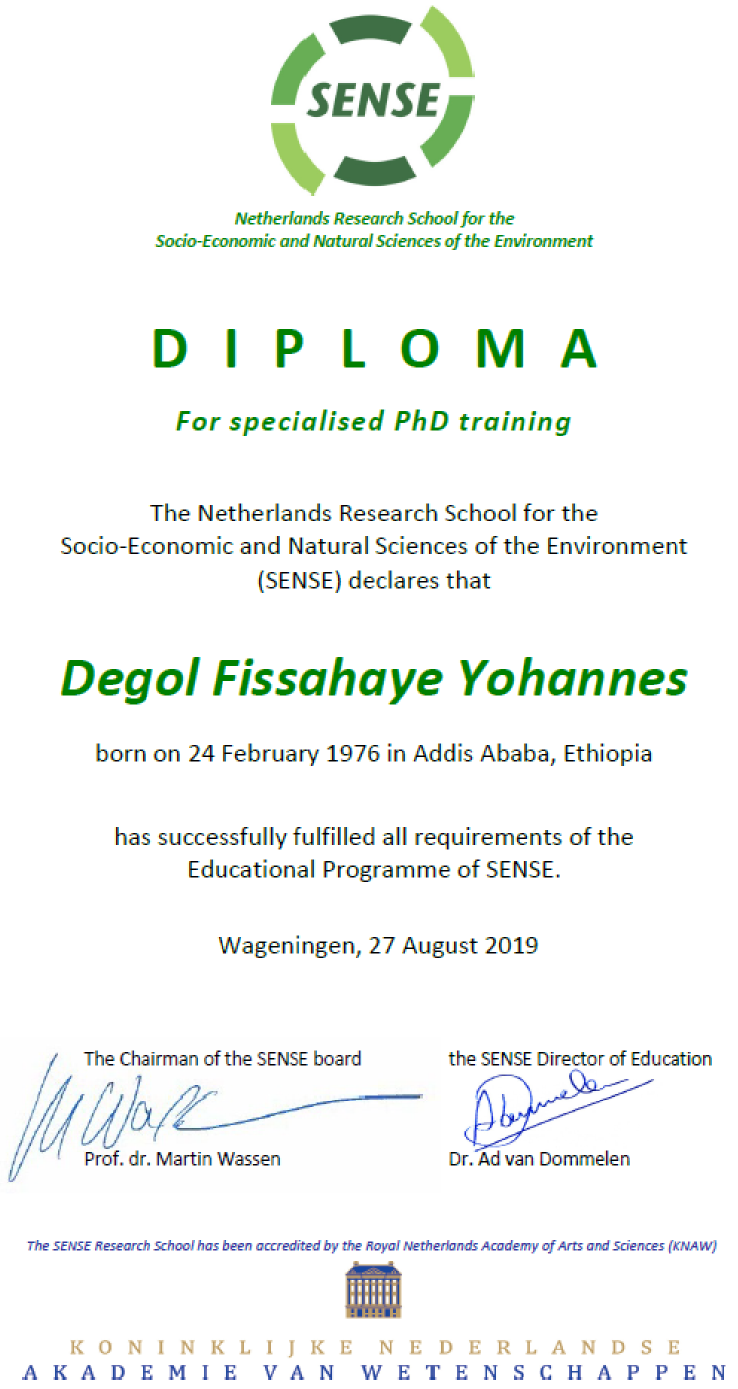

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- Teaching in the BSc course 'Irrigation and Drainage' (2015-2016)
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- Collaborative research and co-authorship, Mekelle University Ethiopia (2017-2018)

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