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Critical review on improving irrigation water use efficiency: Advances, challenges, and opportunities in the Ethiopia context

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ABSTRACT

The demand for fresh water is constantly increasing among all water users. Irrigation in Ethiopia consumes a large amount of water extracted from various sources. Hence, efficient water use and management are currently the major concerns in the country. Thus this paper aims to review the advancements, challenges, and opportunities regarding improving irrigation water use efficiency in Ethiopia. Irrigation in Ethiopia started in the 1950s with traditional irrigation systems. Now modern irrigation, including sprinkler and drip irrigation, is practiced in some parts of the country. The review showed that even though the farmers have practicing irrigation for a long time, still they cannot surpass subsistence farming. Furthermore, improvements in irrigation water use efficiency through proper scheduling and on-farm management are not satisfactory. The paper revealed the challenges that hinder water use efficiency improvement includes crop diseases, socio-economic factors, institution and policy-related issues, limitation in technical and human capacity, lack of agricultural input as well as market and nature-related factors. In the future, increased use of remote sensing techniques, more versatile sensors, simulation, and quantitative models are likely to be seen to improve water use efficiency. In most cases where water is saved as a result of the efficient use of technologies, the spare water ends up being used to expand the irrigation area, which results in an increased income for the household. Hence, to achieve net water savings, water-efficient technologies and practices need to be used in combination with other measures such as incentives for conservation and proper use. Besides, appropriate regulations should be set that limit water allocation and usage. The government and partners should allocate resources for capacity building of farmers regarding irrigation, which in extension will lead to enhancement in WUE.

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1. Introduction

Ethiopia is located in the North-Eastern part of the African continent or what is known as the "Horn of Africa." It lies between 3° N and 15°N latitude and 33°E and 48°E longitude. The country occupies an area of approximately 1,127,127 square km. The climate of Ethiopia is tropical monsoon with a wide topographic-induced variation that is temperate on the plateau and hot in the lowlands. There are two seasons: the dry season prevails from October through May and the wet season runs from June to September. Ethiopia is a country which is rich in geographical diversity. It consists of rugged mountains, flat-topped plateaus, deep gorges, and river valleys. It is erosion, volcanic eruptions, and tectonic movements over the ages that have contributed to the nation's diverse topography. The highest altitude is at Ras Dashen (4,620 m above sea level) and the lowest altitude is at Kobar Sink (120 m below sea level). Ethiopia consists of nine major rivers and nineteen lakes (Awulachew et al., 2007). The Blue Nile, the chief headstream of the Nile, rises in Lake Tana in northwest Ethiopia.

Irrigation in Ethiopia is mainly practiced in small-scale irrigation schemes, which are often characterized by low water productivity. Thus, efficient water use and management are currently major concerns (Derib et al., 2011). Ethiopia is a country endowed with ample water resources with 12 river basins with an annual runoff volume of 122 Bm^3 of water and an estimated 2.6–2.65 Bm^3 of groundwater potential (Awulachew et al., 2007; Makombe et al., 2011; MOA, 2011). Although Ethiopia has abundant rainfall and water resources, its agricultural system does not yet fully benefit from the technologies of irrigation and water management (Awulachew et al., 2010). There appears to be a consensus that irrigated agriculture, in general, is up against a future with less water. This, consequently, call for increased efficiency in the utilization of scarce water resources, a concept that is technically called water use efficiency (WUE). Despite the huge expansion, the performance of most small scale irrigation schemes in Ethiopia is far from satisfactory (Amede, 2015; Awulachew and Ayana, 2011; Carter and Danert, 2006; Teshome, 2003). Agide et al. (2016) stated that the relative irrigation supply (the ratio of irrigation supply to crop water demand) at scheme level for 10 irrigation schemes in Ethiopia ranged between 0.5 (under irrigation) to 5.0 (over-irrigation) for the period of January to May and between 0.8 and 7.0 for the period June to December.

Water use efficiency (WUE) is often defined, using a volumetric or hydrological approach, as the proportion of the water supplied through irrigation that is productively used by the plant (Koech and Langat, 2018). The water use efficiency is defined as the yield of marketable crop produced per unit of water used as evapotranspiration (Tilahun et al., 2011). In this paper, the later definition above is used and sometimes water productivity and WUE are used exchangeably. Although the system is associated with high labor requirements and low WUE, surface irrigation is the main irrigation method used in Ethiopia (Awulachew et al., 2007). Enhancing investment in irrigation development has been identified as a core strategy aimed to de-link economic performance from rainfall (Bank, 2006; MoFED, 2006; MOWR, 2002). Ethiopia is said to have an estimated irrigation potential of 3.5 million hectares (Awulachew et al., 2007). However, the total estimated area of irrigated agriculture in the country in 2005/2006 was 625,819 ha, which constitutes only 18% of the potential (MOWR, 2007). The irrigation subsector is classified as small (less than 200 ha), medium (200–3000 ha) and large scale (over 3000 ha) (Table 1).

The application of deficit irrigation up to 30% of crop evapotranspiration can save a significant amount of irrigation water without substantial yield reduction(Gebremariam et al., 2018). For a humid climate where the soil is dominated by clay and water is a liming factor, the alternate furrow irrigation method with an appropriate irrigation interval is considered by Eba (2018) as a suitable irrigation method. Despite significant efforts of government and other

Table 1
Existing irrigation schemes by region in Ethiopia(Tilahun and Paulos, 2004).

No	Region	Irrigable potential	Current irrigation activities		
			Traditional	Modern	
				Small	Medium& large scale
1	Oromia	1,350,000	56,807	17,690	31,981
2	Amhara	500,000	64,035	5752	–
3	SNNP	700,000	2000	11,577	6076
4	Tigray	300,000	2607	10,000	–
5	Afar	163,554	2440	–	21,000
6	Ben shangul Gumuz	121,177	400	200	–
7	Gambella	600,000	46	70	2000
8	Somali	500,000	8200	1800	–
9	Harare	19,200	812	125	–
10	Dire Dawa	2000	640	860	–
11	Addis Ababa	526	312	–	–
total		4,256,457	138,339	48,074	61,057

stakeholders to improve agricultural water management for enhancing irrigation, different constraints related to policy, institution, capacity, infrastructure, and the market still exist. Even though many recent reviews were conducted on various aspects of irrigation in Ethiopia (e. g Haile and Kasa, 2015; Tesfaw, 2018; Gebrehiwot, 2018), none brings together the diverse aspects of challenges, advancement, and opportunities concerning improving water use efficiency. Therefore, the objective of this paper is to review and put together issues related to advances, challenges, and available opportunities for improving irrigation water use efficiency and highlight possible practical applications in Ethiopia.

1.1. Role of irrigated agriculture in Ethiopia

In Ethiopia, it is clear that agriculture is the dominant activity to sustain the rural community's life and the fundamental for people's basic needs (Tesfaw, 2018; Tilahun et al., 2011). Irrigation is currently considered as a means by which agricultural productivity can be enhanced to satisfy the growing food demand in Ethiopia (S. B. Awulachew et al., 2005). Moreover, to overcome the problem of inadequate rainfall and variability in terms of space and time, irrigation development is the best approach and has been given significant attention in Ethiopia (Ayele et al., 2011; Hagos et al., 2009; Haile and Kasa, 2015). Irrigation development has been identified as an important tool to stimulate economic growth and rural development to improve household food security and poverty reduction in Ethiopia (Garbero and Songsermsawas, 2018; Gebrehiwot, 2015; Hagos et al., 2009; MoFED, 2006.). Irrigation enables a production increase by going from one to two or three harvests per year. It also improves nutrition and livelihood through diversification and increases income by selling high-value cash crops (Aregawi, 2014; Carter and Danert, 2006; Tesfaw, 2018; Teshome, 2003; Wehabrebi, 2014). Irrigation development also enables to offset the negative impact of rapid population growth of 2.6% per year in Ethiopia (CSA, 2007).

Irrigation, in general, can generate an average income of about Birr 2800 per hectare, which is equivalent to USD 323 per hectare (Hagos et al., 2009). In the Mathara sugar cane irrigation scheme, 11,000 jobs were created of which 3700 are permanent. Employees in the scheme have access to free housing, water, electricity, schools, clinics, and other facilities. Similarly, in the Wonji irrigation scheme, 4000 up to 7500 jobs are provided annually, depending on the time of year (Awulachew et al., 2010). Relative to households depending on rain-fed agriculture, households using traditional irrigation had higher crop yields on average and were able to grow a more diverse range of crops. However, the effects were not significant on intermediate outcomes such as investments in farm inputs, including improved seeds, fertilizer, and pesticides and it did not eliminate the food insecurity problem (Garbero and Songsermsawas, 2018; Tesfaye et al., n.d.). IFAD (2005) indicated that in Ethiopia, SSI has resulted in increased production, income, and diet diversification in the Oromia and South regions. Irrigation schemes had a positive role on the education level, usage of improvised, per capital aggregate income, improved standards of living, marketing, and distribution (Furi and GetachewBashargo, 2015). Irrigation brought about change in cropping patterns and increased production and farm income, improved housing, and wage labor employment (Dejene et al., 2008). Despite its role, irrigated production in Ethiopia is far from satisfactory results (Teshome, 2003). Ethiopia comprises 112 million hectares (Mha) of land and cultivable land area estimates vary between 30 and 70 Mha. However, irrigation is not a well-developed sector in Ethiopia and the irrigated area is only about five percent of the country's irrigational potential. Due to this, the contribution of the irrigation sector to the national economy is minimal (Awulachew et al., 2010; MOWR, 2007) (Table 2).

1.2. Current irrigation scheduling

Anac et al. (1999, cited in Demelash, 2011) stated that for optimizing crop production per unit area and for sustaining irrigated agriculture, proper knowledge on time to irrigate and amount of water apply is essential. For reducing the wastage of irrigation water, reducing evaporation loss, reducing leaching below the root depth, allowing crops to exploit the water stored within the soil profile, reducing the accumulation of salts within the soil profile should be an objective. Those objectives can be met, at least partially, by reducing the total irrigation water applied (Greenwood et al., 2009). Where water is the limiting factor for crop production, maximizing water productivity by deficit irrigation is often economically more profitable for the farmer than maximizing yield (Demelash, 2011).

In Ethiopia, poor irrigation scheduling practices have been considered as the major challenge for the sustainability of irrigation schemes because of the lack of simple and practical scheduling techniques, cost, inaccessibility of soil water monitoring tools, lack of local climate data and soil–water parameters (Yohannes et al., 2019). In the Tigray region, irrigation scheduling is decided and practiced by a local water committee and based on the farmer's intuition, without accounting for soil, plant, and weather conditions (Hagos, 2005). In the Tigray region (Hagos, 2005), and most irrigation schemes in the country, over or under irrigation of fields are common (MOA, 2011). Even though many advanced and scientific irrigation scheduling techniques have been developed in recent decades, the adoption by farmers is low, especially in developing countries (Annandale et al., 2011; Fanadzo et al., 2010). The long-term sustainability of increased production in Ethiopia may be damaged by inappropriate watering schedules (Schmitter et al., 2017). In Ethiopia, most irrigation practice is supply-based, which prohibits the promotion of water use efficiency. Regarding scheduling, all groups get water turn by turn. The water distribution method is of rotational type and electric power interruption hinders scheduling (Abshiro and Singh, 2018). In the Beles sugar sprinkler irrigation project, water was applied at a uniform level irrespective of the soil, growth stage, and climate (Abshiro and Singh, 2018). A majority of the fields were under water which caused poor cane growth and reduced the expected yield per hectare (Abshiro and Singh, 2018). Although some farmers irrigate according to the schedule, other farmers negotiate with other groups to use more or earlier irrigation water (Lencha, 2008).

In the Godino irrigation scheme, the amount of water applied is the same regardless of crop type and growth stage. The irrigation

Table 2
Cost and income of HH's before and after using irrigation (Mengiste and Kidane, 2016).

Current cost-income relation	N	Minimum	Maximum	Mean	Standard deviation
Current income of non-irrigator households	151	400	9500	3145.75	1838
Current cost of non-irrigator house holds	151	200	10,000	2905.13	1481.1
Length of irrigation practice(year)	223	3	22	9.251	4.13
House hold income before irrigation	223	70	8000	1978.12	1534.32
Current income (after income)	223	1500	600,000	10,099	7865.59

did not meet the full potato water demand to get acceptable yield, which calls the need for introducing better and more efficient practices (Geremew et al., 2007). Maximum water use efficiency was found in a practical method of scheduling developed by FAO in irrigation seasons (Yohannes et al., 2019). Alternate furrows-scientific scheduling generates the highest water productivity values exceeding traditional irrigation management with 58%. This is an indication of the new concept of "more crop per drop" (Mintesinot et al., 2004).

In northern Ethiopia, where water is limiting rather than labor, every furrow-scientific scheduling can be an option (Mintesinot et al., 2004). Since the neutron probe is capital and skills intensive, site-specific soil water balance calendars which are simpler to use are to be recommended for farmers at the Godino scheme (Geremew et al., 2007). Wetting front detectors seemed to be a better learning tool, given its simplicity, for smallholder farmers in guiding the amount of water to be applied. However, it requires experience and careful monitoring (Tesema et al., 2016). Water use efficiency did not differ significantly between soil water balance and wet front detector treatment groups (Tesema et al., 2016). Water productivity on average improved by 9% due to water savings through improved irrigation scheduling using a waterfront detector that enables to extend of the command area without affecting the total yield when compared with the farmer practices (Endrie, 2017; Schmitter et al., 2017). In Ethiopia, irrigation interval turns are mutually agreed and fixed among growers according to a pre-fixed schedule and they apply water without considering the plant needs (Demelash, 2011; Meta, 2014). In the central rift valley, irrigation scheduling was not supported by improved irrigation technologies (Etissa et al., 2014). Based on Carter and Danert (2006) farmers' knowledge and practices in water management should be the first area of field research priorities. Across Haleku and Golba I irrigation schemes around Ziway, vegetable growers operate under low water use efficiencies Paas (2010, cited in Etissa et al., 2014). A small number of farmers irrigated in the morning, assuming that this time minimized water loss due to mid-day evaporation, which in turn saved fuel costs used for pumping (Etissa et al., 2014). Most growers use a fixed irrigation schedule but some changed their irrigation intervals with crop growth stages (Etissa et al., 2014).

1.3. On-farm irrigation management

The aim of on-farm water management is to narrowing-down yield gaps by optimizing the time of water application to enhance plant water uptake (Rockström and Barron, 2007). Irrigation water is generally limited or mismanaged in all irrigation schemes, and are among the major challenges constraining agricultural production in Ethiopia (Haileslassie et al., 2016). Poor coordination for maintenance of breaching canals, extracting water by illegal means, and damage from animals are identified as the major causes of damage and threats to the safety of the irrigation system (Dejene et al., 2008). Although it is relatively better in Gibe Lemu, there was still a poor record of accomplishments in water management in terms of adequacy, timeliness, and equity in the supply of water, conflict management, and system maintenance (Dejene et al., 2008). Smallholder irrigation schemes in Ethiopia are generally characterized by poor on-farm water management practices and hence poor performances (Derib et al., 2011; Halsema et al., 2001). The poor on-farm water management emanates from both excesses and insufficient allocation of resources (Haileslassie et al., 2016).

Inappropriate irrigation scheduling, non-uniform on-farm water distribution, wrong duration of irrigation are the factors contributing to poor on-farm water management. In the traditional schemes, tail irrigators normally suffer from water shortage and usually practicing forced deficit irrigation by selecting crops with low water demand. Hence they save water while trying to minimize the impact on the yield through crop selection. Possible options, such as the valuation of water and a consumption-based water charge, need to be taken into account in efforts to discourage over-irrigation and enhance equitable water management by smallholders (Haileslassie et al., 2016). Water productivity can be determined based on water delivery in different sections within the irrigation system since it is different due to unavoidable water losses. For onion (Meki, May Nigus, and Megech schemes), the WP value based on field supplies is less than the WP value based on ET demand for all crops, showing that the filed water application is higher than the ET demands. (Haileslassie et al., 2016). Etissa et al. (2014) reported that improved on-farm irrigation practices resulted in better onion and tomato yields around Meki. On the other hand, unimproved traditional irrigation methods led to 48% and 66% extra water being applied to onion and tomato crop fields.

1.4. Waste water irrigation

Concerning wastewater irrigation in Ethiopia, a lot of research has been conducted. For almost all of the researches and studies, the study area is the capital Addis Ababa and the Akaki River (Teklu et al., n.d). The practices in the Akaki River have got great attention due to its high economic advantage and adverse impact on farmers, public health, and the environment. Due to lack proper sanitation and undulating topography almost all wastewater generated in the Addis Ababa drains through a dense network of streams into the Akaki River, which originates in the North and flows via two branches (Little and Great Akaki) to the South of the city (Rooijen et al., 2009). Starting from the 1940s, different vegetables have been produced within and around the city, mainly using water from the Akaki River as a source of irrigation water, and the cultivated area is estimated to be 1240 ha (Rooijen et al., 2009). Wastewater for irrigation has contributed positively to stimulate agricultural production; however, unwise use of wastewater is associated with an adverse impact on environment, public and animal health, farmers and farmer training (Rooijen et al., 2009; Sinshaw, 2011). Legislation that prohibits or permits the use of stream water for crop production is non-existent, although campaigns try to alert people to the related risks. Different quality parameters were used to evaluate the suitability of Akaki Rivers water quality for irrigation use. The total coliforms and E. coli; heavy metals particularly cobalt, chromium, cadmium, manganese, and iron; and miscellaneous constituents such as total suspended solids and biological oxygen demand exceeded the standard limits over the last years (Sinshaw, 2011). Inappropriate sewerage system uses of ancient technology, limited awareness of waste management, weak enforcement strategies for pollution prevention and control, and low level of income of the city dwellers have exacerbated the pollution problem and can be taken as the main challenges of wastewater management (Mohammed, 2007).

2. Challenges hinder wue improvement

The Ethiopian agricultural system is not significantly benefiting from water management technologies and irrigation, procedures that could improve productivity, and reduce vulnerability to climate variability. Despite significant efforts of government and stakeholders to improve agricultural water management and enhance irrigation, many constraints related to policy, institution, technology, capacity, infrastructure, and the market still exist (MOWR, 2007).

Table 3
Table Incidence of conflict between farmers (adopted from Gebreselasie, 2016).

Irrigation Scheme	Total no. of respondent	Had conflict		Did not have a conflict	
		No of responden0t	%	No of respondent	%
Koga	29	18	62.07	11	37.93
Meki	30	1	3.33	29	96.67
May Nigus	32	6	18.75	26	81.25
Waro	35	6	17.14	29	82.86
Hare weir	18	3	16.67	15	83.33
Wukro/Haelom	17	5	29.41	12	70.59
Hare Diversion	30	5	16.67	25	83.33
Megech	30	15	50	15	50

2.1. Crop diseases

The main challenge for improving WUE in Ethiopia is the prevalence and spread of crop diseases since improved and adaptive seeds suitable for irrigation have not been regularly provided (Dejene et al., 2008). In Ethiopia, crops are unable to withstand pests and diseases as a result of these crops being introduced without accompanying pest and disease management programs, which in turn reduces yields and the profitability of irrigation practices (Awulachew et al., 2005; Etissa et al., 2014). In Benishangul-Gumuz regional state, especially at Bambasi woreda, the rural farmers are facing a high risk of crop damage and failure (Yihdego, 2016). In Gobusayo, for example, a crop disease worm, called Tuta absoluta, severely damaged tomatoes (Furi and GetachewBashargo, 2015). Additionally, in the Tigray region, crop failures were attributed to diseases and pests, such as rust, root ruts, ball worm, blights, powdery mildew, gummosis, and waterborne diseases, including tree locust and birds. Damage from wild animals is the reason for crop yield reduction (Gebrehiwot, 2015). Crop damages by *Temchi* (insects) and hippopotamus in recent times are common in Oromia region (OIDA, 2000)

2.2. Socioeconomic

These are challenges related to the social and economic characteristics of rural farmers engaged in irrigation practice in Ethiopia. According to Awulachew et al. (2005) and MOA (2011), these challenges include poor economic background of irrigators and lack of integration in irrigation resource mobilization. This can lead to diversion structures being washed away by floods which create work redundancy and raise the cost of irrigation. Besides, the farmers' involvement in watershed development, management activities, and resource conservation is low. Production in many irrigation systems is affected by a lack of starting capital or access to credit.

No long- or short-term credit supply is provided and the financing need for purchases such as fertilizers, improved seeds, and chemicals is high (Gebremedhin et al., 2006; Etissa et al., 2014; Yihdego, 2016; Nile Basin Initiative, 2001). Water thefts, conflict for land, and water distribution are common problems that appeared in many irrigation schemes in Ethiopia (Etissa et al., 2014; Furi and GetachewBashargo, 2015; Gebrehiwot, 2015). Unplanned water use for communal water sources results in overlapping of critical growth stages and followed by yield reduction (Etissa et al., 2014). Lack of fuel supply for motor pump users is another challenge (Furi and GetachewBashargo, 2015; Gebrehiwot, 2015).

There is no sustainable funding pipeline and the private sector has played almost no role in irrigation development (Awulachew et al., 2010). In the Areta Chufa, irrigation scheme in Arsi, uneven water distribution, and illicit water tapping are reported as a result of insufficient conflict management mechanism (OIDA, 2000). Lack of incentive for the managing entities (WUA) for the time they spent in irrigation management is also a problem (Nile Basin Initiative, 2001). In many irrigation systems, problems with the committee's power and obligations are common. Some members, especially the powerful households, do not follow the rules and usually do not consent to be governed by the committee (Dejene et al., 2008). In addition, the misconception that the more water you apply, the better the result will be, is a problem (Charles, 2018) (Table 3).

2.3. Institution and policy-related

Awulachew et al. (2005) and Birhane (2002), reported that in the traditional development of the irrigation sector water management strategy is not sustainable and reliable; water utilization is not efficient; non-objective-oriented programs and projects exist; uncertainties and ambiguities in planning and lack of stakeholder participation are the challenges for better irrigation practice. The local authority's weak institutional capacity to support decentralized management of small-scale irrigation (SSI), the problem of social incompatibility between the new cropping pattern and the indigenous cropping pattern impedes the productivity of the irrigation system (Dejene et al., 2008). Low institutional capacity to address technical, institutional, and financial aspects of efficient water use, lack of departmental coordination are faced by the irrigation sector (Awulachew et al., 2005; MOA, 2011; Nile Basin Initiative, 2001). In the country, the policy for extension service and input supply is biased both in terms of supply and its timing (Dejene et al., 2008). Lack of clear duties and responsibilities of key stakeholders is another institutional constraints (MOA, 2011). There is little or no community consultation, which prevents the incorporation of indigenous farmers' knowledge into planning and construction of irrigation schemes. The link between research and expansion in the field of irrigation water management is also poor (Awulachew et al., 2005; MOWR, 2007). Farmers have no way or method of estimating irrigation water in their vegetable fields because irrigation water is currently not considered as an economic good (Etissa et al., 2014). The farmer's irrigation practices and water management are mostly based on intuition since scientific support from the extension worker is not satisfactory (Etissa et al., 2014).

Across many levels of the government, there is no standardized approach for mapping and monitoring existing irrigation; lack of project ownership; lack of institutional memory, lower-level administrative and legal entities do not play any meaningful role in water control and conflict resolution (Awulachew et al., 2010). The communication gap between farmers and authorities affects the determination of the command area and the responsibilities (OIDA, 2000). The government lacks a proper regulation for water fees, water rights, water conflict resolution mechanisms, incentives for collaboration between stakeholders; incentives for accurate

Table 4
Major financial management-related tasks of institutions at schemes.

Irrigation Scheme	Tasks					
	Access and collect fee of irrigation	The sanction for late payment or denial of payment	The sanction for stealing water	Maintain financial records	Prepare financial report	Hire and suspend temporary staffs
Koga	a	a	a	A	a	A
Meki	b	b	a	B	a	B
May Nigus	b	b	b	B	a	A
Wukro/Haelom	a	b	b	B	a	A
Hare	a	b	a	A	a	A
Hare diversion	a	a	A	A	a	A
Waro	a	a	A	A	a	A

a: absent.
b available Adopted from (Haileselassie et al., 2016).

reporting, and this leads to risk and uncertainty for many irrigation schemes (Awulachew et al., 2010).

Water quality problems were a major problem for irrigation because rivers and streams are contaminated due to ongoing upstream industrialization and inadequate wastewater treatment of the industries (Berehanu, 2007; Nile Basin Initiative, 2001) (Table 4).

2.4. The technical and human capacity

Problems associated with the technical aspects of irrigation technology and knowledge of its operation, use, and maintenance are lack of human delivery capabilities in technology, agronomy, mapping, and drilling. Poor farming knowledge is also a major problem (Awulachew et al., 2010; MOA, 2011). Lack of trained manpower, inadequate research and extension, shortage or no information and data for planning, lack of private sector participation in irrigation, inadequate operation and maintenance skill and mismanagement of irrigation leads to excessive water use (Nile Basin Initiative, 2001). Farmers are irrigating without knowledge on crop water demand, application method, and irrigation frequency. Limited access to improved irrigation technologies and lack of knowledge on water management has resulted in wastage of water, deterioration of structures, and waterlogging problems (MOA, 2011).

The lack of applied research, lack of manuals for irrigating local crops, non-transparent bidding and selection processes, lack of contract management skills, and lack of controls and balances can all increase project costs, delivery time, and risks. Based on Awulachew et al. (2005) study, poor technology choice, lack of education, lack of extension services, incorrect design, lack of knowledge about the use of modern technology, poor water, and land management, incorrect use of inputs, lack of information and databases are the challenges facing the irrigation sector of Ethiopia. Infrastructures facilities, including roads and farmer training centers in Ethiopia rural areas, are far to purchase inputs, and technologies cost is high (Yihdego, 2016).

Carter and Danert (2006) revealed that small scale irrigation interventions have tended to be dominated by a single discipline, mostly by engineering and many NGOs have performed small scale irrigation work without adequate personnel. Irrigation staffs have the insufficient practical knowledge on water management, including water demand estimation, gate operation, irrigation interval, and monitoring and evaluation of water use. Therefore, the technologies are not well transferred to the farmers, resulting in the overuse of water resources (OIDA, 2000). The quality of irrigation structure has been constrained by the inadequacy of data, limited experience, or dogmatic attitudes to farmers by professional staff (Carter and Danert, 2006). In Ethiopia, the catchment management is generally poor and likely to increase the incidence of failure of structures, both 'durable' and locally made and infrastructure is generally poor (Carter and Danert, 2006). Technical support for modernized schemes is only available in cities that are far from the watersheds and there are no skilled pump maintainers trained in the woredas. Lack of research and innovation on water use in woredas and zone-like drips (Furi and GetachewBashargo, 2015; Haileselassie et al., 2016). Inequity in water distribution across reaches is a serious challenge in almost all the schemes. In semi-modern and traditional schemes upper reaches are generally oversupplied, while tails are undersupplied. These causes water productivity in the head reaches to be lower due to excess application. However, tail irrigators are observed to have higher water

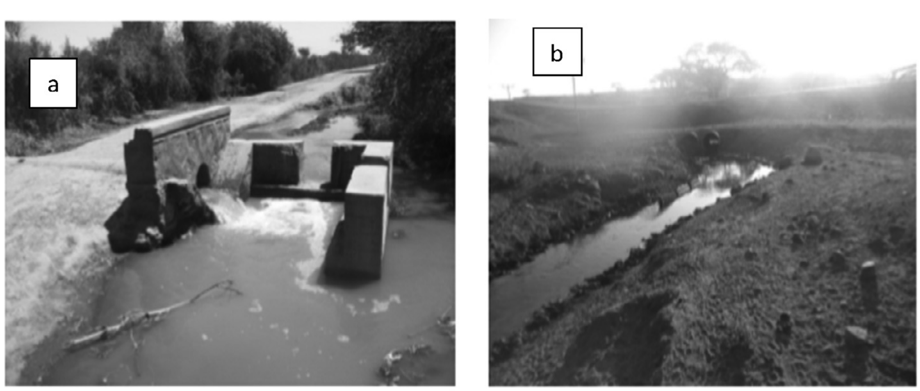

Fig. 1. Damaged water distribution structure in the head reach of Meki scheme (a), Earthen canal at Hare diversion scheme with no flow control structures (b) Adopted from Haileselassie et al. (2016).

Fig. 2. Overtopping of the main canal at Haleku Melka-Tesso Irrigation project adopted from Lencha (2008).

Table 5
Major sources of water and irrigation topology based on Awulachew et al. (2007).

Source of water	Typology of Irrigation			
	RWH	SSI	MSI	LSI
Rainwater	✓	✓(spate)	✓(spate)	
River diversion or pumping		✓	✓	✓
Groundwater	✓	✓	✓(multiple wells)	
Micro and small dams		✓	✓	
Large Dams				✓

Table 6
Reasons for water shortage by farmer's perception Adopted from Banchiamlak (2006).

Reason for irrigation water shortage in the watershed	Number of respondents	percentage
Over application of water by some farmers	14	41%
Naturally available surface water in the dry season is small because of fewer efforts to capture runoff	11	32%
Un fair distribution of water resource over the watershed	7	21%
Low level of water harvesting	2	6%
Total	34	100%

productivity, although their total return is lower (Awulachew et al., 2010). The construction of some irrigation facilities is not made following the design and technical specifications. Compaction of canal bunds and night ponds is not carried out satisfactorily, and this would cause heavy water leakage.

In the Dodicha irrigation scheme, the WUA members are reluctant to take over the responsibility of operation and maintenance of the scheme due to the low quality of some of the facilities (OIDA, 2000). Shortage of water pump technologies, spare parts, and technical problems such as maintenance of motor pumps exists (Gebrehiwot, 2015). Seepage losses, leakages, and limited control; lack of specialized water measuring tools and equipment; inadequate capacity for data capture and management are common problems for the irrigation schemes in Ethiopia (Charles, 2018). Continued soil erosion is the cause of failure of infrastructure and flash floods. Silt-laden soils and debris are all consequences of environmental degradation and poor catchment management that cause severe scouring and damage to concrete river diversion structures (Awulachew et al., 2010; Carter and Danert, 2006) (Figs. 1 and 2, Tables 5 and 6).

2.5. Market and input problem

In Ethiopia, input supply in an organized form, through government or related sources, is often available only for a rain-fed season. Farm inputs, especially fertilizer, are scarce and relatively expensive during the irrigation season and there is poor access to markets for both inputs and outputs (Awulachew et al., 2005; Carter and Danert, 2006; MOWR, 2007). Shortage of seed supply, insufficient market information, and market networks, inadequate improved agricultural input market problem prohibits better crop production (Furi and GetachewBashargo, 2015, MOA, 2011, Gebrehiwot,2015).

2.6. Nature related challenges

The main agenda for better water management is planning and preparedness for the high level of variability in space and time of conditions that affect water-use efficiency. The temperature increase in the Tigray region is expected to increase the net irrigation water requirement by 14% and 25% respectively for onion and maize crops (Gebremedhin et al., 2018). Climate change impacts water balance, photosynthesis, and crop growth, directly by affecting the crop physiological processes or indirectly by affecting the different crop growth factors such as relative humidity, wind speed, soil temperature, and atmospheric evaporative demand

(Berhane, 2018). Climate change will be particularly detrimental to crop production in cropping systems and reduce soil evaporation. This means that zero or minimal tillage, early and vigorous crops, and keeping crops on the soil surface becomes necessary (Awulachew et al., 2005; Kedir, 2017). Higher temperatures and carbon dioxide levels are likely to change the wheat growth pattern by affecting soil water status and crop uptake. Consequently, the duration of the growth cycle will be shortened and phenological steps will change (Tadesse et al., 2016). Climate change will have major implications for water availability in the Awash basin. There is an increase in temperature and subsequent intensification of evapotranspiration causes low water use efficiency (Taye et al., 2018). There are no accurate forecasts that can help improve water management decisions and improve crop operations. Topographic constraints exist to promote irrigation schemes. The Meki river forms a deep v-shaped valley in the upstream reach and a steep-sided narrow gorge of 10–20 m in the alluvial plain, presenting a difficulty in the construction of a diversion structure both technically and economically (Etissa et al., 2014).

3. Potential opportunities for wue improvement

Improvement in water use efficiency is inevitable as pumping costs for irrigation water make the supply more expensive, and food demand increases.

3.1. The commitment of government and NGOs to support irrigation development

In Ethiopia, the growth and transformation plan I (GTP I) from 2010/11 to 2014/2015 stated smallholder irrigation expansion as a priority, and also emphasized community-based soil and water conservation practice for improving agricultural productivity (MoFED, 2010).

The growth and transformation plan II (2014/15–2019/20) was built on GTP I and is aiming to expand irrigation use in Ethiopia (AFDB, 2015). Furthermore, Ethiopia has progressively increased its agricultural sector budget over the years to promote agricultural development (MOA, 2011). Ethiopia's agricultural sector policy and investment framework 2010–2020s aims to include a sustainable increase of agricultural production with priority investments in irrigation development, an extension of workers and farmers' skills development, seed and fertilizer supply, soil fertility management and reducing land and water degradation (MOA, 2011). Donors and NGOs' activities are also in line with the development and improvement of SI, as donors are now funding projects that are supporting smallholder farmers in areas of irrigation, agricultural marketing, rural finance, agricultural research, infrastructure development, soil and water management, and farmers' organizations (Awulachew et al., 2005). There are opportunities for improving knowledge of policymakers, planners, and designers, contractors, and development agencies through education, training, dialogues, and participation (Awulachew et al., 2005).

To improve water conveyance efficiency, water allocation prioritization criteria and fair and transparent management systems can be established by having, technical, demand management and economic measures in mind (Cherre, 2006). Another opportunity is to extend credit facilities and bank loans for irrigation development projects to be executed by local community groups (Cherre, 2006). An opportunity to acquire qualified experts in various higher institutions would be to train the low-level expertise working in different sectors through education, experience sharing, providing technical support when needed, and the opportunity to integrate equality throughout the water development project, from beginning to end (MOWR, 2007).

3.2. Low-cost irrigation technologies and farmers motivation

To improve water use efficiency and reduce the risk of diffuse pollution caused by over-watering, the agricultural irrigation system can be improved. The potential merits of affordable micro-irrigation technologies, like low-pressure drip kits, treadle pumps, small diesel pumps, water conservation practices, small basins, pits and runoff based systems are increasingly recognized by the government and NGOs (Awulachew et al., 2005; Hagos et al., 2012; MOWR, 2007).

Low-cost drip irrigation kits enable the farmer to make use of limited amounts of water and fertilizer to grow high-value crops. It allows the precise application of small amounts of water directly to the root zone (MOWR, 2007). Pitcher irrigation is another indigenous low-cost irrigation system, which uses unglazed fire clay pots that have micropores and is molded by hand. Pitches have high potentials for backyard vegetables and flower production (MOWR, 2007). The tramp pump is cheap ($ 71) and easy to handle, which has made it the choice for most farmers in Tigray (Tadesse and Bheemalingeswara, 2010). Both physical and biological soil conservation is implemented by mobilizing the community for 20 working days per year without payment. Besides, to rehabilitate the environment, implantation of soil and water conservation was practiced through food for work program (Tadesse and Bheemalingeswara, 2010). A more recent trend is making the market work for poor farmers' purchases or loans taking Aeschliman (2002, cited in Awulachew et al., 2005). For treadle pumps, for example, different modes of market-dependent implementation have emerged, followed by different NGOs. Appropriate technology, which has sold over 38,000 pumps in Kenya and Tanzania, is now expanding to other African countries (Awulachew et al., 2005). Micro-irrigation technologies are well suited to the production condition of Ethiopia (Awulachew et al., 2005). Substantial improvements were observed in irrigation water savings and crop yield during conservation agriculture at Dangishata Ethiopia compared with farmers' practices for water application. Average irrigation water use in conservation agriculture was reduced by 18.4%, 45.6%, 19.5%, and 18% for garlic, onion, tomato, and cabbage, respectively. Irrigation water productivity was found to increase significantly under conservation agriculture when compared to conventional tillage (Assefa et al., 2019).

3.3. Role remote sensing for water use efficiency improvement

WUE in any area is achieved by making the timing and quantity of irrigation applications optimum. Since the conventional methods are expensive, time-consuming, and site-specific and cannot be easily automated, remote sensing can be applied for measurement, monitoring, and reporting of water use and management (Koech and Langat, 2018). New approaches are emerging using remotely sensed data to estimate the crop water status and hence irrigation scheduling. The first step uses satellite imagery, which has previously been used in many agricultural contexts, such as yield and irrigation area estimates. Remote sensing in Ethiopia helps irrigators know the ET rate and apply the right amount of water at the right time to ensure that the crop is not stressed. This improves production, especially during critical growth stages (Genanu et al., 2017). The development of scalable and cost-effective technologies (e.g., sensors) would improve water-use management by allowing for more precise 430monitoring of moisture content at high spatial resolution.

The application of the simple method and surface energy balance approach using remotely-sensed data were applied to Rift Valley Lakes for evapotranspiration estimation (Melesse et al., 2009; Ayenew, 2003). The surface energy balance and land surface analysis satellite application facility were used to estimate actual evapotranspiration and both methods were feasible to estimate AET (Gelassie, 2012). An estimate of actual evapotranspiration derived from remote sensing techniques has the potential to improve irrigation water use efficiency. The spatial average of actual ET estimated from remote sensing over the plain was smaller than the Penman-Monteith reference ET0 in relatively drier periods (Enku et al., 2011).

Remote sensing technique is a viable approach to monitor soil moisture on a large scale with better spatial and temporal resolution. Stepwise-Cluster Prediction Mode is an option for soil moisture prediction using remote sensing data, particularly for dealing with soil moisture estimation from multiple satellites. The nonlinear SCA approach can efficiently predict the volumetric residual soil moisture (Ayehu et al., 2019). Recently, there have been substantial improvements in knowledge about the tolerance of crops to water deficit and about the ability of soils to supply water, which has led to the application of deficit irrigation.

Furthermore, advances have been made in understanding the soil–water–plant economy, firstly by the integration of this knowledge into simulation models, secondly by the improvement of sensor techniques for monitoring soil and plant water. Optical and thermal remote sensing has recently been proposed and tested to estimate soil moisture at a resolution high enough to serve applications, such as semi or fully distributed hydrological models, by correlating NDVI and land surface temperature retrieved from remote sensing to ground measured soil moisture (Mekonnen, 2009). The triangle method can simulate soil moisture with better accuracy when a sufficient number of sample points are taken and where there is no large elevation difference (Mekonnen, 2009). Water-use efficiency can be improved through better soil management.

3.4. Simulation models

Simulation models are developing for soil water and its effect on crop growth. Principles about water dynamics in the soil–crop system have been encapsulated into simulation models that calculate changes in soil water and plant growth over time.

3.4.1. FAO CROPWAT model

CROPWAT model is used in any part of the country for estimating crop water demand and irrigation scheduling. CROPWAT model is used to estimate reference evapotranspiration (ETo) at Gambella-1107 in Melkassa agricultural research center, which is located in a semiarid climate zone in Ethiopia (Shenkut et al., 2013). To determine the optimal irrigation levels for tomato production, to assess the effect of limited water supply on its yield, and to estimate yield response to soil water at Melkassa agricultural research center, yield reduction was simulated by CROPWAT. Comparing with the actual yield reduction of field experimentation, model efficiency was found to be 94% (Etissa et al., 2016). The lowest values of reference evapotranspiration were observed for Akaki, followed by Debere Zeit, Alemtena, and Modjo (Desta et al., 2017) using CROPWAT**.** The crop water requirements results for the whole existing and potential irrigation development in the study area were 197844647.3 m^3 (Girma, 2015). Water demand of the major users of Holetta River and the irrigation requirement for major crops at Holetta catchment was calculated using a questionnaire survey, statistical methods, and CROPWAT model (Tibebe, 2015). In the Gurage zone, the crop water requirement of maize was determined using CROPWAT 8.0 window (Abirdew et al., 2018).

3.4.2. FAO AquaCrop model

FAO developed the AquaCrop model to simulate the effects of the aerial environment and soil water on plant processes (Steduto et al., 2009). The model calculates canopy cover, root distribution, stomata opening, the roots' ability to meet transpiration demand, and transpiration. AquaCrop model was calibrated and validated using field experimentation data in Arbaminch, south Ethiopia. The model performed well in stimulating the growth of aboveground biomass, grain yield, and canopy cover for most of the treatments. Due to the model is easy to use, requires fewer input data, and its sufficient degree of simulation accuracy make it a valuable tool for estimating crop productivity under deficit irrigation for improving the efficiency of water use in agriculture (Gebreselassie et al., 2015). Similarly, AquaCrop model was calibrated and validated to simulate the observed WUE, growth, and yield of potato (Gebremedhin et al., 2015), maize (Erkossa et al., 2011), teff (Tsegay et al., 2015; Yihun, 2015) in Ethiopia. It was able to accurately simulate the final dry tuber yield and thus, the model could be used for planning and predicting irrigation management purposes (Gebremedhin et al., 2015). The grain water productivity of maize was increased by 48% and 54%, respectively, with the near-optimal and non-limiting soil fertility conditions. Therefore, this has a huge implication for basin-scale water management planning for various purposes(Erkossa et al., 2011)**.** The model was able to simulate the observed canopy cover, soil water, biomass, and yield of teff satisfactorily (Haileselassie et al., 2016; Yihun, 2015). Water stress in the late season is the most limiting factor for the productivity of tef (Eragrostis tef (Zucc) Trotter) in Tigray, Ethiopia. Early sowing and one irrigation application late in the growing season, were evaluated with the AquaCrop model as management strategies to improve productivity (Tsegay et al., 2015).

4. Success stories

Yield improvement may be attributed to agronomic and management improvement and crop improvement. The result of the Gebreselassie et al. (2015) study indicated that a higher yield of maize crops was found in a treatment that was exposed to water deficits during the mid and maturity stages. Consequently, it saves irrigation water during these development stages. Teff straw is cheap, suitable, and readily available for mulching and drip irrigation practice, which saves water by reducing evapotranspiration (Lakew et al., 2014).

A strategy of stressing maize by one-half at the beginning and end of the growing season, and using the water to irrigate a larger area, results in higher overall production than supplying optimum irrigation amount throughout the entire season for a smaller area (Yenesew and Tilahun, 2009). Applying 70–85% of ETc is recommended to improve both yield and water use efficiency of potato. As a result, farmers, water managers, water–user association, and decision-makers should give more emphasis on the demonstration and popularization of deficit irrigation to improve irrigated agriculture productivity and expand the irrigable area using the available water resources (Gebremariam et al., 2018). In Ethiopia, starting from 2014, about 960 varieties were recommended or released for major crops cereals (wheat, barley, teff, maize, and sorghum), legumes (haricot bean, chickpea, lentil, and faba bean), oilseeds, industrial (cotton), tuber and roots) and horticultural (vegetables, fruit trees, and aromatic spices, medicinal) crops which enables yield improvement in a water shortage situation (Atilaw et al., 2016).

5. Irrigation water use efficiency in African countries

The efficient use of Sub-Saharan Africa's water resources would substantially increase the production of food and export of high-value crops. Currently, as the impact of climate change threatens

Fig. 3. Improved tertiary and field canals Adopted from Charles (2018).

the livelihoods of farmers relying on rain-fed agriculture, an efficient and effective irrigation system is needed more than ever before. Yet past irrigation schemes have failed due to poor operation, lack of appropriate planning, patchy consultation, and lack of sufficient maintenance (Kadigi et al., 2012). The majority of the irrigation systems found in Somalia collapsed at the time of the civil war and the aftermath of El Nino Flood 1997/1998. The loss of the European preferential banana market in 2001 also affected the existence of irrigation systems in the region (Gadain and WMugo, 2009). Most of the small irrigation schemes with canal committees and water use associations exist in the schemes, but there are no clear patterns of water allocation right and appropriate fees (Omuto et al., 2009). If the farmer in Somalia implements technologies that deliver water directly to the root zone, as a drip irrigation system, savings in irrigation water will significantly reduce water stress in all the other sectors in the area (Hassan, 2015). In Uganda, the WUE is low which ranged from 32% to 46% as a result of poor fertilizer usage, inappropriate irrigation schedule, post-harvest loss, and inadequate mobility of extension workers within irrigation schemes.

Prevalence of pest and disease, passive water user association, and lack of market also contribute to low water use efficiency in the country (Charles, 2018). For improving water use efficiency, infrastructure improvement by tertiary canals was lined to reduce seepage losses and to confine flow. Within the turnout for improved control field canals were reconstructed, and bed levels raised to allow easy flow manipulation and diversion to furrows (Charles, 2018) (Fig. 3).

In Tanzania, approaches used for supplying water for the irrigated crops have not been improved; consequently, water use efficiency in most irrigation schemes is very low (Kimaro, 2019). A complex land tenure system, the weak institutional linkage between donors and farmers, and climatic factors influence the water use efficiency in the country (Kimaro, 2019). Irrigation technologies were developed by the Agricultural Research and Extension Authority (AREA) in Egypt to improve irrigation water management at the field level and to calculate the water requirements for certain crops and irrigation planning. But, these technologies are limited and cover only parts of the agro-ecological zones (Hamdan et al., 2006). Although there was a high effort with extension workers, the adoption rate of such interventions by the farmer is very low. In Tanzania, strip-tillage increased water use efficiency by 2% compared with hand hoeing, while disc tillage increased it by 14% compared with hand hoeing tillage (Magaia, 2017). The irrigation water use efficiency is generally low in Ethiopia compared to other African countries.

6. Conclusion and recommendations

This review paper has discussed the role of irrigation, its status, the major constraints associated with water use efficiency improvement, and available promising opportunities. The irrigation potential of the country is high; however, it has not been utilized to significantly improve the farmers' agricultural productivity and food security. Despite many rural farmers in various regions have been practicing traditional irrigation schemes for a long time, they could not surpass the traditional subsistence farming. This has been attributed to various reasons and challenges associated with the irrigation schemes. Examining those constraints and planning to solve accordingly is one of the ways that the government and NGOs could address to develop this arena. From this critical review, different constraints hinder to improve the water use efficiency of irrigation schemes in Ethiopia. First, crop diseases appeared in different parts of the country affecting crop yields at different levels. Since the economical background of most farmers is poor there is a need to supply adequate budget from government and partners for the design and contractions of modern schemes and buying necessary appurtenances. Above all, the marketing system of rural farmers also needs substantial attention. Developing markets and road infrastructures are required to improve farmers' access to markets. To reduce the dissatisfactions related to the cost and maintenance expenses of modern irrigation technologies, there are needs to search for additional options like encouraging private sectors to engage in the sale of spare parts and after-sale services, especially in water lifting technology. Similarly, it is necessary to improve the capacity of farmers, development agents, and extension workers to operate, maintain, and manage irrigation structures. A clear organizational setup is required to improve the functionality of small-scale irrigation schemes and consequently increase WUE. The Government of Ethiopia must build strong and relevant institutional arrangements that can easily cascade downwards to improve coordination between institutions involved in irrigation development and to establish clear duties and responsibilities for various organs in the irrigation sector. Great emphasis has to be given on constructing databases for irrigation schemes at the district level. Finally, the government's commitment to irrigation development, availability, and affordability for irrigation technology and the development of remote sensing, together with the proper use of various sensors and qualitative models, should be improved to improve water use efficiency.

Conflict of interest

The authors do not have any conflict of interest.

References

Abirdew, S., Mamo, G., Mengesha, M., 2018. Determination of crop water requirements for maize in Abshege Woreda, Gurage Zone, Ethiopia. J. Earth Sci. Clim. Change 9 (1). https://doi.org/10.4172/2157-7617.1000439.

Abshiro, F.K., Singh, P., 2018. Evaluation of irrigation scheduling for sprinkler irrigation system under existing condition in Beles Sugar Development Project, Ethiopia. Irrig. Drainage Syst. Eng. 7 (1). https://doi.org/10.4172/2168-9768.1000208.

AFDB. (2015). African Development Bank Group Annual Report 2015. Retrieved from Côte d'Ivoire:

Amede, T., 2015. Technical and institutional attributes constraining the performance of small-scale irrigation in Ethiopia. Water Resour. Rural Dev. 6, 78–91.

Annandale, J., Stirzaker, R., Single, A., Laan, M.v.D., Laker, M., 2011. Irrigation scheduling research: South African experiences and prospects. Water SA 37 (5).

Aregawi, M.H., 2014. The Impact of Small-Scale Irrigation on Rural household Food Security (The case of Emba Alaje woreda) (master). Mekelle University.

Assefa, T., Jha, M., Reyes, M., Tilahun, S., Worqlul, A.W., 2019. Experimental Evaluation of Conservation Agriculture with Drip Irrigation for Water Productivity in Sub-Saharan Africa. Water 11 (530). https://doi.org/10.3390/w11030530.

Atilaw, A., Alemu, D., Bishaw, Z., Kifle, T., Kaske, K., 2016. Early generation seed production and supply in Ethiopia: Status, challenges, and opportunities. Ethiop. J. Agric. Sci. 27 (1), 99119.

Awulachew, S., Ayana, M., 2011. performance of irrigation: an assessment at different scales in Ethiopia. Explor. Agric. 47 (51), 57–69. https://doi.org/10.1017/S0014479710000955.

Awulachew, S., Erkossa, T., Namara, R.E. (2010). Irrigation potential in Ethiopia: Constraints and opportunities for enhancing the system Retrieved from:

Awulachew, S., Yilma, A.D., Loulseged, M., Loiskandl, W., Ayana, M., Alamirew, T. (2007). water Resources and Irrigation Development in Ethiopia. Retrieved from Colombo, Sri Lanka.

Awulachew, S.B., Merrey, D.J., Kamara, A.B., Koppen, B.V., Vries, F.P.d., Boelee, E. (2005). Experiences and Opportunities for Promoting Small-Scale/Micro Irrigation and Rainwater Harvesting for Food Security in Ethiopia. from Colombo, Sri Lanka.

Ayehu, G., Tadesse, T., Gessesse, B., Yigrem, Y., 2019. Soil moisture monitoring using remote sensing data and a stepwise-cluster prediction model: The Case of Upper Blue Nile Basin, Ethiopia. Remote Sensing 11 (125). https://doi.org/10.3390/rs11020125.

Ayele, G.K., 2011. The Impact of Selected Small-Scale Irrigation Schemes on Household Income and the Likelihood of Poverty in THE Lake Tana Basin Of Ethiopia. Cornell University.

Bank, W. (2006). Managing Water Resources to Maximize Sustainable Growth in Ethiopia. Washington DC.

Berehanu, B., 2007. Impact of Industries and Urbanization on Water Resources in the Mojo River Catchment the degree of Master. Addis Ababa University Ethiopia.

Berhane, A., 2018. Climate change and variability impacts on agricultural productivity and food security. J. Climatol. Weather Forecasting 6 (3). ISSN:2332-2594.

Carter, R., Danert, K. (2006). FARM-Africa Ethiopia: Planning for Small-Scale Irrigation Intervention Retrieved from London WC1A 2EA:

Charles, M., 2018. Identified Factors Preventing Farmers and Scheme Management from Increasing Their Water Use Efficiency in Africa: Results of Applied Methodologies in Uganda. Paper presented at the ICID Conference Saskatoon, Canada.

Cherre, S. (2006). Irrigation Policies, Strategies, and Institutional Support Conditions in Ethiopia. Paper presented at the best practices and technology for small scale agricultural water management in Ethiopia, Addis Ababa, Ethiopia.

CSA. (2007). The 2007 Population and Housing Census of Ethiopia.

Dejene, S., Teshome, W., Makombe, G., Bekele, S., Prasad, K. (2008). Institutions, Management Practices and Challenges of Small-Scale Irrigation Systems in Ethiopia: A Case Study of Two Modern Smallholders Irrigation Systems in Western Oromia.

Demelash, N., 2011. Deficit Irrigation Scheduling For Potato Production in North Gondar Zone, Ethiopia. Haramaya University. M.Sc. thesis (Master science).

Derib, S.D., Descheemaeker, K., Haileslassie, A., Amede, T., 2011. Irrigation water productivity as affected by water management in a small-scale irrigation scheme in the Blue Nile basin, Ethiopia. Exp. Agric. 7 (51), 39–55. https://doi.org/10.1017/S0014479710000839.

Desta, F.Y., Abera, K., Eshetu, M., Koech, R., Alemu, M., 2017. Irrigation water planning for crops in the central highlands of Ethiopia, aided by FAO CROP WAT MODEL. Afr. J. Agric. Res. 12 (28), 2329–2335. https://doi.org/10.5897/AJAR2016.11659.

Eba, A.T., 2018. The impact of alternate furrow irrigation on water productivity and yield of potato at small scale irrigation, Ejere District, West Shoa, Ethiopia. J. Plant Sci. Agric. Res. 2 (16).

Endrie, B., 2017. Performance Evaluation of Irrigation Management Practice at Ambomesk Irrigation Unit in Koga Irrigation Scheme, Ethiopia (Master Of Science). Haramaya, Ethiopia.

Enku, T., Tol, C.V.D., Gieske, A.S.M., Rientjes, T.H.M., 2011. Evapotranspiration Modeling Using Remote Sensing and Empirical Models in the Fogera Floodplain, Ethiopia. Springer. DOI:10.1007/978-94-007-0689-7_8.

Erkossa, T., Awulachew, S.B., Aster, D., 2011. Soil fertility effect on water productivity of maize in the upper Blue Nile basin, Ethiopia. Agric. Sci. 2 (3), 238–247. https://doi.org/10.4236/as.2011.23032.

Etissa, E., Dechassa, N., Alamirew, T., Alemayehu, Y., Desalegne, L., 2014. Irrigation water management practices in smallholder vegetable crops production: the case of the Central Rift Valley of Ethiopia. Sci. Technol. Arts Res. Journal 3 (1), 74. https://doi.org/10.4314/star.v3i1.13.

Etissa, E., Dechassa, N., Alemayehu, Y., 2016. Estimation of yield response (ky) and validation of cropwat for tomato under different irrigation regimes. Irrig. Drain. Syst. Eng. 5 (2). https://doi.org/10.4172/2168-9768.1000167.

Fanadzo, M., Chiduza, C., Mnkeni, P.N.S., 2010. Overview of smallholder irrigation schemes in South Africa: Relationship between farmer crop management practices and performance review. Afr. J. Agric. Res. 5 (25), 3514–3523.

Furi, T., GetachewBashargo., 2015. Impact of small scale irrigation schemes on socio-economic condition of smallholder farmers – evidence from East Wollega Zone, Ethiopia. J. Econ. Sustain. Dev. 6 (23).

Gadain, H.M., WMugo, M. (2009). Report on UNICEF Water Interventions Mapping (2005 2009), Technical Report No W-19. Nairobi, Kenya.

Garbero, A., Songsermsawas, T. (2018). Impact of Modern Irrigation on Household Production and Welfare Outcomes 31 IFAD Research Series.

Gebrehiwot, N.T., 2015. Opportunities and challenges of small-scale irrigation and its implications for livelihood improvement: (The Case Of Tigray Regional State, Northern Ethiopia. J. Bus. Manage. Soc. Sci. Res. 4 (4).

Gebremariam, H.L., Welde, K., Kahsay, K.D., 2018. Optimizing yield and water use efficiency of furrow-irrigated potato under the different depth of irrigation water levels. Sustain. Water Resour. Manage. https://doi.org/10.1007/s40899-018-023.

Gebremedhin, A., Shiferaw, H., Zenebe, A., Gebresamuel, G., Habtu, S., Gebretsadkan, T., 2018. The impact of climate change on irrigation water requirement of maize and onion: the case of the gum-selasa smallscale irrigation scheme, Tigray, Ethiopia. J. Drylands 8 (1), 729–740.

Gebremedhin, B., Hoekstra, D., Tegegne, A. (2006). Commercialization of Ethiopian agriculture: extension service from input supplier to knowledge broker and facilitator Improving Productivity and Market Success of Ethiopian Farm. Retrieved from Nairobi.

Gebremedhin, Y., Berhe, A., Nebiyu, A., 2015. Performance of aquacrop model in simulating tuber yield of potato (Solanum tuberosum L.) under various water availability conditions in Mekelle Area, Northern Ethiopia. J. Nat. Sci. Res. 5 (5).

Gebreselassie, Y., Ayana, M., Tadesse, K., 2015. Field experimentation based simulation of yield response of maize crop under deficit irrigation using Aquacrop model Arbaminch, Ethiopia. Afr. J. Agric. Res. 10 (4).

Gelassie, T.Y., 2012. Remote Sensing Evapotranspiration Using GEONETCAST and In Situ Data Stram for Drought Monitoring and Early Warning in the Case of the Amhara Region Ethiopia (Master Science). Enschede, Netherlands.

Genanu, M., Alamirew, T., Senay, G., Gebremichael, M., 2017. Remote sensing based estimation of evapo-transpiration using selected algorithms: The Case of Wonji Shoa Sugar Cane Estate, Ethiopia. J. Environ. Earth Sci. 7 (1).

Geremew, E., Steyn, J., Annandale, J., 2007. Comparison between traditional and scientific irrigation scheduling practices for furrow irrigated potatoes (Solanum tuberosum L.) in Ethiopia. S. Afr. J. Plant Soil 25 (1), 42–48. https://doi.org/10.1080/02571862.2008.10639893.

Girma, H., 2015. Impact Assessment of Irrigation Water Use on Lake Ziway Water Level Degree of Master of Science. Addis Ababa University, Ethiopia.

Greenwood, D.J., Zhang, K., Hilton, H.W., Thompson, A.J., 2009. REVIEW: Opportunities for improving irrigation efficiency with quantitative models, soil water sensors, and wireless technology. J. Agric. Sci. 148, 1–16. https://doi.org/10.1017/S0021859609990487.

Hagos, E., 2005. Development and Management of Irrigated Lands In Tigray, Ethiopia the Degree of Doctor. Wageningen University, Delft, the Netherlands.

Hagos, F., Jayasinghe, G., Awulachew, S.B., Loulseged, M., Yilma, A.D., 2012. Agricultural water management and poverty in Ethiopia. Agric. Econ. 43. https://doi.org/10.1111/j.1574-0862.2012.00623.x.

Hagos, F., Makombe, G., Namara, R. E., & Awulachew, S. B. (2009). Importance of Irrigated Agriculture to the Ethiopian Economy: Capturing the direct net benefits of irrigation.

Haile, G.G., Kasa, A.K., 2015. Irrigation in Ethiopia: A review. Acad. J. Agric. Res. 3 (10), 264–269. https://doi.org/10.15413/ajar.2015.0141.

Haileselassie, H., Araya, A., Habtu, S., Meles, K.G., Gebru, G., Kisekka, I., Foster, A.J., 2016. Exploring optimal farm resources management strategy for Quncho-teff (Eragrostis tef (Zucc.) Trotter) using the AquaCrop model. Agric. Water Manag. 178, 148–158.

Haileslassie, A., Agide, Z., Erkossa, T., Hoekstra, D., Schmitter, P., Langa, S., 2016. On-Farm Smallholder Irrigation Performance in Ethiopia: From Water Use Efficiency to Equity and Sustainability *LIVES Working Paper 19*. International Livestock Research Institute (ILRI), Nairobi, Kenya.

Halsema, G.E.V., Lencha, B.K., Assefa, M., Hengsdijk, H., Wesseler, J., 2001. Performance assessment of smallholder irrigation in the central rift valley oF Ethiopia. Irrigation And Drainage. https://doi.org/10.1002/ird.613.

Hamdan, I., Oweis, T., Hamdallah, G. (2006). AARINENA Water uses efficiency network. Paper presented at the Expert Consultation Meeting, Aleppo, Syria.

Hassan, A. M. (2015). Surface Water Availability and Demand Analysis: Implication for Enhancing Water Resource Planning at Shabelle Basin in Southern Somalia. (MSc), Mekelle.

Kadigi, R. M. J., Tesfay, G., Bizoza, A., Zinabou, G. (2012). Irrigation and water use efficiency in Sub-Saharan Africa. Research Gate.

Kedir, U., 2017. The effect of climate change on yield and quality of wheat in Ethiopia: A review. J. Environ. Earth Sci. 7 (1).
Kimaro, J., 2019. A review on managing agroecosystems for improved water use efficiency in the face of changing climate in Tanzania. Adv. Meteorol.
Koech, R., Langat, P., 2018. Review improving irrigation water use efficiency: A review of advances, challenges, and opportunities in the Australian context. Water 10 (1771). https://doi.org/10.3390/w10121771.
Lakew, W.J., Anteneh, B.A., Ayalew, L.T., 2014. Yield and water use efficiency of mulched drip-irrigated onion in low land region of Amhara, North Central Ethiopia. Univ. J. Agric. Res. 2 (6), 203–210. https://doi.org/10.13189/ujar.2014.020604.
Lencha, B.K., 2008. Water Use Efficiency of Smallholder Irrigation in the Ethiopian Central Rift Valley The case of Haleku MelkaTesso irrigation project (Master of Science). Wageningen University, Netherlands.
Tesfaw, M., 2018. Small scale irrigation development. Irrig. Drain. Syst. Eng. 7 (1). https://doi.org/10.4172/2168-9768.1000206.
Magaia, E., 2017. Technologies for Improved Water Use Efficiency in Small-Scale Maize Production in a Semi-Arid Region Doctoral. Swedish University.
Makombe, G., Namara, R., Hagos, F., Awulachew, S.B., Ayana, M., Bossio, D. (2011). A Comparative Analysis of the Technical Efficiency of Rain-fed and Smallholder Irrigation in Ethiopia. Retrieved from Colombo, Sri Lanka:
Mekonnen, D.F. (2009). Satellite remote sensing for soil moisture estimation Gumara catchment, Ethiopia. (Master), ENSCHEDE, Netherlands.
Melesse, A.M., Abtew, W., Dessalegne, T., 2009. Evaporation estimation of Rift Valley Lakes: Comparison of models. Sensors 9, 9603–9615. https://doi.org/10.3390/s91209603.
Meta, K.M., 2014. The dearth of irrigation planning for potato production in North Gondar, Ethiopia. Int. J. Irrig. Water Manage. Vol.
Mintesinot, B., Verplancke, H., Ranst, E.V., Mitiku, H., 2004. Examining traditional irrigation methods, irrigation scheduling, and alternate furrows irrigation on vertisols in northern Ethiopia. Agric. Water Manage. 64, 17–27.
MOA, 2011. Small-Scale Irrigation Capacity-Building Strategy for Ethiopia. Addis Ababa.
MoFED, M. o. F. a. E. D. (2006). Ethiopia: Building on Progress A Plan for Accelerated and Sustained Development to End Poverty (PASDEP) (2005/06-2009/10). Addis Ababa.
MoFED, M. o. F. a. E. D. (2010). Growth and Transformation Plan (GTP) 2010/11-2014/15. Addis Ababa.
Mohammed, A. (2007). Environmental Analysis of a Hydrologic System: the Case of Tinishu Akaki River, Western Addis Ababa, Ethiopia. As Partial Fulfillment for the Degree of Master of Science in (Master Science), Ethiopia.
MOWR. (2002). Water Sector Development Program Main Report Volume I the Federal Democratic Republic of Ethiopia.
MOWR. (2007). Ethiopia: Agricultural Water Management Policy brief. Ethiopia.
Nile Basin Initiative, N. (2001). efficient water use for agricultural production project documents.
OIDA, O. I. d. A. (2000). Irrigation Sector Overview. Retrieved from Ethiopia:
Omuto, C.T., Vargas R.R., Alim, M.S., Ismail, A., Osman A., H.M, I. (2009). Technical Report L-14: Land Degradation Assessment and a Monitoring Framework in Somalia. Nairobi, Kenya.
Rockström, J., Barron, J., 2007. Water productivity in rainfed systems: an overview of challenges and analysis of opportunities in water scarcity prone savannahs. Irrig. Sci. 25, 299–311. https://doi.org/10.1007/s00271-007-0062-3.
Rooijen, D. V., Biggs, T., Smout, I., & Drechsel, P. (2009). Urban Growth, Wastewater Production, and Use in Irrigated Agriculture: A Comparative Study of Accra, Addis Ababa, and Hyderabad.
Schmitter, P., Haileslassie, A., Desalegn, Y., Chali, A., Langan, S., Barron, J. (2017). Improving on-farm water management by introducing wetting front detector tools to smallholder farms in Ethiopia. Retrieved from Nairobi, Kenya:
Shenkut, A., Tesfaye, K., Abegaz, F., Hordofa, T., 2013. Determination of water requirement and crop coefficient for sorghum (Sorghum bicolor L.) at Melkassa, Ethiopia. East Afr. J. Sci. 7 (1), 41–50.
Sinshaw, T.A., 2011. Understanding the Situation of Wastewater Irrigation in Community-Based Irrigation Schemes. The Case of Akaki catchment, Ethiopia Master Science. Wageningen University, Netherlands.
Steduto, P., Raes, D., Hsiao, T.C., Fcreres, E., 2009. AquaCrop—The FAO Crop Model To Simulate Yield Response To Water: I. Concepts and underlying principles. Agronomy 101 (3). https://doi.org/10.2134/agronj2008.0139s.
Ayenew, T., 2003. Evapotranspiration using thematic mapper spectral satellite data in the Ethiopian rift and adjacent highlands. J. Hydrol. 279, 83–93.
Tadesse, N., Bheemalingeswara, K., 2010. Prospects and constraints of household irrigation practices, Hayelom Watershed, Tigray, Northern Ethiopia. MEJS 2 (2), 87–109.
Tadesse, W., Solh, M., Brown, H.J., Bawm, M., Oweis, T., 2016. Approaches and Strategies for Sustainable Wheat Production. International Centre for Agricultural Research in the Dry Areas, Beirut, Lebanon.
Taye, M.T., Dyer, E., Hirpa, F.A., Charles, K., 2018. Climate change impact on water resources in the Awash Basin, Ethiopia. Water 10 (1560). https://doi.org/10.3390/w10111560.
Teklu, S. (n.d). Wastewater production, treatment, and agricultural use in Ethiopia: the case of Addis Ababa city Ethiopia.
Tesema, M., Schmitter, P., Nakawuka, P., Tilahun, S. A., Steenhuis, T., Langan, S. (2016). Evaluating irrigation technologies to improve crop and water productivity of onion in Dangishta watershed during the dry monsoon phase.
Tesfaye, A., Bogale, A., & Namara, R. E. (n.d). The Impact of Small Scale Irrigation on Household Food Security: The Case of Filtino and Godino Irrigation Schemes in Ada Liben District, East Shoa, Ethiopia.
Teshome, W., 2003. Irrigation Practice, State Intervention, and Farmers' World Life in Drought-Prone Tigray. Wageningen University, Ethiopia.
Tibebe, M., 2015. Water demand analysis and irrigation requirement for major crops at Holetta Catchment, Awash Subbasin, Ethiopia. *J. Nat. Sci. Res.* 5 (15).
Tilahun, H., Paulos, D. (2004). Results to date and plan of research on irrigation and its impact. Paper presented at the Workshop on the impact of irrigation on poverty and environment, Workshop proceedings.
Tilahun, H., Teklu, E., Michael, M., Fitsum, H., Awulachew, S.B., 2011. Comparative performance of irrigated and rainfed agriculture in Ethiopia. World Appl. Sci. J. 14 (2), 235–244.
Tsegay, A., Vanuytrecht, E., Abrha, B., Deckers, J., Gebrehiwot, K., Raes, D., 2015. Sowing and irrigation strategies for improving rainfed tef (Eragrostis tef (Zucc.) Trotter) production in the water-scarce Tigray region, Ethiopia. Agric. Water Manage. 150, 81–91.
Wehabrebi, A.A., 2014. *impact of small scale irrigation on household welfare: the case of laelay days irrigation scheme, Alamata District, Tigray*. (master of science in economics). Mekelle University.
Yenesew, Tilahun, M. (2009). yield and water use efficiency of deficit-irrigated maize in a semi-arid region Of Ethiopia AJFAND, 9(8).
Yihdego, T. G. (2016). Adoption and Impact of Micro Irrigation on Households Income: The case of Bambasi Woreda. Paper presented at the 8th Multi-Disciplinary Seminar, Asosa
Yihun, Y.M., 2015. Agricultural water productivity optimization for irrigated Teff (Eragrostis Tef) in water scarce semi-arid region of Ethiopia Degree of Doctor. Wageningen University, Delft, the Netherlands.
Yohannes, D.F., Ritsema, C.J., Eyasua, Y., Solomona, H., Dam, J.C.v., Froebrich, J., Meressa, A. (2019). A participatory and practical irrigation scheduling in semiarid areas: the case of the Gumselassa irrigation scheme in Northern Ethiopia. Agric. Water Manage. 218.

Further Reading

Muktar, B., Yigezu, T., 2016. Determination of optimal irrigation scheduling for maize (Zea mays) at Teppi, Southwest of Ethiopia. Int. J. Res. Innov. Earth Sci. 3 (5).
Renault, D., Wallenderb, W.W., 2000. Nutritional water productivity and diets. Agric. Water Manage. 45 (45), 275–296.