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ABSTRACT: In this study, we evaluated the present and future irrigation potential and irrigation water requirement (IWR) in Ethiopia's Abbay River Basin using the MIKE HYDRO River modeling software. Relative changes in IWR were determined and analyzed at six irrigation nodes for 19 crops and 23 traits. Four irrigation scenarios were compared: low, medium, full (FULL), and high growth (HIGH). Significant IWR changes were observed in FULL and HIGH irrigation scenarios, with highly intensive irrigation conditions resulting in high IWR. The MIKE HYDRO model was used to simulate the IWR historically for two scenarios: (1) scenario representing the current total irrigable cropland (79,800 ha) and (2) scenario projecting the basin's potential cropland (658,384 ha). As a result, the area under IWR analysis was 738,184 ha. The annual IWR was 9 billion cubic meters (BCM) and 18 BCM in FULL and HIGH irrigation scenarios, respectively. We found that uncertainties in crop migration, cropping patterns, and adaptation rates to climate change significantly affected irrigation and crop production. It is necessary to investigate the effects of HIGH irrigation on yield and economic benefits of FULL irrigation before adopting different irrigation development methods. Further research is required to adapt to changing climate for development of targeted IWR strategies.

KEYWORDS: Abbay River Basin, cropping pattern, irrigation crop, irrigation water requirement, MIKE HYDRO

TYPE: Original Research

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Background

Ethiopia has significant groundwater and surface-water resources. Although studies on groundwater are limited, the Ethiopian Ministry of Water, Irrigation, and Energy (MOWIE) estimated the annual groundwater flow in the country to be 40 billion cubic meters (BCM), and that of surface water to be 122 BCM (MOWIE, 2021). The groundwater potential of the African continent was estimated to be 100 times greater than its freshwater potential (MacDonald et al., 2012). Owing to its abundant surface-water resources, Ethiopia is called the water tower of Africa (Birkett et al., 1999; Hammond, 2013; Swain, 1997). Groundwater use for irrigation is limited in Ethiopia for various reasons, including financial, technological, and technical skill requirements (Awulachew & Ayana, 2011; Awulachew et al., 2010). Annual surface-water flows in Ethiopia are generated from 12 transboundary rivers that deliver water to the neighboring countries, with little left for use in irrigation development. Rugged mountain topography dominates the country's surface area, accounting for 99.7% of the total area, with water bodies covering barely the remaining 0.3%.

Agriculture has been the main driver of the Ethiopian economy, accounting for 40% of the economic value addition and approximately 45% of export earnings. It also serves as a source of income for 75% of the formal labor force (The World Bank, 2016). According to the World Bank, the number of people employed in the agricultural sector in Ethiopia increased from 19.9 million to 30.8 million between 1999 and 2013 (United States of America International Development [USAID], 2017). Ethiopia's agricultural sector is vulnerable to climate change, and the country periodically experiences severe droughts and famine. Therefore, the development of a sustainable and resilient domestic agricultural system could alleviate Ethiopia's future climate disasters.

The country is vulnerable to recurrent droughts and food shortages because of its dependence on rainwater for subsistence and agriculture. A total of 90% to 95% of the crops in the country are produced during the rainy season recording 70% to 90% of precipitation between June and September (Funk et al., 2003; Mario et al., 2010; Worqlul et al., 2017). Furthermore, rainfall is highly variable both spatially and temporally (Seleshi & Camberlin, 2006). Evidently, the challenge is that agricultural production is heavily reliant on the rainy season, which in turn is vulnerable to weather changes.

The population of Ethiopia increased from 22 million in 1960 to 112 million in 2019 (average annual growth rate of 2.5%) and reached 117 million in 2021, while it doubled twice in 1987, 2011, and 2021 from 44, 89, and 117 million, respectively. Approximately 56 million people belong to the working age group. Similarly, the Abbay River Basin has also seen a significant growth in population. In 2014, the total population of this region was approximately 28,590,000 (Abbay Basin Atlas, 2015) and it is estimated to reach 40,300,989 in 2030, accounting for approximately 32% of the country's total population, while the basin area represents only 20% of the country's total area.

By 2050, the global population and grain demand are estimated to increase by 50% compared to that at the beginning of the century (Alexandratos & Bruinsma, 2012; Valin et al., 2014). The availability of arable land is limited, and the most likely method to accommodate the anticipated grain demand based on population growth is to improve agricultural productivity through improved irrigation methods. This can provide long growing seasons by maintaining stable soil moisture levels and can increase cropland productivity. Higher yields can be achieved with agriculture supplemented by adequate irrigation and by maintaining stable soil moisture levels and long growing seasons, rather than depending on rain-fed agriculture (Khan et al., 2006; Mendelsohn & Dinar, 2003).

Irrigated croplands account for approximately 20% of the total global croplands, and 40% of crops are produced by irrigation, with 70% of the global freshwater sources utilized for irrigation (Siebert et al., 2005, 2010). Surface irrigation is the most widely adopted and oldest irrigation system, where the applied water infiltrates the surface soil. Furrow irrigation is used in 95% and 98% of global irrigated land (Zaman et al., 2018) and of Ethiopian land, respectively. Unlike global irrigated areas, Ethiopia's irrigated croplands represent less than 5% of the potential irrigations while irrigation water withdrawals in the Abbay River Basin are less than 1 BCM.

The Abbay River Basin provides opportunities for irrigation and hydroelectric generation in the country (Conway, 2000, 2005; Siam & Eltahir, 2017), despite the significant interannual precipitation variability with a variation coefficient of 9% (Yates & Strzepek, 1998). Interannual variability occurs because of various global, regional, and local factors, such as the El Nio Southern Oscillation, large-scale climate teleconnections, and topography (Block & Rajagopalan, 2007; Camberlin, 1997; Conway, 2000; Diro et al., 2009; Gissila et al., 2004; Korecha & Barnston, 2007; Segele & Lamb, 2005; Segele et al., 2009; Zhang et al., 2016).

Irrigation areas determine the socio-economic and environmental effects in the region, the intensity of the required irrigation methods, and agricultural production per unit area (Boserup, 1965). The size of the irrigated area and adopted operations such as intensive irrigation affect crop yields and the application of irrigation water (Dillon, 2011; Puy et al., 2017; Wisser et al., 2008). Irrigation affects the duration, intensity, and frequency of precipitation in areas adjacent to the irrigated land, particularly when irrigation occurs in the direction of the wind (Alter et al., 2015; Cook et al., 2011). The amount and frequency of irrigation water withdrawals affects the sustainability of water resources (de Graaf et al., 2019). Although Ethiopia's population is rapidly increasing and the country is facing food shortages, its current irrigation potential is less than 5%. Hence, expansion of cropland and development of irrigation methods is crucial (Shen et al., 2008; Shiklomanov & Rodda, 2003). Global irrigated land expanded at a rate of 2.6%, from 95 million ha in 1940 to 250 to 280 million ha in the early 1990s (FAO, 2016, 2017; Salmon et al., 2015; Siebert et al., 2013; Thenkabail et al., 2009; Meier et al., 2018). These studies suggest that, in addition to climate change, a significant increase in irrigated land and competitive uses of water among various sectors would impact the availability of water (Meier et al., 2018; Siebert et al., 2013). Some studies have determined the impact of irrigation on climate change at both global and local scales. Landmass-atmospheric interactions are significant because they play an essential role in energy and mass transfer, particularly sensible and latent heat transfer (Jimenez et al., 2014). Additionally, increased anthropogenic activities, such as deforestation, land degradation, and urbanization have already altered soil properties and land surface coverage (Bagley et al., 2014). However, the role of irrigation in the modeling of regional climate systems remains unclear.

Previous studies investigating the impact of irrigation on hydrometeorology and climate systems (Barnston & Schickedanz, 1984; Harding & Snyder, 2012; Leng et al., 2013) have confirmed that the local impacts of irrigation are related to evapotranspiration (ET) and temperature (Boucher et al., 2004; Gordon et al., 2005; Kueppers et al., 2007; Lobell et al., 2008). However, the causes of climate change are complex and the influence of these factors may not be thoroughly explained by soil moisture (Kawase et al., 2008), evapotranspiration (Kanamitsu & Mo, 2003; Lo & Famiglietti, 2013), and soil memory (Koster & Suarez, 2001; Seneviratne et al., 2006). Furthermore, some researchers state that irrigation increases precipitation (Gordon et al., 2005; Segal et al., 1998), while others state that it decreases precipitation by deflecting sensible heat and preventing convection formation (Ek & Holtslag, 2004; Lohar & Pal, 1995). Advantages of expanding irrigation to downwind areas are indicated in previous studies. The increase in precipitation in leeward areas of irrigation contributes to moisture transpiration, cloud formation, and boundary layer evolution (Puma & Cook, 2010; Wei et al., 2013).

Although studies have suggested that warmer temperatures may shorten growing seasons of crops, their actual impact on the future crop growing seasons is not yet evident (Wang et al., 2013; Zhang et al., 2013). Furthermore, it has been reported that altering the cultivar in crops could prolong the growing seasons (Liu et al., 2009; Sacks & Kucharik, 2011). Therefore, climate change may influence irrigation water requirements (IWR) by changing the precipitation rate and duration, temperature, crop evapotranspiration rate, and by affecting planting and growing times (Evans & Sadler, 2008).

IWR has been extensively studied using simple (Döll & Siebert, 2002; Fischer et al., 2007; Shen et al., 2013; Xu et al., 2019) and complex analysis methods (Elliott et al., 2014; Konzmann et al., 2013), since it is a valuable parameter for understanding the water quantity required to ensure optimal crop growth and productivity. The IWR analysis uses crop evapotranspiration rate and precipitation data, both historical (Döll & Siebert, 2002; Shen et al., 2013; Wriedt et al., 2009) and predictive (Fischer et al., 2007; Shahid, 2011; Xu et al., 2019).

Since water requirement is minimal during crop seeding stage, owing to the low temperature and loss of soil water through evaporation, crops become less sensitive to water availability. However, the use of water increases during crop growth stages as the leaves of the crops grow and temperature increases.

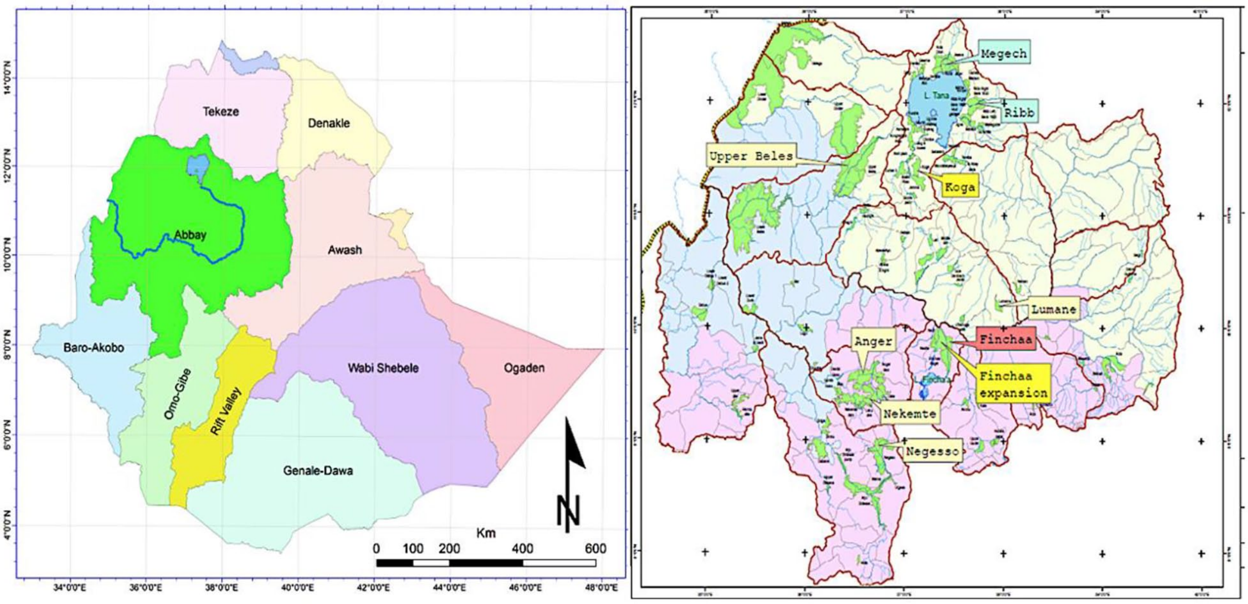

Figure 1. Irrigation nodes in the Abbay River Basin.
Source. Abbay Master Plan.

Water demand increases during crop growth and reproductive stages; hence, crop sensitivity to water availability also increases. Studies conducted on wheat in China and India, and on onions in Mexico confirmed these scenarios (Al-Jamal et al., 2000; Li, 1990; Singh, 1981; Zhang & Oweis, 1999; Zhang et al., 1999).

Higher irrigation efficiency has been established as a tool for water conservation by researchers and endorsed by policy-makers, including the United Nations High-Level Panel on Water. However, high irrigation efficiency may also lead to increased consumption of irrigation water (United Nations [UN], 2018). Non-beneficial water losses that occur through transpiration from weeds, evaporation from wet soil, open water sources, and foliage increase water consumption and total IWR. Furthermore, with the higher irrigation efficiency scheme, a decrease in return flow was observed with the total application of 30% and 5% irrigation water through surface and drip irrigation, respectively (Grafton et al., 2018).

The purpose of this study was to evaluate the available irrigable croplands and investigate the future crop IWR in selected irrigation nodes in the Abbay River Basin. In this region, a baseline climate scenario of 1.5°C was used for projection scenarios for 2040. The Paris Agreement aims to maintain current global warming at an average surface temperature of 2°C and reduce the temperature increase to 1.5°C by 2,100. Therefore, the impact of 1.5°C and 2°C global warming on water resources calls for immediate attention (Shi et al., 2018; Tobin et al., 2018).

The Shared Socioeconomic Pathway 2, the Middle of the Road scenario, in which large population growth affects climate change mitigation and adaptation, combined with Representative Concentration Pathways of 6 (little or no mitigation) and 2.6 (high mitigation), is the model most likely to achieve the Paris Agreement goal of 1.5°C global warming by 2040 (Fricko et al., 2017; Shi et al., 2018). Ethiopia's mean annual temperature is estimated to increase from 1.1°C to 3.1°C by 2070 (IPCC, 2014; McSweeney et al., 2010). In this context, all Ethiopian highlands are expected to get warm with slight increase in the temperature by 1°C (IPCC, 2014; Niang et al., 2014).

Thus, this study aims to estimate the IWR in different scenarios to contribute to the existing knowledge of the IWR and water balance scenarios in the Abbay River Basin based on forecasted climate outcomes. The irrigation system in the Abbay River Basin has received limited attention compared to hydro-electric development. Therefore, this study does not focus on the MIKE HYDRO model calibration process, but instead emphasizes the modeling results to encourage Ethiopian water resource policymakers to prioritize irrigation development. Under the condition of a 1.5°C global warming limit, the Abbay River Basin IWRs through 2040 were simulated using historical baseline between 1955 and 2014. This model presents a comprehensive basin-wide water demand and availability framework for integrated water resource management. Our study may focus on the Abbay River Basin in Ethiopia, but the applied analysis approach and the development of IWRs under different irrigation development scenarios could be applicable for similar future research.

Materials and Methods

Study area

The Abbay River Basin, located in northwest Ethiopia between 7°030′N and 12°051″N latitude and 34°025′E and 39°049″E longitude, is the largest basin in the country. The basin occupies an area of 200,000 km^2 and accounts for 20% of the country's land area. The basin experiences considerably high interannual rainfall variability. In the lowlands, the annual rainfall ranges from 1,400 to 1,800 mm, with a minimum of 1,000 mm, whereas the mean annual rainfall in the highlands is approximately 1,420 mm, with a maximum of 2,200 mm. Approximately 85% of the annual precipitation occurs during summer, between July and October (Awulachew et al., 2007; Awulachew et al., 2005).

The maximum and minimum temperatures in the basin very between 28°C and 38°C and 15°C and 20°C, respectively. In the heads of the basin, the temperature range is 12°C to 20°C, with minimum values of −1°C and 8°C. The annual potential evapotranspiration in the basin ranges between 1,056 and 2,232 mm. Abbay River Basin has high potential for irrigation and hydropower, and the areas with potential for irrigation in various catchments of the river basin are shown in Figure 1.

Methods

Various water allocation instruments are available for different catchment areas, including CaWAT (Cai et al., 2014), CWAM (Wang et al., 2008), MIWA (Dai & Li, 2013), and REALM (George et al., 2008). However, the complexity and longer processing time of these models hinder their applicability and suitability for large river basins, such as the Abbay River Basin. However, the MIKE HYDRO model provides an alternative solution. Its advanced combined simulation of temporal and spatial variability with low processing time makes MIKE HYDRO suitable for larger basins. It is a wide-ranging physics-based deterministic modeling tool. MIKE HYDRO integrates modular hydrology and hydrodynamics with basic computational modules to simulate water supply, demand, flow, crop growth, and soil moisture.

The MIKE HYDRO map layer includes catchments and rivers, the tabular layer includes data requirements and parameters, and the resulting layer contains simulation results. Furthermore, MIKE HYDRO comprises modules for crop irrigation, climate variability, soil moisture, channel flow, overland flow, and the interaction between groundwater and surface-water flows.

In this study, IWR was estimated using the MIKE HYDRO modeling package following the approaches specified in FAO-56 (Allen et al., 1998). The estimated crop water requirements were then revised to account for losses in the water conveyance, distribution, and field-level water application systems. The published values of irrigation efficiency were used to estimate these losses. Leaching was not considered because most irrigation systems use surface irrigation, and the total irrigation water applied was assumed to offset the leaching requirements.

The IWR was calibrated using data collected from the Nile Basin Initiative (NBI) and the Ethiopian government. The crop water requirement was calculated using the FAO Penman-Monteith equation with a combined function of radiation, vapor pressure, temperature, and wind speed (DHI, 2014; Hatfield, 1990). The method is recognized as the global standard for daily evapotranspiration estimations, as described in the Irrigation and Drainage Paper 56 by the FAO. This is supported by the theoretical background and estimation of variables commonly included in the Penman-Monteith equation. The analysis of the Abbay River Basin catchment discharges was simulated under a 1.5°C climate scenario. The MIKE HYDRO model simulates the irrigation water demands for different crops at different irrigation nodes along the river system. We assumed that sufficient surface water in the Abbay River Basin would meet the irrigation water demands. The irrigation water supply must meet the total water requirements, including crop water requirements, applications, and transport losses (FAO, 2020).

In estimating irrigation water withdrawals, the necessary irrigation start and stop times and the irrigation method to be applied were also considered. The estimated irrigation differed for different irrigation nodes in the basin. The most intensive irrigated areas were located in irrigation group 6, and the efficiency of total irrigation was 50% (Table 1).

Cropping pattern

Cropping patterns for Ethiopia were obtained from the Cooperative Regional Assessment Documents of the Eastern Nile Irrigation and Drainage Study (ENTRO-IDS, 2009), supplemented by data from the Baro-Akobo-Sobat and Tekeze Master Plans of Ethiopia (BCEOM [French Engineering Consultants], 1998; BCEOM-BRGM-ISL, 1997, 1998; NEDECO, 1997, 1998) (Table 1).

Cropped and equipped area

The cropped areas varied depending on the portion of irrigation-equipped areas covered by crops in a particular year and whether more than one crop was planted. The cropped areas represent values obtained from various sources along with data obtained from NBI and Ethiopia's Abbay Basin Development Authority. Equipped area refers to the physical area that is cultivated without considering multiple cultivations within the same year. Part of the equipped area is not regularly irrigated for various reasons, or the equipped area is sometimes cultivated more than once a year (Figure 2).

Return flow

The return flow fraction represents the proportion of water applied to irrigation fields that returns to the water source, that is, rivers. The return flow fraction depends on the type of irrigation method used and the availability of a drainage system

Table 1. Irrigation Nodes in the Abbay River Basin.

INDEX	NODE	AREA (HA)	CROPPING ROUND	EFFICIENCY (%)	EXISTING (HA)	PLANNED (HA)
Group 1						
1	Abbay_at_Kessie	58,141	1	50	21,500	36,641
2	Gilgel Abbay	17,244	1	50		17,244
3	Koga	14,500	1	50	7,000	7,500
4	Middle Birr	4,670	1	50		4,670
5	Lake Tana	104,551	1	50	15,000	89,551
6	Tis Abbay	44,660	1	50	21,500	23,160
Group 2						
7	Lower Beles	85,000	2	50		85,000
8	Lower Dinder	50,000	2	50		50,000
9	Rahad	55,000	2	50		55,000
10	Upper Dinder	16,600	2	50		16,600
Group 3						
11	Amerti-Neshe	11,870	3	50	7,200	4,670
12	Fincha	7,600	3	50	7,600	0
13	Upper Beles	53,720	3	50		53,720
Group 4						
14	Anger	35,106	4	50		35,106
15	Lower Dabus	15,400	4	50		15,400
16	Lower Didessa	31,671	4	50		31,671
17	Lower Guder	21,015	4	50		21,015
18	Shegoli	10,604	4	50		10,604
19	Upper Dabus	4,081	4	50		4,081
20	Upper Didessa	45,138	4	50		45,138
Group 5						
21	Muger	7,444	5	50		7,444
22	Upper Guder	9,819	5	50		9,819
Group 6						
23	Beko Abo	14,549	7	50		14,549
24	Karadobe	6,120	7	50		6,120
25	Mendaya	13,681	7	50		13,681
	Total				79,800	658,384.00

that channels excess water from the irrigated fields back to the river. Among the three irrigation methods, drip irrigation resulted in almost no return flow, whereas the surface gravity method resulted in some return flow. In the current version of the baseline model, the return flow fraction is assumed to be zero and should be explored further in future studies.

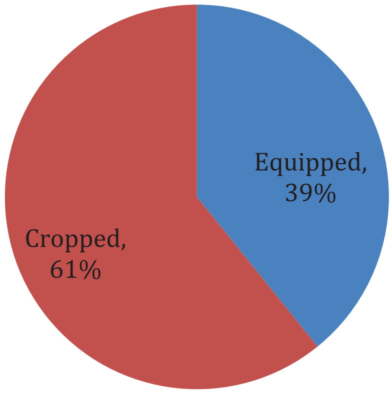

Figure 2. Equipped versus cropped irrigation areas.

Materials

Data on irrigated areas in the Nile Basin were obtained from various reports and studies conducted by NBI (Bart et al., 2011; NBI-NELSAP, 2012; Nile Basin Initiative Eastern Nile Technical Regional Office [NBI-ENTRO], 2009, 2014; Nile Basin Initiative Water Resource Planning Management [NBI-WRPM]., 2013) and previous publications, such as FAO Aquatat (FAO, 2017). For the simulation period of 1955 to 2014, the flow volumes estimated and observed by the model of the Abbay River Basin were similar, with a difference of approximately 0.54%.

The NBI data were used to refine the baseline data used in this study. A calibrated Nile model was used to estimate the water supply (availability), demand, and actual use for irrigation. In this study, four irrigation scenarios and their respective irrigation water demands were developed and evaluated. The irrigation areas were (a) low development, (b) medium development, (c) full development (FULL), and (d) high-growth irrigation (HIGH) development scenarios. Low irrigation development refers to low level of irrigation development without intensification. Medium development indicates irrigation intensified to some degree. Full irrigation development refers to all irrigation nodes that are fully equipped and operated at full capacity. Finally, high growth irrigation development refers to the highest level of irrigation efficacy and intensification, along with dense irrigated areas that receive increased irrigation.

The irrigation nodes considered in this study were divided into six categories, and 19 crops and 23 traits with different cropping patterns were selected. A crop pattern was identified for irrigation node 1, two crop patterns for irrigation node 2, three crop patterns for irrigation node 3, four crop patterns for irrigation node 4, five crop patterns for irrigation node 5, and seven crop patterns for irrigation node 6. Table 2 provides a complete list of crops grown in the irrigation categories.

The total identified irrigation area was 738,184 ha, with future irrigation accounting for 658,384 ha, and current irrigation accounting for 79,800 ha. The areas under irrigation nodes 1 to 6 were 243 and 766, 206 and 600, 73 and 190, 163 and 15, 17 and 263, and 34 and 350 ha, respectively (Figures 3 and 4).

Results and Discussion

After categorizing the four scenarios for irrigation development, the areas of current and future irrigation potentials of the basins were evaluated using the MIKE HYDRO model (Figure 4) to identify the distributions of crops and percentages of irrigated areas in the basin (Figure 5).

The water supply distribution for each irrigation node is shown in Figure 6. High irrigation water supply was distributed during lean seasons, and the IWR decreased during wet seasons for all the irrigation nodes. The annual value of the irrigation water supply was 9,617.96 BCM under FULL, while it was 18,274.12 BCM under HIGH, doubling the water requirement.

The crop water requirement refers to the actual withdrawal of water from the river system to supply water to irrigation fields, taking into account canal leakages as distribution system losses. The losses were modeled using conveyance and field application efficiency factors, which considered the percentage of water loss during the delivery and field application. The efficiency values depended on the irrigation technologies used in each country and the dominant soil types.

Water requirement was estimated by considering the existing irrigation water consumption rate, duration, and level of irrigation technologies in the basin. Irrigation schemes were estimated to be consistent with existing irrigation practices in terms of irrigation rate and duration. This ensured that the water requirements of the existing and estimated irrigated areas matched well. However, further investigation is required regarding the water cycles in the Abbay River Basin.

Most of the irrigation water demand was found to occur during lean seasons between November and June, with a minimum to no IWR between July and October, in all six irrigation nodes. This pattern corresponds to the rainy seasons of the Ethiopian highlands in the Blue Nile Basin, thus, establishing the temporal variation in irrigation water demands and precipitation, emphasizing the importance of adequate storage facilities to mitigate water shortages (Figure 6).

Upon calculation of irrigation demands, the model then simulated the river system to allocate water to the various irrigation-demand nodes for the available water resources. The actual water used for irrigation depends not only on the demand but also on the water available from the sources connected to the demand nodes, reach of the river, and storage dams. Therefore, to allocate water to a particular irrigation-demand node, the model considers the temporal distribution of demand and loss in transmission and field application systems.

Table 2. Crops Grown in the Nile Basin and Their Cropping Patterns.

NO.	CROP	CROPPING PATTERN	IRRIGATION NODE	NO.	CROP	CROPPING PATTERN	IRRIGATION
1	Cotton wet	1	Node I	33	Fruit	4	Node IV
2	Fruit	1		34	Grapes	4	
3	Maize dry	1		35	Groundnut wet	4	
4	Maize wet	1		36	Fruit	5	Node V
5	Noug	1		37	Grapes	5	
6	Onion	1		38	Maize dry	5	
7	Potatoes	1		39	Maize wet	5	
8	Red pepper	1		40	Noug	5	
9	Sorghum	1		41	Onion	5	
10	Teff	1			Potatoes	5	
11	Sugar cane	1		42	Red pepper	5	
12	Sunflower dry	1		43	Sorghum	5	
13	Castor beans	2	Node II	44	Teff	5	
14	Cotton wet	2		45	Soybean	5	
15	Maize dry	2		36	Sugarcane	5	
16	Maize wet	2		47	Wheat wet	5	
17	Noug	2		48	Wheat dry	5	
18	Potatoes	2		49	Cotton wet	7	Node VI
19	Red pepper	2		50	Groundnut wet	7	
20	Sorghum	2		51	Groundnut dry	7	
21	Teff	2		52	Maize dry	7	
22	Soybean dry	2		53	Maize wet	7	
23	Sugarcane	2		54	Onion	7	
24	Sunflower dry	2		55	Potatoes	7	
25	Tobacco	2		56	Red pepper	7	
26	Groundnut wet	3	Node III	57	Sorghum	7	
27	Maize dry	3		58	Teff	7	
28	Maize wet	3		59	Sugar cane	7	
29	Noug	3		60	Sunflower dry	7	
30	Red pepper	3		61	Sunflower wet	7	
31	Sudan grass	3					
32	Sugarcane	3					

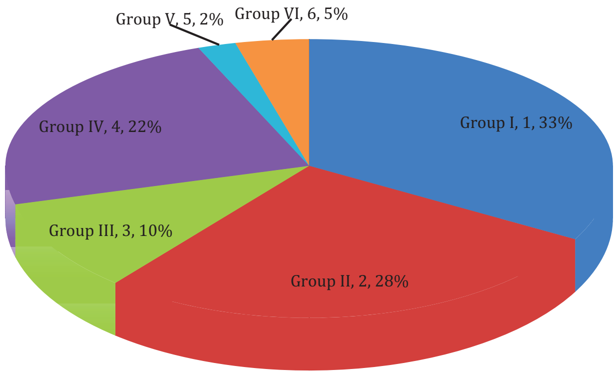

Figure 3. Total irrigation area by sub-basins.

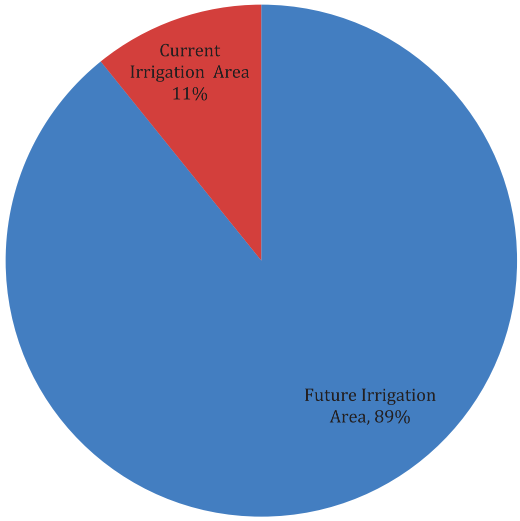

Figure 4. Total irrigation area by current and future.

Subsequently, the demand for irrigation water in the Abbay River Basin was investigated under the four development scenarios. The corresponding irrigation water demands for each irrigation development scenario, as shown in Table 3, were: 2,404.49 BCM/year for low; 4,808.98 BCM/year for medium; 9,617.96 BCM/year for FULL; and 18,274.12 BCM/year for HIGH.

Furthermore, related studies conducted on irrigation efficiency in Rajasthan, India (Birkenholtz, 2017); Snake River, Idaho (McVeigh & Wyllie, 2018); Maha Illuppallama, Sri Lanka; Chiredzi, Zimbabwe; and Souss, Morocco; and Tensift Basins, Morocco (Molle & Tanouti, 2017) exhibited that efficient irrigation uses more water. For example, in Rajasthan, India, drip irrigation has expanded the irrigated area; however, it requires higher water volume (Birkenholtz, 2017). Similarly, in the Snake River, although the irrigation efficiency was improved and rainfall increased, the volume of the Snake Plain aquifer was reduced (McVeigh & Wyllie, 2018). The improved drip irrigation scheme in the Souss and Tensift Basins in Morocco resulted in over-exploitation of aquifers due to intensified crop growth (Molle & Tanouti, 2017). Overall, an increase in irrigated area, denser plantation, planting of crops with high water use, and low return flow can often be associated with the increase in IWR under the HIGH irrigation development scenario.

The IWR under full irrigation development was 9 BCM with acceptable irrigation efficiency; however, it was doubled to 18 BCM under the HIGH scenario. As discussed in the previous studies (Perry, 2017; Xu et al., 2019), HIGH irrigation in the Abbay River Basin consumes higher volume of water than the actual requirement (Figure 7). Therefore, irrigation in the Abbay River Basin must undergo complete development. These results could be significant for policymakers in developing water resource management strategies and irrigation development plans. In this study, uncertainties in the estimated IWR could arise from the datasets used as inputs, as well as from simplified models and assumptions. Although MIKE HYDRO NAM was used to conceptualize the estimations, and biases were eliminated, there was still some uncertainty in future interannual variability estimations (Abatzoglou & Brown, 2012) (Figure 7).

The irrigation efficiency of total water withdrawals considers the water loss when it travels through canals and crop fields (Brouwer et al., 1989). Considering losses during conveyance, on field, and through evaporation, the total withdrawals were higher than the net IWR. Thus, the irrigation efficiency represents the ratio of gross IWR to net IWR. It determines the amount of water available for crop use compared to the water withdrawn from the source (Brouwer et al., 1989; Döll & Siebert, 2002; Wisser et al., 2008). In this study, in the FULL scenario, the crop water requirement is 4,773.5 BCM, the application losses are 2,046.1 BCM, the cannel losses are 2,798.4 BCM, and the water supply is 9,618.0 BCM (Table 3). The irrigation water requirement for the selected irrigation nodes under the FULL scenario is shown in Table 4. Evidently, conveyance losses were higher than application losses, indicating space for water conservation by improving the irrigation infrastructure. However, conveyance loss could continue under HIGH scenarios and contribute to a high IWR, among other factors. The water losses determined in this study were compatible with a furrow irrigation efficiency of 50%. This percentage refers to the actual water required for evapotranspiration and the amount of water necessary for crop growth subtracted by the effective rainfall. The model uses the precipitation time series provided in the soil-water calculations to solve the soil column water balance. The amount of rainwater that cannot be stored in the soil surface layer, which is called surplus water, is removed from the field as excess surface runoff. This excess surface runoff does not contribute to the water available to crops and is assumed to be lost from the system. Therefore, effective precipitation is the amount of precipitation that contributes to the soil water balance. The crop water demand was estimated using the FAO approach (FAO 56); this value also considers the contribution of rainfall (ie, adequate rainfall).

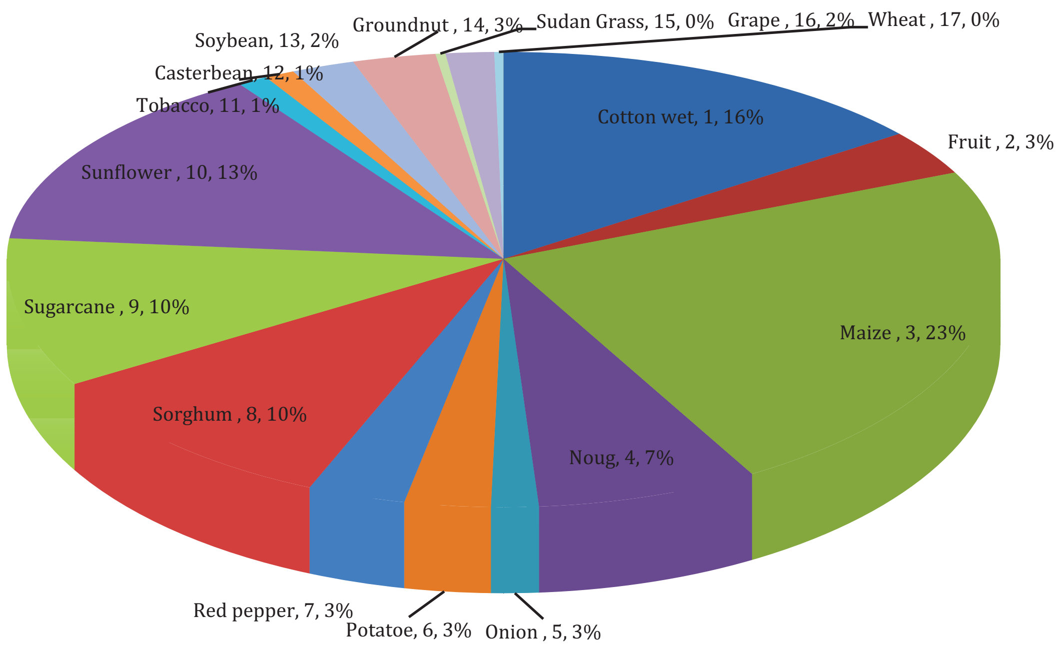

Figure 5. Crop distributions.

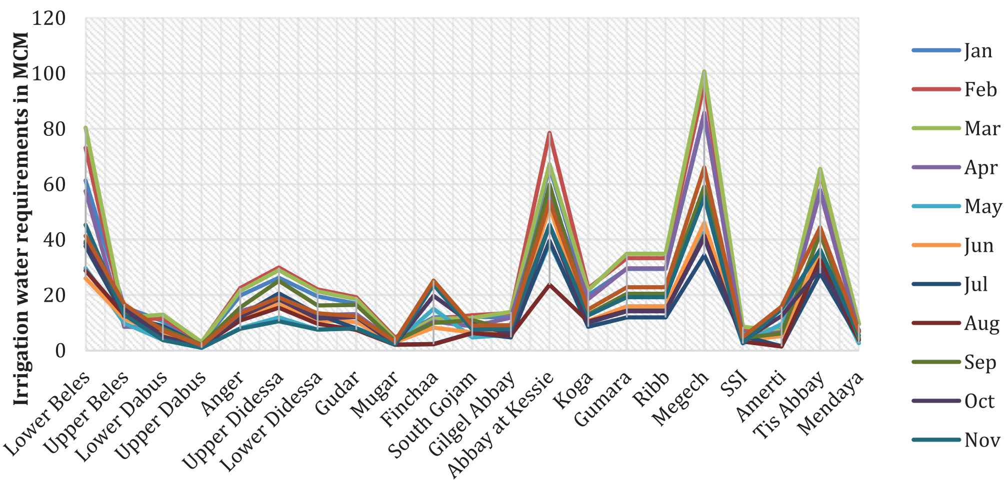

Figure 6. Monthly irrigation water requirements per irrigation node (unit: MCM/month).

After taking into account the considerable fluctuations of interannual rainfall in the river basin, it could be concluded that the irrigable areas were suitable for sustainable irrigation on an annual timescale. Seasonal water variability or higher water demand during lean seasons would be offset by annual water availability using water storage. Thus, the increased irrigation water demand during dry seasons of *Bega (winter)* could be offset by the wet seasons of *Kiremt (summer)* by using water from wet seasons as supplementary water for dry seasons through water storage. Therefore, conflicting irrigation demand and precipitation periods could reduce the monthly water flow of the basin during high irrigation times due to a lack of water storage rather than water shortage.

In the Abbay River Basin, seasonal and interannual variability is estimated to increase owing to climate change. As a result, Ethiopia might lose nearly 1 million ha of cropland without irrigation water storage, which could save more water than the annual irrigation water withdrawals. Water storage will be beneficial for a sustainable irrigation system, to overcome the monthly utilization deficit and for enhanced production. However, these water-transport mechanisms would require financial support to develop the necessary infrastructure and higher-capacity warehouses.

If there was no expansion of irrigation or change in cropping patterns in the basin, the withdrawal of irrigation water estimated under the four development scenarios would not interfere with the minimum water flow required to maintain the environmental system of the river basin. Furthermore, if Ethiopia could expand sustainable irrigation areas in the Abbay River Basin to 2.5 million ha under FULL irrigation development, while maintaining the current crop distribution, there would be less than 50% utilization of the annual flow of the

Table 3. Irrigation Water Requirement Under the Different Irrigation Development Scenarios (Unit: Million Cubic Meters (MCM)/Year).

SL. NO.	IRRIGATION SCHEME	LOW (MCM)	MEDIUM (MCM)	FULL (MCM)	HIGH GROWTH (MCM)
1	Lower Beles	285.22	570.44	1,140.88	2,167.67
2	Upper Beles	77.96	155.91	311.82	592.46
3	Lower Dabus	47.10	94.21	188.42	357.99
4	Upper Dabus	11.44	22.89	45.78	86.98
5	Anger	86.48	172.97	345.93	657.28
6	Upper Didessa	122.96	245.92	491.84	934.49
7	Lower Didessa	84.28	168.55	337.10	640.50
8	Gudar	76.52	153.04	306.08	581.56
9	Mugar	18.73	37.45	74.91	142.32
10	Finchaa	58.03	116.06	232.11	441.01
11	S_Gojam	53.93	107.86	215.71	409.85
12	Gilgel Abbay	52.52	105.04	210.09	399.16
13	Abbay_at_Kessie	319.72	639.44	1,278.89	2,429.89
14	Koga	87.80	175.60	351.19	667.26
15	Gumara	132.92	265.85	531.69	1,010.22
16	Ribb	132.92	265.85	531.69	1,010.22
17	Megech	384.15	768.30	1,536.61	2,919.55
18	Small scales	29.80	59.60	119.20	226.49
19	Amerti	36.53	73.06	146.13	277.64
20	Tis Abbay	268.08	536.15	1,072.31	2,037.38
21	Mendaya	37.40	74.79	149.58	284.20
	Total (BCM)	2,404.49	4,808.98	9,618.0	18,274.12

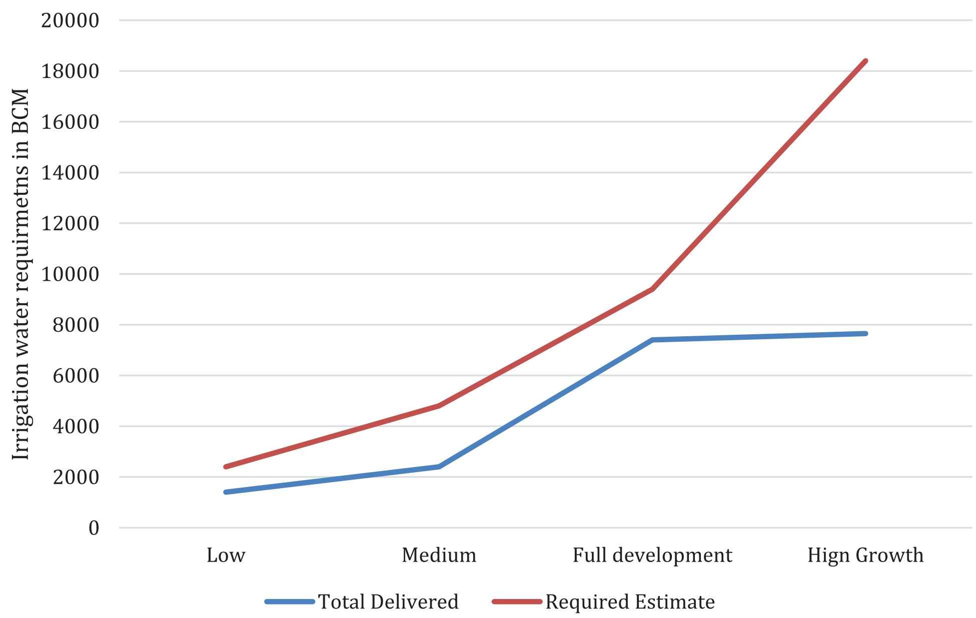

Figure 7. Irrigation water allocations (unit: BCM/year).

Table 4. Irrigation Water Requirement Under FULL Scenario (Unit: MCM/Year).

SL. NO.	IRRIGATION NODES	CROP WATER REQUIREMENT	APPLICATION LOSS	CONVEYANCE LOSS	SUPPLY REQUIREMENT
1	Lower Beles	559.0	239.6	342.3	1,140.9
2	Upper Beles	152.8	65.5	93.5	311.8
3	Lower Dabus	92.3	39.6	56.5	188.4
4	Upper Dabus	22.4	9.6	13.7	45.8
5	Anger	169.5	72.6	103.8	345.9
6	Upper Didessa	241.0	103.3	147.6	491.8
7	Lower Didessa	165.2	70.8	101.1	337.1
8	Gudar	150.0	64.3	91.8	306.1
9	Mugar	36.7	15.7	22.5	74.9
10	Finchaa	151.1	64.8	16.2	232.1
11	S_Gojam	105.7	45.3	64.7	215.7
12	Gilgel Abbay	102.9	44.1	63.0	210.1
13	Abbay_at_Kessie	626.7	268.6	383.7	1,278.9
14	Koga	172.1	73.8	105.4	351.2
15	Gumara	260.5	111.7	159.5	531.7
16	Ribb	260.5	111.7	159.5	531.7
17	Megech	752.9	322.7	461.0	1,536.6
18	Small scales	58.4	25.0	35.8	119.2
19	Amerti	95.1	40.8	10.2	146.1
20	Tis Abbay	525.4	225.2	321.7	1,072.3
21	Mendaya	73.3	31.4	44.9	149.6
				Total	9,618.0

Abbay River, which would be 27 BCM of the annual water flow of 56 BCM.

In this study, it was assumed that the current crop distribution in the basin would remain unchanged through 2040 to 2050. However, socio-economic and human climate adaptation factors can complicate the cropping systems in the basin. In such cases, cropping patterns or crops grown in the basin can be changed by referring to the list of crops identified in the present study. Further, crops can be planted earlier or later according to human adaptations to climate (Sacks & Kucharik, 2011), and the crop can be migrated from one location to another (Cho & McCarl, 2017). Therefore, future studies focusing on crop migration, changes in crop types and planting seasons, and people's adaptation activities are necessary in the Abbay River Basin.

Conclusions

This study examined the current and future irrigation potential and IWR of four irrigation development scenarios in the Abbay River Basin, assuming a baseline of 1.5°C global warming scenario, using MIKE HYDRO model. This study is the first to report the total IWR for the Abbay River Basin and considers the intensity, irrigated crops, cropping patterns, irrigation efficiencies, and available mapped irrigation areas in the selected catchments. The uncertainties of the input data were corrected by examining the available data and using the concepts and parameters of the model to generate information related to incomplete and uncertain data. Therefore, the results provide a scientific basis for decisions on irrigation development plans that consider water conservation under climate change forecasts.

IWR under the HIGH irrigation development plan was significantly higher than that under the FULL irrigation development plan, suggesting more attention be given to these plans by water resource planners and managers. Our results demonstrated the relationship between irrigation development and IWR, and included a simulation of the optimal irrigation development pattern and IWR under the FULL scenario.

Furthermore, it is estimated that the Abbay River Basin experienced high rainfall variability. Approximately 85% of the precipitation occurs in summers, between July and October, whereas the highest IWR demand occurs in dry seasons. This situation requires water transportation from the wet seasons to dry seasons, through water storage, to achieve a sustainable irrigation system in the basin. With the existing cropping pattern and estimated irrigation areas under the FULL irrigation development scenario, Ethiopia could irrigate approximately 2.5 million ha with less than 50% of the annual flow of the Abbay River. These data imply that the nation might foster a climate-resilient and profitable agricultural system while reducing anthropogenic deforestation and land degradation. For example, from 2003 to 2015, Ethiopia expanded its cropland by 5 million ha through deforestation and land degradation. This is a high-risk situation in which forests and grasslands are turned into croplands. Such a production scenario is the prime reason of anthropogenic emissions as well as ecosystem degradation. Therefore, suitable investment and infrastructure is required for the expansion of irrigation.

Irrigation plays a vital part in Ethiopia's food supply and offers room for improvement, since only around 5% of the country's irrigation capacity is presently used. This study provides a potential baseline for determining the IWR, future irrigation area, cropping patterns, and irrigation efficiency, considering the expansion of irrigation with population growth and the reduction of rain-fed agriculture. It is critical to develop crop cultivation systems that require less water and are water efficient, especially given the longer time scale of adaptation to climate change when agricultural productivity must increase with restricted water supply. Therefore, given the uncertainty of future climate change, the IWR can vary depending on the average dry or wet conditions of the basin within a given period. It is important to consider both the gross water withdrawal and net water consumption under different climatic conditions, along with an expanded irrigation area in future studies.

The interaction between climate and irrigation is an important factor in estimating the IWR. Globally, studies have shown that irrigation lowers the temperature in the given area and increases the occurrence of precipitation. Therefore, precipitation decreases with decrease in availability of water. This warrants a reduction in streamflow requiring harmonization of the development of water resources between government agencies and riparian states. However, even if rainfall does not decrease, the general sustainability of irrigation is uncertain; as the demand for irrigation is rapidly increasing, investigating the potential for the use of groundwater in irrigation is imperative.

Finally, irrigation efficiency and the level of water withdrawal are constantly changing, and they differ by the types of crops grown, climatic conditions, and seasons. Therefore, to incentivize irrigators to conserve water, it is critical to study the basin's water valuation and pricing methods. Additionally, for a resilient irrigation development plan, water resource planners must examine and limit irrigation water withdrawal to assure regional water security. Future studies should be conducted to investigate the effect of climate change on crop growth pattern, growth time, and migration to determine the future IWR in basin areas.

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