Journal of
Water & Climate Change

 Journal of Water and Climate Change Vol 14 No 2, 559 doi: 10.2166/wcc.2023.400

Green, blue and economic water productivity: a water footprint perspective from the Upper Awash Basin, Central Ethiopia

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ABSTRACT

The rise in global freshwater consumption, inefficient water use and population growth are the main drivers of water scarcity and food insecurity. This study analyzed the green, blue and economic water productivity (GWP, BWP and EWP, respectively) of the rainfed (*teff*, maize and sorghum) and irrigated (sugarcane) crops along with green water scarcity (GWS) in the Upper Awash Basin using water footprints (WFs) approaches. *Teff* has the lowest average GWP (~0.3 kg/m^3) and the highest average WF (4205 m^3/ton) between 2000 and 2010 with an average EWP of ~0.3 USD/m^3 which is higher than those of other rainfed cereal crops (maize and sorghum). The highest GWS of maize was recorded in Metehara (269 mm/growing period) and the lowest in Debrezeit (70 mm/growing period) with an intermediate value of 90 and 117 mm in Wonji and Melkassa, respectively. All the rainfed crops have lower EWP (less than 0.3 USD/m^3) compared with the irrigated sugarcane in the basin. This study demonstrates that increasing the value per unit of green/blue water through increasing yield per unit of supply and switching from high to low WFs crops has significant implications for addressing the water scarcity problem by setting a WP benchmark in the basin.

Key words: Awash Basin, freshwater consumption, green water scarcity, green-blue-economic water productivity, water footprint

HIGHLIGHTS

- Green, blue and economic water productivity (WP) of crops was examined.
- Eastern Upper Awash Basin depicted more green water scarcity than the western parts.
- *Teff* has the lowest green WP compared with maize and sorghum.
- Rainfed crops have lower economic WP than irrigated sugarcane.
- This water footprint approach in quantifying WP can be used to establish the WP benchmarks in similar water-stressed basins in the world.

1. INTRODUCTION

Earth's freshwater resources face tremendous pressure due to anthropogenic activities, particularly from the agricultural sector which accounts for 70% of freshwater uses (Molden *et al.* 2010; Fader *et al.* 2011). Future prediction of freshwater use in agriculture shows that it will increase to 5,600 km^3/year in 2050 without water productivity (WP) gains. This amounts to three times the consumption of water for irrigation use throughout the globe during the 2000s (Rockström & Barron 2007).

An increase in the consumption of water for various purposes also contributes to freshwater scarcity, forcing one-third of the global population to live in water-scarce areas (Dessu *et al.* 2014; Khan *et al.* 2021). In addition, rapid population growth, climate change and environmental pollution heavily impacted the availability of freshwater (Hanjra & Qureshi 2010; Steffen *et al.* 2015). Sub-Saharan African (SSA) countries are characterized as food-insecure regions and more than 95% of the available green water (soil moisture reserve exclusively from precipitation) is used by rainfed agriculture (Rockström *et al.* 2007, 2009a, 2009b; Hadebe *et al.* 2017; Hirpa *et al.* 2022). These countries have high blue and green water resource potential but require enormous water infrastructural development and management to meet the ever-growing water demands for various purposes (Schuol *et al.* 2008; Rockström *et al.* 2009a, 2009b). Furthermore, this region where Ethiopia is located will face economic water scarcity by the year 2025 (Barker *et al.* 1999). This economic water scarcity has been experienced earlier than the predicted period by Barker *et al.* (1999) in many of the densely populated river basins in Ethiopia, such as the Awash River Basin (Adeba *et al.* 2015).

The water footprint (WF), water sustainability and WP concepts are used to investigate water and food security (Xu *et al.* 2019; Adetoro *et al.* 2021). The implementation and application of these concepts are rising and produce significant outcomes in developed countries compared with developing countries (Adetoro *et al.* 2021). WF is defined as the volume of freshwater consumed and polluted to make a certain product (Hoekstra 2003; Mekonnen & Hoekstra 2011a). This concept is used to enhance the WP and sustainability of water use within the watershed (Lovarelli *et al.* 2016; Hoekstra 2017; Adetoro *et al.* 2021) and it is a comprehensive approach considering the green water consumption and the analysis of water pollution in addition to quantification of the blue water consumption for water resource management (Hoekstra 2017). In addition, the WF perspective reflects the real demand and utilization of water resources and the consequence of human and societal dependence on water sources and the environment (Chenoweth *et al.* 2014; Hoekstra 2017; Xu *et al.* 2019).

The traditional WP methods do not distinguish between blue (surface and groundwater) and green water (a moisture reserve mainly from precipitation). However, the application of WF accounts for the blue, green and grey (the water required to assimilate the load of pollutants) components of water (Hoekstra *et al.* 2011; Shu *et al.* 2021; Hirpa *et al.* 2022). The WP concept is closely related to the WF principle and is defined as the ratio of the mass of agricultural output to the amount of water used (Molden *et al.* 2007; Chouchane *et al.* 2015). The physical WP is specifically expressed as either the blue water or total (green plus blue) water consumption for crop production or the amount of crop produced per unit of water used; and it is important for understanding the relationship between water consumption and food production (Zwart & Bastiaanssen 2004, 2007; Liu *et al.* 2007; Chukalla 2017). When water use is measured as green plus blue water consumption, physical water productivity (PWP in ton/m^3) is given as an inverse of the green plus blue WF (in m^3/ton) (Chukalla 2017). Furthermore, in order to define the economic benefits, the concept of 'economic water productivity (EWP)' has been introduced, which is the value of agricultural output derived per unit of water used (Molden *et al.* 2007; Garrido *et al.* 2010; Chouchane *et al.* 2015).

The water resources in the Upper Awash Basin experienced high competition by various users such as densely populated urban centers, floricultural and horticultural production near the peri-urban centers, intensive agricultural practice on the highlands of central Ethiopia, industrial zone expansions in the central parts of the basin and extensive agricultural practice in the Main Ethiopian Rift (MER) (Adane *et al.* 2020a, 2020b). All these consumptive uses, along with the rising population and concurrent demand for more food, put tremendous pressure on the already scarce water resources in the basin. The Awash Basin is considered a water deficit basin with 325 m^3 per person per year compared with the Baro Akobo (eastern Nile River Basin) with water availability of ~3,432 m^3 per person per year (Adeba *et al.* 2016). Furthermore, the annual average surface water demand exceeds the availability by 0.03 billion m^3 in the Awash Basin (Adeba *et al.* 2015). On the other hand, the green water requirement for food production in SSA will increase from 450 km^3/year in 2007 to 2,300 km^3/year in 2050 (Rockström & Barron 2007). Thus, to meet the future food demands in SSA, more blue and/or green water is required, which will exacerbate the already scarce water resources in the region, such as in the Awash Basin.

Estimating the green, blue and economic WP of the dominant crops in the basin from WFs perspective will provide a holistic view of the water resources usage. This will in turn provide insights on how to reduce blue water scarcity via improving the utilization of green water storage and blue water optimization. The current study uses various inputs of WFs from locally measured data sets (climate, soil types, yields, fertilizer applicant rate, onset of wet spells, end of wet spells, length of growing periods, etc.), which proved to be advantageous over similar analyses using globally averaged data (Hirpa *et al.* 2022). Similarly, Hirpa *et al.* (2022) quantified the WFs (green WFs, blue WFs and grey WFs) of rainfed crops (*teff*, maize and sorghum) in the Upper Awash Basin and the WFs estimates were generally comparable with the respective global WFs but significantly different from the national estimates of WFs made by Mekonnen & Hoekstra (2011a, 2011b, 2011c).

Most previous studies on SSA countries, including Ethiopia (Yihun *et al.* 2013; Hadebe *et al.* 2017; Edreira *et al.* 2018), have not specifically distinguished water consumption types in determining the WPs of agricultural products, except Rockström *et al.* (1999a) and Rockström & Barron (2007) which analyzed green WP for rainfed savannah farming using the evapotranspiration loss in m^3 per produced ton of grain.

In our current study, we quantified these separately and determined the green and blue WP. In addition, the study has been compared with and validated by the regional and global findings of WP of rainfed and irrigated crops. Furthermore, the green water scarcity (GWS), economic WP (EWP) of both green and blue as well as the blue water demand prices for rainfed crops have been analyzed.

The novelty of this study lies in the fact that (a) none of the previous research applies the WFs concepts considering green and blue WFs components to quantify different variables of WP (GWP, BWP and EWP). Besides, this study considers both the rainfed and irrigated crops in the basin; (b) only Rockström & Barron (2007) attempted to analyze the GWP for rainfed systems in developing countries but these concepts are neglected and do not provide much emphasis on the potential of green water (moisture reserve exclusively from precipitation) where 95% of it is used for rainfed agriculture, particularly in SSA countries; (c) unlike other previous studies in SSA, this study integrates the WF, WP and the GWS concepts; and (d) this study indicates there is room for improving the potential GWP and thus reducing the pressure on blue water resources for irrigation purpose in the water scarce Awash Basin. Thus, the quantification of GWP and BWP and the economic benefits from the agricultural products (EWP) from the WFs perspective provide new insights for improved water management strategies in a similar set of other developing countries across the globe. Furthermore, this study will contribute to set a benchmark for identifying the WP gaps and formulating a means to reduce the water consumption per unit crop produced. In addition, the results can serve as input in formulating a strategic policy for water resource development and management in the Awash River Basin.

2. METHODOLOGY

2.1. Study area

The Upper Awash Basin is located in central Ethiopia, straddling the Northwestern Ethiopian highlands to the NW, the MER and the Southeastern Ethiopian highlands to the SE (Hirpa *et al.* 2022; Figure 1). The seasonal rainfall distribution in the basin is influenced by the Inter-Tropical Convergence Zone (ITCZ) (Getahun & Haj 2015). The annual rainfall averages in Debreziet, Wonji, Melkassa and Metehara stations are 889, 830, 768 and 610 mm, respectively. The mean temperature in the basin ranges between 18 and 25 °C (Adane *et al.* 2020a).

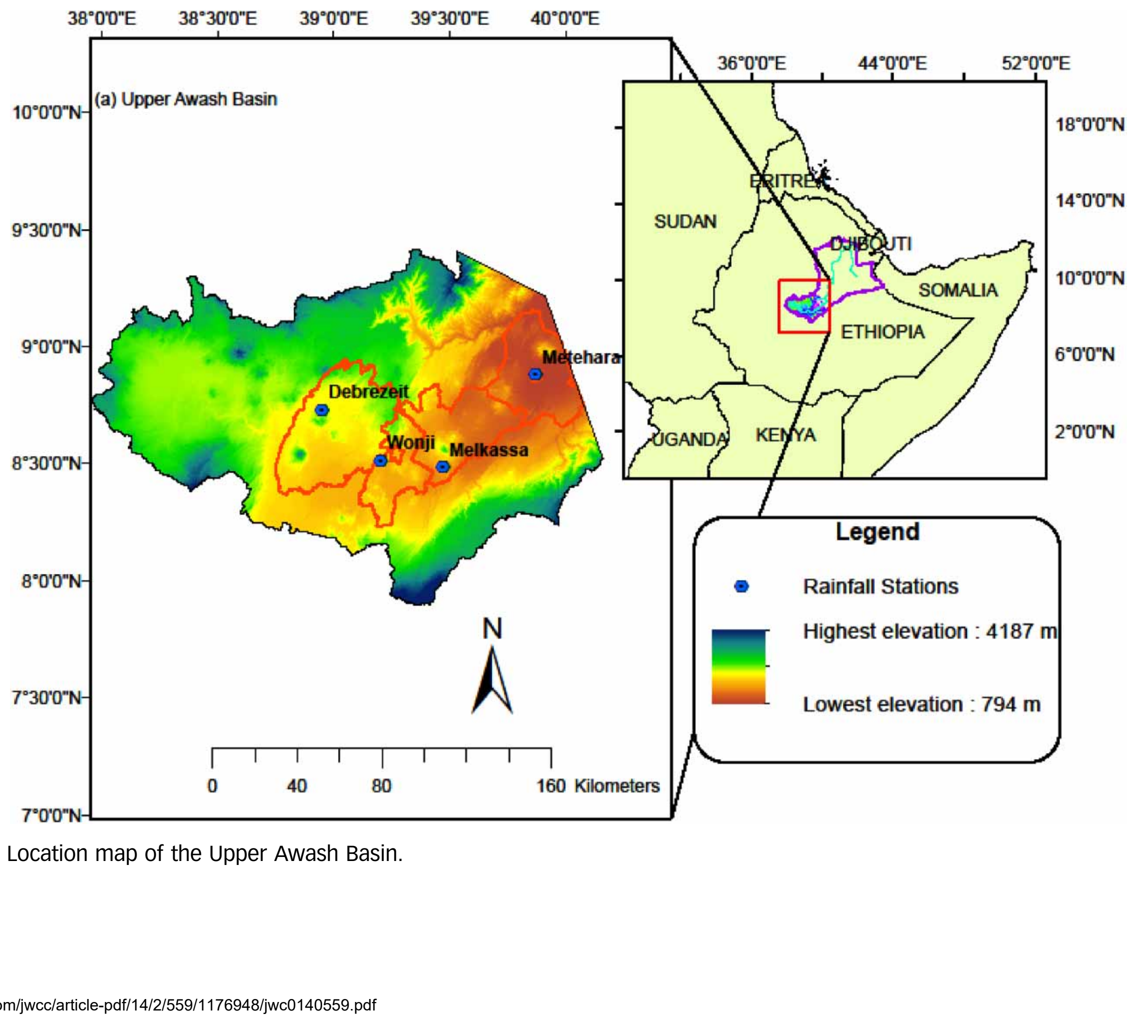

Figure 1 | Location map of the Upper Awash Basin.

Small-, medium- and large-scale irrigation schemes are actively engaged in agricultural activities in the basin using seasonal rainfall and/or irrigation mainly diverting from the Awash River. Rainfed crops such as *teff*, maize and sorghum grow widely in the basin. Besides, extensively irrigated sugarcane which covers more than 22,000 ha is currently cultivated by the Wonji and Metehara sugar estate farms. In addition, some vegetables and horticultural products are also cultivated in the basin. This study mainly focused on the Debreziet (for *teff* and maize), Wonji (for sugarcane and maize), Melkassa (for maize and sorghum), and Metehara (for maize and sugarcane) areas.

2.2. Data sources

Data sources are summarized in Table 1. Climate data for the period 2000–2010 were collected from the National Meteorological Agency, while soil data has been collected from Agricultural Research centers in the basin and the Ethiopian Sugar Development Corporation. Results on wet spell length, length of growing periods and WFs are from our previous works in the basin (Adane *et al.* 2020b; Hirpa *et al.* 2022). Crop yield data is from the Ethiopian Central Statistical Agency. Crop values are from FAO and water prices in Ethiopia are from the Ethiopian Ministry of Water and Energy. The spatial and temporal data for Debrezeit, Wonji, Melkassa and Metehara areas are indicated in Table 1.

3. METHODS

The study uses the value of WFs for rainfed (green WF) and irrigated (green and blue WFs) from Hirpa *et al.* (2022). Here, we only use the consumptive green and blue water use excluding the assimilative grey WF. Thus, the WP is calculated using the WFs approach based on the crop WF. The methodological flow diagram of WP using the WF concept is indicated in Figure 2.

Table 1 | Data inputs for computations of the water productivity in the Upper Awash Basin

Data input[a]	Data type/resolution	Remark/Data source
Climatic data: rainfall, minimum temperature, maximum temperature, wind speed, relative humidity, sunshine hour, relative humidity	Dekadal data (2000–2010)	National Meteorological Agency (NMA)
Soil data: soil groups, bulk density, the field capacity and permanent wilting point and others		Debreziet research center, Melkassa research center, Metehara and Wonji sugar estate farms, Sugar Corporation Research and Development Center of Ethiopia; Hirpa *et al.* (2022)
Crop yield data	2000–2010 (yield per growing season in ton/ha)	Central Statistical Agency (CSA) specifically for the eastern Shoa zone; Hirpa *et al.* (2022)
Crop evapotranspiration	Dekadal data (2000–2010) in mm	Hirpa *et al.* (2022)
Onset, end of wet spells, length of wet spells and length of growing period (LGP)	2000–2010 in days	Adane *et al.* (2020a, 2020b)
Water footprint for both rainfed and irrigated crops	2000–2010 in m^3/ton	Hirpa *et al.* (2022)
Crop values (producer price) of Ethiopia	2000–2010 and 2021 in dollar/kg	*Teff*, maize and sorghum time-series price; retrieved from: FAO/GIEWS Food Price Monitoring and Analysis Tool (https://fpma.apps.fao.org/giews/food-prices/tool/public/#/dataset/domestic)
	2000–2010 and 2018 in $/kg	Sugarcane producer price; retrieved from: FAOSTAT (https://www.fao.org/faostat/en/#data/PP)
Water pricing data[b]	Birr/1,000 m^3 and Birr/ha/year	From the Ethiopian Ministry of Water and Energy and literature on the Awash River Basin
Time-series data of the exchange rate of the Ethiopian Birr to USD	2000–2010	World Bank Database (https://data.worldbank.org/indicator/PA.NUS.FCRF?locations=ET) and literature

[a]All data inputs collected for Debrezeit, Wonji, Melkassa and Metehara area.
[b]The pricing data converted with the currency in $ during that period; Birr is the Ethiopian currency.

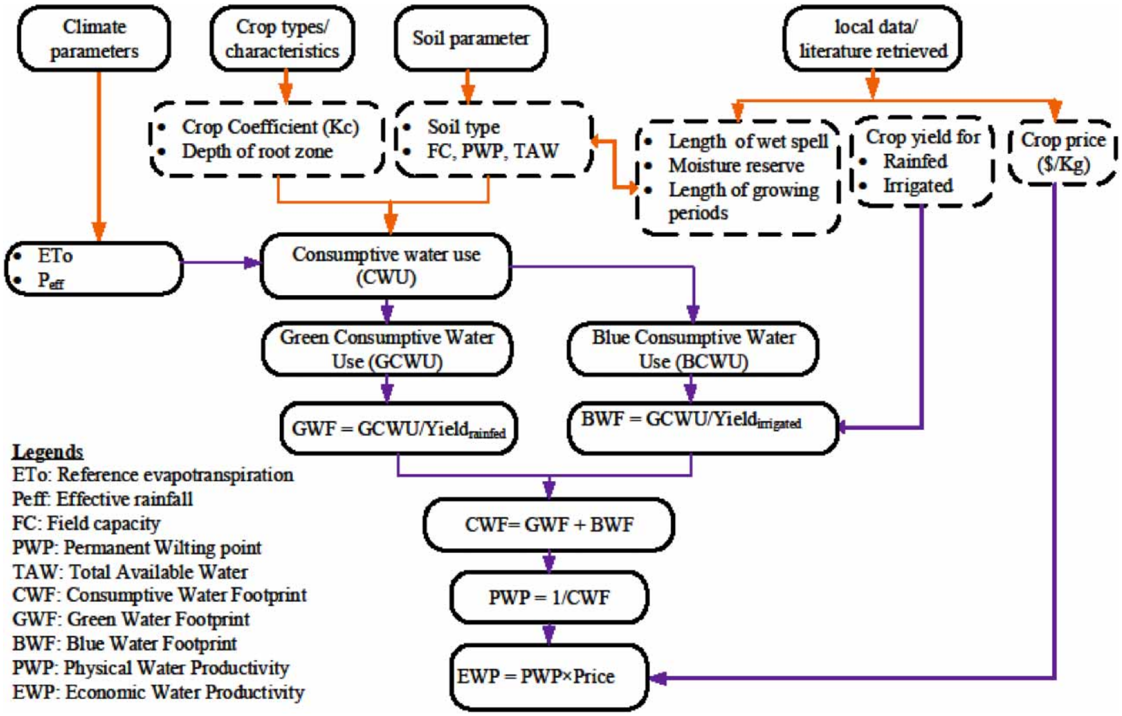

Figure 2 | Methodological flow diagram of water productivity (WP) using water footprint (WF) concept.

3.1. WFs as input for WP

Hoekstra *et al.* (2011) defined the total WFs as the sum of blue, green and grey WFs and this water is consumed (blue and green WFs) and assimilated (grey WF) during the entire growing period (Equation (1)).

$$WF_{total} = WF_{blue} + WF_{green} + WF_{grey} \tag{1}$$

where WF_{total} is the WF of crop production (m^3/ton); WF_{blue} is the blue WF (m^3/ton); WF_{green} is the green WF (m^3/ton); and WF_{gray} is the grey WF (m^3/ton).

Green water footprint (WF_{green}) is defined as the green water use of a crop (CWU_{green}, m^3/ha) per given yield (ton/ha) produced. Similarly, the blue water footprint (WF_{blue}) considers the blue water uses of a crop (CWU_{blue}, m^3/ha) as a result of the applied irrigation water per yield produced (Equations (2) and (3)). The detail of methodologies on consumptive water uses and WFs are given by Hirpa *et al.* (2022) and Hoekstra *et al.* (2011).

$$WF_{green} = \frac{CWU_{green}}{Y} \tag{2}$$

$$WF_{blue} = \frac{CWU_{blue}}{Y} \tag{3}$$

where WF_{green} is the green water footprint in m^3/ton; WF_{blue} is the blue water footprint in m^3/ton.

3.2. Physical WP

Water use is measured as green plus blue water consumption and is known as physical WP (PWP in kg/m^3). It is expressed as the inverse of consumptive water footprint (CWF) as indicated in Equation (4) (Hoekstra *et al.* 2011; Chukalla 2017).

$$PWP_i = (WF_{green,i} + WF_{blue,i})^{-1} \tag{4}$$

where PWP_i is the physical water productivity for the ith year; $WF_{green,i}$ and $WF_{blue,i}$ is the green and blue WFs for the ith year in m^3/ton and are converted into m^3/kg; the total consumptive WF is the sum of the green and blue WFs.

The green water productivity for the ith year (GWP_i) for the rainfed crops is computed using Equation (5)

$$GWP_i = \left(\frac{1}{WF_{green,i}}\right) \tag{5}$$

The blue water productivity for the ith year (BWP_i) for irrigated sugarcane is computed using Equation (6):

$$BWP_i = \left(\frac{1}{WF_{blue,i}}\right) \tag{6}$$

The statistics of the WP are explained using minimum, maximum, average, standard deviation, median, coefficient of variations and quantiles (25 and 75%) as indicated in Burgan *et al.* (2017).

3.3. Economic WP

EWP is defined as the value derived per unit of water used (Molden *et al.* 2007; Garrido *et al.* 2010; Chouchane *et al.* 2015) and is computed using Equation (7):

$$EWP_i = PWP_i \times CP_i \tag{7}$$

where EWP_i is the economic water productivity for the ith year; CP_i is the crop price in (US$/kg) for the ith year.

The time-series data of the producer price for rainfed (*teff*, maize and sorghum) and irrigated crops (sugarcane) for the year 2000–2010 and the recent available price of crop value (2018 for irrigated sugarcane and 2021 for rainfed crops) were used to estimate the economic WP of the basin (Supplementary Tables S1 and S2).

3.4. Green water scarcity and blue water demand price in the basin

The green water shortage or the blue water demand required to satisfy the crop evapotranspiration throughout the length of the growing period is considered as GWS for that specific crop. Therefore, the GWS in terms of depth of water required (in mm) was analyzed for each rainfed crop (*teff*, maize and sorghum) from 2000 to 2010. The analyzed result of blue water demand (m^3/ha) retrieved from Hirpa *et al.* (2022) was used as input to compute the GWS.

The water pricing for diverting surface water or groundwater in the Awash River Basin has a charging rate (water fee) of 3 Ethiopian Birr (ETB) per 1,000 m^3 with a service charge of 78.18 ETB per hectare per year for the service rendered by the then Awash Basin Authority and now Awash Basin Development Office (Teklay & Ayana 2014). This water rating has not changed for more than two decades but Ethiopia's currency (Birr) has been significantly devaluated during this period and the exchange rate with USD varied significantly. The USD exchange rate considered for this study is from 2000 to 2010, 2018 and 2021 for computation of the economic blue water demand price which will be diverted from the Awash River or groundwater in the basin.

4. RESULTS

4.1. Water footprint and physical water productivity

4.1.1. Green/blue WFs of crops

Hirpa *et al.* (2022) characterized the WFs (the green, blue and grey WFs) of dominantly cultivated crops in the Upper Awash Basin using both rainfed and irrigation systems (Table 2). For the current study, we used only the green WF, blue WF, and blue water demands to compute the PWP and later analyze the EWP. The decadal (2000–2010) average green WFs of rainfed crops vary from the highest in Debreziet (3,648 m^3/ton for *teff* and 1,741 m^3/ton for maize) to the lowest in Wonji (1,514 m^3/ton for maize). Melkassa recorded an intermediate average GWFs with 2,205 m^3/ton for sorghum and 1,535 m^3/ton for maize (Table 2). The CWFs, which is the sum of green and blue WFs, of the irrigated sugarcane range from 112 to 198 m^3/ton in Wonji and 106 to 157 m^3/ton in Metehara (Table 2). The large share of the CWF of the irrigated sugarcane is a contribution from the blue water and therefore the PWP in irrigated sugarcane is considered as BWP (Table 2).

Table 2 | Average WFs (m^3/ton) for rainfed and irrigated crops in the Upper Awash Basin (from Hirpa *et al.* (2022))

Location	Conditions	Crop type	Decadal average WF (m^3/ton)			Average annual BWD[a] (m^3/ha)
			Green	Blue	CWF[b]	
Debrezeit	Rainfed	*Teff*	3,648	–	3,648	1,157
		Maize	1,741	–	1,741	701
Wonji	Rainfed	Maize	1,514	–	1,514	902
	Irrigated	SC-1[c]	78	120	198	–
		SC-2[d]	42	70	112	–
Melkassa	Rainfed	Sorghum	2,205	–	2,205	1,039
		Maize	1,535	–	1,535	1,171
Metehara	Rainfed	Maize	–	–	–	2,688
	Irrigated	SC-3[e]	40	117	157	–
		SC-4[f]	23	83	106	–

[a]Blue water demand (BWD) is considered as green water scarcity expressed in m^3/ha.
[b]CWF, consumptive water footprint (green plus blue WF).
[c]Sugarcane variety with 24-months LGP in Wonji.
[d]Sugarcane variety with 14-months LGP in Wonji.
[e]Sugarcane variety with 20-months LGP in Metehara.
[f]Sugarcane variety with 14-months LGP in Metehara.

4.1.2. Decadal physical and economical WP

The decadal average PWP for irrigated and rainfed crops is indicated in Table 3. The lowest PWP (0.27 kg/m^3) is observed for *teff* compared with the other cereal crops (maize and sorghum). The PWP for rainfed maize is equivalent to GWP and it was found to be 0.66, 0.57 and 0.45 kg/m^3 in Wonji, Debrezeit and Melkassa, respectively (Table 3). The rainfed crops exhibited lower PWP compared with the irrigated sugarcane which ranges from 5 to 9 kg/m^3 in Wonji and ~6.4 to 9.4 kg/m^3 in Metehara.

The EWP is computed based on the decadal average WFs values, and it ranges between 0.20 and 0.27 USD/m^3 for rainfed crops, while it ranges from 0.5 to 0.9 USD/m^3 in Wonji and ~0.65 to 0.95 USD/m^3 in Metehara for the irrigated sugarcanes depending on the LGPs of sugarcane varieties (Table 3). The short-duration sugarcane (SC-2 and SC-4) has the highest EWP compared with the long-duration sugarcane (SC-1 and SC-3) (Table 3; Figure 3). In general, the EWP in the basin is less than 1 USD/m^3 for irrigated sugarcane and less than 0.3 USD/m^3 for rainfed crops (Table 3).

Table 3 | PWP and EWP for irrigated and rainfed crops based on the average WF values in the Upper Awash Basin

Location	Conditions	Crop type	GWF (m^3/kg)	BWF (m^3/kg)	CWF (m^3/kg)	PWP (kg/m^3)	Price ($/kg)	EWP ($/$m^3$)
Deberezeit	Rainfed	*Teff*	3.65	0	3.65	0.27	0.97[a]	0.27
		Maize	1.74	0	1.74	0.57	0.40[a]	0.23
Wonji	Rainfed	Maize	1.51	0	1.51	0.66	0.4	0.26
	Irrigated	SC-1[b]	0.08	0.12	0.2	5.04	0.10[c]	0.5
		SC-2[d]	0.04	0.07	0.11	8.92	0.10	0.89
Melkassa	Rainfed	Sorghum	2.21	0	2.21	0.45	0.45[a]	0.2
		Maize	1.54	0	1.54	0.65	0.4	0.26
Metehara	Rainfed	Maize	–	–	–	–	–	–
	Irrigated	SC-3[e]	0.04	0.12	0.16	6.39	0.10	0.64
		SC-4[f]	0.02	0.083	0.11	9.38	0.10	0.94

GWF, green water footprint; BWF, blue water footprint; CWF, consumptive water footprint; PWP, physical water productivity; EWP, economic water productivity.
[a]Producer price of the year 2021 for rainfed crops in Ethiopia (https://fpma.apps.fao.org/giews/food-prices/tool/public/#/dataset/domestic).
[b]Sugarcane variety with 24-months LGP in Wonji.
[c]2018: producer price of the year 2018 for irrigated sugarcane in Ethiopia (https://www.fao.org/faostat/en/#data/PP).
[d]Sugarcane variety with 14-months LGP in Wonji.
[e]Sugarcane variety with 20-months LGP in Metehara.
[f]Sugarcane variety with 14-months LGP in Metehara.

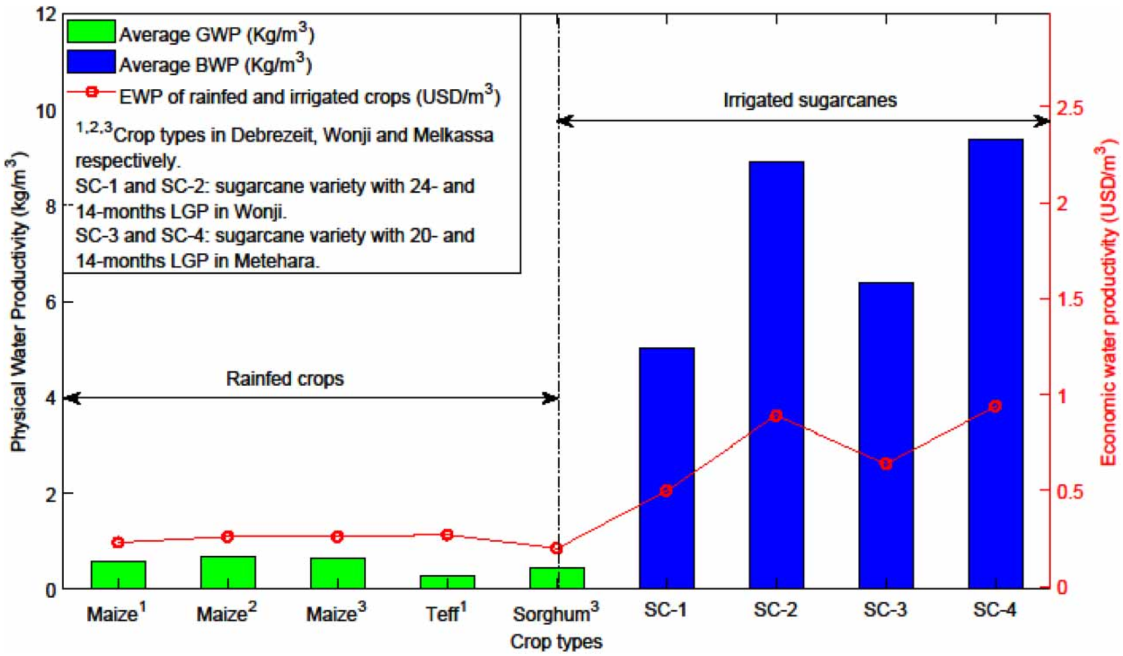

Figure 3 | Average green, blue and economic water productivity of the rainfed and irrigated crops.

4.2. Temporal and spatial variability of green water productivity

In the Debrezeit area, the minimum and maximum GWP of maize were recorded as 0.43 and 0.80 kg/m^3 in 2000 and 2006, respectively (Figure 4(a)). In the Wonji area, the highest GWP was observed in 2002 and 2006 with 0.98 and 0.96 kg/m^3, respectively. The highest GWP (1.04 kg/m^3) in the basin was recorded in the Melkassa area in 2002. Similarly, in 2006 and 2009, the second highest GWP of maize with ~0.80 kg/m^3 was recorded in Melkassa compared with the 11-year time series (2000–2010) data (Figure 4(a)). The minimum GWP in Wonji (~0.49 kg/m^3) and Melkassa (0.53 kg/m^3) were noted in 2000 and 2004, respectively.

The GWP of maize which is lower than 0.6 kg/m^3 is recorded in ~46% (in Debrezeit and Wonji) and 36% (in Melkassa) of the time series considered. The remaining is above 0.6 kg/m^3 and depicts a maximum of 0.80 kg/m^3 in Debrezeit and ~1 kg/m^3 in both Wonji and Melkassa. *Teff* shows the lowest GWP among the selected crops and ranges between 0.18 (in 2000) and 0.39 kg/m^3 (in 2002) (Figure 4(b)). Similarly, sorghum also recorded the second-lowest GWP (0.32–0.67 kg/m^3) between the 2000 and 2010 periods (Figure 4(b)).

4.3. Temporal and spatial variability of blue water productivity

The time series (for 2000–2010) of the sugarcane BWP with different lengths of growing period (LGPs) were analyzed using the blue WFs calculated by Hirpa *et al.* (2022). The BWP of short-duration (14-months LGPs) sugarcane varieties (SC-2 in Wonji and SC-4 in Metehara) show higher BWPs compared with the long-duration sugarcane varieties of 24-month and 20-month LGPs in Wonji and Metehara, respectively (Figure 5). The statistics of the WP are summarized in Table 4. The BWP of irrigated sugarcane ranges from ~4 to 6 kg/m^3 (SC-1 of 24-month LGPs) and ~7 to 10 kg/m^3 (SC-2 of 14-month LGPs) in Wonji (Figure 5(a); Table 4), and from ~5 to 7 kg/m^3 (SC-3 of 14-month LGPs) and ~7 to 11 kg/m^3(SC-4 of 14-month LGPs) in Metehara (Figure 5(b); Table 4). In 2007–2009, the lowest WPs which are less than 4.5 (in SC-1) and 8 kg/m^3 (in SC-2) were recorded in Wonji (Figure 5(a); Table 4). Whereas less than 6.5 (in SC-3) and 8.5 kg/m^3 (in SC-4) were recorded between 2000 and 2003 in Metehara (Figure 5(b); Table 4). The detailed interpretation of the statistics is indicated in the Discussion section.

4.4. Economic water productivity

The EWP of rainfed maize in the Debrezeit, Wonji and Melkassa areas ranges from ~0.05 USD/ m^3 in 2001 to 0.3 USD/m^3 in 2008 and declined to 0.1 USD/m^3 in 2010 (Figure 4(a)). The increment in EWP of maize was noted between 2000 and 2008.

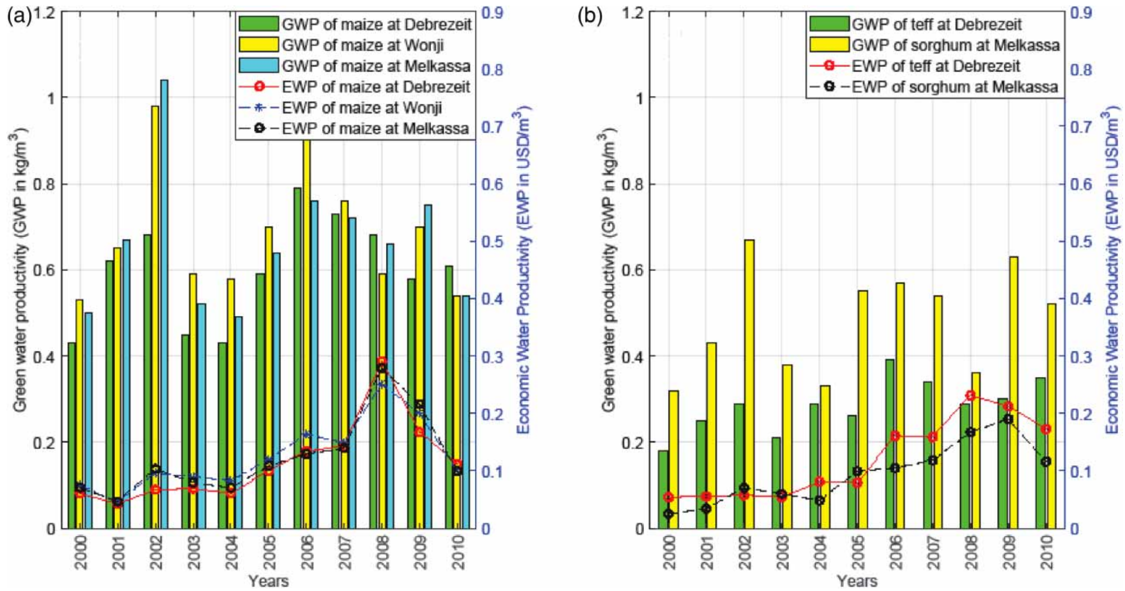

Figure 4 | Temporal and spatial GWP and EWP of rainfed crops for (a) maize; (b) *teff* and sorghum.

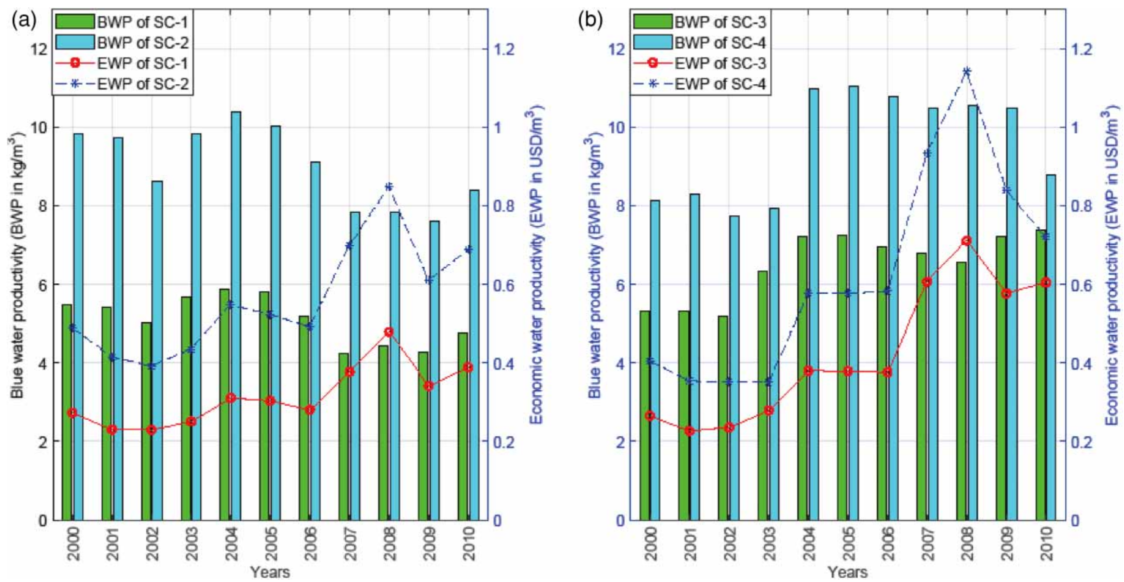

Figure 5 | Temporal and spatial BWP and EWP of irrigated crops at (a) Wonji and (b) Metehara. SC-1, sugarcane variety with 24-month LGP in Wonji; SC-2, sugarcane variety with 14-month LGP in Wonji; SC-3, sugarcane variety with 20-month LGP in Metehara; SC-4, sugarcane variety with 14-month LGP in Metehara.

Similar trends of an increase in EWP for *teff* (0.05–0.23 USD/m^3) were also noted for the same period (2000–2008) but declined in 2009 and 2010. The highest EWP of sorghum (0.19 USD/m^3) was recorded in 2009 and the lowest (0.03 USD/m^3) was in 2001/02 (Figure 4(b)). The producer cost for cereal crops has shown a reduction in price per kg during the 2008–2010 periods.

The EWP of blue water as a result of irrigating sugarcane plantations shows a general increasing trend between 2000 and 2008 in all sugarcane varieties in both Wonji and Metehara areas (Figure 5). However, the short-duration sugarcane (SC-2 and SC-4) has the highest EWP compared with the long-duration sugarcane (SC-1 and SC-3). The highest EWP is recorded in 2008 both in Wonji (0.48 USD/m^3 in SC-1 and 0.85 USD/m^3 in SC-2) and Metehara (0.71 USD/m^3 in SC-3 and 1.14 USD/m^3 in SC-4) (Figure 5). The EWP of sugarcane declined between 2008 and 2010. This is because of a decline in allocated

Table 4 | Statistics of the green and blue water productivity for rainfed and irrigated crops

	GWP_{Maize}					$BWP_{Sugarcane}$			
						Wonji		Metehara	
Statistics	Debrezeit	Wonji	Melkassa	GWP_{Teff} Debrezeit	$GWP_{Sorghum}$ Melkassa	SC-1	SC-2	SC-3	SC-4
Maximum (kg/m^3)	0.79	0.98	1.04	0.39	0.67	5.89	10.40	7.38	11.04
Minimum (kg/m^3)	0.43	0.53	0.49	0.18	0.32	4.23	7.62	5.18	7.74
Average (kg/m^3)	0.60	0.67	0.66	0.30	0.48	5.11	9.02	6.50	9.57
SD (kg/m^3)	0.12	0.16	0.16	0.10	0.12	0.61	1.00	0.85	1.36
Median	0.61	0.65	0.66	0.29	0.52	5.19	9.11	6.80	10.48
CV	0.20	0.23	0.24	0.21	0.26	0.12	0.11	0.13	0.14
Q_1 (kg/m^3)	0.45	0.58	0.52	0.25	0.36	4.42	7.84	5.33	8.12
Q_3 (kg/m^3)	0.68	0.76	0.75	0.34	0.57	5.68	9.84	7.22	10.79

GWP, green water productivity; BWP, blue water productivity; SD, standard deviation; CV, coefficient of variation; Q_1, 25% quantile; Q_3, 75% quantile.

producers' costs for sugarcane from 0.11 to 0.08 USD/kg (FAO, https://fpma.apps.fao.org/giews/food-prices/tool/public/#/dataset/domestic).

4.5. Green water scarcity and blue water demand price

The green water is scarce to fully satisfy the evapotranspiration demands of the dominant crops in the basin. The blue water demand for rainfed crops is considered as GWS. The GWS is higher in the Metehara area and requires more blue water to meet the evapotranspiration demand of maize during the study period (Figure 6(a)).

A depth (volume) of water with a minimum of 139 mm (1,390 m^3/ha) in 2010 and a maximum of 398 mm (3,980 m^3/ha) in 2002, with a decadal average of 268.8 mm (2,688 m^3/ha), was noted as GWS in Metehara (Figure 6(a)). In addition, average GWSs of 70, 90 and 117 mm were recorded in Debrezeit, Wonji and Melkassa, respectively (Table 5; Figure 6(a)). These specified amounts of water are required to supplement the green water in these areas and support the evapotranspiration demand of maize in the basin. A minimum depth of 49 mm in 2000 and a maximum depth of 186 mm in 2002 with a decadal average depth of water of ~116 mm was recorded as a green water shortage for *teff* in Debrezeit (Table 5; Figure 6(a)). A minimum of 35 mm in 2010 and nearly 170 mm in 2004 with a decadal average depth of water of 104 mm was required for sorghum in Melkassa (Table 5; Figure 6(b)). The economic blue water demand price shows a declining trend during the 2000–2010 periods due to a relative reduction in green water shortage (Figure 6).

5. DISCUSSION

5.1. Physical water productivity and water scarcity

The global blue water consumption for agricultural production will significantly increase in the next three decades (Rockström & Barron 2007). Inefficient use of blue and green water resources and poor agricultural practices largely contribute to water quality and quantity scarcity (Yin & Xu 2020). The blue water demands in the Awash Basin exceed their surface water availability by 0.03 billion m^3 in densely populated areas of the basin during 1980–2012 (Adeba *et al.* 2015). Therefore, the blue water users for irrigation and other purposes are facing water scarcity problems ahead of the predicted time in the basin. In the Upper Awash Basin, higher total WFs in rainfed crops were noted compared with the irrigated sugarcane (Hirpa *et al.* 2022). Similarly, the current study shows lower GWP for the rainfed crops compared with the irrigated sugarcane in Wonji and Metehara. For instance, the average GWP of maize spatially varies and ranges from 0.57 kg/m^3 in Debrezeit to 0.66 kg/m^3 in Wonji. In addition, *teff* has the lowest average GWP (0.27 kg/m^3) with high total WFs (4,205 m^3/ton) and GWS (1,157 m^3/ha) compared with other cereal crops.

The CV for rainfed maize, *teff* and sorghum ranges between 0.20 and 0.26 in the Upper Awash Basin (Table 4). The GWP of maize shows lower CV in Debrezeit (0.2) with a lower standard deviation (0.61 kg/m^3) relative to its mean (0.60 kg/m^3) compared with that in Wonji and Melkassa, whereas a maximum GWP of 1.04 kg/m^3 was noted in Melkassa with a minimum in Debrezeit (0.43 kg/m^3) during 2000–2010 (Table 4). The mean GWP of Maize in the Upper Awash Basin ranges from 0.60 kg/m^3 in Debrezeit to ~0.70 kg/m^3 in Wonji and Melkassa. The 25 and 75% quantile range of GWP for maize ranges

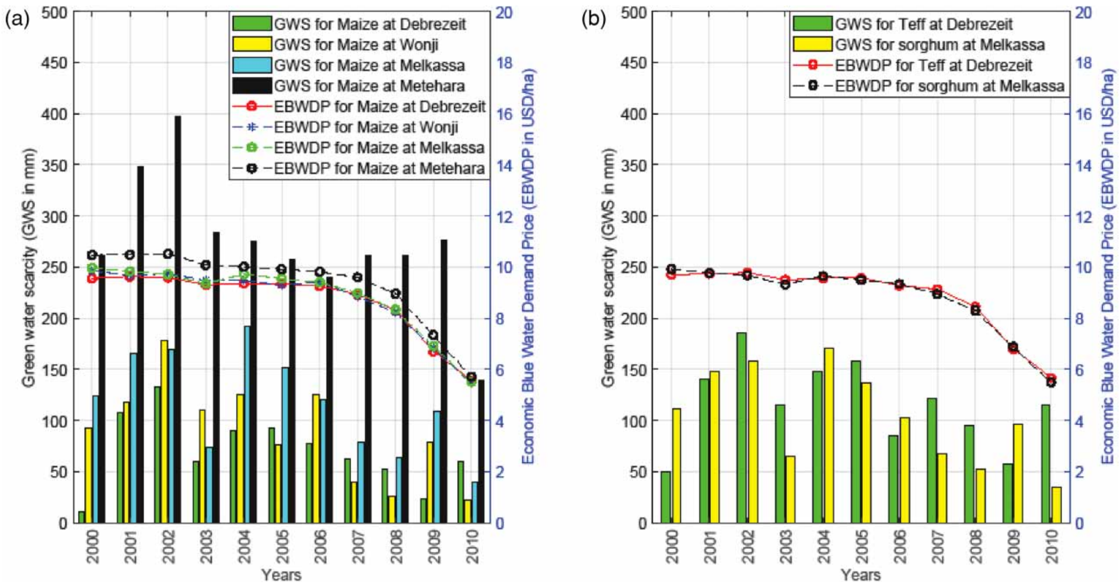

Figure 6 | Temporal and spatial green water scarcity (GWS) for (a) maize; (b) *teff* and sorghum.

Table 5 | Statistics of green water scarcity (GWS) for rainfed crops in the Upper Awash Basin

Location	Crops	D_{min} (mm)	D_{max} (mm)	DD_{GWS} (mm)	Decadal average GWS (m^3/ha)
Debrezeit	Maize	10.8	132.4	70.1	701
	Teff	49.4	185.8	115.7	1,157
Wonji	Maize	21.60	178.1	90.2	902
Melkassa	Maize	40	192.5	117.1	1,171
	Sorghum	34.7	170.3	103.9	1,039
Metehara	Maize	138.9	397.6	268.8	2,688

D_{min}, minimum depth of water required between 2000 and 2010; D_{max}, maximum depth of water required between 2000 and 2010; DD_{GWS}, decadal average depth of GWS between 2000 and 2010.

from ~0.5 to ~0.7 kg/m^3 in Debrezeit, ~0.6 to ~0.8 kg/m^3 in Wonji and ~0.5 to ~0.8 kg/m^3 in Melkassa (Table 4). The average GWP of *teff* at Debrezeit records the lowest (0.3 kg/m^3) among other types of crops in the basin. In addition, sorghum also depicts a lower GWP (0.48 kg/m^3) but has comparatively higher GWP than *teff* in Debrezeit. The deviation from a mean (1 and 1.36 kg/m^3) is higher in the short-duration (14-month LGPs) sugarcane varieties than the long-duration irrigated sugarcane which exhibited 0.61 kg/m^3 in Wonji with 24-month LGPs and 0.85 kg/m^3 in Metehara with 20-month LGPs. The sugarcanes with shorter LGPs (SC-2 and SC-4) have higher average BWP (~9–10 kg/m^3) compared with the long-duration sugarcane varieties of 24- and 20-month LGPs (~5–7 kg/m^3). The BWP of irrigated sugarcane shows a lower CV (0.11–0.14) compared with the green water-dependent crops (Table 4).

In the Metehara area, green water availability was not able to support the maize crop (Adane *et al.* 2020b). Hirpa *et al.* (2022) also estimated the highest blue water demand required to meet the maize evapotranspiration requirements for Metehara (2,688 m^3/ha) with intermediate values in Melkassa (1,323 m^3/ha) and Wonji (902 m^3/ha) and the lowest in Debrezeit (701 m^3/ha). The highest GWS of maize is observed in the MER (Metehara, Wonji and Melkassa) compared with the central highlands (Debrezeit). Similarly, the BWP of short-duration sugarcane varieties has a higher WP (1.8 times in Wonji and 1.5 times in Metehara) compared with the long-duration sugarcane varieties. Passioura (2006) explains a better cultivar with short duration, agronomic practice and a moisture conservation method improves the WP to tackle the growing water scarcity problems. Brauman *et al.* (2013) provided global analysis on improvements in crop WP to increase the water sustainability and food security. Their estimates show that if the lowest water productivities were improved to the 20th percentile, it can help save more than one quarter of the current water consumption on the irrigated croplands (i.e., 7.7×10^{10} m^3/year). Marston *et al.* (2020) explained the possibilities of reducing water scarcity by improving the WP in the US.

They found that the depletion of river flow (blue water) across the western U.S. region can be reduced on average by 6.2–23.2% without affecting the economic production.

In general, the GWP of the rainfed crops is low in the basin compared with the BWP. In Ethiopia, the rainfed crops which are dependent on green water had a productivity of 10 times less compared with the irrigated WP (blue water either from surface or groundwater) (Makombe *et al.* 2007). Thus, improving PWP, which is exclusively green and blue WP, plays a significant role in ensuring water and food security. SSA countries, including Ethiopia, are almost entirely dependent on the available green water for rainfed agriculture (Rockström *et al.* 2007; Schuol *et al.* 2008). Thus, the green water potential for increasing WP should not be ignored in Ethiopia, where food insecurity and water scarcity are common.

The available green water in three of the stations, except in Metehara, has the potential to increase GWP through effective agricultural land and water management practices (Hirpa *et al.* 2022). The conventional land management practices – such as bunds and fanya juu – improve the green water availability by reducing the on-site erosion of the specific agricultural land via conserving the blue (runoff) water in Ethiopia. However, these physical land management technologies consume a large portion of scarce productive lands (Belete 2022). For instance, soil bunds in experimental plots around the central Rift Valley of Ethiopia occupy 8.6% of the cultivable land (Adimassu *et al.* 2012). According to Biratu *et al.* (2021), introducing soil bunds and fanya juu reduced grain yields in the agricultural landscape of Ethiopia by 24 and 22%, respectively. Thus, the trade-off between the physical land management strategies with improving the grain yields should be carefully coined to enhance GWP, particularly in the rainfed-dominated agricultural system. In addition, integrating the conventional land management practice with ecohydrological-based landscape restoration strategies will significantly improve both land and water productivity by underpinning the limitations of physical land management strategies (Belete 2022). These will contribute to reducing the WFs of the dominantly cultivated crops, or will provide options to transform into less water-intensive varieties of crops and access more productive land in the basin. Furthermore, the water resource management practices, particularly for managing the blue water resources, should focus on maximizing the crop production per unit of water consumed instead of considering the production per unit area.

5.2. Economic water productivity

Agricultural products contributed 45–48% of the GDP of Ethiopia between 2000/01 and 2004/05 and declined to 41% of the GDP in 2010/11 and to 36.3% in 2016/17 (NBE 2006, 2011, 2017). The largest share of the agricultural sector in 2016/17 was crop production which comprised 65% of all the agricultural products. The GWS for rainfed crops was noted in all stations to varying degrees, and it is more in MER compared with the central highlands. Thus, to meet the evapotranspiration demand of rainfed crops, the diversion of an enormous volume of surface/groundwater is required. Our results show a declining trend of the blue water demand price for rainfed/irrigated crops. Among the contributors to the decline of blue water demand prices are the fact that the price tag (water fee) set by the Awash Basin Development Office has remained unchanged for several decades, and prices are set in the devaluated ETB during this period.

The producer's cost of agricultural products both for the rainfed/irrigated crops increased during 2000–2008 and shows an increment in EWP. Despite the producers' costs of *teff* showing a relative increase in ETB during 2009, the devaluation of the local currency and the continual reduction in producers' cost of agricultural products (*teff*, maize, sorghum and sugarcane) in the basin between the 2008 and 2010 periods have led to an apparent decline in EWP of the rainfed/irrigated crops in terms of USD.

5.3. Comparison of global, regional and local WPs

The global, regional and local comparison of the general WP and green-blue WP from the perspective of WF is indicated in Table 6. The BWP of irrigated *teff* from field experiments was recorded as 0.6–1.2 kg/m^3 (Yihun *et al.* 2013). This is very low compared with other cereal crops under irrigated conditions (Table 6). Our result for rainfed *teff* shows a very low GWP (~0.3 kg/m^3), which was expected to be lower compared with the BWP under irrigated conditions (Table 6). The GWP of maize ranges from 0.57 to 0.66 kg/m^3, varying spatially in three locations of the Upper Awash Basin. However, these values exceed the general estimate of WP of maize (below 0.4 kg/m^3) for SSA countries (Edreira *et al.* 2018). Zwart & Bastiaanssen (2004) reviewed the WP of maize around the globe and found a large range of variations between 0.22 and 3.99 kg/m^3. In 67% of the cases, the maximum value exceeds 1.6 kg/m^3 and the WP of maize around the globe is in the range of 1.1–2.7 kg/m^3 (Zwart & Bastiaanssen 2004). However, this study did not indicate whether the WP estimates were from blue or green water consumption.

Table 6 | Global, regional and local comparison of WPs from various studies

References	Study period	Study area	Crop type	WP (kg/m^3)
Global studies				
Mekonnen *et al.* (2020)	1990–2014	USA, Nebraska (23 districts)	Maize	1.72–2.39[a] 0.72–1.58[b]
Doorenbos & Kassam (1979)		Global		0.8–1.6
Edreira *et al.* (2018)	10–20 years data	Global (west Europe)		2.6[c]
Zwart & Bastiaanssen (2004)	25 years data	USA and China		1.1–2.7
Sharma *et al.* (2018)	2009–2011	India (24 districts)		0.41–2.67
Sharma *et al.* (2018)	2009–2011	India (10 districts)	Sugarcane	4.54–6.88
Teixeira *et al.* (2016)	2001–2007	Brazil, Sao Paulo state		2.8–6.0
Leal *et al.* (2017)		Brazil		11.45–18.45[d]
Sub-Saharan Africa (SSA) studies				
Edreira *et al.* (2018)	10–20 years data	Global (SSA)	Maize	<0.4[c]
Hadebe *et al.* (2017), Mativavarira *et al.* (2011)	2007–2008	Zimbabwe	Sorghum	0.6–2.7
Yihun *et al.* (2013)	2010–2011	Melkassa, Ethiopia	*Teff*	0.6–1.2
Gemechu *et al.* (2020)	2009–2019	Wonji, Ethiopia Metehara, Ethiopia Fincha, Ethiopia	Sugarcane	7.5 (7.6–9)[e] 4.3 (6.7–10) 7 (7.3–11.2)
Admasu *et al.* (2019)	2017–2018	Melkassa	Maize	0.67–0.98
This study (in Ethiopia) using decadal average green or blue WP	2000–2010	Debrezeit	*Teff*	0.27[b]
			Maize	0.57[b]
		Wonji	Maize	0.66[b]
			SC-1	5.04[a]
			SC-2	8.92[a]
		Melkassa	Sorghum	0.45[b]
			Maize	0.65[b]
		Metehara	SC-3	6.39[a]
			SC-4	9.38[a]

SC-1, sugarcane variety with 24-months LGP in Wonji; SC-2, sugarcane variety with 14-months LGP in Wonji; SC-3, sugarcane variety with 20-months LGP in Metehara; SC-4, sugarcane variety with 14-months LGP in Metehara; SSA, Sub-Saharan Africa.

[a]BWP of irrigated crops.

[b]GWP of rainfed crops.

[c]Global average value of water productivity.

[d]The values of sugarcane in Brazil are experimental and under controlled environment in a green house.

[e]The values in parentheses in this column are the maximum BWP in sub-irrigation scheme of Wonji, Metehara and Fincha Sugar estate.

The BWP of irrigated sugarcane in our study is comparable with the estimates of Gemechu *et al.* (2020) who showed values ranging between 7.6 and 9 kg/m^3 in Wonji and 6.7 and 10 kg/m^3 in Metehara (Table 6). However, they show variations with the global WP ranges of sugarcane which vary between ~5 and 7 kg/m^3 in India and 3–6 kg/m^3 in Sao Paulo, Brazil due to the variations related to the soil type, sugar cane varieties, climate and management practices. The short-duration sugarcane in both Wonji and Metehara show a higher BWP (~9 kg/m^3) compared with the global average. It should be noted that a higher BWP of sugarcane (11.45–18.45 kg/m^3) was obtained under greenhouse experimental conditions (Leal *et al.* 2017).

The GWP of rainfed crops in the Upper Awash Basin can be increased by improving crop management practices, increasing soil fertility and constructing various green infrastructures to enhance the soil moisture reserve such as detention ponds, and percolation pits, among others. It is also possible to increase the BWP by integrating green water conservation methods (moisture conservation) with various blue water application methods such as furrow (conventional, alternate or fixed), sprinkler or drip irrigation methods. For instance, Jemal & Agegnehu (2020) experimented with various types of furrow irrigation in combination with green water conservation (mulching) in the southern MER (Hawassa area) and obtained a higher BWP of maize (2.43 kg/m^3).

5.4. Implications of this study

From the perspective of WF, there are almost no studies on rainfed and irrigated crop productivity in SSA countries, including Ethiopia. The green and blue WPs of maize we estimated in the current study exceed the general estimates made for maize in SSA countries but are lower than the global estimates made by Zwart & Bastiaanssen (2004). On the other hand, we estimated a much lower GWP for sorghum compared with other studies (Table 6). Our results are based on separate considerations of green and blue water consumption. In addition, we used locally measured data in the estimation of the WFs. Though the total WF of Ethiopia accounted for 97% of the green WF, 2% of blue WF and 1% of gray WF for crop production (Mekonnen & Hoekstra 2011b), there is less GWP and EWP in the Upper Awash Basin. Similarly, the large share of green water potential for rainfed agriculture is underestimated both at the global and SSA countries' levels.

About 59% of the world's population will face a blue water shortage, and 36% of them will also experience both green and blue water shortages by 2050 (Rockström *et al.* 2009a, 2009b). However, the global green water consumptive use on cropland is four times that of blue water, indicating a large potential for increasing the GWP of agricultural land (Rost *et al.* 2008; Rockström *et al.* 2009a, 2009b). Thus, improving the WP via integrating and managing the use of both green and blue water to meet the growing food demand will help to mitigate the impact of future water shortages ahead of time.

This suggests that bridging blue-green water and bridging the conventional soil and water management practices with ecohydrological-based land scape restoration works can increase both the GWP and BWP of the Upper Awash Basin. This will help to achieve the Sustainable Development Goals (SDGs) 2: Zero Hunger and SDG 6: To ensure availability and sustainable management of water and sanitation for all, more specifically on 'Substantially increasing water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and reduce the number of people suffering from water scarcity' (Vanham *et al.* 2018).

6. CONCLUSION

Water is the limiting production factor for improving the WP and gaining economic benefits, particularly in green water-dependent agriculture in SSA. The use of blue water offers a significant potential improvement to the productivity of water as observed in the irrigated sugarcane farms in Wonji and Metehara. A short-duration (14-month) irrigated sugarcane recorded higher BWP and EWP compared with long-duration (24/20-month LGP) sugarcane. Therefore, focusing on short-duration sugarcane variety will save a large amount of blue water withdrawal for irrigation purposes at least for large irrigation schemes which cover more than 22,000 ha of sugarcane plantation in the basin. The rainfed cereal crops showed lower PWP and EWP, and higher WFs compared with the irrigated sugarcane in the basin. For instance, *teff* showed the lowest PWP with high green WFs compared with the maize and sorghum that are grown in the basin. The GWS for rainfed crops is significantly higher in Metehara (the eastern catchment of the basin) and decreases toward the west (Melkassa and Wonji areas). However, the central and western catchments of the basin receive larger rainfall but experienced high GWS and low GWP.

Based on the above conclusions, the following recommendations are drawn:

- Improving the green water storage by bridging conventional soil and water management practices with ecohydrological-based landscape restorations in the cultivated area largely increases the GWP and reduces the pressure on blue water resources for irrigation purpose both at the highlands and upper valley of the basin.
- Increasing the value per unit of green/blue WP by increasing yield per unit of supply and changing from high-to-low WFs crops, and growing short-duration sugarcane has vital implications for farmer decisions, economic growth and regional water resource development in the basin.
- The results of this study can serve for setting a benchmark and identify the WP (green-blue and economic WP) gaps by formulating a means to reduce the water consumption per unit crop production in the Upper Awash Basin.

ACKNOWLEDGEMENTS

The authors acknowledge the National Meteorological Agency (NMA), Melkassa Agricultural Research Center, Deberezeit Agricultural Research Center, Wonji Sugar Factory and Metehara Sugar Factory for providing us with data that was the basis for this study. In addition, we acknowledge Mr Dereje Bishaw of the Ethiopian Sugar Corporation Research and Development Center for providing data on the Wonji-Shoa and Metehara sugarcane farms. Furthermore, the FAO and World Bank databases and the Ethiopian Ministry of Water and Energy are credited for providing us with data free of charge.

AUTHORS CONTRIBUTION

Conceptualization and Methodology: B.A.H.; Formal analysis and investigation: B.A.H. and G.B.A.; Data curation: B.A.H. and G.B.A.; Writing – original draft preparation: B.A.H. and A.A.; Writing – review and editing: B.A.H., G.B.A., A.A. and D.N.; Resources: B.A.H. and G.B.A.; Supervision: B.A.H., A.A. and D.N. All authors have read and agreed to the final version of the manuscript.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 13 October 2022; accepted in revised form 13 January 2023. Available online 30 January 2023