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Evaluating the Water Footprints of Ethiopia's Major Cereal Crops across Diverse Agro-Ecological Zones

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***Abstract*—Sustainable water resource management requires a clear understanding of crop water footprints to improve agricultural water use efficiency. This study quantified the green and blue water footprints of five major cereal crops (barley, maize, sorghum, teff, and wheat) across Ethiopia's major agroecological zones from 2004 to 2018. Green and blue evapotranspiration were simulated using the AquaCrop-OS model coupled with MATLAB, and the results were analyzed using generalized linear models to evaluate the effects of year, crop type, evapotranspiration, and agroecological zone on water footprint. The analysis revealed significant spatial variation in water footprint among crops and agroecological zones ($p < 0.001$). Teff exhibited the highest average green-blue water footprint (1957.31 m^3 t^{-1}), particularly in the highland and midland agroecologies, whereas maize showed the lowest average water footprint (1010.65 m^3 t^{-1}), with the greatest water use efficiency observed in the lowlands. Temporal variation was relatively small for most cereal crops over the 15-year study period. These findings provide a comprehensive assessment of cereal water footprints across Ethiopia and offer valuable evidence for developing crop- and location-specific water management strategies to improve agricultural water productivity.**

***Keywords*—Green-blue water footprint, Water scarcity, Crop-water productivity, Aqucrop-OS, Agroecologies, Ethiopia**

I. INTRODUCTION

Effective management of water resources is paramount for sustainable development, particularly in countries where rainfed agriculture is a key economic driver, such as Ethiopia [1]. Increasing populations and expanding human activities are driving a rise in water demand across various sectors, with agricultural water use being especially critical [2, 3]. Indeed, agriculture is a high water-demanding sector, which consumes about 87% of global water resources [4], and the water challenges thus affect the agriculture sector the most. These challenges are further complicated by climate change, underscoring the need for sustainable and effective water management strategies [5], especially given the limited rates of freshwater renewal. In this context, understanding the development of consumption, production, and trade patterns of water resources, using a supply-chain perspective, can contribute to sustainable water use by both companies and consumers [6].

The water footprint (WF) concept, introduced by Hoekstra and Chung [7], provides a framework for understanding different components of water accounts, namely green (rainwater), blue (surface and groundwater which is often termed evapotranspiration [8], and grey (pollution-related water) WF, thereby aiding in the management of water use and pollution from production to consumption [9]. A crop's WF measures the total direct and indirect freshwater usage during its production and consumption, reflecting its overall impact on freshwater resources [10, 11]. The WF concept yields spatiotemporally explicit data on water resource appropriation across various human activities, including crop cultivation [12, 13], and its determination can support broader environmental, social, and economic impact assessments [14-16]. Distinguishing between green and blue WF is crucial due to their differing economic, environmental, social, and hydrological impacts [9, 17, 18].

Ethiopia, often referred to as the "Water Tower" of Africa due to its substantial freshwater resources [19, 20], faces increasing pressure on this abundance resource from interconnected challenges. Rapid population growth and urbanization are significantly increasing water demand across domestic, agricultural, and industrial sectors [21] coupled with the impacts of climate change, [22], leading to more frequent and intense droughts and variable rainfall patterns [23], this is causing increased water stress nationwide, with a significant portion of the population in water-stressed basins experiencing declining per capita availability [21]. Furthermore, the quality of Ethiopia's water resources is degrading due to pollution

from urban centers, industry, and agriculture, impacting surface and groundwater [24, 25].

Previous studies have highlighted general challenges in Ethiopian water management, often attributing them to weaknesses in coordination, institutional capacity, and rapid population growth, rather than inherent scarcity [26]. The heavy reliance on rainfed agriculture, further exacerbates vulnerability to climate variability [27, 28]. Moreover, poor water use efficiency [29]; a lack of understanding of water allocation for various uses based on green, blue, and grey WF aimed at reducing consumption water use is a challenge to the country's freshwater use. To cope with the freshwater use challenges of the country, analyzing freshwater consumptive and degradative use indicators such as the WF to set further management options [3, 30-32] are essential. While some studies have estimated green and blue WF for specific cereal crops like teff in particular regions Yimam and Çapar [33] in Tigray, SNNPR, and Amhara regions; Ulatu, *et al.* [34] for Salale Zone or focused on broader basin-level water productivity [35] for Upper Awash Basin, and others have explored climate change impacts on green water availability and yield of major cereals across Ethiopia [36, 37], a comprehensive and detailed understanding of the WF of different cereal crops across varying agroecological zones and multiple seasons in Ethiopia, remains a significant research gap.

Given the dominance of cereal production in Ethiopia's agriculture [38], these water resource challenges have a direct and significant impact. The reliance of Ethiopian agriculture, especially cereal crops, on rainfall makes it highly vulnerable to spatiotemporal precipitation variations and increasing droughts due to climate change [39, 40]. Water scarcity and stress can reduce cereal yields, threatening food security and livelihoods [41]. Therefore, a nuanced understanding of the WF of different cereal crops across varying agroecological zones and seasons is crucial. Identifying water-intensive practices and regions with higher water stress in cereal production can inform targeted interventions and improved water management to enhance crop water productivity, including exploring drought-resistant varieties and efficient irrigation practices. Addressing Ethiopia's water resource challenges is thus integral to ensuring the sustainability and resilience of its cereal production, a cornerstone of its food security and economic well-being.

II. Materials and Methods

A. Study Area Description

Ethiopia, an East African nation situated between 3°00'N to 15°00'N latitude and 32°00'E to 48°00'E longitude "Fig. 1", is characterized by its significant geographical diversity and a rapidly growing population. As of mid-2024, its population is estimated to be around 130 million people, making it Africa's second-most populous country [42]. The total area of the country is 1.1 million km2. Approximately 35% of Ethiopia's land area is situated at an altitude of 1500 meters or higher [43]. The country has 12 river basins with an annual runoff volume of 124.4 billion m3 (BCM) of water and an estimated range between 12 and 30 BCM of groundwater potential [19, 44].

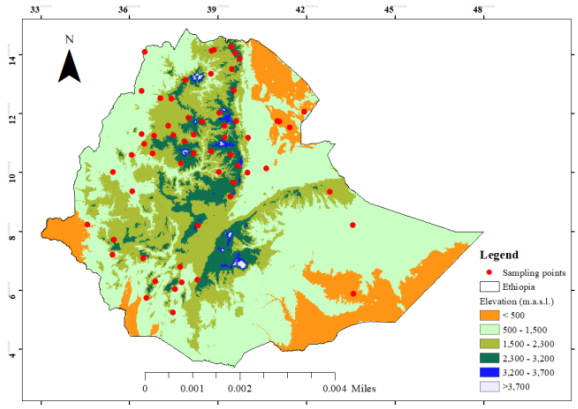


Fig. 1. The study area that describes the distribution of the three agro-ecological zones (based on elevation) across Ethiopia along with the location of climate data sample stations (points)

B. Methodology: AquaCrop-OS Modeling for Yield and Water Footprint Analysis

The WF was calculated based on green and blue water evapotranspiration (ET). This was primarily estimated using the AquaCrop-os model, an Open Source version of AquaCrop implemented in MATLAB software [45]. The AquaCrop-os model was employed following the principles outlined Steduto, *et al.* [46], Hsiao, *et al.* [47] and Dirk, *et al.* [48]. The AquaCrop model was selected for its user-friendly interface and transparency, simulating yield with a limited set of crop parameters [49]. This model simulates crucial processes including crop cover development, crop transpiration (Tr), above-ground biomass accumulation, and crop yield. Its integration with WF calculations enhances the accuracy of yield prediction and facilitates the correlation between yield variability and WF [50]. This approach provides flexibility to simulate the effects of diverse agronomic, irrigation, and management practices on both WF and yield. Specifically, the AquaCrop model is a robust, straightforward, balanced, and precise tool for simulating soil water balance, crop growth, and yield processes [46]. The model facilitates the simulation of both crop transpiration (Tr) and soil evaporation (E). Daily biomass accumulation is derived from daily Tr, utilizing the crop's normalized biomass water productivity as described by Steduto, *et al.* [46]. Soil evaporation (E) is calculated by multiplying the evaporative power of the atmosphere (ETo) by factors accounting for water stress and the proportion of the soil surface not covered by the canopy. Consequently, canopy cover emerges as a critical component of AquaCrop's water-driven simulations [51]. The canopy cover for each crop was set as specified in the AquaCrop reference manual [52].

The AquaCrop simulations relied on daily climatic data collected over a 15-year period (2004-2018) from meteorological stations located within each agroecological zone of the study area "Fig. 1". This climatic data included daily minimum temperature (0C), maximum temperature (0C), precipitation (mm), and reference evaporation (mm). For the simulations, it was assumed the soil was at field capacity at the start of each growing season, ensuring optimal initial moisture conditions. All simulations were specifically parameterized for clay loam soil, which is the dominant soil type identified

in the study area. Crop-specific input parameters ('crop phenology', 'crop transpiration', 'biomass production and yield formation' and 'stresses' for the selected cereals were primarily derived from Dirk*, et al.* [52]. However, we made targeted modifications to planting dates and growing period lengths to align accurately with local agro-climatic conditions.

To accurately quantify the contributions of different water sources, a post-processing methodology was applied to the outputs generated by the AquaCrop model. This process systematically partitioned both soil water content and all associated water fluxes into distinct green and blue water components. Within the daily water balance, precipitation (P) was exclusively allocated to the green soil water stock. Conversely, irrigation (I) was designated as the sole contributor to the blue soil water stock. Daily evaporative (E), transpirative (T), and drainage (Dr) fluxes were subsequently disaggregated into their respective green and blue components based on the proportional composition of green and blue water within the soil at that specific time step. Similarly, surface runoff (RO) occurring on any given day was apportioned into its green and blue constituents based on the relative contributions of rainfall and irrigation to the total water input. This approach enabled the precise estimation of daily changes in green soil water stocks originating from rainfall (Sg) and blue soil water stocks derived from irrigation (SbI). These estimations were performed using Equations "(1)" and "(2)", consistent with established methodologies in the scientific literature [30, 53].

$$Sgt = Sgt - 1 + Pt - ROt\left(\frac{Pt}{It + Pt}\right) - (Dt + ETt)\left(\frac{Sgt - 1}{St - 1}\right) \quad (1)$$

$$Sbt = Sbt - 1 + It - \left(\frac{It}{It + Pt}\right) - (Dt + ETt)\left(\frac{Sbt - 1}{St - 1}\right) \quad (2)$$

Where Sg is the green soil water content (mm), Sb the blue soil water content (mm), P is precipitation (mm), I is irrigation (mm), RO is the surface runoff (mm), D is deep percolation (mm), E is soil evaporation (mm), and T is crop transpiration (mm), the subscript 't' denotes time.

C. Consumptive Water Use Calculation

The consumptive green and blue crop water use (CWU, m3 ha-1) was calculated by an accumulation of daily ET, (mm day-1) from rain "(3)"or irrigation "(4)" over the complete growing period as follows:

$$CWUg = 10\sum_{t=1}^{lgp}\frac{Sgt}{St}ETt \quad (3)$$

$$CWUb = 10 \times \sum_{t=1}^{lgp}\frac{SbIt}{St}ETt \quad (4)$$

Where: *CWUg* represents the green water consumption (m^3), and *CWUb* the blue water consumption (m^3) over the entire growing season. *Sg* denotes the green soil water content (mm) and *Sb* the blue soil water content (mm). *ETt* signifies the total green and blue evapotranspiration accumulated over the growing period (mm), A conversion factor of 10 is applied to transform water depths in millimeters (mm) into water volumes per land surface in cubic meters per hectare m^3/ha. All summations are performed from the day of planting (t = 1) until the day of harvest (*lgp*, representing the length of the growing period in days).

D. Water Footprint Calculation

Then to get the WF for each component of the water, green or blue CWU was divided by the marketable yield obtained after harvest (Hoekstra, et al., 2011) for each selected crop "(5)" and "(6)" as follows:.

$$WFg = CWUg/Y \quad (5)$$

$$WFb = CWUb/Y \quad (6)$$

Where:

WFg is the green water footprint and

WFb is the blue water footprint, both in m^3/t,

Y is the yield of the crop (t).

Crop-specific simulations were performed only in the agro-ecological zones where each crop is predominantly cultivated in Ethiopia to ensure realistic water footprint estimates. Prior to statistical analysis, the assumptions of normality and homogeneity of variance were evaluated. As the WF data did not satisfy the normality assumption, generalized linear models (GLMs) with a Gamma distribution and inverse link function were used instead of classical ANOVA. Type II likelihood ratio tests were then performed to evaluate the effects of evapotranspiration, crop type, and agroecological zone. All statistical analyses were conducted using R software [54].

E. Data Sources

1) Crop data Cereals are the cornerstone of Ethiopia's agricultural sector and the primary source of food for its population. They dominate both the cultivated land area and the total production volume in the country [38]. In Ethiopian agriculture, cereals are the predominant food crops. Over a ten-year period (2010 to 2019), data from the Central Statistical Agency (CSA) indicated that cereals occupied approximately 70.1% of the total crop area, amounting to 9,943,448.11 hectares. The average production of cereals during this period constituted 69.3% (22,697,895 tons) of the total crop production in the country (CSA, 2010-2019). The major cereal crops such as teff, maize, wheat, and sorghum are major contributors to both the cultivated area and overall production. Barley is also a significant cereal crop in

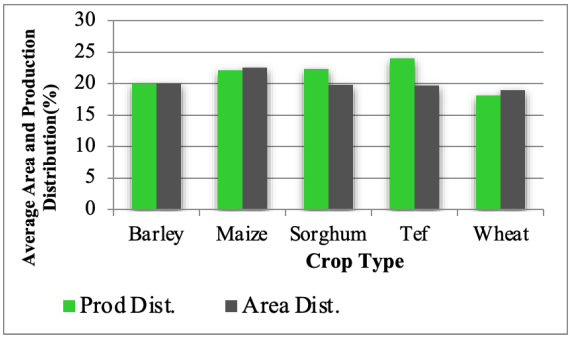


Fig. 2. Illustrates15-years average Area and Production distribution percentage of selected crops in Ethiopia (Source: Central statistical Agency of Ethiopia (CSA) from 2004 to 2018) (CSA, 2004-2018)

Ethiopia "Fig. 2". These five crops form the core of Ethiopia's agriculture and food economy [55]. While these cereals are grown throughout Ethiopia, output levels vary considerably by region [56]. More recently according to the World Bank [57], in 2022, the cultivated land area for cereals in Ethiopia was approximately 11.2 million hectares, with a total production exceeding 31.6 million metric tons [58]. Therefore these five major cereals are selected for this research. Crop input parameters for those selected crops were adopted from Dirk, *et al.* [52].

2) Climate and soil data Climatic data, including daily minimum and maximum temperature and daily precipitation for the primary stations of Ethiopia from 2002 to 2018, were obtained as unpublished data from the Ethiopian Meteorological Institute (2025, personal communication). The reference evapotranspiration data required to run the AquaCrop-OS model were obtained from the MERRA-2 reanalysis dataset provided by the National Aeronautics and Space Administration (NASA) Global Modeling and Assimilation Office (GMAO), accessed via the Climate Engine website (https://app.climateengine.com/climateengine), based on the selected location of primary meteorological stations of Ethiopia found in each agroecology "Fig. 1". Soil texture data for Ethiopia were extracted from data available at the ISRIC - World Soil Information website (https://www.isric.org/), and the textural proportion values were identified using the soil textural triangle [59].

III. Results and Discussions

This study presents a comprehensive analysis of the green and blue WFs of Ethiopia's major cereal crops. To statistically evaluate the observed spatial and temporal patterns, Type II likelihood ratio tests were performed using generalized linear models with a Gamma distribution and inverse link function (Table I). The results showed that evapotranspiration, crop type, and agroecological zone had significant effects on the green, blue, and total WF ($p < 0.001$). In contrast, year had a significant effect on the green and total WFs but not on the blue WF. These findings provide statistical support for the observed spatial variation among cereal crops and agroecological zones, while indicating that temporal changes were evident only for the green and total WF.

TABLE I. Type II likelihood ratio tests for the effects of year evapotranspiration, crop type, and agroecological zone on green, blue, and total water footprints.

WF	Predictor	LRX^2	Df	Pr_Value
WFg	Year	41.35	1	<0.0001
	ET	29.74	1	<0.0001
	Crop_Type	1667.89	4	<0.0001
	Agroecologies	220.11	2	<0.0001
WFb	Year	0.182	1	>0.5
	ET	273.134	1	<0.0001
	Crop_Type	112.266	4	<0.0001
	Agroecologies	35.681	2	<0.0001
WFT	Year	47.7	1	<0.0001
	ET	1085.0	1	<0.0001
	Crop_Type	5410.5	4	<0.0001
	Agroecologies	98.7	2	<0.0001

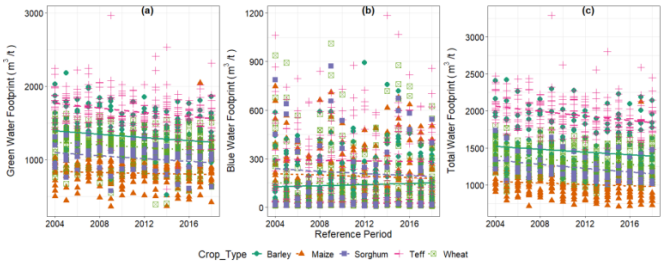


Fig. 3. Indicates the mean green (a), blue (b), and total water footprint (c) of the selected crops in Ethiopia for the growing seasons from 2004 to 2018

A. Temporal Variation of Water Footprint (2004–2018)

The overall statistical analysis, the temporal variation in WF was further examined over the 2004–2018 study period "Fig. 3". The generalized linear model indicated that year had a significant effect on the green and total WF Table I ($p < 0.001$), confirming the presence of temporal variation. However, the magnitude of these changes differed among the cereal crops. As shown in "Fig. 3c", barley, maize, sorghum, and wheat exhibited relatively small fluctuations in total WF throughout the study period, whereas teff showed a clear and consistent decline from 2004 to 2018. A similar pattern was observed for the green WF "Fig. 3a". In contrast, no clear temporal trend was evident for the blue WF "Fig. 3b", which agrees with the statistical analysis indicating that year had no significant effect on blue WF. The declining trend observed for teff may reflect improvements in crop productivity, changes in climatic conditions, or other factors influencing water use efficiency over time [39, 40]. Given teff's relatively high WF, these findings highlight opportunities to improve water use efficiency through targeted management practices and productivity-enhancing interventions[1, 30].

B. Spatial variation of WF across agroecologies

Building on the overall statistical analysis, the spatial variation in WF across Ethiopia's three major agroecological zones was further examined "Figs. 4 and 5". The generalized linear model showed that agroecological zone had a significant effect on the green, blue, and total WFs Table I ($p < 0.001$), confirming significant spatial variation. "Fig. 4" illustrates

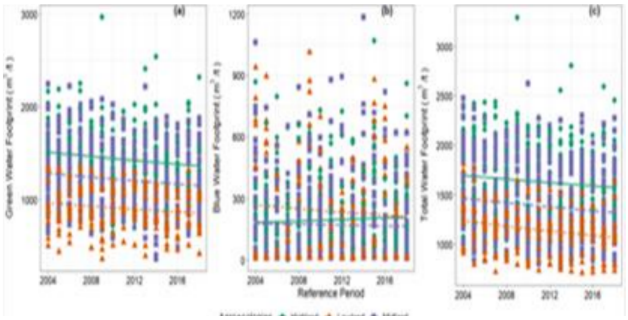


Fig. 4. The mean total annual water footprint (green(a) blue (b) and total (c)) across the three agroecologies over the reference period of 2004-2018

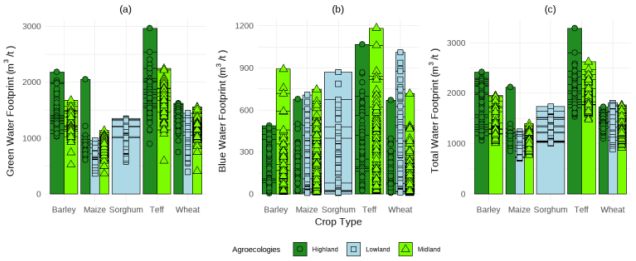


Fig. 5. Displays bar graph illustrating the consumptive water footprint (a=green, b=blue and c= green + blue) (WFT in $m^3\ t^{-1}$) for the selected crops across the three agro-ecologies

the temporal distribution of green, blue, and total WF within each agroecological zone from 2004 to 2018, while "Fig. 5" summarizes the average consumptive WF of each cereal crop across the three agroecological zones.

As shown in "Figs. 4 and 5", the highland agroecology generally exhibited the highest green and total WFs, whereas the lowland agroecology consistently showed the lowest values, with the midland agroecology falling between the two. These spatial differences are likely associated with variations in climatic conditions, effective rainfall, crop productivity, and crop water use characteristics across the three agroecological zones. "Fig. 5" further demonstrates that this pattern was consistent for most cereal crops, although the magnitude of the differences varied among crop species.

The spatial variation observed in this study is consistent with previous findings. Hirpa*, et al.* [35] reported higher WF for major cereal crops in the highland and midland areas of the Upper Awash Basin than in the lowlands. Similarly Yimam and Çapar [33], found higher green and blue WF for teff in predominantly highland and midland regions, while Nouri*, et al.* [53] demonstrated substantial differences in WF across climatic zones. These findings highlight the importance of considering agroecological variability when evaluating crop WF and developing location-specific water management strategies.

C. Mean Green-Blue Water Footprint Values

The mean green–blue WF values were further summarized for each agroecological zone and cereal crop Table II. The analysis showed that the mean WF ranged from 1137.43 $m^3\ t^{-1}$ in the lowland agroecology to 1536.37 $m^3\ t^{-1}$ in the highlands. Consistent with the spatial patterns presented in "Figs. 4 and 5", the lowlands exhibited the lowest mean WF, indicating relatively higher water use efficiency, whereas the highlands recorded the highest mean WF. These differences are closely associated with variations in crop productivity and agroecological conditions. As shown in Table III, cereal yields were generally lower in the highlands than in the lowlands, particularly for teff and barley. Since WF is expressed as the volume of water consumed per unit of crop production ($m^3\ t^{-1}$), lower yields resulted in higher WF values despite comparable crop water use.

Among the individual cereal crops, teff consistently exhibited the highest green–blue WF, reaching 2019.47 $m^3\ t^{-1}$ in the highlands, followed by barley (1469.87 $m^3\ t^{-1}$). In contrast, maize cultivated in the lowlands recorded the lowest WF (892.66 $m^3\ t^{-1}$), followed by sorghum (1241.11 $m^3\ t^{-1}$). These findings demonstrate that teff is the most water-intensive cereal crop on a unit production basis, primarily because of its relatively low grain yield, whereas maize achieves the greatest water use efficiency owing to its comparatively high productivity across the study agroecologies.

The observed low WF for maize agrees with the global assessment of Mekonnen and Hoekstra [60] , who identified maize as one of the most water-efficient cereal crops. In contrast, while Mekonnen and Hoekstra [61] reported sorghum as having the highest global WF, the present study identified teff as the most water-intensive crop across Ethiopia's agroecological zones. This difference is likely explained by teff's relatively low yield under Ethiopian production conditions, which increases the amount of water required to produce one tonne of grain. Furthermore, teff was not included in their global assessment because its cultivation is largely confined to Ethiopia and Eritrea.

The present findings are also comparable with previous studies conducted in Ethiopia. Yimam and Çapar [33] reported an average green–blue WF of 1772 $m^3\ t^{-1}$ for teff, approximately 12% lower than the maximum value observed in the Ethiopian highlands in this study. This difference may reflect the longer study period (2004–2018) used in the present analysis, which captured greater inter annual variability in climate and crop water use than a single-season assessment. Likewise, Hirpa*, et al.* [35] reported substantially higher WF values for teff (4205 $m^3\ t^{-1}$) and sorghum (2539 $m^3\ t^{-1}$) in Debre Zeit and Melkasa. These differences are likely attributable to differences in study scale, climatic conditions, input datasets, methodology, and the production environments considered.

D. Evapotranspiration and Water Footprint Relationships

The generalized linear model analysis showed that ET had a highly significant effect on the green, blue, and total WF ($p < 0.001$); Table I, confirming that ET is one of the principal factors influencing consumptive water use across Ethiopia's cereal production systems. "Fig. 6" illustrates the relationship between ET and WF for the individual cereal crops. In general, total WF increased with increasing ET, although the strength of this relationship differed among crops. Barley, sorghum, and wheat exhibited a clearer positive response,

TABLE II. SIMULATED YIELDS (THA^{-1}) OF SELECTED CROPS IN EACH YEAR ACROSS THE THREE AGROECOLOGIES

	Highland				Midland				Lowland		
Year	*Barley*	*Maize*	*Teff*	*Wheat*	*Barley*	*Maize*	*Teff*	*Wheat*	*Maize*	*Sorghum*	*Wheat*
2004	2.47	4.06	1.60	2.89	2.40	3.97	1.67	2.88	4.15	2.55	2.56
2005	2.47	4.09	1.51	2.9	2.40	4.00	1.69	2.89	4.17	2.53	2.59
2006	2.49	4.08	1.53	2.99	2.40	4.04	1.66	2.92	4.22	2.47	2.53
2007	2.50	4.17	1.49	2.96	2.42	4.13	1.66	2.95	4.23	2.51	2.66
2008	2.50	4.18	1.61	2.87	2.41	4.12	1.66	2.90	4.19	2.45	2.60
2009	2.54	4.02	1.44	2.93	2.43	4.12	1.77	2.91	4.12	2.61	2.7
2010	2.55	3.89	1.49	3.01	2.46	4.24	1.59	2.98	4.29	2.50	2.78
2011	2.55	4.23	1.54	2.97	2.44	4.31	1.74	2.96	4.22	2.66	2.75
2012	2.57	4.15	1.59	3.02	2.46	4.07	1.78	2.99	4.29	2.45	2.60
2013	2.60	4.28	1.54	3.03	2.47	4.12	1.62	3.01	4.37	2.55	2.63
2014	2.60	4.12	1.44	3.01	2.50	4.23	1.60	3.02	4.43	2.61	2.73
2015	2.59	4.27	1.62	2.93	2.50	4.25	1.68	2.94	4.15	2.70	2.76
2016	2.59	4.10	1.67	3.04	2.49	4.34	1.79	2.99	4.31	2.62	2.80
2017	2.62	3.32	1.63	2.99	2.48	4.26	1.57	2.98	4.34	2.58	2.67
2018	2.66	3.93	1.64	3.10	2.53	4.24	1.70	3.05	4.28	2.67	2.76
Av.	2.55	4.06	1.56	2.98	2.45	4.16	1.68	2.96	4.25	2.56	2.67

TABLE III. RESULTS OF WATER FOOTPRINT (M^{3}T^{-1}) FOR MAJOR CROPS ACROSS THE THREE AGROECOLOGIES

	Highland			Midland			Lowland			
Selected Crops	*Green*	*Blue*	*Green-Blue*	*Green*	*Blue*	*Green-Blue*	*Green*	*Blue*	*Green-Blue*	*Average Green-Blue*
Barley	1461.91	140.32	1602.23	1199.47	138.04	1337.51				1469.87
Maize	883.23	221.87	1105.10	851.34	182.86	1034.19	693.07	199.58	892.66	1010.65
Teff	1708.36	311.11	2019.47	1626.23	268.92	1895.15				1957.31
Wheat	1314.29	104.37	1418.66	1194.19	97.23	1291.42	987.65	290.88	1278.52	1329.53
Sorghum							1027.84	212.93	1241.11	1241.11
Average	1341.95	194.42	1536.37	1217.81	171.76	1389.57	902.85	234.46	1137.43	1354.46

whereas maize and teff showed comparatively weaker trends, reflecting differences in crop physiology, productivity, and water-use characteristics. These findings are consistent with previous studies that identified ET as a major determinant of consumptive WF [50, 53]. who emphasize ET as a primary driver of the consumptive WF. “Fig. 7” presents the same relationship across the three agroecological zones. Although ET remained a statistically significant predictor of WF Table I, the relationship was less distinct when the data were grouped by agroecological zone. This is expected because each zone contains different crop types, climatic conditions, and management practices, which increase variability and reduce the apparent strength of the relationship. Nevertheless, the lowland zone exhibited a relatively stronger increase in blue WF with increasing ET, reflecting greater dependence on irrigation under warmer and drier environmental conditions.

Overall, these findings demonstrate that ET is a key driver of cereal WF in Ethiopia. However, the magnitude of its influence depends on crop type and agroecological conditions, highlighting the need for crop- and location-specific water management strategies to improve agricultural water productivity.

While the results provide comprehensive insights into the spatial and temporal variation of cereal WF across

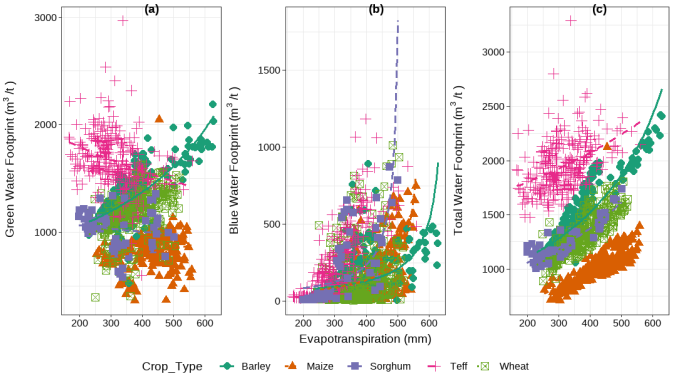


Fig. 6. Relationship between evapotranspiration and the green (a), blue (b), and total (c) water footprints of the selected cereal crops.

Ethiopia and highlight their implications for improving agricultural water management, they should be interpreted in light of several study limitations. First, all AquaCrop-OS simulations were conducted using a uniform clay loam soil to ensure a consistent comparison among agroecological zones. Although this approach minimized variability arising from soil parameterization, it does not fully represent Ethiopia’s diverse soil conditions, which may influence the partitioning

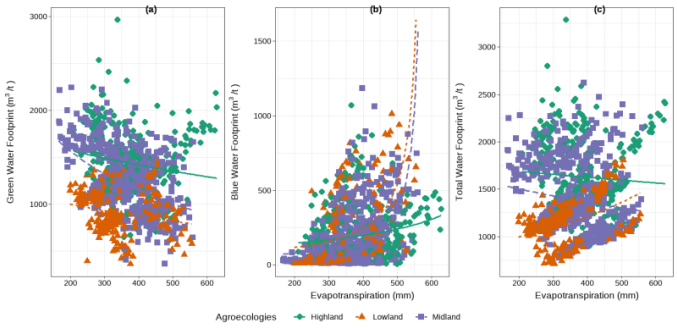


Fig. 7. Relationship between evapotranspiration and the green (a), blue (b), and total (c) water footprints across Ethiopia's agroecological zones.

of green and blue water. Future studies should incorporate spatially distributed soil properties to improve the accuracy of WF estimates. Second, the simulated crop yields and ET were not validated against long-term observed data because consistent field measurements were unavailable for all crops and agroecological zones throughout the study period. Despite this limitation, the model was implemented using standardized datasets, established AquaCrop-OS procedures, and consistent input parameters, providing a robust basis for comparative WF assessment. Future research should integrate long-term field observations to validate the simulated outputs and further strengthen confidence in the estimated WF.

IV. CONCLUSION

This study quantified the green and blue WF of Ethiopia's major cereal crops across different agroecological zones over a 15-year period using the AquaCrop-OS model. The results demonstrated significant spatial variation in water footprint among crops and agroecological zones, while temporal variation remained relatively small for most cereals. Teff consistently exhibited the highest WF, particularly in the highland and midland agroecologies, whereas maize grown in the lowlands showed the lowest WF, indicating greater water-use efficiency under these conditions. The statistical analysis further confirmed that evapotranspiration, crop type, and agroecological zone significantly influenced WF patterns.

These findings emphasize that improving agricultural water productivity requires crop- and location-specific water management strategies rather than uniform recommendations across Ethiopia. Particular attention should be given to reducing the WF of teff through improved agronomic practices, increased productivity, and the adoption of water-efficient technologies. Conversely, the relatively high water-use efficiency of maize in the lowlands demonstrates the potential for optimizing cereal production under suitable agroecological conditions.

Overall, this study provides the first comprehensive spatial and temporal assessment of cereal WF across Ethiopia's major agroecological zones. The findings provide a valuable scientific basis for developing targeted irrigation and water management strategies that support sustainable agricultural production, efficient water resource use, and long-term food security under increasing climate and water resource pressures.

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References

[1] E. Teferi, T. Kassawmar, W. Bewket, G. Zeleke, G.T. Ayele, G. O'Donnell, C. Walsh, Rainfed agriculture in Ethiopia: a systematic review of green water management pathways to improve water and food security, Frontiers in Agronomy 7 (2025). https://doi.org/https://doi.org/10.3389/fagro.2025.1418024.

[2] K.M. Rakesh, Fresh water availability and its global challenge, British Journal of Multidisciplinary Advanced Studies: 4(3) (2023) 1-78. https://doi.org/https://doi.org/10.37745/bjmas.2022.0207.

[3] S.J. Zwart, W.G.M. Bastiaanssen, C. de Fraiture, D.J. Molden, WATPRO: A remote sensing based model for mapping water productivity of wheat, Agricultural Water Management 97(10) (2010) 1628-1636. https://doi.org/https://doi.org/10.1016/j.agwat.2010.05.017.

[4] B. Wu, F. Tian, M. Zhang, S. Piao, H. Zeng, W. Zhu, J. Liu, A. Elnashar, Y. Lu, Quantifying global agricultural water appropriation with data derived from earth observations, Cleaner Production 358 (2022) 131891. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.131891.

[5] S.M.F. Islam, Z. Karim, Water: The Consequences of Climate Change, in: V.V.a.A.H.T. Mohammad Hossein Davood Abadi Farahani (Ed.), Desalination - Challenges and Opportunities, IntechOpen2020, p. 57. https://doi.org/10.5772/intechopen.85919.

[6] A. Hoekstra, L. Zhuo, The effect of different agricultural management practices on irrigation efficiency, water use efficiency and green and blue water footprint, Frontiers of Agricultural Science and Engineering 4(2) (2017). https://doi.org/10.15302/j-fase-2017149.

[7] A. Hoekstra, P. Chung, Virtual water trade: a quantification of virtual water flows between nations in relation to international crop trade., VALUE OF WATER RESEARCH REPORT SERIES NO. 11, IHE Delft, 2002.

[8] J. Liu, A.J.B. Zehnder, H. Yang, Global consumptive water use for crop production: The importance of green water and virtual water, WATER RESOURCES RESEARCH 45 (2009). https://doi.org/10.1029/2007WR006051.

[9] A. Hoekstra, A.K. Chapagain, M.M. Aldaya, M.M. Mekonnen, The Water Footprint Assessment Manual Setting the Global Standard, Earthscan London, 2011. https://doi.org/https://doi.org/10.4324/9781849775526.

[10] A. Hoekstra, A.K. Chapagain, M.M. Aldaya, M.M. Mekonnen, Water Footprint Manual:State of the Art 2009. , Water Footprint Network., Enschede, The Netherlands: , 2009.

[11] L. García-Herrero, D. Gibin, M. Damiani, E. Sanyé-Mengual, S. Sala, What is the water footprint of EU food consumption? A comparison of water footprint assessment methods, Journal of Cleaner Production 415 (2023) 137807. https://doi.org/https://doi.org/10.1016/j.jclepro.2023.137807.

[12] R.J. Hogeboom, The water footprint concept and water's grand environmental challenges, One Earth 2(3) (2020) 218-222. https://doi.org/https://doi.org/10.1016/j.oneear.2020.02.010.

[13] A. Arabi, A. Alizadeh, Y. Vahab Rajaee, K. Jam, N. Niknia, Agricultural Water Foot Print and Virtual Water Budget in Iran Related to the Consumption of Crop Products by Conserving Irrigation Efficiency, Journal of Water Resource and Protection 04(05) (2012) 318-324. https://doi.org/10.4236/jwarp.2012.45035.

[14] R.H. Pérez-Espejo, R.M. Constantino-Toto, H.R. Dávila-Ibáñez, Water, food and welfare: water footprint as a complementary approach to water management in Mexico, SpringerNature2016. https://doi.org/https://doi.org/10.1007/978-3-319-28824-6.

[15] A.M. Boulay, A.Y. Hoekstra, S. Vionnet, Complementarities of water-focused life cycle assessment and water footprint assessment, Environ Sci Technol 47(21) (2013) 11926-7. https://doi.org/https://doi.org/10.1021/es403928f.

[16] K. Feng, K. Hubacek, J. Minx, Y.L. Siu, A. Chapagain, Y. Yu, D. Guan, J. Barrett, Spatially explicit analysis of water footprints in the UK, Water 3(1) (2010) 47-63. https://doi.org/https://doi.org/10.3390/w3010047.

[17] C. Makate, R. Wang, S. Tatsvarei, Water footprint concept and methodology for warranting sustainability in human-induced water use and governance, Sustainable Water Resources Management 4 (2017) 91-103. https://doi.org/ https://doi.org/10.1007/s40899-017-0143-2.

[18] I. Kim, K.-s. Kim, Estimation of water footprint for major agricultural and livestock products in Korea, Sustainability 11(10) (2019) 2980. https://doi.org/https://doi.org/10.3390/su11102980.

[19] B. Berhanu, Y. Seleshi, A.M. Melesse, hydropolitics, Surface water and groundwater resources of Ethiopia: potentials and challenges of water resources development, in: A. Melesse, Abtew, W., Setegn, S. (eds) (Ed.), Nile River Basin, Springer,2014. https://doi.org/Cham. https://doi.org/10.1007/978-3-319-02720-3_6.

[20] H. Verhoeven, The Grand Ethiopian Renaissance Dam: Africa's Water Tower, Environmental Justice & Infrastructural Power, Daedalus 150(4) (2021) 159-180. https://doi.org/https://doi.org/10.1162/DAED_a_01878.

[21] A.K. Bojer, M.W. Abshare, S. Nadarajah, Evaluating the effect of climate change and fast population growth on water supply and demand in Jimma town, Ethiopia, using the WEAP modeling tool, Journal of Water and Climate Change 16(4) (2025) 1586-1617. https://doi.org/https://doi.org/10.2166/wcc.2025.751.

[22] T. Abraha, A. Tibebu, G. Ephrem, Rapid urbanization and the growing water risk challenges in Ethiopia: the need for water sensitive thinking, Frontiers in Water 4 (2022) 890229. https://doi.org/https://doi.org/10.3389/frwa.2022.890229.

[23] A.A. Mekonen, A.B. Berlie, M.B. Ferede, Spatial and temporal drought incidence analysis in the northeastern highlands of Ethiopia, Geoenvironmental Disasters 7 (2020) 1-17. https://doi.org/https://doi.org/10.1186/s40677-020-0146-4.

[24] E. Assegide, T. Alamirew, Y.T. Dile, H. Bayabil, B. Tessema, G. Zeleke, A synthesis of surface water quality in Awash Basin, Ethiopia, Frontiers in water 4 (2022) 782124. https://doi.org/https://doi.org/10.3389/frwa.2022.782124.

[25] W.K. Wakejo, B.T. Meshesha, N.G. Habtu, Y.G. Mekonnen, Anthropogenic nitrate contamination of water resources in Ethiopia: an overview, Water Supply 22(11) (2022) 8157-8172. https://doi.org/

[26] https://doi.org/10.2166/ws.2022.377.

[27] A.K. Jewaro, İ.J.A.A.T. Diler, The state of water management in Ethiopia: problems and solution approaches, 17(4) (2021) 556-568. https://doi.org/https://doi.org/10.22392/actaquatr.915819.

[28] T. Sinore, F. Wang, Impact of climate change on agriculture and adaptation strategies in Ethiopia: A meta-analysis, Heliyon 10(4) (2024). https://doi.org/https://doi.org/10.1016/j.heliyon.2024.e26103.

[29] T. Belay, T.M. Lebeza, Livelihood vulnerability of rural households to climate variability and change: An agroecological system-based approach in northwestern Ethiopia, Heliyon 10(23) (2024). https://doi.org/https://doi.org/10.1016/j.heliyon.2024.e40570.

[30] A. Abera, N.E. Verhoest, S.A. Tilahun, T. Alamirew, E. Adgo, M.M. Moges, J. Nyssen, Performance of small-scale irrigation schemes in Lake Tana Basin of Ethiopia: technical and socio-political attributes, Physical Geography 40(3) (2019) 227-251. https://doi.org/https://doi.org/10.1080/02723646.2018.1516445.

[31] A.D. Chukalla, M.S. Krol, A.Y. Hoekstra, Green and blue water footprint reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching, Hydrology and Earth System Sciences 19(12) (2015) 4877-4891. https://doi.org/10.5194/hess-19-4877-2015.

[32] M.M. Mekonnen, A.Y. Hoekstra, A global and high-resolution assessment of the green, blue and grey water footprint of wheat, Hydrology and Earth System Sciences 14(7) (2010) 1259-1276. https://doi.org/https://doi.org/10.5194/hess-14-1259-2010, 2010.

[33] E. Shtull-Trauring, I. Aviani, D. Avisar, N. Bernstein, Integrating high resolution water footprint and GIS for promoting water efficiency in the agricultural sector: A case study of plantation crops in the Jordan Valley, Frontiers in Plant Science 7 (2016) 1877. https://doi.org/https://doi.org/10.3389/fpls.2016.01877.

[34] M.T. Yimam, G. Çapar, Evaluation of teff production in Ethiopia using water footprint analysis for food security, Harran Tarım ve Gıda Bilimleri Dergisi 29(1) (2025) 49-64. https://doi.org/https://doi.org/10.29050/harranziraat.1578338.

[35] H.A. Ulatu, T.L. Tola, M.T. Adugna, Estimating Green and Blue Water Footprint of Major Cereal and Vegetable Crops in Salale Zone, Oromia, Ethiopia, Journal of Water Resource and Protection 21(1) (2023) 83-96. https://doi.org/https://doi.org/10.2965/jwet.21-156.

[36] B.A. Hirpa, G.B. Adane, A. Asrat, D. Nedaw, Spatio-temporal variability and trend of water footprints in the upper Awash basin, central Ethiopia, Journal of Hydrology 608 (2022) 127686. https://doi.org/https://doi.org/10.1016/j.jhydrol.2022.127686.

[37] M.T. Wakjira, N. Peleg, J. Six, P. Molnar, Green water availability and water-limited crop yields under a changing climate in Ethiopia, Hydrology and Earth System Sciences 29(4) (2025) 863-886. https://doi.org/https://doi.org/10.5194/hess-29-863-2025.

[38] A.T. Hordofa, O.T. Leta, T. Alamirew, A.D. Chukalla, Climate change impacts on blue and green water of Meki River Sub-Basin, Water Resources Management 37(6) (2023) 2835-2851. https://doi.org/https://doi.org/10.1007/s11269-023-03490-4.

[39] W. Gizaw, D. Assegid, Trend of cereal crops production area and productivity, in Ethiopia, Journal of Cereals and Oilseeds 12(1) (2021). https://doi.org/ https://doi.org/10.5897/JCO2020.0206

[40] K. Lewis, Understanding climate as a driver of food insecurity in Ethiopia, Climatic Change 144 (2017) 317-328. https://doi.org/https://doi.org/10.1007/s10584-017-2036-7.

[41] T. Alemu, A. Mengistu, Impacts of climate change on food security in Ethiopia: adaptation and mitigation options: a review, in: P. Castro, Azul, A., Leal Filho, W., Azeiteiro, U. (Ed.), Climate Change-Resilient Agriculture and Agroforestry, Climate Change Management. Springer, Cham2019, pp. 397-412. https://doi.org/https://doi.org/10.1007/978-3-319-75004-0_23.

[42] A.Y. Kassaye, G. Shao, X. Wang, E. Shifaw, S. Wu, Impact of climate change on the staple food crops yield in Ethiopia: implications for food security, Theoretical Applied Climatology 145(1) (2021) 327-343. https://doi.org/https://doi.org/10.1007/s00704-021-03635-8.

[43] World
Bank, World Bank Open Data: Population, total - Ethiopia. . https://data.worldbank.org/indicator/SP.POP.TOTL?locations=ET, 2024.

[44] A.W. Worqlul, J. Jeong, Y.T. Dile, J. Osorio, P. Schmitter, T. Gerik, R. Srinivasan, N. Clark, Assessing potential land suitable for surface irrigation using groundwater in Ethiopia, Applied geography 85 (2017) 1-13. https://doi.org/https://doi.org/10.1016/j.apgeog.2017.05.010.

[45] MoWR, GW-MATE, Ethiopia: strategic framework for managed groundwater development. Ministry of Water, Energy and Irrigation., MoWR, 2011.

[46] T. Foster, N. Brozović, A. Butler, C. Neale, D. Raes, P. Steduto, E. Fereres, T.C. Hsiao, AquaCrop-OS: An open source version of FAO's crop water productivity model, Agricultural water management 181 (2017) 18-22. https://doi.org/https://doi.org/10.1016/j.agwat.2016.11.015.

[47] P. Steduto, T.C. Hsiao, D. Raes, E. Fereres, AquaCrop—The FAO crop model to simulate yield response to water: I. Concepts and underlying principles, Agronomy Journal 101(3) (2009) 426-437. https://doi.org/https://doi.org/10.2134/agronj2008.0139s.

[48] T.C. Hsiao, L. Heng, P. Steduto, B. Rojas-Lara, D. Raes, E. Fereres, quaCrop—The FAO Crop Model to Simulate Yield Response to Water: III. Parameterization and Testing for Maize, Agronomy Journal 101(3) (2009). https://doi.org/10.2134/agronj2008.0218s.

[49] R. Dirk, S. Pasquale, H.T. C, F. Elias, AquaCrop—the FAO crop model to simulate yield response to water: II. Main algorithms and software description, Agronomy Journal 101(3) (2009) 438-447. https://doi.org/doi:10.2134/agronj2008.0140s.

[50] E. Vanuytrecht, D. Raes, P. Steduto, T.C. Hsiao, E. Fereres, L.K. Heng, M.G. Vila, P.M. Moreno, AquaCrop: FAO's crop water productivity and yield response model, Environmental Modelling Software 62 (2014) 351-360. https://doi.org/http://dx.doi.org/10.1016/j.envsoft.2014.08.005.

[51] M.K. Mehla, M. Kothari, P.K. Singh, S.R. Bhakar, K.K. Yadav, Water footprint assessment and its importance in Indian context: a meta-review, Water Supply 23(8) (2023) 3113-3127. https://doi.org/

[52] https://doi.org/10.2166/ws.2023.174.

[53] R. Sandhu, S. Irmak, Assessment of AquaCrop model in simulating maize canopy cover, soil-water, evapotranspiration, yield, and water productivity for different planting dates and densities under irrigated and rainfed conditions, Agricultural Water Management 224 (2019) 105753. https://doi.org/https://doi.org/10.1016/j.agwat.2019.105753.

[54] R. Dirk, P. Steduto, C. Hsiao, E. Fereres, Reference Manual, Annexes–AquaCrop, Version 7.0–August 2022, FAO, Rome, 2022.

[55] H. Nouri, B. Stokvis, A. Galindo, M. Blatchford, A.Y. Hoekstra, Water scarcity alleviation through water footprint reduction in agriculture: The effect of soil mulching and drip irrigation, Sci Total Environ 653 (2019) 241-252. https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.10.311.

[56] R Core Team, R: A Language and Environment for Statistical Computing., (Version 4.4.2), R Foundation for Statistical Computing, 2024.

[57] A.S. Taffesse, P. Dorosh, S.A. Gemessa, Crop production in Ethiopia: Regional patterns and trends, ESSP II Working Paper No. 0016, International Food Policy Research Institute, Ethiopia Strategy Support Program II (ESSP II), Ethiopia, 2012, p. 53.

[58] CSA, Agricultural Sample Survey 2021/22 (2014 E.C.) Volume I: Report on Area, Production and Yield of Major Crops (Meher Season). https://ess.gov.et/download/the-2014-ec-meher-season-report-on-area-and-production-of-major-crops_final-1/, 2022 1).

[59] World Bank, Ethiopia - Land Under Cereal Production (hectares). https://tradingeconomics.com/ethiopia/land-under-cereal-production-hectares-wb-data.html, 2022 (accessed Jan 23 2025).

[60] World Bank, Ethiopia - Cereal Production (metric Tons) https://tradingeconomics.com/ethiopia/cereal-production-metric-tons-wb-data.html, 2022 (accessed Jan 23 2025).

[61] K.E. Saxton, W. Rawls, Soil water characteristic estimates by texture and organic matter for hydrologic solutions, Soil science society of America Journal 70(5) (2006) 1569-1578. https://doi.org/ https://doi.org/10.2136/sssaj2005.0117.

[62] M.M. Mekonnen, A. Hoekstra, The green, blue and grey water footprint of crops and derived crop products, Hydrol. Earth Syst. Sci 15(5) (2011) 1577-1600. https://doi.org/https://doi.org/10.5194/hess-15-1577-2011, 2011.

[63] M.M. Mekonnen, A. Hoekstra, Water footprint benchmarks for crop production: A first global assessment, Ecological indicators 46 (2014) 214-223. https://doi.org/http://dx.doi.org/10.1016/j.ecolind.2014.06.013.