Tanzania Journal of Science 50(1): 103-114, 2024
ISSN 0856-1761, e-ISSN 2507-7961

Green and Blue Water Footprints of Major Crops in the Wami/Ruvu Basin, Tanzania: Implications for Water Scarcity and Sustainability

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Received 7 August 2023, Revised 9 Feb 2024, Accepted 29 March 2024, Published April 2024
https://dx.doi.org/10.4314/tjs.v50i1.8

Abstract

Accurate estimation of the blue and green water requirements of the various crops cultivated in a water basin is essential for planning specific plant/crop irrigation schedules. In this study, the crop water requirements of the major crops grown in the Wami/Ruvu basin were determined using the FAO-CROPWAT model based on meteorological parameters: monthly maximum and minimum temperature, wind speed, mean relative humidity, sunshine hours, rainfall data, and effective rainfall for 23 hydro-meteorological stations distributed in the study area. The studied crops are rice, maize, beans, tomatoes, and sugarcane. The crop reference evapotranspiration (ET_o) and actual evapotranspiration (ET_c) for each crop were determined using crop coefficients (K_c) of various growth stages of crops. The results indicated that the total annual reference evapotranspiration (ET_o) was 1604 mm, whereas an average ET_o per month was 134 mm. The highest total irrigation water requirements were recorded in sugarcane, followed by rice, while the lowest water requirements were observed in beans and tomatoes. The results presented in this study may facilitate plant-specific water irrigation implementation and maximize crop production while conserving the environment.

Keywords: CLIMWAT database; Crop coefficient; Crop evapotranspiration; Reference evapotranspiration; CROPWAT model

Introduction

Water is a vital resource of critical importance to humans and the ecosystem. Globally, water is the most important natural resource due to its usage by all living systems (Gleick 2000). The threat of a decrease in freshwater is increasing due to agricultural production and, industrial and domestic usage (UNESCO 2009). The demand is projected to increase by 55% by 2050 due to growing demands from manufacturing (400%), thermal electricity generation (140%) and domestic use (130%) (UNESCO 2016). Most agricultural production is to feed the global population, which is increasing; the demand for food is expected to increase by 70% in 2050 to cope with a 40% increase in world population from seven billion to 9.3 billion between 2011 and 2050 (UNESCO 2012). According to the Bank of Tanzania 2020/21 annual report (URT 2021), agricultural activities contributed 26.9% of Tanzania's GDP in the 2020/2021 financial year. UNESCO (2018) points out that more than half of the global population will live in areas that suffer water scarcity for at least a month each year by 2050. Climate change is one of the factors for food and water security threats due to variabilities in precipitation (Kang et al. 2009, World Bank 2016). Therefore, the little water available needs to be used efficiently and effectively.

Water footprint and virtual water are considered to be effective tools to improve water-use efficiency (Zhang et al. 2019). The water footprint of agricultural products is the sum of the green and blue water footprints. The green water footprint is defined as the volume of rainwater evaporated and the blue water footprint is defined as the amount of surface water evaporated in the production process (ibid). Hoekstra et al. (2011) prepared the water footprint assessment manual with global standards whereby footprint concept, goal, scope, and methodology are stipulated therein. Green water refers to the portion of precipitation that infiltrates to become soil moisture or remains temporarily on top of the soil or vegetation, then eventually returns to the atmosphere via transpiration and evaporation. Bluewater refers to water that flows through either on or below the land surface and can be stored in aquifers, lakes, and reservoirs (Hoekstra et al. 2011).

Various research on water footprints has been conducted at global, local, and basin scales. Hoekstra et al. (2012) did monthly water scarcity globally on blue water footprints versus blue water availability. The findings were that growth in blue water footprint due to growing populations, changing food patterns, and increasing demand for biofuels together with the effects of climate change on runoff patterns, are likely to result in a worsening and expansion of water scarcity in many river basins. Similarly, some studies estimated green and blue water footprints at the national level. Ayres (2014) studied Germany's water footprint of transport fuels, the findings were that water footprint is a multidimensional indicator in capturing the water used in the production processes since it accounts for all freshwater used for the production or consumption of given commodities, including rain-fed agricultural production, diverted ground, and surface water and it enables the volumes of water that are used and polluted to be measured and located. Vincent et al. (2011) did water footprint in Belgium where it was observed that a very high proportion of the water footprint is associated with agricultural products. Despite the aforementioned studies, limited attention has been dedicated to characterizing water footprints along basins within subtropical environments, and evaluation of water footprints has predominantly focused on a restricted number of crops.

This paper aims to assess the amount of green and blue water utilized by major crops: Paddy, Maize, Tomato, Bean, and Sugarcane in the Wami/Ruvu Basin using water footprint techniques. Particularly, the paper estimated each crop's crop reference evapotranspiration (ET_o) and actual evapotranspiration (ET_c) within the basin. Studies of this nature may significantly reduce water scarcity by assessing water use efficiency and plant stresses.

Materials and Methods

Description of the study area

Wami/Ruvu basin is one of the nine water basins in mainland Tanzania, located in the East-Central area of Tanzania with an area of approximately 66,899 km^2. It is located between 4^0 54' 29'' to 7^0 38' 10'' South and longitude 35^0 38' 22'' to 39^0 16' 22'' East (Figure 1). The catchment forests of the Wami and Ruvu sub-basins are parts of the Eastern Arc Mountains that stretch from Tanzania to Southern Kenya. The Eastern Arc Mountains have several thousand species of flora and fauna, with some of the highest concentrations of endemism on Earth, that is, plants and animals not found anywhere else in the world (Burgess et al. 2007).

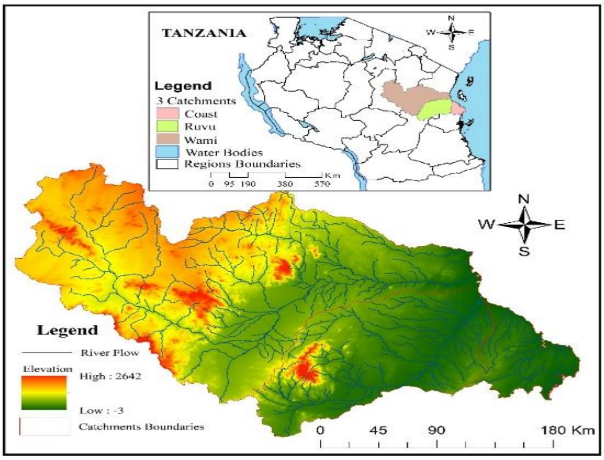

Figure 1: Location of Wami/Ruvu basin on the map of Tanzania (Source: URT 2019).

The water in the basin comes from two major rivers, Wami and Ruvu, that flow onward to the Indian Ocean. The Equatorial Intertropical Convergence Zone (ITCZ) influences the climate of the Wami/Ruvu basin. The basin consists of three sub-basins: Wami, Ruvu, and Coast. The basin has seven catchments: Kinyasungwe, Mkondoa, Wami, Upper Ruvu, Ngerengere, Lower Ruvu, and Coast (Figure 2).

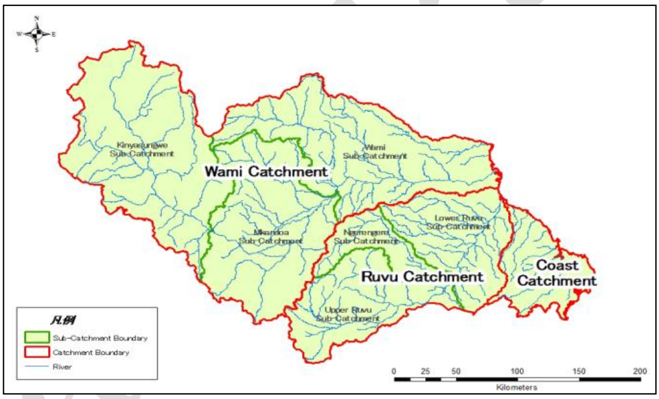

Figure 2: Sub-basins of Wami/Ruvu basin (Source: URT 2019).

The Basin intersects six regions: Dar es Salaam, Pwani, Morogoro, Tanga, Manyara and Dodoma, the latter being the national capital of Tanzania. Increased anthropogenic activities within the Wami/Ruvu basin have resulted in rapid population growth with various socio-economic activities, which have placed the basin under great threat of water scarcity.

General methodological approach

Flow diagram

The study was based on the schematic flow chart shown in Figure 3.

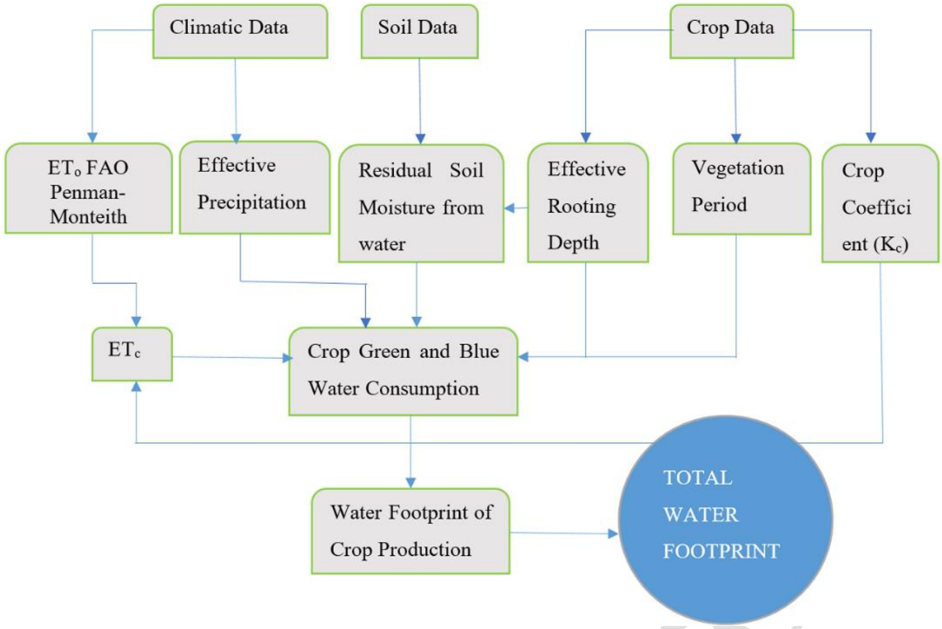

Figure 3: Flow diagram for calculation of water footprint of major crops in Wami/Ruvu basin (Adopted and modified from Yerli and Sahin 2022).

Data and sources

The major input data for the CROPWAT 8 model are soil type, weather/meteorological data, and Crop data.

Table 1: Data used and sources of information

Data type	Data source	Description
Weather	Tanzania Meteorological Agency (TMA) and FAO software CLIMWAT database	Precipitation, Temperature, Wind Speed, Sunshine Hours, and Relative Humidity
Soil	SOTERAF, National Soil Service and SUA	Soil characteristics
Crop	Integrated water management and development plan for Wami/Ruvu Basin (IWRMDP)	Paddy, Maize, Tomato, Bean and Sugarcane

Meteorological data

The Weather data: Temperature, Relative humidity, Sunshine Hours, Wind speed, and Precipitation are climatic data required for the model. These data were obtained from FAO software CLIMWAT database (FAO 2018) which were cross-checked by the same data from the Tanzania Meteorological Agency (TMA). To run the CROPWAT 8 model, the default medium weather was selected depending on the location of the weather station (Figure 4) for 23 climatic stations distributed in the Wami/Ruvu basin (USAID 2008, FAO 2018).

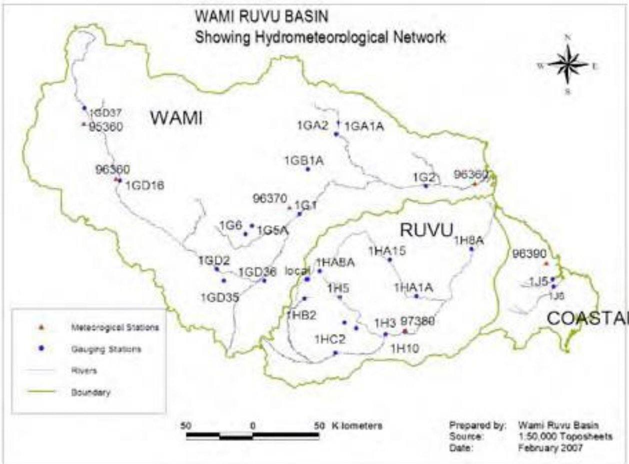

Figure 4: Wami/Ruvu basin gaging and meteorological Stations (source: USAID 2008).

Soil data

Soil data such as soil moisture, infiltration rate, rooting depth and moisture depletion were obtained from the soil and terrain database for Africa (SOTERAF) (Dijkshoorn, 2003) and other soil research studies in Tanzania, including the National Soil Service, 1993, and Sokoine University of Agriculture (SUA). The basin is characterized by a variety of soil types, including Sandy soils, predominantly in coastal areas; red soils, predominantly in Kinyasungwe Catchment and eastern parts of Mkondoa Catchments; and Vertisol called mbuga black soil, spread across most of the Basin (URT 2019). To run the CROPWAT model, the default medium soil type was selected depending on the area's location within the study area. The available soil maps were used to select the dominant soil type within a catchment.

Crop data

The major cultivated crops in the study area are paddy, maize, beans, tomatoes and sugarcane (URT 2019). Despite climate variability across the Wami/Ruvu basin, farmers who were interviewed reported crop planting date 31st December while the harvesting dates are as itemized in Table 2.

Table 2: Harvesting dates for the 5 major crops in Wami/Ruvu basin

Cropping pattern name: CROPS

No.	Crop file	Crop name	Planting date	Harvest date	Area %
1.	...ata\CROPWAT\data\crops\FAO\MAIZE.CRO	MAIZE (Grain)	31/12	19/05	
2.	...CROPWAT\data\crops\FAO\BEANS-DR.CRO	Dry beans	31/12	19/04	
3.	...Data\CROPWAT\data\crops\FAO\RICE.CRO	Rice	31/12	29/04	
4.	...ROPWAT\data\crops\FAO\SUGARCAN.CRO	Sugarcane (Ratoon)	31/12	30/12	
5.	...\CROPWAT\data\crops\FAO\TOMATO.CRO	Tomato	31/12	24/05	

Reference Evapotranspiration (ET_0)

According to Pereira et al. (2015), the FAO Penman-Monteith method Reference Evapotranspiration (ET_o) is given by equation 1.

$$ET_O = \frac{0.408\Delta(R_n - G) + \gamma(\frac{900}{T} + 273)\mu_2(e_s - e_a)}{\Delta + \gamma(0.34\mu_2)} \quad (1)$$

where R_n = net radiation (MJ/m^2/day); G = soil heat flux density (MJ/m^2/day); T = mean daily air temperature at 2 m height (^{0}C); μ_2 = wind speed at 2 m height (m/s); (e_s - e_a) = vapor pressure deficit of the air (kPa); Δ = slope of the vapor pressure (kPa $^0C^{-1}$); γ=the psychrometric constant (kPa ($^0C^{-1}$)). The FAO Penman-Monteith method Pereira et al. (2015) was preferred for use in this study in the determination of the reference evapotranspiration (ET_0) since it is reported to provide very consistent values on actual crop water use data worldwide (Allen et al. 2005, Cai et al. 2007).

Actual Evapotranspiration (ET_c)

The green and blue water footprints of crop production in this study were estimated based on the water footprint assessment methodology presented in the Water Footprint Assessment Manual (Hoekstra et al. 2011). The actual crop evapotranspiration (ET_c, mmday−1) depends on climate parameters as itemized in equation 1 (which determines potential evapotranspiration), crop characteristics, and soil water availability (Ewaid et al. 2019) in equation 2.

$$ET_c[t] = K_c[t] x K_s[t] x ET_O[t] \quad (2)$$

Where K_c is the crop coefficient,
K_s [t] a dimensionless transpiration reduction factor dependent on available soil water with a value between zero and one,
ET_o[t] is the reference evapotranspiration (mm day−1).
The crop coefficient varies in time as a function of the plant growth stages as follows:

- K_c, ini- the crop coefficient during the initial stage
- K_c, mid- the crop coefficient during mid-season stages
- K_c, end- the crop coefficient during late season stage
- During the crop development stage, K_c is assumed to increase from K_c, ini to K_c mid linearly.
- In the late season stage, K_c is assumed to decrease linearly from K_c, mid to K_c, end.

Effective Rainfall (P_{eff})

Effective rainfall is defined by Anshu et al. (2017) and Obreza et al. (2002) as the fraction of rainfall stored in the soil profile and helps in the growth of crops, which Hoekstra et al. (2011) refer to as green water. Effective rainfall is given by Allen et al. (2005) as per equation 3.

$$P_{eff} = \frac{P_{tot}(125 - 0.2xP_{tot})}{125} \; for P_{tot} < 250 \text{ mm (per month)} \quad (3)$$

$$P_{eff} = 125 + 0.1P_{tot} \; for P_{tot} > 250\text{mm (per month)} \quad (4)$$

where P_{eff} = effective rainfall (mm); P_{tot} = total rainfall (mm).

The Irrigation Water Requirement (IWR)

IWR is defined by Alemayehu et al. (2009) as the amount of water needed to fulfill the crop water requirement after an effective rainfall, which, according to Ewaid et al. (2019), is part of Bluewater.

$$IWR = ET_c[t] - P_{eff} \quad (5)$$

Where; ET_c[t] = Evapotranspiration (mm);
P_{eff} = Effective Rainfall (mm).

Validation of the Model

According to Xu et al. (2022), validation of the water footprint model can be carried out with the same products produced at the same site. In this study, the water footprint model was validated by comparing the obtained results to the one published in URT (2019).

Results and Discussion

Reference Evapotranspiration (ET_0)

The mean annual reference evapotranspiration (ET_o) is estimated at 1604 mm (Table 2). The average (ET_o) per month was 134mm; most months except October, November, and December have relatively high values, greater than the average per month, while the lowest monthly values of ET_o were observed in April, May, June and July. The observed differences in (ET_o) are due to the variation of weather parameters in the study area. The low relative humidity and escalating temperatures resulted in increased evapotranspiration. Low values of ET_o in

April, May, June, and July could have been caused by the dry season, where low sunshine hours and low radiation. The relatively high ET_o at the beginning of the year in January, February, and March and at the end of the year in October, November, and December is characterized by higher temperatures and average relative humidity. Wambura et al. (2017) support these results from their study on the Evaluation of Evapotranspiration. However, they made use of Principal component analysis of MODIS satellite images covering the Wami sub-basin.

Irrigation/Blue Water Requirement (IR) and Crop Evapotranspiration (ET_o)

The blue (irrigation) water requirements per crop for the different high-value crops that are majorly grown in the Wami/Ruvu Basin are given in Figure 5.

Table 3: Monthly Evapotranspiration (ET_o) of Wami/Ruvu Basin

Month	**Min Temp °C**	**Max Temp °C**	**Humidity %**	**Wind km/day**	**Sun hours**	**Rad MJ/m²/day**	**ET_o mm/Month**
January	21.3	30.9	77.3	195.1	6.5	19.7	140.34
February	21.0	31.0	78.1	177.7	6.8	20.4	128.76
March	20.8	31.1	80.4	160.6	6.3	19.3	134.23
April	20.3	29.9	82.3	161.7	5.5	17.0	113.23
May	18.8	29.0	79.4	196.3	6.1	16.5	114.66
June	16.5	28.3	75.3	218.6	6.9	16.8	112.84
July	15.7	27.9	72.9	227.0	6.7	16.9	118.42
August	16.2	28.6	70.6	239.4	6.9	18.4	132.90
September	16.9	29.7	70.9	251.9	7.0	19.8	142.37
October	18.2	30.8	72.0	264.1	7.5	21.3	160.71
November	19.9	31.5	72.0	239.4	7.6	21.4	155.87
December	21.2	31.4	74.4	217.1	6.9	20.2	149.46
Average	**18.9**	**30.0**	**75.4**	**212.4**	**6.7**	**19.0**	**1603.80**

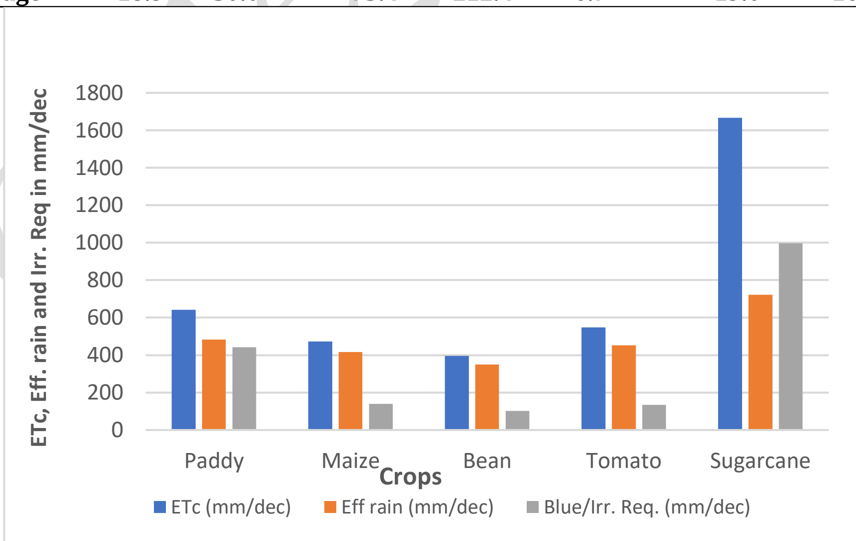

Figure 5: Crop evapotranspiration (ET_c), effective rainfall (Eff rain) and blue/irrigation water requirements (Irr. Req) in mm/dec for Major crops grown in Wami/Ruvu Basin.

Table 4 records the 10-day (decade) average Bluewater was computed to estimate the required irrigation water amounts for each crop. The highest total irrigation water requirement is recorded in sugarcane at 997 mm, followed by rice at 461 mm, while the lowest is recorded in beans at 102 mm, followed by Tomato at 135mm. The highest cumulative crop evapotranspiration (ΣET_c) was found in Sugarcane and rice at 1667 mm and 694 mm, respectively, while bean and maize had the lowest at 395 mm and 472 mm, respectively. Based on a comparison between the results and crop growing seasons in Table 2, the results showed that crop evapotranspiration (ΣET_c) was significantly higher in crops with long growing seasons than those with short growing seasons. These findings are similar to those obtained by Acharjee et al. (2017) and Onyancha et al. (2017). The same was evidenced by Wambura et al. (2017), who pointed out that rice and sugarcane evapotranspirate much as plants with deeper roots.

The ET_c varies considerably as the crop develops through growth stages as it is affected by the amounts of water received through rainfall and varies significantly with seasonal variations (Bouraima et al. 2015). From these results, it can be inferred that planning a scientific water requirement is of great importance for the stated crops to achieve higher productivity using the most optimum amount of water once all the other agronomic practices are considered (Mehta et al. 2013).

Table 4: CROPWAT outputs on crop coefficient (K_c), mean (mm/day) cumulative value (mm) of crop evapotranspiration (ΣET_c), effective rain (mm) for Major crops in the Wami/Ruvu Basin.

	Growth Stage	**Length Days**	**K_c Coeff.**	**ET_c mm/day**	**ΣET_c mm/dec**	**Eff rain mm/dec**	**Irr. Req. mm/dec**
	Nurs	0-29	1.20	0.61	0.61	2.67	0.61
	Padd	30-34	1.13	3.09	61.76	61.79	109.51
	Init	35-54	1.09	5.07	106.41	60.04	158.69
Rice	Deve	55-84	1.12	5.10	158.06	81.44	76.64
	Mid	85-124	1.17	5.22	198.06	121.90	76.13
	Late	125-155	1.10	4.30	169.19	147.73	39.21
		Total			**694.09**	**475.57**	**460.80**
	Init	0-24	0.30	1.39	30.30	61.16	2.81
Maize	Deve	25-64	0.70	3.20	120.67	103.37	27.26
	Mid	65-105	1.17	5.00	204.83	137.60	69.36
	Late	106-140	0.78	3.00	116.54	114.71	39.87
		Total			**472.34**	**416.84**	**139.30**
	Init	0-19	0.40	1.87	20.40	31.93	1.90
Bean	Deve	20-59	0.60	2.73	84.40	81.44	15.57
	Mid	60-89	1.11	4.95	187.90	121.90	66.03
	Late	90-110	0.83	3.33	102.73	114.71	18.90
		Total			**395.43**	**349.99**	**102.40**
	Init	0-29	0.60	2.77	57.74	60.09	7.56
Tomato	Deve	30-69	0.83	3.74	181.17	138.91	44.53
	Mid	70-114	1.12	4.53	185.94	155.16	42.97

	Late	115-145	0.94	3.51	122.50	97.41	39.59
		Total			**547.36**	**451.57**	**134.64**
Sugarcane	Init	0-29	0.53	2.45	40.31	60.09	6.54
	Deve	30-59	0.71	3.19	186.16	175.19	28.06
	Mid	60-269	1.25	4.99	918.84	281.17	648.54
	Late	270-365	1.01	5.16	521.49	205.06	314.21
		Total			**1666.80**	**721.50**	**997.36**

Note: Init represents the initial phase of crops' cycles, Deve - development phase, Mid - middle phase, Late - late phase, (Padd-padding stage only for Rice), Σ- cumulative, Eff - effective rainfall and IR - irrigation requirement.

Table 4 shows the ET_c rising through the growth stages and dropping slightly at the later stages. The variations observed here can be due to the crop coefficient (K_c), expressed by the ratio of ET_c to ET_o, as shown in Equation 2. Although the K_c varied little, it was not constant in any phenological stage (Azevedo, 2007). This also expresses the seasonal crop water needs. The cumulative ET_c (ΣET_c) was also considered using the crop's development stages to ensure the analysis was accurate. During the initial stages of growth of crops, the cumulative ET_c (ΣET_c) values were relatively low compared to the other growth stages. ΣET_c values increased during the development cycle and are highest at midseason. The values fall drastically as the crop reaches the last stage of growth. The ET_c values were observed to be low at the start and end when the crops were productive and greater in the mid stages during the observation period. This was observed in all the five crops. Here, the findings are that much water is required at the mid-seasonal stage compared to the rest of the crop growth stages. Generally, the ET_c varied significantly throughout the development cycle of the crops, majorly due to the prevailing climatic conditions and the development of the crop during the growth stages. The current water footprint model was validated by comparing the obtained results to the one published in URT (2019). The results resembled to each other, since the URT (2019) reported that irrigation encompassed 59.87% of total water in the whole basin for all crops grown in the basin. The current study indicates irrigation requirement of 1834.5 mm/dec which is equivalent to 43.17% (Table 4). The difference of 16.7% between URT (2019) and the current study is counted to the irrigation of the remaining crops which were not considered in the current study. The results indicate the good performance of the water footprint model.

Conclusion and Recommendations

The crop water requirement of major crops grown in the Wami/Ruvu basin, including rice, maize, bean, tomatoes, and sugarcane, was calculated using the FAO CROPWAT 8.0 model. Computations of annual reference (ET_o) and crop evapotranspiration (ET_c) were also done. From the results, effective rainfall was lower than the crop water requirements for all the crops under the study. Therefore, it is recommended that more irrigation schemes be established in the study area to supplement rainfall for higher crop production. The results also revealed that more blue water was required for crops with prolonged growing seasons compared to those with short growing seasons. The average values of ET_c varied concerning weather changes fluctuating throughout the growth cycles of crops. This emphasizes the need for scientific planning on water resources used for irrigation. Blue water. These results can thus be used to enhance water use efficiency by better-managing irrigation water withdrawal and application amounts in the Wami/Ruvu Basin. The research findings lead to proper planning for irrigation scheduling that enables effective use of water to meet the respective crop water requirements while avoiding wastage of water. In return, it conserves the Environment while maximizing crop production and eventually guarantees food security. It is recommended to determine the water footprint for livestock and extend the study to the rest of the eight water basins.

Funding
This work was supported by the research and consultancy unit of the Ardhi Institute Morogoro.

Declaration of competing for interest
The manuscript has no competing interests.

Acknowledgments
The authors would like to acknowledge the financial support of the Ardhi Institute Morogoro through the research and consultancy unit of the Institute. The authors would also like to recognize and extend generous gratitude to the Wami/Ruvu Basin Water Board and the Basin and Tanzania Meteorological Agency management for their cooperation and delivery of valuable information for this study.

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