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Determination of Water Footprint for the Cotton and Maize Production in the Küçük Menderes Basin

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Abstract: Considering the effects of rapid population growth, urbanisation and climate change in recent years, the protection of freshwater resources, the prevention of water pollution and the proper sharing of freshwater resources among different sectors have become important issues. Water footprint (WF) is a sign of freshwater use and is not only an indicator that can be used in the climate crisis, but also to protect water against nitrate pollution. In this study, the Küçük Menderes Basin was chosen as the study area due to different crop varieties. Agricultural crop patterns were classified using Rapideye and Sentinel-2 satellite images of the study area obtained in 2017. Thus, the cultivated areas were obtained for cotton and maize (grain and silage) in the basin. In particular, agricultural crop patterns were considered in which agricultural production was intensive and blue water was used predominantly. As a result, the first-crop corn production, which has a high blue WF of 3840 m^3/ton in the basin, has the highest greywater footprint due to the use of intensive chemical fertilisers. This was followed by cotton with 2331 m^3/ton, and the second-crop silage corn production had the lowest greywater footprint. Agriculture's water footprint assessment provides a solid foundation for planning climate change adaptive crop production, managing nitrate-sensitive areas and anticipating future regional changes.

Keywords: agriculture; water footprint; climate-changing; remote sensing; Küçük Menderes Basin

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1. Introduction

Water is consumed and polluted in large quantities as a result of modern human activities, such as industrialisation, climate change effects, rapid population growth and urbanisation. When considering these effects, issues such as the protection and improvement of freshwater resources, the prevention of water pollution and proper duty sharing among different sectors become increasingly important. More than 70% of water across the globe is used in agricultural production. However, industries also consume and pollute a considerable amount of water. There is conflict in the water demands of these sectors and the water needed for the sustainability of natural life and the environment [1–7].

The fact that the cultivated area of the agricultural crop pattern is not accurately known constitutes the most important deficiency in calculating water footprint (WF). For this reason, remote sensing techniques should be used in determining the cultivated area for crops.

The WF can present new approaches to address the increasing pressure on global freshwater resources and generate solutions. The concept of WF was first introduced by Arjen Hoekstra in 2002 at UNESCO-IHE [8]. WF is measured based on the amount of water consumed and/or contaminated per unit of time [9]. The concept of WF is an alternative indicator for water use. WF examines the amount of water consumed instead of the amount of water that subsided from the system and is therefore different from traditional water statistics [9]. This concept shows the water volume, type of water used and when and

where it was used. In this context, blue, green and grey WFs can be defined as three components in a multidimensional indicator of water use and quality [10].

Blue WF represents the total volume of the surface and underground freshwater resources needed to produce agricultural products; this is traditionally associated with freshwater.

Green WF is the total rainwater used to produce crops. Green WF is relevant in both rain-fed and irrigated agriculture [11].

Grey WF is an indicator of water pollution and is predominantly due to the nutrient load of fertilisers used in agriculture, sewage and industrial wastewater [12,13]. It is one of the important parameters that can also be used in the land management of the nitrate-vulnerable zone.

The production WF corresponds to the amount of water used for industrial and agricultural purposes, regardless of where the products are consumed. It also provides an understanding of how water is used and whether its use is appropriate and sustainable [14]. WF studies have shown the largest contribution of agricultural WF. Therefore, the calculation and evaluation of WF originating from agricultural activities are important tools for evaluating the sustainability of water resources. In particular, the calculation and analysis of the WF of crops at different scales using crop models form the basis of WF studies [15–19]. Initial studies started on a global scale. Pfister and Bayer [20] estimated monthly water stress due to green and blue water consumption in agricultural productions globally. Regional and local studies were conducted in the following years. In this context, Zhuo et al. [21] showed the impact of variation in the WF of agricultural production on the degree of blue water shortage in the Yellow River Basin. Cao et al. [22] highlighted that ignoring WF studies would negatively affect the awareness of the water crisis in arid regions. As a result of these studies, it has been understood that WF studies revealing how important water management is in agriculture should be continued. Wu et al. [23], as a result of their study in China, revealed that WF data in agriculture can be used for agricultural water conservation. Wang et al. [24] reported that the WF study conducted in the Tarim River Basin can be evaluated for the sustainable use of water. Several studies have been conducted on how WF can be used to measure the negative effects of climate change and how to deal with these problems [25–27]. Some studies have evaluated that blue, green and grey water footprints in agriculture can be used not only for water management, but also for fertiliser management. The results of many studies indicate that the WF is an important tool for monitoring and evaluating water and providing water management at a regional scale. In addition, WF has an important role in guiding the development of agricultural water management strategies.

The analysis of the WF production in Türkiye showed that it is approximately 139.6 billion m^3/year. In Türkiye, 64% of the WF resulting from the production is WF_{green}, 19% is WF_{blue} and 17% is WF_{grey}. Agriculture has the largest share at 89%, whereas domestic water use and industrial production account for 7% and 4% of the total WF, respectively [28].

Therefore, in this study, we analyse the WF of agricultural products that require intense water and fertilisers usage. Thus, it can be used as an indicator in the evaluation of crops against the climate crisis and the development of new strategies for water and land management. The study was specifically based on the agricultural crop pattern from May to October when agricultural production is intense and mainly blue water is used. Using satellite data, the WF values of vegetative production were calculated for cotton and maize (grain + silage), which are widely grown in the basin. We expect that this study will make a significant contribution to the national and international literature [29–33], especially in terms of using remote sensing techniques in calculating WF.

2. Materials and Methods

2.1. Study Area

The Küçük Menderes Basin, one of Türkiye's most productive basins and where intense agricultural activities are carried out, was chosen as the study area. Its total surface area is 702.931 ha. Its geomorphological structure is in the form of a valley (Figure 1).

Figure 1. Map of the study area.

The Küçük Menderes Basin has Mediterranean precipitation regime characteristics. The observed annual precipitation is approximately 680 mm and takes place over winter; the precipitation amount during summer is very low. The annual average temperature in the basin is 17 °C. The average temperature over the period characterised as the cold period is approximately 8 °C, whereas the average temperature in summer months, characterised as the hot period, is approximately 26 °C. In the Küçük Menderes Basin, the number of consecutive dry years has been increasing in recent years. It is predicted that reductions of up to 16% in total precipitation values in 10-year averages will occur by the 2050s [34].

In this context, the Küçük Menderes Basin (İzmir), which is important in terms of agricultural activities, was selected as the study area. Aside from the intensive cotton, grain and silage maize, alfalfa, wheat–barley and tomato farming in the permeable alluvial soils of the study area, olive farming is dominant, especially in sloping areas where colluvial soils are present. In the past few decades, corn farming has intensified due to livestock subsidies and increasing meat prices. This situation has increased both the intense water demand and the use of nitrogen fertilisers. Moreover, a water salinity problem exists in the western parts of the basin that limits the use of water for agricultural purposes. In the study area, apart from agriculture, domestic and industrial usages are the other important water stakeholders.

In this study, data on the use of fertilisers for grey WF calculation were gathered through face-to-face surveys with farmers. Accordingly, an average of 285 kg/ha of pure nitrogen was used for maize cultivation in the basin and 242 kg/ha for cotton. Irrigation water in the basin is provided from groundwater resources. The dominant irrigation system is in the form of furrow irrigation.

2.2. Data

Remote sensing data: In this study, Rapideye and Sentinel-2 satellite images of the study area taken in 2017 were used. Primarily, radiometric, atmospheric and geometric corrections were made in satellite images, and enrichment procedures were then carried out. Appropriate band composites for plant covers were created and made ready for interpretation. Image Analyst [35] and PCI Geomatics [36] software were used to process and interpret satellite images, and ArcGIS [37] software was used to build a parcel scale map of the study area.

Agricultural crop patterns were classified by considering the reflection values of the corrected satellite data. Thus, the cultivated area (ha) was obtained for cotton and maize (grain and silage), the target plants in the Küçük Menderes Basin.

Classification Methods: In this study, the maximum likelihood classification (MLC) method was conducted on high-resolution multispectral satellite imagery to classify crop patterns in the basin. MLC-supervised classification is a technique based on the statistics of training areas representing different ground objects selected subjectively by users based on their knowledge or experience [38]. In this study, MLC, the most common classification method in remote sensing, was used to derive land cover categories. In this method, the pixel is assigned to the class with the highest probability of pixels. MLC is based on Bayes' Theorem [39–41]. In the classification stage of satellite data, 4937 training and 498 validation samples were determined.

Harvest and yield data: Corn- and cotton-planted areas were determined as a result of the classification of satellite images. The yield information of these plants per unit area (kg/ha) was obtained from the local statistics archive of the Ministry of Agriculture and Forestry.

2.3. Water Footprint Calculations

2.3.1. Crop Water Requirement and Effective Rainfall Calculations

The green, blue and grey WFs of targeted crops were calculated using the methodology described in Hoekstra and Chapagain [42] and Hoekstra et al. [43]. The reference evapotranspiration of crops calculated by CROPWAT with the FAO Penman–Monteith method is provided in Equation (1) [44]. The climate data required as input into the CROPWAT model were taken from the Turkish State Meteorological Service.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where ET_o is reference evapotranspiration (mm day^{-1}), R_n is the net radiation (MJ m^{-2}day^{-1}), G is the soil heat flux density (MJ m^{-2}day^{-1}), T is the mean daily air temperature at 2 m height (°C), U_2 is the wind speed at 2 m height (m s^{-1}), e_s is saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), $e_s - e_a$ is the saturation vapour pressure deficit (kPa), Δ is the slope vapour pressure curve (kPa °C^{-1}) and γ is the psychrometric constant (kPa °C^{-1}).

Crop evapotranspiration was calculated using Equation (2):

$$ETc = ET_o \times Kc \quad (2)$$

where Kc is the crop coefficient given in Table 1. ETc values were taken from calculations for the Odemis meteorological station from the crop evapotranspiration guide of irrigated plants in Türkiye [45].

Table 1. Crop coefficient for different stages.

Crop	Kc_{ini} [1]	Kc_{mid}	Kc_{late}
Cotton	0.2	1.2	0.6
Corn (first pr.)	0.24	1.18	1.07
Corn (silage)	0.24	1.23	0.53
Corn (silage second pr.)	0.06	1.21	0.51

Kc_{ini}: initial; Kc_{mid}: mid-season; Kc_{late}: late season.

Not all rainfall can be used by crops, as some is lost through runoff (RO) and deep percolation. The remaining water is usable and considered effective rainfall. Depending on the soil type and initial water content, stored water from effective rainfall (Pe) was calculated as 80% of the rainfall. It was assumed that irrigation was applied when available water depletion reaches 50%, and effective root deep was considered 90 cm for all crops. The total available water capacity for one-metre-deep sandy, loamy sand, sandy loam, loam, silty clay loam and clay soils were considered 40, 70, 105, 160, 175 and 170 mm, respectively [46].

2.3.2. WF Calculations

The blue (WF_{blue}) and green (WF_{blue}) components were calculated for cotton, first-crop maize and first-crop maize for silage and crop maize silage in 2017. Calculation details are given as Equations (3)–(6):

$$WF_{green} = CWU_{green}/Y\ (m^3/ton) \tag{3}$$

$$WF_{blue} = CWU_{blue}/Y\ (m^3/ton) \tag{4}$$

where

$$CWU_{green} = 10 \times \sum/ET_{green}\ (volume/area) \tag{5}$$

$$CWU_{blue} = 10 \times \sum/ET_{blue}\ (volume/area) \tag{6}$$

Crop Water Use (CWU) converts water depths in millimetres into water volumes per land surface in m^3/ha; then, WF values were multiplied by 10. ET_{green} represents green water evapotranspiration, and ET_{blue} represents blue water evapotranspiration [18].

WF_{grey} is the volume necessary to assimilate the pollutant load caused by production processes based on the existing ambient water quality standards.

The greywater used to grow crops (WF_{grey}, m^3/t) is defined as the volume of freshwater required to assimilate the pollutant load based on the ambient water quality standards and is calculated using Equation (7) following the methodology developed by Hoekstra et al. [18]:

$$WF_{grey} = \frac{(\delta AR)/(C_{max} - C_{nat})}{Y}\ (m^3/t) \tag{7}$$

where AR is the chemical application rate per ha (kg/ha), δ is the leaching–RO fraction (%), C_{max} is the maximum acceptable nitrogen concentration (kg/m^3), C_{nat} is the natural concentration of the pollutant considered in the receiving water body (kg/m^3) and Y is the crop yield (t/ha).

In agricultural production, nitrogen is usually responsible for WF_{grey} because most of the fertilisers used in agricultural areas in this basin are nitrogenous fertilisers. Data on the number of nitrogen fertilisers used were calculated from the data obtained from the field study. In this study, we considered a rate of nitrogen leaching equal to 10% of the nitrogen application rate and used the permissible limit of 50 mg NO_3/lt as per the EU Nitrate Directives to estimate the water volume necessary to dilute leached nitrogen to the permissible limits.

After obtaining all the data, green, blue and grey WFs were calculated separately by targeted crops in 2017.

3. Results and Discussion

3.1. Image Classification

To calculate the WF, the agricultural crop cultivated area information constitutes the basic data. Remote sensing was used to accurately determine the area of crops cultivated in the Küçük Menderes Basin. In this study, the MLC method, one of the commonly used pixel-based image classification methods, was chosen. In particular, MLC has been used in various land cover determination studies, and successful results have been obtained [47,48]. We also preferred the MLC method to calculate the land cover type in our study. After the training processes, the classification phase of satellite images was completed, and the cultivated areas of cotton and corn were calculated (Figure 2, Table 2).

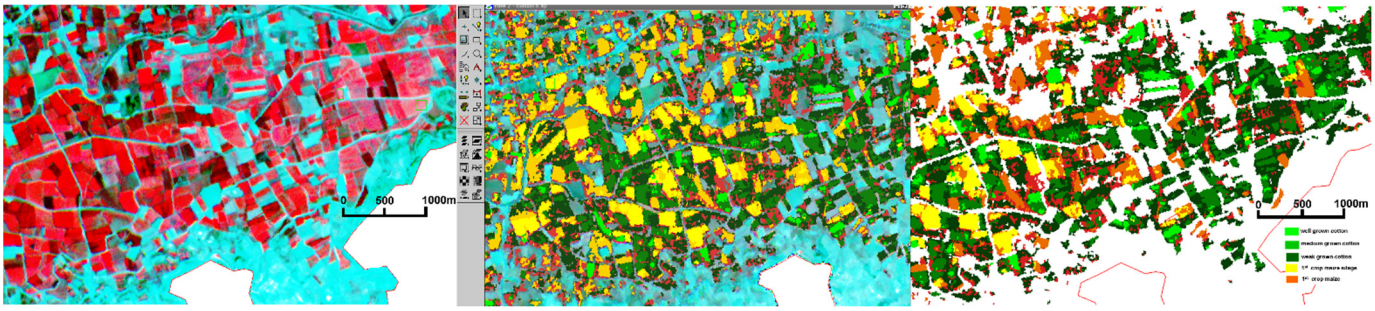

Figure 2. Land cover classification map of the middle part of the study area.

Table 2. Area of cultivated crop pattern in the Küçük Menderes Basin.

Crops	Area (ha)
Cotton	1260
1. Crop Maize	11,160
1. Crop Maize (Silage)	385
2. Crop Maize (Silage)	39,769
Other Crops	25,300

3.2. Water Footprint of Cotton Production

Worldwide, cotton is the most important natural fibre used in the Turkish textile industry. With a 7% share, Türkiye is one of the world's most important cotton producers. Textiles constitute 8% of Türkiye's gross domestic product and 20% of Türkiye's total exports. Thus, an observable increase in cotton cultivation areas was observed in Türkiye with increased agricultural subsidies in recent years.

High-quality cotton production requires a high level of irrigation water use. In this context, considering that it increases water consumption on the one hand and negatively affects water quality on the other, cotton production has a high environmental impact. To this end, satellite images were used to monitor cotton cultivation areas in the Küçük Menderes Basin, and WF was used as an index to assess its environmental impact.

Table 3 displays the WF of cotton production estimated for the Küçük Menderes Basin taking into account climate data, soil characteristics, irrigation water requirement, cultivated area, yield information and concurrent fertiliser values in 2017.

Table 3. The water footprint (WF) of cotton production in the study area.

	WF_{green}	WF_{blue}	WF_{grey}	WF_{total}
		(m^3/t)		
Cotton	292	2331	155	2778

In Türkiye, cotton is among the industrial plants with the highest WF in the basin. As shown in Figure 3, 84% of cotton production's WF in the study area is blue WF, which

demonstrates the close relationship between cotton production and surface and groundwater sources.

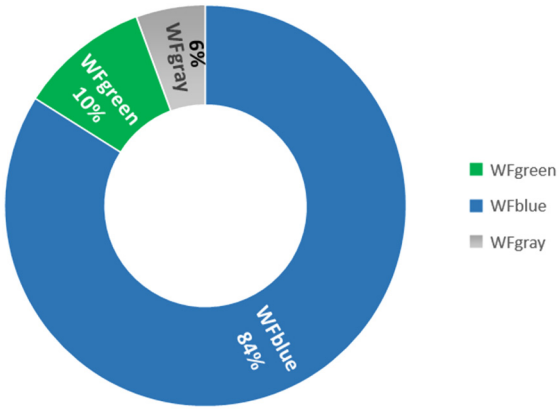

Figure 3. Three different WF components in cotton production.

L. Zhuo et al. [21] calculated WF values of cotton in their study conducted in the Yellow River Basin (YRB) and determined WF_{green}, WF_{blue} and WF_{grey} values as m^3/t of 1205, 494 and 3366, respectively. These values correspond to 24%, 10% and 66% of the WF_{total} value, respectively. In the same study, relevant values were compared with the results obtained from Mekonnen and Hoekstra [49]. The values obtained for WF_{green}, WF_{blue} and WF_{grey} are 1386, 343 and 601 m^3/t, respectively. These values correspond to 59%, 15% and 26% of the WF_{total} value. As can be seen from these values, the WF_{blue} value obtained in our study is higher than that of the aforementioned studies. It is understood that surface water and underground water are mainly used for cotton production in the Küçük Menderes Basin.

3.3. The Water Footprint of Maize Production

Maize (Zea mays) farming is carried out in >150 countries worldwide. In Türkiye, maize takes third place among cereals after wheat and barley in terms of cultivation area and production. Grain maize production in Türkiye was 6.4 million tons in 2017 according to data from TUIK, and silage maize production was 20.14 million tons [50].

Since maize is an important crop in human and animal nutrition, its cultivation is increasing in the Küçük Menderes Basin. The intensive use of water and fertiliser for higher yields in the limited parcels that are suitable for field farming to supply feed at the amounts and quality required for animal husbandry has attracted attention in the study area. As mentioned, the WF is an important index in evaluating the environmental effects of intensive agricultural activities. Due to increased animal husbandry utilities in the study area, maize production areas are classified as first-crop maize (grain), first-crop silage maize and after-crop maize for silage.

Table 4 shows the WF of maize production, determined by considering climate data, soil characteristics, irrigation water requirements, cultivated area and yield information alongside the consumed fertiliser values of the Küçük Menderes Basin in 2017.

Table 4. The water footprint (WF) of maize production.

	WF_{green}	WF_{blue}	WF_{grey}	WF_{total}
		(m^3/t)		
1. Crop Maize (Grain)	773	3840	606	5219
1. Crop Maize Silage	209	769	146	1124
2. Crop Maize Silage	192	483	99	774

Examining the blue WF of maize plants that are produced in different areas within the basin, the first-crop maize (grain) production has the highest value at 73%, followed by the

first-crop maize (for silage) at 68% and the second-crop (after-crop) maize (silage) at 62% (Figure 4).

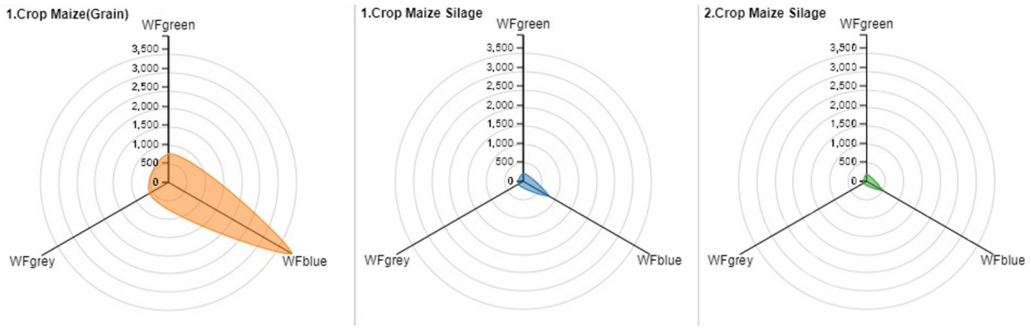

Figure 4. Three different components of the maize production WF.

Swelam et al. [51] calculated the WFs of crops such as wheat and maize in different agro-climatic regions and determined the effects of climate on them. The results showed that the mean values of WF for maize were 1067, 1395 and 1655 m^3/ton in old lands and 1395, 1634 and 2232 m^3/ton in new lands under the three climate regions. When these results are compared with our obtained data, the first-crop silage maize is compatible with WF, whereas the first-crop maize WF is high in our study basin. The main reason for this is thought to be the preference for furrow irrigation systems and the lack of irrigation management in the Küçük Menderes Basin.

As the blue WF functions for consumptive water use and produced yield, Mekonnen and Hoekstra [49] found that about 57% of the global blue WF of crop production is unsustainable because it exceeds the available renewable water resources. This emphasises the critical importance of improving irrigation efficiency through technical innovations that save water.

Mekonnen and Hoekstra [52] concluded that the average WF_{green} was 410 kg/kg, WF_{blue} was 91 kg/kg and the total WF was 501 kg/kg for the Lombardia region. Huang et al. [53] found that WF was 868 m^3/t (48.5% green, 0.5% blue and 51.0% grey) in corn production. Nana et al. [54], in their study conducted in the Po Valley region in Italy, determined that the WF value for maize grain was 479 kg/kg (41% green and 59% blue). According to Cao et al. [55] in their study on water use and productivity, results for maize, soybeans and potatoes showed that the water used for all plants was 43% blue water and 57% green water. These results show that WF_{blue} values are significantly high for all maize varieties produced in the Küçük Menderes Basin. This situation will increase the pressure on surface and groundwater resources with climate change.

Consequently, considering cotton and all types of maize production across the basin, we can determine that the production of first-crop maize (grain) has the highest water consumption, followed by cotton production. Despite intensive agriculture in the study area, the blue WF of silage maize production was relatively low due to both the short vegetation period and the high efficiency obtained from the unit area.

In addition, the environmental dimension of agricultural production was determined using the calculated WF_{grey} data. In this context, the first-crop maize (grain) with high WF_{blue} was the crop pattern that mostly polluted the environment due to the use of intensive chemical fertilisers, followed by cotton and first-crop silage maize, and the lowest WF_{grey} belonged to the second-crop silage maize production (Figure 5).

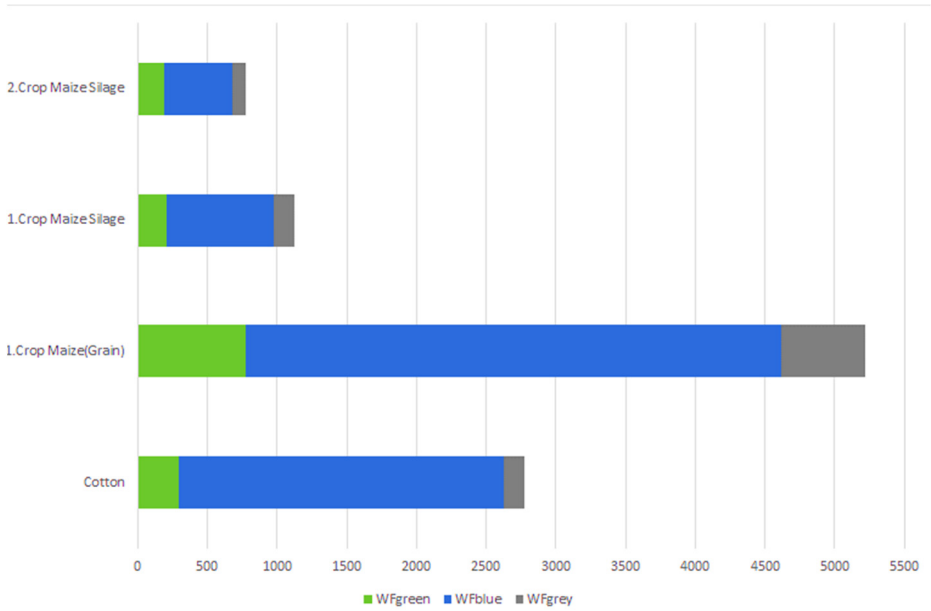

Figure 5. The total WF of all targeted production.

When we examine WF studies worldwide, the global average for WF_{grey} in cotton production is 440 (m^3 t^{-1}), whereas the production in the Küçük Menderes Basin is 155 (m^3 t^{-1}), which is below average. However, the WF_{grey} of the first-crop maize (grain) production is well above the global average (194 m^3 t^{-1}).

4. Conclusions

Increased consumption and climate change as a result of population growth mean that water security will be a major global problem in the coming years. Therefore, countries should assess their water demand and impact and take a comprehensive approach to their economic forecasts and plans.

In this context, cotton and maize, with production that covers a large area in the Küçük Menderes Basin, and which we believe increase the intensive use of fertilisers and water, were selected as target plants. Examining the production patterns for these target plants, the WF_{blue} for all plant patterns was determined to be considerably higher than WF_{green}. Considering the average yield values in the basin, cotton (4.7 tons ha^{-1}) and first-crop silage maize (6.0 tons ha^{-1}) have high yields. Considering the economic return and sustainability factors, we believe that an alternative production pattern should be adopted instead of producing first-crop maize (grain) in the basin. Studies have indicated the need to apply improved irrigation methods in the basin to reduce the high WF_{blue}. If good agricultural practices become widespread, 10% less use of fertiliser can be implemented with balanced fertilisation, resulting in an average water saving of 14–23% in irrigation.

Globally, >70% of water is used in agricultural production, whereas 89% is used in Türkiye. WF data can be used as ancillary data for the management of healthy and sustainable water resources. As the WF concept is not the only instrument used when making water management decisions because it brings together the factors for each sector in the sustainability framework, it offers opportunities to make important contributions.

Remote sensing technique is the most important tool to obtain agricultural crop cultivated area to correctly calculate WF.

In future studies, we will focus on making WF estimations regarding climate change-induced water use values in the research region and devising necessary water management strategies in water resource management in response to these values.

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