# Assessing the Blue and Green Water Resources Use for Regional Crop Production in a Semi Arid Area (The Cap Bon Case Study, Tunisia)

**Insaf Mekki and Rim Zitouna-Chebbi**

**Abstract** Because of the strong expected effects of climate change on water resources and food production it is important to use efficiently, as well as sustainable, water for agriculture production including both components rainfed "green water" and irrigated "blue water". This is particularly important in the Cap Bon region northeastern Tunisia, where irrigation has increased in the past few decades, using intensively groundwater resources resulting in their degradation as well as their conflicting uses. Efficient management strategies that allow for compromises between agriculture production and water resource preservation are therefore needed. Such strategies require initial assessment of the sustainability of blue and green water resources management for crop production. For this purpose, the Global Water Footprint Standard approach has been used in the Cap Bon region. We calculated the volumetric blue and green water footprint related to wheat, tomato and citrus production as major crops in the region. The results show that the average of total WF of crop production was about 1821 $Mm^3$/yr (85% green, 15% blue) over the period 1999–2008. The total WF (green + blue) of tomato and citrus crops averaged 131 $m^3$/ton, 445 $m^3$/ton, respectively. The green WF of wheat obtained in this study was about 1670 $m^3$/ton, which is equal to the calculated world average (1620 $m^3$/ton) by previous studies. This indicates that large opportunities for improving water footprint are found in low yielding farming systems, particularly in rainfed agriculture (water productivity is already higher in irrigated agriculture because of better yields). The assessment of sustainability of water use showed that the crop growth period when tomato and citrus need water is basically the same as the no precipitation period. The irrigation water requirement furthermore corresponds to the period where the water scarcity is high.

**Keywords** Crop water use · Rainfed/irrigated agriculture · Water productivity · Agriculture production · Tunisia

I. Mekki (✉) · R. Zitouna-Chebbi
INRGREF, University of Carthage, B.P. 10, 2080 Ariana, Tunisia



F. Khebour Allouche et al. (eds.), *Agriculture Productivity in Tunisia Under Stressed Environment*, Springer Water, https://doi.org/10.1007/978-3-030-74660-5_12

## 1 Introduction

Pressures on water resources have drastically increased in recent years due to human activities, the rapid changes in land use and the observed effects of climate change. Climate change projections [1] reveal that the Mediterranean region will be particularly affected by the drier and hotter conditions combined to the decrease of the renewable water resources to by up to 50% within the next 100 years. However, the extent and the accuracy remain imprecise, it is expected that climate change will result in a significant reduction in rainfall and an increase in the frequency of droughts. It is expected that water demand by 2030 is likely to exceed the conventional resources available. In Tunisia, agriculture represents 80% of all water abstraction in the country and 74% of the total consumption for the sector comes from groundwater [2] inducing aquifers overexploitation of 26% of them at an average rate of 146%. The efficient use of water for agriculture production will therefore be necessary to improve the productivity and ensure the better management of both components rainfed "green water" and irrigated "blue water". This nomenclature was introduced by [3], who in complement named as "green" water the part of precipitation that is stored initially in the unsaturated zone of the soil and lost by plant transpiration "productive" or soil evaporation unproductive. Both kinds of waters are important for sustainable farming systems. Green water is the main component of the water balance and is a basic resource for crop evapotranspiration in the semiarid areas [4]. It directly stems from the local infiltration of rainfall into the soil and, consequently, does almost not require any specific energy expense from the farmer. However, as estimated by [5], its average residence time is 5 months, which is not enough to allow for mitigating the effect of long dry periods. The blue water requires energy for its use as irrigation water. But, given its much larger residence time, 2.7 years on average after [5], it may be used to reallocate water from periods without or with small water shortage to periods with intense water scarcity, which helps to decrease the risk of complete crop failure. There is therefore a need to define and manage the best balance between green and blue water resources for sustainable farming systems. Land use is a major instrument through which blue and green water can be manipulated. It is known to largely influence the partition of rainfall into blue and green water [4]. The water footprint (WF) offers a useful tool to assess the use of water resources in crop production and can, therefore, support the prediction of the water consumption in rainfed and irrigated agriculture [6–10]. It is described as the volume of fresh water that is utilized during all process of crop production. WF accounting can be done at catchment, subnational, national, regional and global level, and it can be assessed from a consumer or producer perspective [11]. The bio-physical water productivity (WP, $Kg/m^3$) in crop production is in fact the inverse of the green–blue WF of crop production [9]. In order to grasp the effect of crop production on the sustainable use of water resources, facilitate decision-making processes, and to guide actions levers for better water management, the WF has been used [9, 10]. This is particularly important in the Cap Bon region northeastern Tunisia, where irrigation has increased in the past few decades, using intensively groundwater resources resulting in their degradation as well as their conflicting uses. Efficient management strategies that allow for compromises between agriculture production and water resource preservation are therefore needed. Such strategies require initial assessment of the sustainability of blue and green water resources management for crop production. For this purpose, the Global Water Footprint Standard approach has been used in the Cap Bon region in Tunisia to calculate the volumetric blue and green water footprint related to wheat, tomato and citrus production as major crops in the region.

## 2 Water Resources and Agriculture in the Cap Bon Region

### *2.1 Description of the Study Site*

The study focuses on the Cap Bon region, it covers 2822 Km$^2$, located in the north-eastern Tunisia (Fig. 1). The Cap Bon is a peninsula surrounded by the Mediterranean Sea on both sides. The Cap Bon landscape includes three zones (upstream, intermediate and downstream) according to geomorphologic, geological and land cover-land use criteria. A continuous ecosystem gradient is observed along the upstream–downstream transect. There are mainly three different soil groups: i) shallow, unstructured skeletal soils, poor in organic matter and sandy texture, ii) deep soils on alluvion in major river beds, silty-clay to clay-clay texture, moderately fertile, and iii) soils

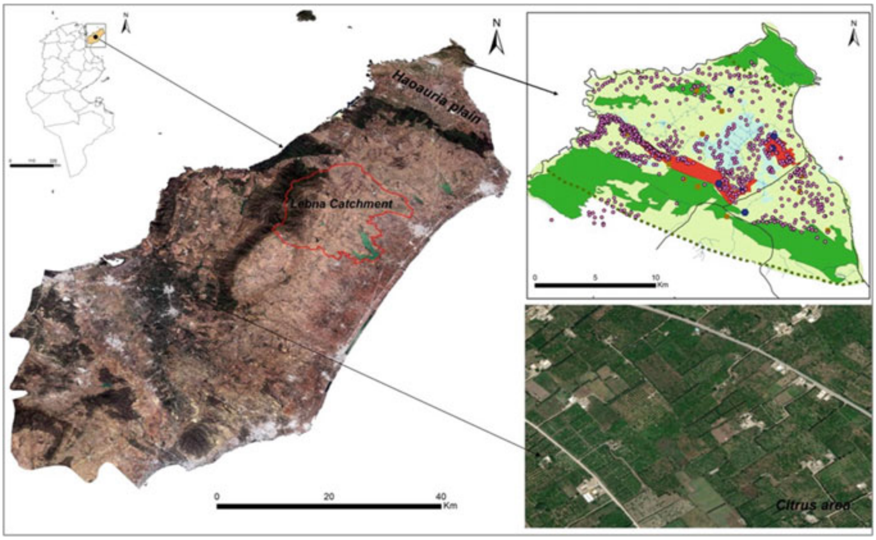


**Fig. 1** The Cap Bon region northeastern Tunisia with its main dams, Lebna catchment (rainfed agriculture), the citrus area (irrigated from Madjerda Cap bon) and the Haouaria coastal irrigated plain from groundwater resources

representing all hills and plateau's. The depth of the soil varies from a few mm on the rocky outcrops and in the wadi beds to more than 2 m in the plains and on some accumulated slopes. The watersheds are subject to soil erosion and subsequent dam's reservoirs siltation.

Representing 4% of SAU of the country area, le Cap Bon participate with 14.3% of national agricultural production. The region has known an important development of the agricultural activities and tourism. The forest and the shrubs covers the mountainous areas. The natural vegetation areas include the steepest parts, as well as the shores of the hill reservoirs, lakes and wadis. One third of the agricultural area is devoted to arboriculture. The olive tree is the oldest species introduced to Cap Bon, and is found everywhere, grown in forest or in small numbers in intercropping plots. Vineyards and citrus orchards are intensively irrigated. In hilly catchments, agricultural systems are mainly based on rainfed mixed farming and livestock. As in other rainfed agricultural systems in North Africa [11], the rainfed agriculture mainly includes cereal production, although its climate increases the crop diversity. Annual crop areas spread over 30% of the area. The annual crops include grain cereals (mainly wheat), fodder crops (mainly barley, oats and triticale), spices (mainly coriander) and legumes (mainly fava bean). Agriculture suffers from fragmented and small-scale holdings. Within the Cap Bon region, the cultivated landscape consists of a mosaic of very small agricultural fields, and the average field area is less than 1 ha. Livestock husbandry includes cattle, sheep and goat breeding. The land of the plain with high agronomic potential allows the practice of intensive agriculture with vegetables and citrus. The Cap Bon region is a regional hotspot for potential trade-offs in green- and blue-water resources between upstream and downstream users. The use of irrigation remains important options for cropping patterns in the irrigated plains that have long consisted of traditional irrigated crops in rotation with fodder crops for livestock. An important portion of economic development is focused on the continuous increase of production for export of tomato and citrus. 85% of national citrus production is from the Cap Bon [14].

### *2.2 Characteristics of the Climate*

The climate regime is between the Mediterranean upper subhumid and semiarid with a hot and dry summer and a mild and rainy winter season. The Fig. 2 shows the main average isohyets (mm/year), the annual rainfall at the Lebna and Kamech meteorological stations and the ombrothermic graph for two coastal zones. The mean annual rainfall and the mean annual evapotranspiration (Penman-Monteith reference crop evapotranspiration) range from 450 mm (averaged over 90 years at the nearest station meteorological located at Kelibia) to 800 mm and from 1000 to 1500 mm, respectively [12–14]. The long-term ombrothermic graph for the coastal zones shows near water deficiency conditions exist for the months of April–May to September–October. This indicates that crops grown during this season generally have an unfavorable water

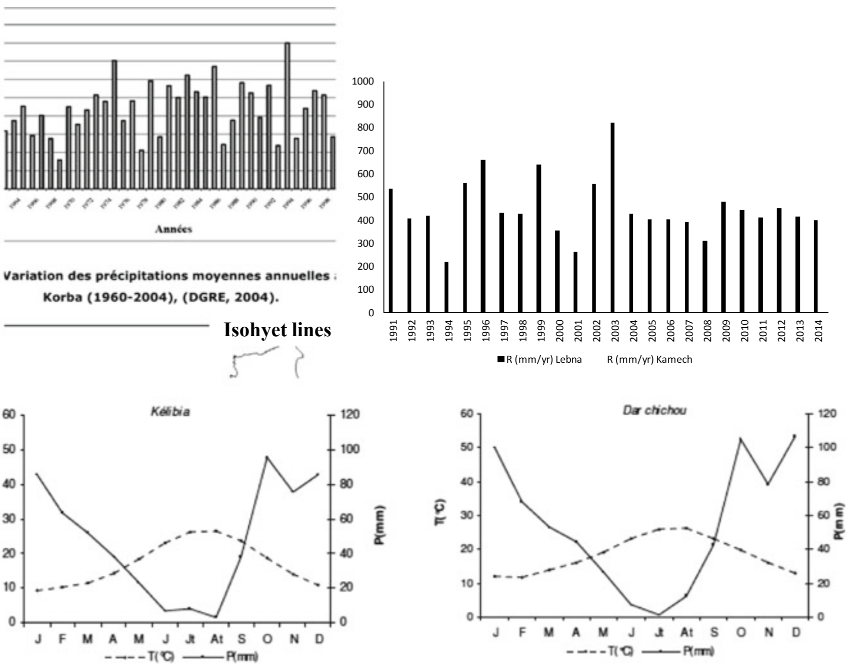


**Fig. 2** The main average isohyets (mm/year), the annual rainfall at the Lebna and Kamech meteorological stations and the ombrothermic diagrams for two coastal meteorological stations in the Cap Bon region

and temperature relations during these months.Rainfall mainly occur from October to April while the main dry season lasts from May to September.

## 2.3 *Blue and Green Water Resources Situation*

The blue water supply for the Cap Bon region stems from groundwater and surface water resources in local dams, surface water transfer coming from the channel Medjerda-Cap-Bon in Northern Tunisia. The canal which transfers the northern water from several dams built on the Medjerda, the country’s longest river, and allows their transport to several public irrigated areas of the region, located in the coastal areas. Groundwater, estimated at 260 $Mm^3$, originates from main six aquifers. They are marked by increasing pressure and persistent drawdown of water tables. For instance, in Haouaria plain aquifer, the increasing number of shallow wells led to significant groundwater abstraction and withdrawal rates of 60 $Mm^3$/year in the shallow aquifer, more than twice the natural recharge year, and high salinity levels (1.5–5 g/l with an average value of 3.2 g/l) observed in 2014 [14, 15]. Surface water is estimated at 150 $Mm^3$ of which 100 $Mm^3$ can be mobilized by important hydraulic infrastructure such as reservoirs and channels: 7 dams (mainly Lebna reservoir with capacity of storage of 30 $Mm^3$), 33 hilly dams and 53 hilly reservoirs (e.g. Kamech hill reservoir). From the water stored in these hydraulic infrastructures, the Regional Planning Commission for Agricultural Development (CRDA) of Nabeul has set up a program for the artificial recharge of the water tables during high water demand periods. Despite the strategies to mobilize water resources, the water scarcity continues to worsen. The reduction of surface water allocation to irrigated agriculture in order to meet the growing demand of competing uses (urbanization, industry and tourism activities) implies increasing irrigation pressures on ground water resources inducing their over-exploitation.

## *2.4 Characteristics of the Irrigated and Rainfed Agriculture*

The Cap Bon region is one of the most productive agricultural area for irrigated exported crops (tomato and citrus) in Tunisia. Rainfed farming systems are predominantly based on food cereal, legume grains production and fodder crops for livestock. Intensive irrigation activities in this region have caused a substantial increase of groundwater extractions, and consequently the depletion of groundwater resources along with the degradation of their quality (salt intrusions, salinization of irrigated land). The sustainability of irrigated agriculture in the Cap-Bon region is questionable and decision makers are facing difficulties to manage and allocate the resources [15, 16]. Access to water resources is collective or private. Collective irrigation is based on the water management rules via water user associations that regulated water partitioning.

Tomato is the second most important commodity produced in terms of quantity by the country and it is grown annually on an averaged area of around 28,000 ha (30% in the Cap Bon region). The averaged total production in the Cap Bon area is about 400,000 tons (36% of the national production) in 2013. The average yield between 1991 and 2017 was 45 tons per hectare. The tomato has one main season which is all open field and runs from April till September. Citrus plantations cover an area of about 22,000 ha in 2018. Cap Bon remains the main production zone, accounting for almost 70% of total citrus farming area. The total area dedicated to oranges has increased over the last twenty years due to expansion of irrigated areas and also as a result of increased crop densities. The number of trees has increased by 26% since 1999 [14]. Rainfall is almost absent during the high evaporative demand period for citrus and the irrigation practices generally starts in April and stopped in December.

Wheat is one of the main agricultural productions at the base of the Tunisian food security as olives and tomatoes. Durum wheat is the most produced cereal [17], accounting for more than half of production (56.7%). In 2009, the harvested wheat area covered 53% of consumption requirements. The study of [18, 21] showed that the preceding crop is one of the important factors impacting significantly the maximum yield of wheat. The authors of the former study observed that the highest yield (5.8 t $ha^{-1}$) was obtained for wheat following legumes (excluding chickpea), followed by vegetables and chickpea and the lowest Ymax (3.5 t $ha^{-1}$) was found for wheat in cereal-wheat rotation.

# 3 Impact of Climate Change

Under the Representative Concentration Pathway (RCP), the projections indicate an increased risk of soil moisture drying in the Mediterranean, consistent with projected changes in the Hadley Circulation and increased surface temperatures, and surface drying in these regions is likely (high confidence) by the end of the century under RCP8.5 [1]. The study performed by [17] for Tunisia show a general increase in average temperature (average over the entire territory) between 1.6 and 1.9 °C in 2050 and between 2 and 3.9 °C in 2100 relative to the reference period. They also show for, RCP8.5, a general decrease in rainfall between −14 and −22 mm in 2050 and between −23 and −45 mm in 2100 relative to the reference period. The decrease trend is not significant for some local zones, seasons and for the RCP4.5 scenario.

## *3.1 Water Resources*

The general decrease in rainfall, and the drought events will have an impact on the runoff and significantly decrease the inputs to dams by 5%. The increase in crop water requirements could lead to more exploitation of groundwater and the degradation of their quality. In addition, the rapid rise in sea level would also have a negative impact on the quality of coastal groundwater and might contribute to decrease their irrigation potential [17]. A prediction of 50% loss of current resources from the aquifers (nearly 150 million $m^3$) due to the increased sea level by 2030.

## *3.2 Irrigated and Rainfed Agriculture*

Increasing water scarcity is the most pressing climate change impact (extension of dry periods and rising temperatures) on the agriculture production. Although the effects are unclear at local scale, the observed inter and intra-annual variability of temperature shortened the development cycle of crops. The water demand from irrigated agriculture will increase and competition between other different sectors will also increase. The availability of surface and groundwater resource will be affected by the higher costs of energy for pumping.

The study of [17] on rainfed cereal production under different climate change scenarios and varying rainfall, predicted a loss of rainfed production potential. Losses were estimated at 10%−20% of production area. The competing demands of the water between the different sectors (agriculture, industry, tourism and domestic consumers) will increase and, therefore generate tensions.

Different studies and authors claim that the difference in farm strategies, and consequently resilience to cope with climate change in the South Mediterranean area, can be explained by the diversities observed in terms of cultivated cropping systems (cereals vs. orchards; rain-fed vs. irrigated) [22, 31], types of farming systems(small farms vs. big farms; mixed farms vs. cereal farms) [31] and the availability and quality of water, land and labour resources [19, 31, 32]. Studies on the impact of climate change recommend a period of at least 20–30 years to have a significant change of the driving forces [25]. However, for such a long-time horizon, there is a strong uncertainty regarding the technical and socio-economic evolutions. For example, as far as the economic domain is concerned, the volatility of product prices and the evolution of agricultural policies are the main reasons for such uncertainty [19, 24].

### *3.3 Climate Change Adaptation*

Rainfed agriculture has suffered from insufficient policy and institutional support for improving water management for production in changing climate. The focus over the past 50 years at the farm level has been mainly on soil conservation, and to a lesser extent in-situ water conservation (maximizing rainfall infiltration) through various strategies. Government programs in relation to water saving in irrigated agriculture are partially used to recover the investments in irrigation equipment. For catchment levels, policies have focused on remediating the negative effects of water upstream (erosion control and water conservation) to reduce the downstream impact. In recent decades, however, the focus has shifted from water management for conservation to water management for production upstream. Water harvesting, small irrigation and marginal water use can help improve water availability. Farmers' strategy for coping with climate change was to reduce the area of the less profitable irrigated winter forage which is then replaced by purchased hay and feed concentrates [19, 24].

## 4 Methodology and Used Data

The study adds to earlier studies of water footprint for Tunisia [8, 10] by addressing the regional dimension in a comprehensive national water footprint assessment.

As defined by [26], "the WF of a product is the volume of fresh water used to produce the product, measured over the full supply chain". The WF of a crop is generally expressed in terms of $m^3$/ton [26]. The water productivity (WP) is the inverse of the green–blue WF of crop production [9]. [23] defined the physical WP as "the ratio of agricultural output to the amount of water consumed". The water consumption is estimated from the blue water extraction or the total amount evapotranspiration from green and blue water.

### 4.1 Calculating Blue and Green Crop Water Use

[26] explain the water footprint of the process of growing a crop (WF) as the sum of the WF of the different sources of water following the Eq. (1):

$$WF(volume/mass) = WFblue + WFgreen \tag{1}$$

The blue (WF, blue, $m^3$/ton) and green (WF, green, $m^3$/ton) components of the water footprint were calculated as the amount of water supplies for irrigation and the effective rainfall (IWU, $m^3$/ha, ER, $m^3$/ha) divided by the crop yield (Y, ton/ha) following Eq. (2) and Eq. (3):

$$WFblue(m^3/ton) = IWU/Y \tag{2}$$

$$WFgreen\left(m^3/ton\right) = 10 \times Eff.R/Y \tag{3}$$

We consider the blue water (water supplied in crop production from the irrigation “IWU” from surface and groundwater sources). We consider the green water (water supplied in crop production from the effective rain “Eff.R” [27]. The factor 10 was used to convert effective rain water depths in millimeters into water volumes per land surface in $m^3$/ha.

We divided the amount of crop production by its corresponding water footprint in 1999 and 2018 to get the crop water productivity at the Cap Bon regional level over time.

### 4.2 Used Data

The rainfall data for the period (1999–2018) was gathered from 2 meteorological stations thus allowing for calculation of the green water consumption for different crops.

Agricultural data (crop yield and area sown) are obtained from the CRDA. Data on surface water, groundwater, and water withdrawals for irrigation were also obtained from the CRDA. Annual water diversions into different irrigated perimeters. Because these datasets were restricted to official records, they did not reflect private and uncontrolled abstractions. The resulting database was mostly fragmentary, and the gathered information was analyzed to ensure data reliability. Data on harvested tomato, citrus and wheat areas in Tunisia were also obtained from the CRDA statistical reports. Statistics on total crops production between 1999 and 2014 were obtained from the CRDA. The dataset used for implementing WF involved the Cap Bon regional scale corresponded to the management of water resources by the CRDA institutional service.

# 5 Results and Discussion

## *5.1 Water Foot Print*

The blue WF has been taken as being equivalent to the proportion of the consumed irrigation water by the crops yields. The total production WF for the irrigated schemes in the region is the summation of blue and green WF of each irrigated scheme. The Fig. 3 shows the high variability of the annual blue WF among different irrigated schemes in the Cap Bon region in 2014. The blue WFs average is about 1.49 $Mm^3$ per year and varied from 0.06 $Mm^3$ to 9.62 $Mm^3$ per year. Differences in the estimated blue WF values among irrigated schemes reflect the different agro-climatic conditions, the crop type and the overall management practices that affect the application efficiency. For the blue WF, the irrigation efficiency should possibly be indicated. Therefore, it reveals the significant potential for improving the efficiency of irrigation water resources management. The annual blue water footprint in all the Cap Bon region and for all the irrigated crops together is fluctuating and gradually increased from 40 $Mm^3$ in 1999, peaked in to 63 $Mm^3$ in 2008 and kept relatively stable around 55 $Mm^3$/yr between 2008 and 2014 (Fig. 3). High amounts of WF corresponding to the occurrence of meteorological drought periods and lower amounts related to wetter years. Over the period, 1999–2008, the average of total blue WF for crop production was about 351 $Mm^3$/yr. Evidence from water balance analyses on farmers' fields in the hilly Kamech catchment (Cap Bon) shows that only a small fraction of rainfall (generally less than 20%) generates blue water flow (runoff), and (about 70%) is used as productive green water flow (plant evapotranspiration) supporting plant growth [4].

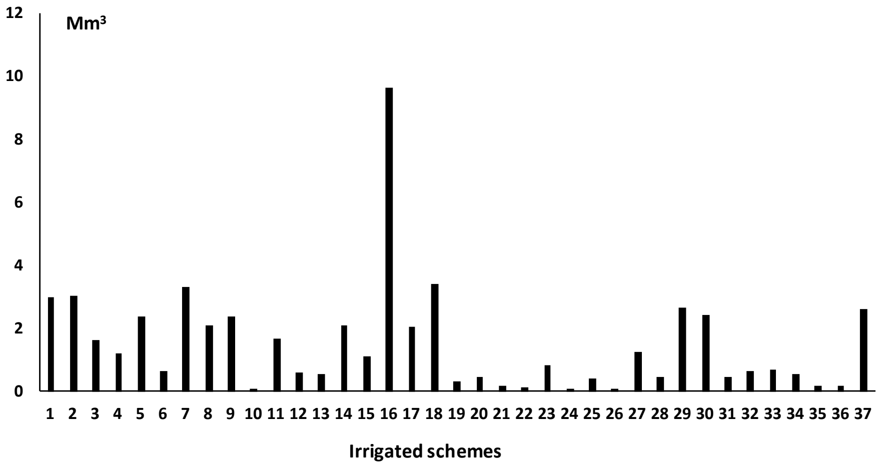


**Fig. 3** Production water footprints (blue) per irrigated schemes in the Cap Bon region in Tunisia for 2014. *Source:* [28]

The annual average (between 1991 to 2014) of green WF, which corresponds to the total precipitation infiltrated in the soil for crop production, is equal to 1470 $mm^3$. It varies from about 730 $Mm^3$ in 1994 to 2400 $Mm^3$ in 2003. According to our estimation in rainfed Lebna catchment (210 $km^2$) in the central Cap bon, the average amount of green water stored in the soil between 1991 and 2014 is about 90 $Mm^3$. It varies from 45 $Mm^3$ (1994) to 150 $Mm^3$ (2003). Its value approximates three to five times the amount of the blue water stored at the reservoir storage capacity at its construction (30 $Mm^3$). It represents a renewable water resource if is managed efficiently and used by crops.

The overall temporal dynamics of the different sources of blue WF fluctuated (Fig. 4). This can be explained by the inter-annual rainfall variability and the development of irrigated citrus area that led to the WFblue increase. But as we can see, the irrigated tomato area is reduced in relation to socioeconomic reasons. We observe that the temporal dynamics of total crop production (either citrus or tomato) were similar to the dynamics of WF of irrigated agriculture in the Cap Bon region.

The yields for tomato are 41% higher in average in comparison to citrus. It is evident that wheat generally have lower yields than tomato and citrus and consequently have higher green WFs despite its lower crop water consumption per hectare.

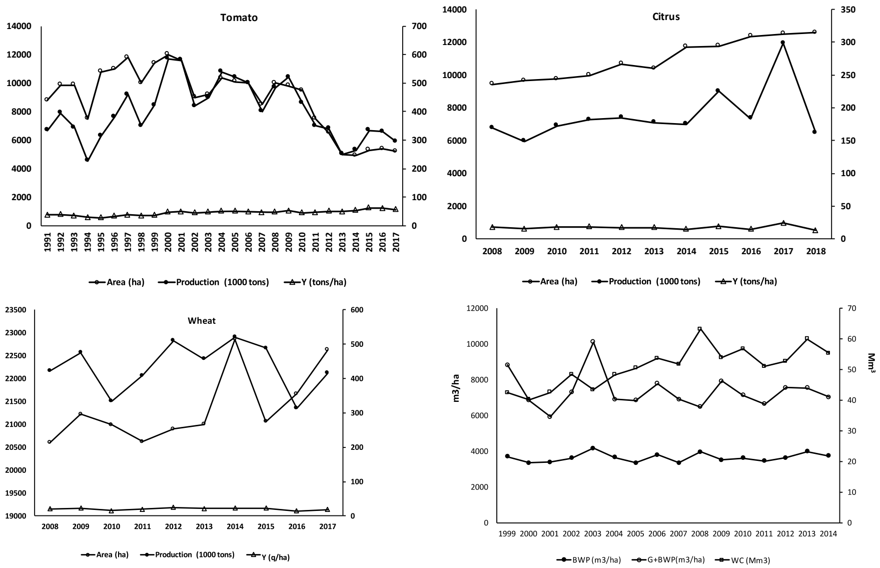


**Fig. 4** Temporal dynamics of different types of water footprints (blue and green) and average annual irrigation water use per ha from 1999 to 2014 (d). Evolution of harvested areas, total annual production and yields **a** tomato, **b** citrus fruit production, and **c** wheat in the Cap Bon region in Tunisia

**Table 1** WF and WP for wheat production

| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | Average |
|---|---|---|---|---|---|---|---|---|
| WP (kg/m$^3$) | 0.82 | 0.51 | 0.45 | 0.62 | 0.62 | 0.61 | 0.69 | 0.61 |
| WF (m$^3$/ton) | 1224.4 | 1964.3 | 2212.5 | 1603.7 | 1607,7 | 1634,7 | 1445,0 | 1670 |

**Table 2** Comparison of the results of this study (Cap Bon, Tunisia) with the green WF values of some countries in the world [6]

| Country | Iran | Russia | Turkey | USA | Cap Bon | Syria | Iraq | India | World | China | Egypt |
|---|---|---|---|---|---|---|---|---|---|---|---|
| WFgreen (m$^3$/ton) | 2412 | 2359 | 2081 | 1879 | 1670 | 1511 | 1226 | 635 | 1279 | 820 | 216 |

## 5.2 *Green Water Footprint of Wheat*

Table 1 illustrates that wheat have a high green WF per ton of production across all years. The Table 2 shows the WF of wheat in m$^3$/ton for main countries producing wheat in the world. The Cap Bon WF per ton of wheat (1670 m$^3$/ton) obtained in this study is equal to the world average (1620 m$^3$/ton) [20, 22, 29]. This is in contrast with crop water use per hectare, which is the lowest for all climatic seasons. It is evident that wheat generally have lower yields than citrus and tomato, consequently have higher green WFs despite their lower crop water consumption per hectare compared to the two high consumption crops. The annual average green water productivity in the Cap Bon region for wheat crops is also fluctuating (Table 1). The average crop water productivity is about 0.61 kg/m$^3$ decreased from 0.82 kg/m$^3$ in 2008 to 0.45 kg/m$^3$ in 2010. Water productivity is very low in rainfed agriculture, thus providing significant opportunities for producing more crops with less water. It could be seen that productivity remains very low in spite of significant total rainfall amount during the winter season. The occurrence of drought spells and infrequent rainfall events during the post an thesis period are the most likely causal factors of low yields.

Green water, has a lower opportunity cost compared to the blue water [6–8, 29]. There are still opportunities to lower the green WF by increasing production from the rainfed, which will reduce the need for production from the irrigated water, and thus reduce blue water use.

## 5.3 *Blue and Green Water Footprint of Tomato*

Table 3 shows that tomato have the smallest WF with an average of 131.28 m$^3$/ton.WF values estimated in this study are significantly different from those reported by [7, 8] as global averages for WF total (214 m$^3$/ton), WFgreen (108 m$^3$/ton), WFblue (63 m$^3$/ton).

**Table 3** WF and WP for tomato production

| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | Average |
|---|---|---|---|---|---|---|---|---|
| WP (kg/m$^3$) | 9.44 | 6.89 | 7.66 | 7.61 | 7.00 | 8.10 | 7.15 | 7.70 |
| WF (m$^3$/ton) | 105.9 | 145.1 | 130.4 | 131.4 | 142.7 | 123.6 | 139.8 | 131.28 |

**Table 4** WF and WP for citrus production

| | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | Average |
|---|---|---|---|---|---|---|---|---|
| WP (kg/m$^3$) | 2.76 | 1.83 | 2.34 | 2.53 | 2.18 | 2.26 | 2.05 | 2.28 |
| WF (m$^3$/ton) | 361.5 | 545.6 | 426.4 | 394.3 | 456.9 | 442.4 | 487.5 | 444.9 |

The annual average crop blue-green water productivity in all the Cap Bon region for tomato crops is also fluctuating (Table 3). The average crop water productivity decreased from 9.44 kg/m$^3$ in 2008 to 7.15 kg/m$^3$ in 2014. Comparisons across seasons revealed that in an average year, approximately 80% of crop water requirements were met through blue water and 20% via green water. On average, blue water use increased in the dry year and decreased in the wet year. This was primarily due to the difference in climatic conditions for each year.

There is a trade-off between higher crop water productivity and increasing water pollution resulting from the loss of fertilizer to the groundwater system. This trade-off needs to be considered carefully because maximizing water productivity may result in deteriorating water quality through nutrient pollution and salinization.

### *5.4 Blue and Green Water Footprint of Citrus*

Table 4 shows that citrus mainly *Maltaise* have an average WF of 445 m$^3$/ton. The annual average crop blue-green water productivity in all the Cap Bon region for citrus crops is also fluctuating (Table 4). The average crop water productivity is about 2.28 kg/m$^3$ and decreased from 2.76 kg/m$^3$ in 2008 to 1.83 kg/m$^3$ in 2009.

### *5.5 Sustainability of the Water Footprint*

The blue WF that specifically relates to groundwater consumption represents 62% of the total renewable groundwater resources, which means that the region is facing severe water scarcity related to the groundwater [23]. The consumptive use of groundwater exceeds the renewable groundwater available in this region.There is tremendous pressure on water resources due to the increasing demand of production of tomato and citrus with major exports. With free access to irrigation water, individual strategies varied tremendously between farmers. Drip irrigation is primarily used to achieve the highest yield; however, the water demand is not reduced. The improved technologies (powerful pumps, drip fertigation) induced a substantial increase in water productivity by optimizing the production process, conversely, it did not save irrigation water and did not decrease the water demand. Changing high water consumption cropping systems, developing efficient water-saving irrigation technology should be considered for the future agricultural management to help ensure water use sustainability and agricultural production simultaneously.

The first result of this study shows that wheat in the Cap Bon region are embedding a higher volume of green WF compared to citrus trees and tomato crops. Wheat has the largest WF per unit of weight. Policy for water governance to increase agricultural production, should be conveyed to upgrade rainfed agriculture by implementing new levers of sustainable management. Investments in rainfed agriculture have focused on remediating the negative effects of water upstream (erosion control and water conservation) to reduce the downstream impact. Field studies in Cap Bon region have shown that watersheds can have green water yields up to 3 times greater than blue water production at the reservoir downstream. Investments in crop technologies and integrated watershed management interventions could bring a shift in cropping pattern, increased yields and use more sustainable the water resouces. Crop diversification with inclusion of higher value crops such as vegetables, medicinal and aromatic plants could make the systems more sustainable and remunerative. The reduction of WF values could be achieved through irrigation management strategies that increases the water use efficiency [24]. As observed by [30] across the different climate regions of the world, large increase in crop yields is achievable for most crops through proper nutrient, water and soil management. The case study of WF of irrigated sugarcane by [25] in a rainfall scarce region of Nigeria, indicated high values of blue WF resulting from high irrigation water dependency. However, although climatic and soil factors are important in determining evapotranspiration from crop fields and yields, the green–blue WF of crops is largely determined by crop management [8, 20, 21, 23]. Generally rainfed yields depends on the additional water, but also on used crop varieties and the nutrient supply.

## *5.6 Spatial and Temporal Scales*

The local scale is important when considering water issues. The high variability of the individual and the collective strategies of water management might explain the high variability of the WF. The evaluation of the WF considering space and time is prerequisite to distinguish levers for best water resource management.Higher spatio-temporal resolution of maps based on either local measurements or remote sensing may help to reduce the uncertainties in the assessment of WF. Specific local conditions including the daily rain pattern and partitioning between green and blue water, the cropping cycle pattern (planting and harvesting dates and thus the length of the growing period type, the rooting depth) and the local irrigation management may affect the water footprint estimates. As an example, a crop grown during wintertime can have less water consumption than when grown during spring–summer time, simply because the evaporative demand of the atmosphere is less in the winter than in the spring–summer. Similarly, the same crop grown in different locations having different evaporative demand of the atmosphere (locations more in the north or more in the south of a region), may have different water consumptions. A way to formalize this concept is through the formulation of the crop water requirement.

## 6 Conclusion and Perspectives

This study provided a quantitative calculation of the crop production WF over the Cap Bon region, northesstern Tunisia with semiarid climate and rainfed and irrigated farming practices. Although this study did not provide a comprehensive environmental and socio-economic assessment (considering the farming system, the growing cycle and the varieties), it did provide a useful method to facilitate an integrated water resources management. WF and WP indicators can be used in weighing up decisions and highlighting potential issues that could be investigated further so that better recommendations can be made. The available data along the last decades allowed us to assess the green and blue WF values for wheat, tomato and citrus crops. The results show that the average of total WF of crop production was about 1821 $Mm^3$/yr (85% green, 15% blue) over the period 1999–2008. The total WF (green + blue) of tomato and citrus crops averaged 131.28 $m^3$/ton, 445 $m^3$/ton, respectively. The green WF of wheat obtained in this study was about 1670 $m^3$/ton, which is equal to the calculated world average (1620 $m^3$/ton) by previous studies. This indicates that large opportunities for improving water footprint are found in low yielding farming systems, particularly in rainfed agriculture (water productivity is already higher in irrigated agriculture because of better yields). Also, the development of irrigated agriculture, and significant improvements in blue WF induced a large pressure on water resources. The few degrees of freedom for blue water development, calls for increased efforts to develop green water flows and upgrade rainfed agrosystems to capture the local blue water resources and increased consumption of green water before rainfall turns into blue runoff flows. One main conclusion perhaps is the need for a better assessment of green water needs for the sustainability of the agrosystems. Another relevant pending question is how to cope with the great variability of rainfed agriculture due to the normal climate variability, independently of the relevance of climate change.We acknowledge, though, that further studies may refine the quatification of WF and WP into local scale, based o applied water and on claculated crop evapotranspiration to account for the climatic variability. Also, investigating the upstream-downstream water flows of regional agricultural production is needed.

## References


1. IPCC (2013) Climate change 2013: the physical science basis. contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.) Cambridge University Press, Cambridge, 1535 p
2. Elloumi M (2016) La gouvernance des eauxsouterrainesen Tunisie, Report No. 6, IWMI Project Publication 'Groundwater governance in the Arab World', Cairo, Egypt
3. Falkenmark M (1995) Land-water linkages: a synopsis. In: Land and water integration and river basin management, vol 1. FAO Land and Water Bulletin, Rome, pp 15–16
4. Mekki I, Zitouna Chebbi R, Jacob F, Ben Mechlia N, Prévot L, Albergel J, Voltz M (2018) Impact of land use on soil water content in a hilly rainfed agrosystem. A case study in the Cap Bon Peninsula in Tunisia. AGROFOR Int J 3(1):64–75
5. Savenije HHG (2000) Water scarcity indicators: the deception of the numbers. Phys Chem Earth (B) 25:199–204
6. Mekonnen MM, Hoekstra AY (2010) A global and high-resolution assessment of the green, blue and grey water footprint of wheat. Hydrol Earth Syst Sci 14:1259–1276
7. Mekonnen MM, Hoekstra AY (2011) The green, blue and grey water footprint of crops and derived crop products. Hydrol Earth Syst Sci 15:1577–1600
8. Mekonnen MM, Hoekstra AY (2014) Water footprint benchmarks for crop production: a first global assessment. Ecol Ind 46:214–223
9. Chahed J, Besbes M, Hamdane A (2015) Virtual-water content of agricultural production and food trade balance of Tunisia. Int J Water Resour Dev 31:407–421
10. Hoekstra AY (2017) Water footprint assessment: evolvement of a new research field. Water Resour. Manag. 31:3061–3081
11. Latiri K, Lhomme JP, Annabi M, Setter TL (2010) Wheat production in Tunisia: progress, inter-annual variability and relation to rainfall. Eur J Agron 33:33–42
12. Zitouna Chebbi R, Mahjoub I, Mekki I, Ben Mechlia N (2017) Comparing evapotranspiration rates estimated from atmospheric flux, soil water balance and FAO 56 method of a small orange orchard in Tunisia. In: Marsal J, Girona J (eds) Proceedings of VIII international symposium on irrigation of horticultural crops. ActaHortic. ISHS 2017, vol 1150. https://doi.org/10.17660/ActaHortic.2017.1150.4
13. Mekki I, Bailly JS, Jacob F, Chebbi H, Ajmi T, Blanca Y, Zairi A, Biarnès A (2018) Impact of farmland fragmentation on rainfed crop allocation in Mediterranean landscapes: a case study of the Lebna watershed in Cap Bon, Tunisia. Land Use Policy 75:772–783
14. Mahjoub I, Zitouna Chebbi R, Mekki I, Ben Mechlia N (2017) Assessing irrigation scheduling by FAO method using soil-plant-atmosphere water stress indictors on four orange varieties (Citrus sinensis (L.) Osbeck). In: Marsal J, Girona J (eds) Proceedings of VIII international symposium on irrigation of horticultural crops. ActaHortic. ISHS 2017, vol 1150. https://doi.org/10.17660/ActaHortic.2017.1150.20
15. Mekki I, Ghazouani W, Closas A, Molle F (2017) Perceptions of groundwater degradation and mitigation responses in the Haouaria region in Tunisia. Groundwater Sustain Dev 5:101–110
16. Frija I, Frija A, Chebil A, CheikhM'Hamed H, Speelman S, Makhlouf M (2014) Marginal water productivity of irrigated durum wheat in semi-arid Tunisia. J Agric Sci 6:84–95
17. Acterra, Gret et Suez Consulting group (2020) Analyse des effets des scénariosde changement climatique RCP 4.5et RCP 8.5. Tunisie-Contribution aux éléments de laphase préparatoiredu processus du Plan Nationald' Adaptation (Axe 2), 169 p
18. Ben Zekri Y, Barkaoui K, Marrou M, Mekki I, Belhouchette H, Wery J (2018) On farm analysis of the effect of the preceding crop on N uptake and grain yield of Durum wheat in Mediterranean conditions. Arch Agron Soil Sci. https://doi.org/10.1080/03650340.2018.1514111
19. Souissi I, Boisson JM, Mekki I, Theronds O, Flichman G, Wery J, Belhouchette H (2017) Assessing the resilience of farming systems to climate change in the South Mediterranean area: a Tunisian case study. Regional Environ Change. https://doi.org/10.1007/s10113-017-1130-8

20. Hoekstra AY, Chapagain AK, Aldaya MM, Mekonnen MM (2011) The water footprint assessment manual: setting the global standard. Earthscan, London
21. Aldaya MM, Allan JA, Hoekstra AY (2010) The strategic importance of green water in international crop trade. Ecol Econ 2010(69):887–894
22. Ewaid SH, Ali Abed S, Al-Ansari N (2019) Water footprint of wheat in Iraq. Water 11:535. https://doi.org/10.3390/w11030535
23. Chouchane H, Hoekstra AY, Krol MS, Mekonnen MM (2015) Water footprint of Tunisia from an economic perspective. Ecol Ind 52:311–319
24. Luan XB, Yin YL, Wu PT, Sun SK, Wang YB, Gao XR, Liu J (2018) An improved method for calculating the regional crop water footprint based on a hydrological process analysis. Hydrol Earth Syst Sci 22:5111–5123. https://doi.org/10.5194/hess-22-5111-2018
25. Yuguda TK, Li Y, Zhang W, Ye Q (2020) Incorporating water loss from water storage and conveyance into blue water footprint of irrigated sugarcane: a case study of Savannah Sugar Irrigation District, Nigeria. Sci Total Environ 715:1368–1386. https://doi.org/10.1016/j.scitotenv.2020.136886
26. Hoekstra AY, Chapagain AK, Aldaya MM, Mekonnen MM (2011) The Water Footprint Assessment Manual: Setting the Global Standard. Earthscan, London
27. Aldaya MM, Allan JA, Hoekstra AY (2010) The strategic importance of green water in international crop trade. Ecol Econ 69:887–894
28. CRDA-Nabeul (2018) Annual Report of 2018 Activities. Technical report Regional planning Commission for Agricultural Development, Nabeul Tunisia (in French)
29. Molden D (2007) Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. Earthscan/International Water Management Institute, London/Colombo
30. Mueller N, Gerber J, Johnston M et al (2012) Closing yield gaps through nutrient and water management. Nature 490:254–257
31. Reidsma P, Ewert F, Lansink AO, Leemans R (2010) Adaptation to climate change and climate variability in European agriculture: the importance of farm level responses. Eur J Agron 32(1):91–102
32. Rodriguez D, deVoil P, Power B, Cox H, Crimp S, Meinke H (2011) The intrinsic plasticity of farm businesses and their resilience to change. An Australian example. Field Crops Res 124:157–170. https://doi.org/10.1016/j.fcr.2011.02.012