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ORIGINAL ARTICLE

Impact of Irrigation Technologies and Strategies on Cotton Water Footprint Using AquaCrop and CROPWAT Models

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Abstract Different irrigation technologies and strategies have been proposed as means to improve the overall irrigation management and thus the rational use of the available water resources. The water footprint has been proposed as an index of the rational use of the water needed to produce goods and services. In agriculture, the water footprint is defined as the ratio of the sum of crop's cumulative evapotranspiration plus the amount of freshwater polluted during the cultivation process against final yield, and is further discerned to green, blue and gray components. In this study, we used two FAO's agronomic models named AquaCrop and CROPWAT, as well as two water footprint methodological frameworks to assess the impact of irrigation technology and strategy on the reduction of cotton water footprint in Northern Greece. Results showed that the impact of both irrigation technology and irrigation strategy in the green, blue and total water footprints was better estimated by AquaCrop model while CROPWAT model seems to be able to evaluate only the changes in the irrigation strategy. The drip technology could reduce the total water footprint by 5%, when compared to sprinkler, while deficit irrigation by roughly 12%, when compared to full. Lastly, in all cases the green water footprint was approximately 55% of the total.

Keywords CROPWAT · AquaCrop · Water footprint · Evapotranspiration · Cotton irrigation · N. Greece

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1 Introduction

Nowadays, the agricultural sector is responsible for the consumption of roughly 51.4% and 31% of the total freshwater withdrawals in Europe and USA, respectively (EEA 2017; Kenny et al. 2009). Climate change is expected to exacerbate the pressure on the planet's available water resources with a parallel increase in the irrigation water requirements by up to 70–90% until 2050 (Garrote et al. 2015; Kreins et al. 2015). As a result, the shortage of the existing resources threatens the stability of the agricultural crop production and will overwhelm the planet's food security in the near future.

One of the potential prospects promising to alleviate the increasing water scarcity is to exploit the available for irrigation surface and groundwater in a more sustainable way. This can be achieved through the optimization of field and irrigation management. The latter consists of two fundamental elements, the irrigation technology and the irrigation strategy. Today the most widespread irrigation technologies for arable crops are the sprinkler and the drip systems, as well as the furrow irrigation technique. Recent studies indicate that the use of drip irrigation systems could result in better yields, compared to furrow and sprinkler systems, when the same amount of water is applied on arable crops and vegetables (Rashidi and Keshavarzpour 2011; Al-Said et al. 2012; Tsakmakis et al. 2017). Although, more innovative technologies like subsurface drip or variable rate drip irrigation systems have been introduced lately, promising to enhance even more the irrigation management efficiency, their limited use and the lack of robust research evidence does not allow any reliable quantification of their potentiality at the moment. Regarding the irrigation strategy, full irrigation stands as the reference irrigation practice which guarantees the achievement of maximum crop production, as plants are supplied with the required water to counterbalance the evapotranspiration demand (Allen et al. 1998). Any irrigation scheduling applying less water than that applied in the full irrigation is considered as a deficit irrigation strategy. The effects of deficit irrigation on the final crop production and water consumption has been studied extensively for a variety of arable crops and vegetables (Qiu and Meng 2013; Bakhsh et al. 2012; Jinxia et al. 2012; Igbadun et al. 2012; Tsakmakis et al. 2017). It is summarized that deficit irrigation has the potential to decrease the water consumption per unit of crop yield, compared to the full irrigation strategy (Geerts and Raes 2009).

Water footprint (WF) is a recently-introduced theoretical concept, estimating the amount of water needed to produce each of the goods and services we use in our everyday socio-economic activities (Hoekstra et al. 2011; Hoekstra 2017). More specifically, in agriculture, the water footprint of a given crop is defined as the ratio of the sum of the cumulative actual evapotranspiration, throughout the cultivating period plus the amount of fresh water polluted by fertilizers and chemical substances from pesticides during the cultivation process, divided by crop final yield. This ratio is the inverse of the so-called crop water productivity (CWP) which is defined as the final crop yield against the actual evapotranspiration (Molden et al. 2010). These ratios have been used as indices of irrigation water rational use (Amarasinghe and Smakhtin 2014). Going one step further, Hoekstra et al. (2011) discerned crop evapotranspiration, and consequently the corresponding consumptive water, into two fractions: the green and the blue. The green fraction represents the amount of water of natural origin (precipitated water), while the blue fraction stands for the irrigated water. Both fractions have been infiltrated, stored in the soil profile and eventually evapotranspired during the cultivation period. By dividing each of the green and blue evapotranspiration fractions with crop final yield, we obtain the green and blue water footprints, respectively. Many studies have been conducted to determine the water footprint of various crops in different countries, utilizing models and datasets ranging from national to regional levels, providing estimates of the current status (Chapagain et al. 2006; Zeng et al. 2012; Bocchiola et al. 2013; Ababaei and Etedali 2014; Cao et al. 2014; Starr and Levison 2014; Morillo et al. 2015; Zoidou et al. 2017; Zotou and Tsihrintzis 2017).

The Water Footprint Assessment Manual (Hoekstra et al. 2011) proposed FAO's CROPWAT model as appropriate for calculating the green, blue and total water footprint of a crop (in this paper, total water footprint refers to the sum of green and blue, since gray water footprint is not calculated). According to their instructions, the model should be executed initially under rainfed conditions and the simulated actual crop evapotranspiration is assumed to be the green evapotranspiration fraction. Then, the model should be re-executed utilizing an irrigation schedule. The difference between the actual crop evapotranspiration obtained from irrigated and rainfed simulations is considered as the blue evapotranspiration fraction. In a more recent work, Chukalla et al. (2015) used AquaCrop model for the same purpose. However, they utilized equations based on model's descriptive water balance calculations to keep track on the green and blue evapotranspiration fractions in a daily time step.

In this paper, we present a systematic model study for cotton (*Gossypium hirsutum*) irrigation management in Northern Greece, utilizing both CROPWAT and AquaCrop models, as well as two methodologies proposed for the estimation of the green and blue water footprints. Models were calibrated using data obtained from a precision irrigation experiment carried out at farm scale level during 2013–2015. Both models were run for full irrigation and deficit irrigation scenarios to examine the potential water footprint reduction through irrigation strategy component, while all irrigation scenarios were run for both sprinkler and drip irrigation technologies. Finally, the results of the present study were compared to the findings of previous studies for cotton around the globe.

2 Materials and Methods

2.1 Data

The meteorological and soil data used as input in the models in the current work were obtained during a precision irrigation project, named FIGARO, carried out in a field (Fig. 1) located in Xanthi coastal plain in Northern Greece (41.046°N; 24.892°E; 13 m altitude). The field was cultivated with cotton Pioneer ST402 variety, from 2013 to 2015. A detailed description of the experiment is reported in Tsakmakis et al. (2017). Due to intensive rainfalls during July and October 2014, cotton production was severely damaged and thus these data were excluded from the current work.

2.2 CROPWAT and AquaCrop Water Balance and Crop Growth Simulation Models

The CROPWAT model (FAO 2009) utilizes the concepts of reference evapotranspiration (ET_0) and crop coefficient (K_c), introduced by Allen et al. (1998), to estimate the water requirements of a crop for different climate conditions and soil profiles. The model requires: (a) a soil file,

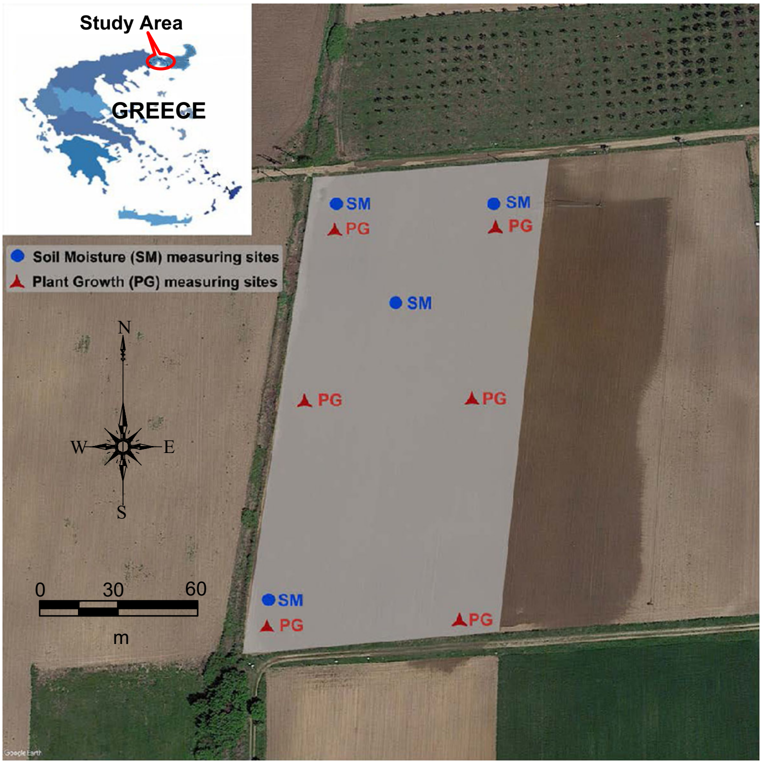

Fig. 1 Experimental field site

where the saturated hydraulic conductivity (K_{SAT}) and the total available root zone water content on sowing date are defined; (b) a crop file, which includes information about the duration of the different crop development stages, the corresponding values of crop coefficient for initial, mid and late stages (K_c), the planting and harvest dates, the yield response factor to potential water stresses (K_y), as well as the water depletion levels at which these stresses are triggered. Then, the model solves the water balance equation (Allen et al. 1998) utilizing daily ET_0, precipitation and irrigation data as inputs. The potential crop evapotranspiration is calculated as follows:

$$ET_C = K_C \times ET_0 \tag{1}$$

where: ET_c is the potential crop evapotranspiration (mm/d); K_c is the crop coefficient; and ET_0 is the reference evapotranspiration (mm/d).

If the total available water (TAW) in the root zone is not adequate to cover the evapotranspirative demand, then the model incorporates a water stress coefficient and calculates the adjusted crop evapotranspiration as follows:

$$ET_{Cadj} = K_W \times K_C \times ET_0 \tag{2}$$

where: ET_{Cadj} is the adjusted crop evapotranspiration (mm/d); and K_W is a dimensionless water stress coefficient.

For CROPWAT, any water deficit and thus a transition from ET_c to ET_{Cadj} is interpreted as a proportional reduction in the potential crop yield using the following equation:

$$1 - \frac{Y_a}{Y_p} = K_y \left(1 - \frac{ET_{Cadj}}{ET_C} \right) \tag{3}$$

where: Y_a is the actual crop yield (t); Y_p is the potential maximum crop yield (t); and K_y is the yield response factor between relative yield decline and relative decline in evapotranspiration. Subroutines for the estimation of the final crop yield are not incorporated in the model.

When the model is executed in the "daily soil moisture balance mode", it estimates the ET_{Cadj}, the moisture deficit of the soil profile and the total water losses. Losses are the sum of rainfall and irrigation surface runoff and deep percolation amounts, which are calculated in two steps: (a) if the rainfall or irrigation exceeds the K_{SAT} value, the excess water is lost as surface runoff and the rest infiltrates in the soil profile; (b) if the soil profile is already at field capacity, the excess infiltrated water is lost as deep percolation, otherwise water added to the soil water reservoir. Even though in the output there are not descriptive daily data about the amount of rain and irrigation water lost via surface runoff and deep percolation, the model reports the cumulative rainfall and irrigation losses at the end of the growing season.

More recently, FAO introduced the AquaCrop model, a water driven model able to simulate the annual growing cycle of grains, vegetables and root-tuber crops (Raes et al. 2009; Steduto et al. 2009). Similarly to CROPWAT, the model is based partially to the work of Allen et al. (1998), but it also incorporates the relatively novel concept of crop water productivity (WP) in order to transform the estimated crop evapotranspiration to final crop yield (Steduto et al. 2007). Input data requirements are very similar to those of CROPWAT for the climate file, but more detailed information is needed for soil and crop files, making AquaCrop a more sophisticated model. For instance, the soil profile could be divided in up to 5 soil horizons with different hydraulic characteristics each, while the crop file describes details about the cultivar's root maximum depth and growing patterns. Consequently, the output results of AquaCrop, in addition to the water balance data (evapotranspiration, irrigation, rainfall), include information regarding the crop's final dry aboveground biomass, harvest index (HI) and yield.

While CROPWAT uses Eq. (2) to calculate ET_{Cadj}, AquaCrop model approaches the ET_{Cadj} from a different perspective. It considers that it is the sum of crop adjusted evaporation (E_{Cadj}) and crop adjusted transpiration (Tr_{Cadj}), as follows:

$$ET_{Cadj} = E_{Cadj} + Tr_{Cadj} \tag{4}$$

$$E_{Cadj} = K_r \times K_e \times ET_0 \tag{5}$$

$$Tr_{Cadj} = K_S \times Kc_{Tr} \times ET_0 \tag{6}$$

where: K_r is the evaporation reduction coefficient, fluctuating between 0 and 1, with lower values to occur when insufficient water to supply the evaporative demand of the atmosphere is available in the upper 30 cm soil layer; K_e is the soil evaporation coefficient, being proportional to the fraction of the soil surface not covered by canopy, taking the value 0 when a field is completely covered by canopy and 1 when there is no canopy cover at all; K_s is the soil water stress coefficient, being equal to 1 when the soil is at field capacity and 0 at permanent wilting point; and Kc_{Tr} is the crop transpiration coefficient (0–1).

Once the daily transpiration is calculated, the model transforms it to plant biomass by multiplying it with crop's water productivity:

$$B = WP^{*} \times \sum \frac{Tr_{Cadj}}{ET_0} \tag{7}$$

where: B is the daily produced dry aboveground biomass (tn/ha/d); and WP^{*} is the crop water productivity adjusted for atmospheric CO_2 concentration (g/m^2). Finally, the crop yield is derived as a portion of the cumulative B on harvest day:

$$Y = HI \times B \tag{8}$$

where: Y is the crop production (tn/ha); and HI is the harvest index (%).

During the initial crop file parameterization, HI is given a reference value, but this value may differ substantially at the end of the season, positively or negatively. A severe water stress or water logging conditions due to prolonged rainfalls may result in a reduction of the reference value, while a regulated deficit irrigation strategy may improve HI by controlling the plants' vegetative growth and boosting their yield formation. The latter is not true for all crops, as some of them, like maize, are very sensitive to water stress and any water deficit is more likely to result in the final crop yield reduction (Kang et al. 2000), but other crops, like cotton, are more tolerant to these practices (Zwart and Bastiaanssen 2004). Thus, the correct parameterization of all variables determine the HI is of high importance.

In this study, a calibrated and validated AquaCrop crop file was used under the deficit irrigation FIGARO experiments (Tsakmakis et al. 2017). The maximum canopy cover value was set equal to 98%, the maximum rooting depth was set at 1.3 m and was reached 106 days after sowing (Farahani et al. 2009), and the reference HI was set at 35% (García-Vila et al. 2009). In the case of CROPWAT, all crop coefficients and yield response factors proposed by Allen et al. (1998) for the different cotton growing stages were utilized (initial stage $K_c = 0.35$, $K_y = 0.20$; mid-season $K_c = 1.15$, $K_y = 0.5$; harvest stage $K_c = 0.5$, $K_y = 0.25$), while the corresponding duration of each stage was again based on the observations of FIGARO project.

2.3 Irrigation Management

2.3.1 Irrigation Technology

The irrigation technologies examined in this paper are a classic drip irrigation system and a hose pull traveller irrigation system composed of a large hose reel, a gun-type sprinkler and a large semi rigid polyethylene hose. These systems are used by the majority of farmers in the region with the latter counting for roughly 70–80% of the cases.

CROPWAT model does not give the option to the user to choose between different irrigation technologies, considering that all events are performed with a sprinkler system. On the contrary, in AquaCrop this option has been integrated, thus the user could choose from sprinkler, drip and furrow options. The actual difference between them is the wet portion of the field surface after an irrigation event. For sprinklers this portion is by default 100% while for drip this portion could vary between 30 and 50%. In our case, an irrigation file was created for sprinkler irrigation technology, simulating the hose pull traveller and another for drip with 30% wet coverage.

2.3.2 Irrigation Strategy

Three main different irrigation strategies were followed. First, a full irrigation scheduling was devised for both sprinkler and drip systems. To do so, an irrigation schedule was generated by AquaCrop model given the following criteria: (a) for the drip system, a 15 mm water depletion was allowed before an irrigation event of 15 mm of water occurs; (b) for the sprinkler system, a 35 mm water depletion was allowed before an irrigation event occurs applying 35 mm of water. The depletion levels were based on the amounts of water usually applied per irrigation event by farmers in the study region, intending to create realistic irrigation schedules. Moreover, for both systems a constraint of no irrigation events scheduled after September 7 was included. Again, this is a default practice implemented by the farmers in the region, aiming to halt the vegetative growth of plants and accelerate the boll ripening. This way the cotton is usually harvested at the first week of October, minimizing the chances that the opened cotton balls will be damaged by the mid-autumn rains.

Successively, and based on the irrigation scheduling obtained above, the 80% sustained deficit irrigation (DI) strategy was formulated. To do so, an irrigation schedule with the same irrigation events as in the case of full irrigation was created, but the amount of water applied at each event was reduced by 20%. This way the overall deficit was evenly distributed throughout the season (sustained deficit). Then, we devised an 80% regulated DI schedule, applying the same amount of water as in the case of the 80% sustained deficit schedule, but allocating it in uneven amounts within the season with an ultimate goal to enhance season's HI.

Lastly, two irrigation strategies which have been implemented in practice in the region are used as well. These schedules stand for 50% Regulated DI in 2013, and 60% Regulated DI in 2015.

All the above-mentioned irrigation schedules were inserted to CROPWAT model through the "irrigate at user defined intervals" and "user defined application depth" options. In all cases, the irrigation system efficiency was considered to be 100%. The various irrigation management scenarios examined in this paper are summarized in Table 1.

Table 1 Irrigation scenarios description

Scenario	Irrigation Technology	Irrigation Strategy	Applied Year
1	Sprinkler	Full Irrigation	2013, 2015
2	Sprinkler	80% Sustained Deficit Irrigation	2013, 2015
3	Sprinkler	80% Regulated Deficit Irrigation	2013, 2015
4	Sprinkler	50% Regulated Deficit Irrigation	2013
5	Sprinkler	60% Regulated Deficit Irrigation	2015
6	Drip	Full Irrigation	2013, 2015
7	Drip	80% Sustained Deficit Irrigation	2013, 2015
8	Drip	80% Regulated Deficit Irrigation	2013, 2015
9	Drip	50% Regulated Deficit Irrigation	2013
10	Drip	60% Regulated Deficit Irrigation	2015

2.4 Water Footprint

According to the definitions and the methodological framework introduced by Hoekstra et al. (2011), the green and blue components of crop water requirements (CWR) are calculated by the accumulated data on daily crop evapotranspiration ET_c (mm/day), over the complete growing period, as follows:

$$CWR_{green} = 10 \times \sum_{d=1}^{lp} ET_{green} \tag{9}$$

$$CWR_{blue} = 10 \times \sum_{d=1}^{lp} ET_{blue} \tag{10}$$

where: CWR_{green} and CWR_{blue} are the green and blue components of crop water requirements (m^3/ha), respectively; ET_{green} represents the rainwater lost by evapotranspiration (green water) (mm/d); and ET_{blue} the irrigated water lost by evapotranspiration (blue water) (mm/d) during the cultivation period. The summation is done over the period from the planting day (d = 1) to the day of harvest (d = lp; lp is the length of growing period in days).

The ET_{green} and ET_{blue} evapotranspiration fractions were estimated in this study in two different ways. In the first approach (Hoekstra et al. 2011), the two models were executed initially under rainfed conditions. The cumulative ET_{Cadj} at the end of the season was considered equal to ET_{green}. Then, the models were run again under the ten different management scenarios presented in Table 1. For each scenario the ET_{blue} was calculated as:

$$ET_{blue} = ET_{Cadji} - ET_{green} \qquad i = 1, 2, 3\ldots, 10 \tag{11}$$

The green component of water footprint for growing a crop ($WF_{crop,green}$, m^3/tn) is calculated as the green component in crop water requirements (CWR_{green}, m^3/ha) divided by the crop yield (Y, tn/ha). Similarly, the blue component of water footprint ($WF_{crop,blue}$, m^3/tn) is defined as the ratio of the blue component in crop water requirements (CWR_{blue}, m^3/ha) divided by the crop yield:

$$WF_{crop,green} = \frac{CWR_{green}}{Y} \tag{12}$$

$$WF_{crop,\mathrm{blue}} = \frac{CWR_{blue}}{Y} \tag{13}$$

For the calculations in Eqs. (12) and (13) and in the case of the irrigation management scenarios 4, 5, 9 and 10, the experimentally measured seed cotton yield values were utilized, while for the rest of the scenarios the corresponding simulated by AquaCrop final seed cotton yields were used.

The water footprint of the process of growing crops or trees (WF_{crop}, m^3/tn) is the sum of the green and blue components:

$$WF_{crop} = WF_{crop,green} + WF_{crop,blue} \tag{14}$$

In a different perspective, Chukalla et al. (2015) considered that the total soil water content (S) is the sum of a green component (S_g) and a blue component (S_b). The former one originated from rainfall water while the latter from irrigated water. Assuming that at the sowing date S has a specific composition, i.e., 60% S_g and 40% S_b, the daily changes in the two components until the end of the season are given by the following equations:

$$\frac{dSg}{dt} = R - \left(Dr + ET_{Cadj}\right)\left(\frac{S_g}{S}\right) - RO\left(\frac{R}{I+R}\right) \tag{15}$$

$$\frac{dSb}{dt} = I - \left(Dr + ET_{Cadj}\right)\left(\frac{S_b}{S}\right) - RO\left(\frac{I}{I+R}\right) \tag{16}$$

where: dt is the time step of the calculation (1 d); R is the rainfall (mm); I is the irrigation (mm); Dr is the deep percolation (mm); and RO is the surface runoff (mm). Subsequently, the daily ET_{green} and ET_{blue} values are calculated as follows:

$$ET_{green} = ET_{Cadj}\left(\frac{S_g}{S}\right) \tag{17}$$

$$ET_{blue} = ET_{Cadj}\left(\frac{S_b}{S}\right) \tag{18}$$

Then, Eqs. (9), (10) and (12)–(14) are used again to estimate the green and blue water footprint as well as their sum, which was considered, as mentioned before, as the total cotton water footprint.

In the current study, S at the sowing day was assumed to be equal to S_g as all available soil water at the beginning of the cultivation season comes from the winter and early spring rainfalls.

3 Results and Discussion

3.1 Field and Crop

The minimum and maximum monthly values of air temperature and cumulative monthly rainfall depth in 2013 and 2015 are presented in Fig. 2. In 2013, from April to December, the rainfall depth was 408.4 mm, while the annual rainfall depth in 2015 was 829.8 mm. The common cultivation period of cotton in Northern Greece is from mid-April to early October and the corresponding rainfall amounts within this period for the years 2013 and 2015 were 142.6 mm and 148.6 mm, respectively. Almost no rainfall events occurred in July and August, while at least 50 mm of rain fell in June for both years. Cumulative ET_0 from April to October was found to be 964.9 mm and 852.9 mm for 2013 and 2015, respectively. Lastly, the average maximum and minimum air temperatures were almost similar in both years.

Cotton was sowed in May and harvested in October resulting in an overall growing cycle of approximately 163 calendar days. In both years the cotton seeds germinated approximately 10 days after sowing. Once they emerged, it was observed that the cotton plants needed roughly 100 additional days to reach their maximum canopy cover, and then, after 7–10 days, the canopy started to decline gradually, while the cotton bolls started to form and ripen until the

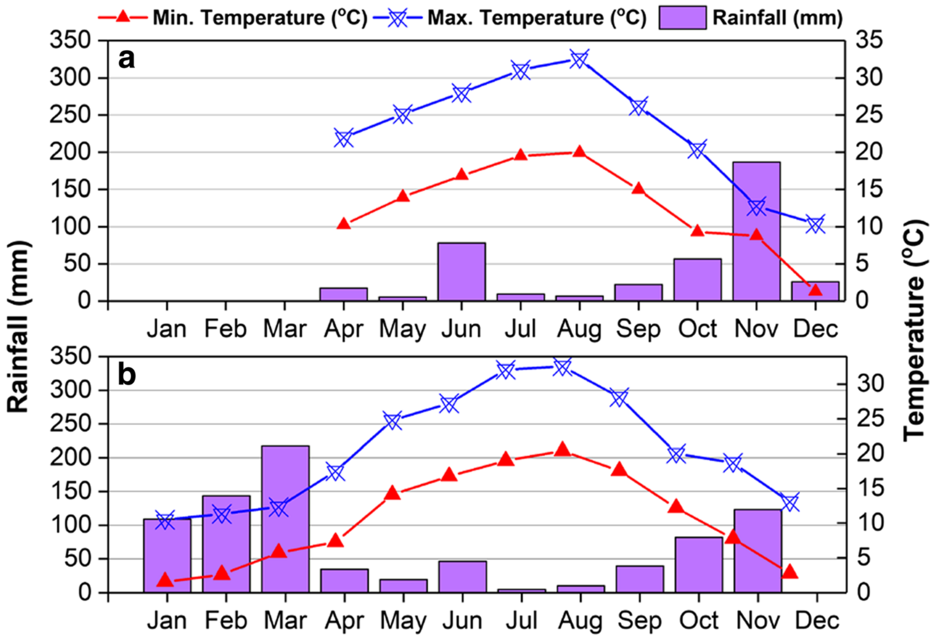

Fig. 2 Maximum and minimum monthly air temperature values and monthly rainfall depth in years: (**a**) 2013; and (**b**) 2015

end of the season. The maximum rooting depth was set at 1.3 m (Farahani et al. 2009), reached approximately 106 days after planting. The seed cotton yield at the end of the 2013 and 2015 cultivation periods was measured at 3.39 and 3.97 tn/ha, respectively. The corresponding AquaCrop estimations for the seasons were 3.34 and 4.10 tn/ha, and are considered satisfactory.

Table 2 shows the texture and hydraulic characteristics of the various soil layers. TAW in the 1.3 m maximum rooting zone was equal to 256 mm, while the moisture deficit at the sowing dates in both years was measured at 22 mm.

3.2 Impact of Irrigation Management on Evapotranspiration, Biomass Production, HI and Yield

The descriptive data derived from both model simulations are presented in Table 3. AquaCrop estimated higher actual crop evapotranspiration values (ET_{Cajc}) in all irrigation management scenarios when compared to CROPWAT (Fig. 3). This is the result of the fundamentally different approaches the two models follow in their computational processes (Eqs. 2, 4–6). The difference between the ET_{Cajc} estimation by the two models was 69.8 ± 23.6 mm in 2013 and 57.1 ± 21.6 mm in 2015, respectively.

Table 2 Soil texture and hydraulic characteristics at the soil profile layers

Layer Depth (m)	Sand (%)	Silt (%)	Clay (%)	Saturation (%)	Field Capacity (%)	Wilting Point (%)	K_{SAT} (mm/d)
0.3	52.4	23.2	24.4	36.7	25.3	11.5	94.3
0.4	30.8	19.2	50.0	43.9	41.3	20.0	73.2
1.0	31.2	22.8	46.0	42.8	39.3	17.7	92.4

Table 3 Irrigated amounts and AquaCrop and CROPWAT results for actual cotton evapotranspiration (ET_{Cadj}), effective rainfall and cotton production in the different irrigation management scenarios

Irrigation scenario	Total irrigation (mm)	Number of irrigation events	Average irrigation amount per irrigation event (mm)	AquaCrop							CROPWAT	
				ET_{Cajc} (mm)	E_{Cajc} (mm)	Tr_{Cajc} (mm)	Effective Rainfall (mm)	Biomass (t/ha)	HI (%)	Yield (t/ha)	ET_{Cajc} (mm)	Effective Rainfall (mm)
2013												
1	630.0	18	35.0	788.7	209.5	579.2	141.6	13.112	35.1	4.596	696.7	134.8
2	504.0	18	28.0	783.8	207.0	576.8	141.7	13.022	35.6	4.638	671.0	134.8
3	502.0	16	31.4	745.0	179.7	745.5	141.9	12.802	37.5	4.804	677.2	139.6
4	352.0	11	32.0	627.2	184.7	442.5	138.1	10.060	33.7	3.393	558.7	142.3
6	585.0	39	15.0	748.8	170.6	578.2	136.1	13.107	35.0	4.588	701.1	107.5
7	468.0	39	12.0	743.5	164.8	578.7	139.3	13.092	35.4	4.632	668.3	125.5
8	468.0	37	12.6	721.1	149.7	571.4	140.5	12.922	37.0	4.776	672.6	141.2
9	271.0	19	14.3	566.1	148.4	417.7	140.7	9.316	35.9	3.344	520.2	141.7
2015												
1	525.0	15	35.0	674.5	192.3	482.2	143.8	13.220	35.0	4.630	601.7	136.7
2	420.0	15	28.0	674.4	191.9	482.5	144.7	13.199	35.3	4.661	581.9	138.7
3	413.0	13	31.8	626.0	153.7	472.3	145.3	12.950	36.5	4.721	571.3	145.8
5	325.0	10	32.5	606.1	172.5	433.6	148.6	11.522	35.2	4.053	539.1	145.1
6	510.0	34	15.0	659.4	175.7	483.7	148.6	13.232	35.0	4.631	606.3	119.1
7	408.0	34	12.0	638.3	155.6	482.7	143.8	13.210	35.1	4.641	586.5	122.4
8	404.0	25	16.2	581.4	112.3	469.1	144.6	12.870	36.7	4.729	562.9	148.6
10	303.0	17	17.8	561.9	120.0	441.9	143.7	11.693	35.1	4.101	515.8	145.1

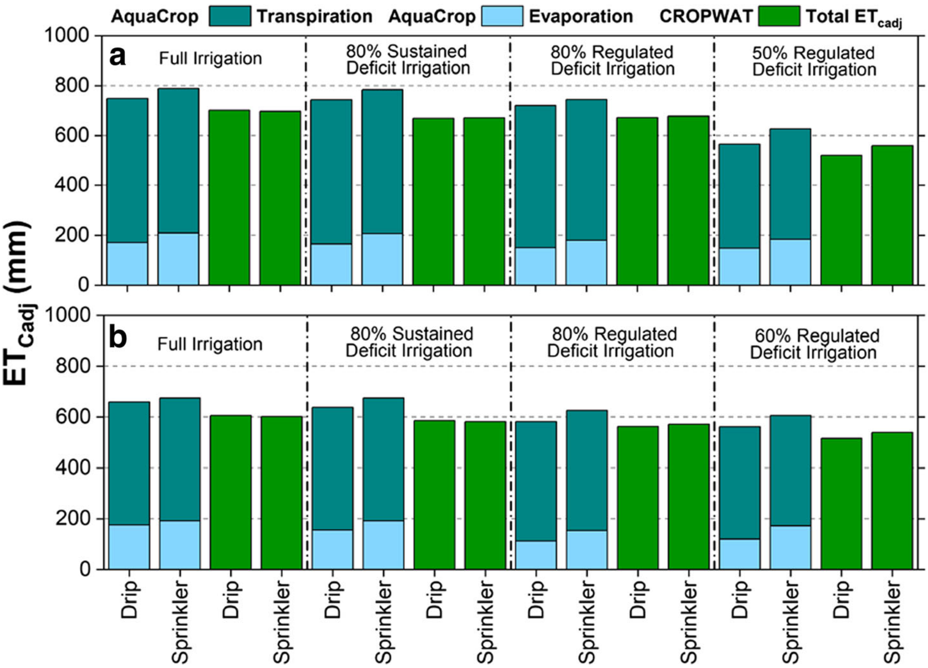

Fig. 3 AquaCrop and CROPWAT actual cotton evapotranspiration (ET_{Cadj}) estimation for the various irrigation scenarios and years: (**a**) 2013; (**b**) 2015

In Fig. 3, it is clearly shown that for all years, for a given irrigation strategy (e.g., full irrigation) the estimated by AquaCrop ET_{Cadj} is always higher in the case of sprinkler than drip irrigation. This is obviously attributed to the larger amount of water lost through evaporation in the case of sprinkler. By observing closely, the evaporation (E_{Cajc}) and transpiration (Tr_{Cadj}) results in Table 3, it is clear that under the same irrigation management (e.g., irrigation management scenarios 1 and 6; Table 1), the evaporation values were at least 20 mm higher in the case of the sprinkler compared to drip. This difference in the case of Tr_{Cadj} was found to be lower than 5 mm. On the contrary, the CROPWAT estimations do not show any striking differences when ET_{Cajc} is calculated for the sprinkler and drip irrigation technologies under the same irrigation treatment (e.g., full irrigation) (Fig. 3). This finding was expected, as for CROPWAT the percentage of the field wetted surface per irrigation event is always 100% and the only actual differences between these scenarios were the changes in the irrigation dates and the applied water amounts.

Despite the differences in their estimations both models resulted in higher ET_{Cajc} values for 2013. This agrees with the highest ET_0 which was estimated during this year and results in high irrigation demands (Table 3).

Figures 4 and 5 present the estimated by AquaCrop biomass, HI and seed cotton yield values against ET_{Cajc}, for the different irrigation management scenarios in 2013 and 2015, respectively. For both years, beginning from full irrigation and moving step by step to 80% sustained DI, 80% regulated DI and ending to the 50% DI schedule in 2013 (Fig. 4) and 60% regulated DI schedule in 2015 (Fig. 5), we observe that for both sprinkler and drip curves, the ET_{Cajc} is reduced with a simultaneous reduction in biomass production. It is noteworthy, that even though the Tr_{Cadj} is larger for the drip and sprinkler full irrigation scenarios in 2013

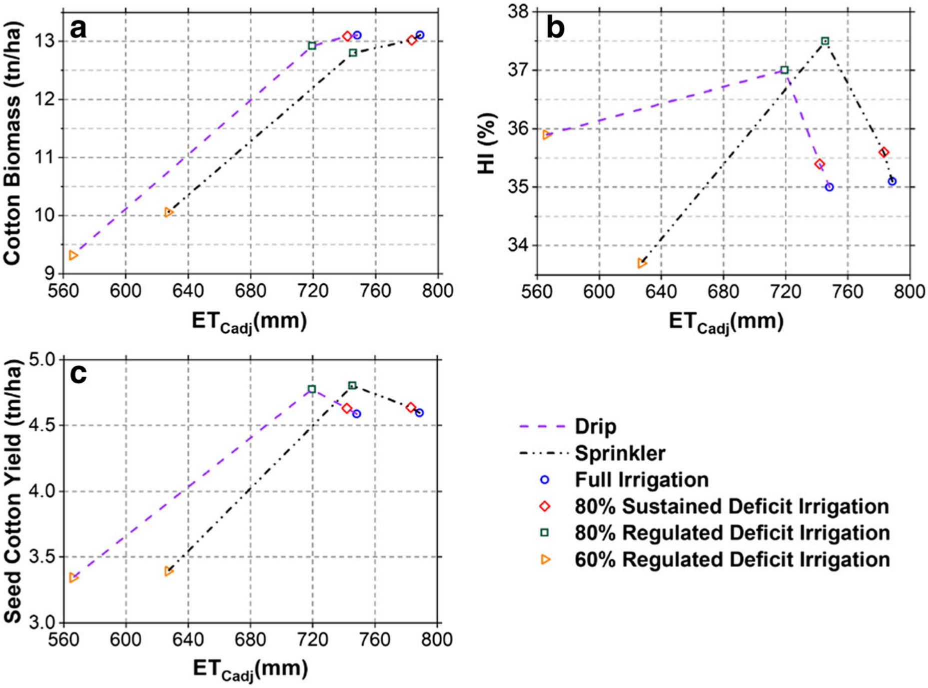

Fig. 4 AquaCrop simulated actual cotton evapotranspiration in 2013 as function of: (**a**) biomass; (**b**) harvest index (HI); (**c**) Seed Cotton Yield

(Table 3), the maximum biomass production was obtained in 2015. This is attributed to the fact that the ratio $\Sigma(Tr_{Cadj}/ET_0)$ in Eq. (7) was marginally higher in 2015, as well as to the slight increase equal to 0.1 g/m^2 in the WP^* value which was observed this year. From full irrigation to 80% regulated DI, the biomass reduction rate was roughly 6.9 kg/ha/mm and 5.1 kg/ha/mm in 2013 and 2015, respectively. The 50% regulated DI schedule which was implemented in 2013, resulted in a considerable reduction in biomass production approximately 3 tn/ha, while a moderate decrease equal to 1 tn/ha was observed in the case of the 60% regulated DI in 2015. Overall, for all the irrigation strategies, the drip irrigation system compared to sprinkler achieved almost the same biomass production with a parallel reduction in ET_{Cajc} equal to 34.7 mm ± 9.4 and 31.9 mm ± 15.2 for 2013 and 2015, respectively.

In 2013, moving from full irrigation to 80% sustained DI, the HI showed a 5% increase for both drip and sprinkler systems. In sprinkler curve, the HI value increased to 37.5% when moved further to 80% regulated DI strategy but then decreased to 33.7% in the case of 50% regulated DI treatment. The corresponding trend in the drip curve was similar when moving from sustained DI to regulated DI irrigation strategy, and resulted to a substantial HI increase (37%). Nevertheless, the downward trend followed towards 50% regulated DI strategy was not so intense as in the case of the sprinkler system, resulting in a HI equal to 35.9%. The maximum seed cotton yield was scored, for both drip and sprinkler irrigation technologies, in the case of the 80% regulated DI irrigation strategy, as in this scenario the marginal decrease observed in the biomass production was overwhelmed by the increase in the HI. Moreover, for the 80% regulated DI irrigation strategy, the drip system achieved roughly the same yield as sprinkler consumed 23.9 mm less water. This difference found to be approximately 60 mm in the case of 50 regulated DI, but with a substantial lower yield (~3.3 tn/ha).

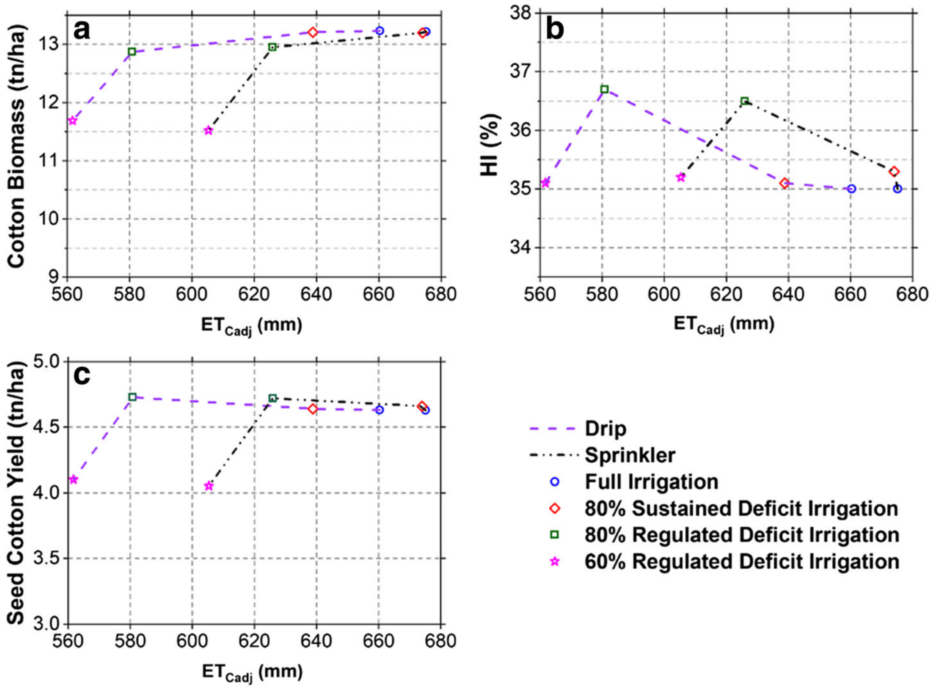

Fig. 5 AquaCrop simulated actual cotton evapotranspiration in 2015 as function of: (**a**) biomass; (**b**) harvest index (HI); (**c**) Seed Cotton Yield

Similarly, in 2015, the maximum HI was obtained under the 80% regulated DI scenario for both irrigation technologies. However, moving from 80% regulated DI to 60% regulated DI the HI values stayed above the reference value (35%) for both drip and sprinkler. This was not the case in 2013 when in the case of sprinkler, the HI value plummeted. Again, the 80% regulated DI irrigation strategy achieved the maximum yield, with a parallel decrease compared to full irrigation equal to 80 mm and 50 mm in the case of drip and sprinkler technologies, respectively. The 60% regulated DI strategy resulted in a fair seed cotton yield (> 4 tn/ha) for both irrigation technologies with a simultaneous substantial decrease in the ET_{Cadj} equal to 100 mm in the case of drip and 70 mm in the case of sprinkler irrigation.

The overall better performance of the drip system over the two cultivating seasons and all the irrigation scenarios is attributed to the saving of the non-productive water lost through evaporation in the case of the sprinkler system. This saving seems to increase as the DI strategy followed becomes more severe.

3.3 Water Footprint

The calculated green, blue and total water footprint, using both methods for the years 2013 and 2015, are illustrated in Figs. 6 and 7, respectively. The graphs show that for the same irrigation management, CROPWAT model derived a lower total water footprint, compared to AquaCrop, in all cases. This is a consequence of the lower ET_{Cajc} values calculated by the model compared to those of AquaCrop.

The total water footprint estimated by the two-methods (i.e., Chukalla et al. 2015; Hoekstra et al. 2011) for the same irrigation management strategy was similar. However, moderate differences are observed in the contributions of green and blue components. When the

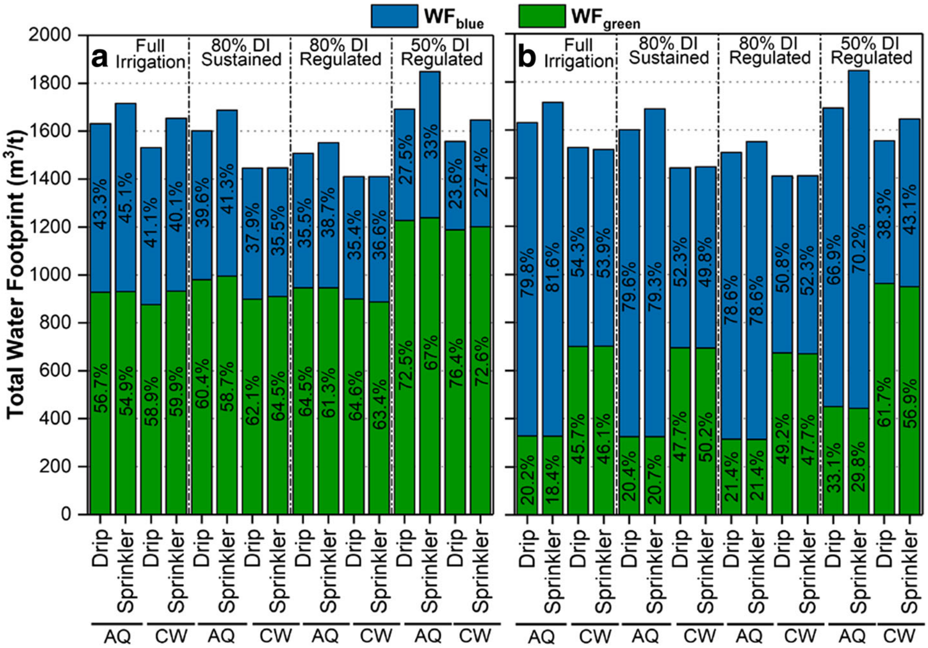

Fig. 6 Total, green and blue water footprint for 2013 calculated with the methods proposed by: (**a**) Chukalla et al. (2015); (**b**) Hoekstra et al. (2011)

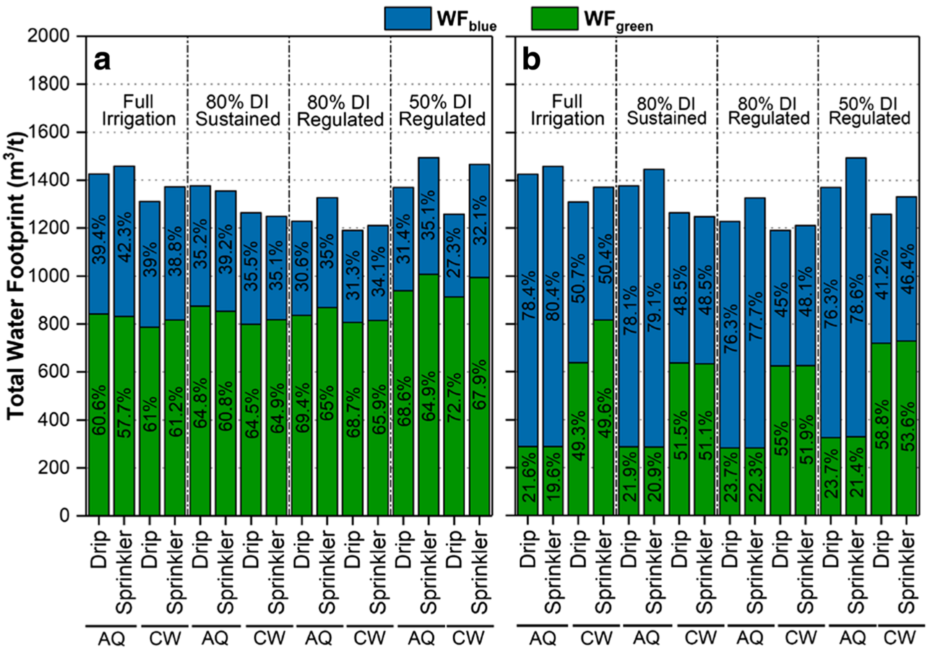

Fig. 7 Total, green and blue water footprint for 2015 calculated with the methods proposed by: (**a**) Chukalla et al. (2015); (**b**) Hoekstra et al. (2011)

methodology proposed by Hoekstra et al. (2011) was implemented via AquaCrop, the model resulted in no seed germination under the rainfed scenario, and thus, the cumulative evapotranspiration estimated at the end of these runs was actually the water evaporated from the bare field surface during these seasons. This is clearly depicted in Figs. 6b and 7b, with the contribution of green water component in the total footprint to be roughly 22% for all the irrigation management scenarios. Looking carefully in Figs. 6a and 7a, we observe that even the total water footprint deviated considerably between the two models and the different irrigation strategies, the contribution of the green and blue component in all cases is 53.1% ± 2.7 and 46.9% ± 2.7, respectively. When the method proposed by Chukalla et al. (2015) was implemented, the corresponding contributions of the green component were found to be 63.7% ± 6 and 64.9% ± 4 in 2013 and 2015, respectively, while in the case of the blue component these values were 36.3% ± 6 and 35.1% ± 4. Overall, it seems that Chukalla et al. (2015) approach results in a higher green water footprint than that estimated by Hoekstra et al. (2011) method.

For drip irrigation technology and full irrigation strategy, the total water footprint is calculated equal to 1631.6 m^3/t and 1425.6 m^3/t for 2013 and 2015 by AquaCrop, and 1531.3 m^3/t and 1310.4 m^3/t by CROPWAT, respectively. Still for drip technology but 80% sustained DI, 80% regulated DI and 50% regulated DI schedules, the total water footprints in 2013 were found to be 1602.0 m^3/t, 1507.4 m^3/t and 1692.6 m^3/t by AquaCrop and 1445.0 m^3/t, 1409.8 m^3/t and 1557.1 m^3/t by CROPWAT. These values were considerably lower in 2015, and were equal to: 1228.1 m^3/t (AquaCrop) and 1190.1 m^3/t (CROPWAT) in the case of 80% regulated DI; and 1369.5 m^3/t (AquaCrop) and 1258 m^3/t (CROPWAT) in the case of 60% regulated DI. Following the same logical order for the sprinkler system and based on AquaCrop model outputs, the total water footprints in 2013 were 1715.9 m^3/t, 1688.3 m^3/t, and 1551.9 m^3/t for full irrigation, 80% sustained DI and 80% regulated DI strategies, respectively, and in 2015, 1458.8 m^3/t, 1354.6 m^3/t, and 1326.6 m^3/t, respectively. In the case of 50% regulated DI and 60% regulated DI strategies, the total water footprints were 1848.9 m^3/t and 1493.8 m^3/t, respectively. As in the case of drip, CROPWAT resulted in lower total water footprints for all irrigation strategies.

The drip irrigation technology combined with the 80% regulated DI strategy achieved to reduce the total water footprints by 12% and 16% in 2013 and 2015, respectively, which is likely due to different climatic conditions. Normalization with each season's total growing degree days would render the total water footprint independent of air temperature, and thus, the reported values would be more cohesive. For the same irrigation strategy, i.e., full irrigation, this reduction between the two systems was roughly 5% in favor of drip.

In a similar study, Chapagain and Hoekstra (2004) calculated cotton total water footprint under full irrigation for different countries around the globe. They estimated values equal to 1534 m^3/t for Greece, 1325 m^3/t for Spain and 2320 m^3/t for Turkey. Prieto and Angueira (1999), in a study conducted in Santiago del Estero in Argentina from 1990 to 1995, investigated the effect of water stress in the different cotton development stages on the final seed cotton yield, and reported total water footprint values ranging between 787.0–2000.0 m^3/t. In a same experiment carried out by Orgaz et al. (1992) between 1985 and 1986 in Cordoba Spain, the total water footprints were found to vary from 1408.5 to 2222.0 m^3/t. Waheed et al. (1999), in a study that took place in Pakistan from 1991 to 1994, estimated a mean cotton total water footprint equal to 2040.8 m^3/t. In Turkey, in an experiment regarding deficit cotton irrigation conducted in Bornova-Izmir, Anac et al. (1999) found total water footprint values ranging from 2083.3 to 2631.6 m^3/t, while Ertek and Kanber (2001) reported for Cukurova values from 1190.5 to 2631.6 m^3/t. The discrepancies observed on the reported in the literature values are mainly attributed to: (a) the different geographic locations where the experiments were conducted, and consequently, the different climatic conditions; (b) the duration on cotton growing cycle; (c) the various cotton varieties which were used in the experiments; (d) the different textural and hydraulic soil characteristics of each area; and (e) the diversity of irrigation schedules followed during the cultivation seasons which were varied from full irrigation to several DI strategies.

The total water footprint cotton values found in this study were very close to those reported by previous works for Greece and Spain, but also within the lower range of the estimated values from Argentina and Turkey. The relatively low total water footprint values estimated here compared to the previous works, even under the full irrigation scheduling, may be attributed to some extend to the better irrigation scheduling devised in this study, the improvement of the cotton varieties productivity from 1990s until today, and potentially, to the increase of the atmospheric CO_2 concentration and subsequently the WP^* values (Zwart and Bastiaanssen 2004). Climate change seems to have a positive impact on the crop WP^* through the increase of CO_2 concentration. This means that when comparing WF values, among other parameters, the year of each study should always be included.

4 Conclusions

In this study the calculation of green, blue and total water footprint was performed with two different methodological frameworks. When the two methods were implemented for ten irrigation scenarios, it was found that they give comparable total water footprint but different green and blue footprints. Despite these differences, it is evident from the results that more than half of the water consumed during the cotton cultivation in Northern Greece came from the available water stored in the soil profile at the sowing day, which originated from winter and spring rainfalls and the rainfall events during the cultivation season.

AquaCrop model showed to have the ability to assess the impact of both irrigation technology and irrigation strategy in the green, blue and total water footprints while CROPWAT was able to evaluate only the changes in the irrigation strategy. Subsequently, AquaCrop seems to be more suitable for the robust study of irrigation management impacts.

Drip irrigation technology confirmed to have a great potential to improve the rational use of the available water resources in the region by saving the un-productive water which is lost through evaporation when sprinkler systems are used. In 2015, the 60% regulated DI strategy resulted in total water footprint lower than the corresponding full scenario. However, the lowest water footprint for the same year was obtained under the 80% regulated DI strategy, due to increased cotton yield. Such a practice though would require almost 100 mm more water compared to the 60% regulated DI. Considering that in the broader region are cultivated annually approximately 32×10^3 ha of cotton, such a change in the irrigation strategy would increase the pressure to the local water reservoirs by 32×10^6 m^3.

Water footprint is only an environmental indicator for the rational use of water. Other factors, such as the availability of the water resources during the cultivation period as well as the irrigation cost per m^3, are not integrated. These factors vary significantly among regions, countries and continents. Consequently, future research on the field should be heading towards a more sustainable framework by incorporating in the water footprint calculation process the economic dimension and introducing local level socio-economic constraints, with an ultimate goal to obtain an optimal, environmentally and economically viable water footprint for each region.

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