Water Utility Journal 32: 29-43, 2023.

Estimation of water use indicators of cotton under different irrigation regimes using CropSyst model

P. Koukouli[1*], M. Kokkora[1], P. Georgiou[1], D. Karpouzos[1], F. Bilias[1] and D. Gasparatos[2]

[1] *Department of Hydraulics, Soil Science and Agricultural Engineering, School of Agriculture, Aristotle University of Thessaloniki, Thessaloniki, Greece*
[2] *Department of Natural Resources Management and Agricultural Engineering, Agricultural University of Athens, Athens, Greece*
[*] *e-mail: pkoukoul@agro.auth.gr*

Abstract: Climate change is projected to increase the pressure on available water resources. Freshwater scarcity implies less water availability for agricultural production, thus threatening food security. Consequently, integrated and sustainable water management in irrigated agriculture is required to decrease the risks associated with food security. The objective of the study was to estimate the water use indicators for effective on-farm water management and to optimize on-farm irrigation. In this study, the following water use indicators: crop water use efficiency (WUE_c), total water productivity (WP_{Total}), irrigation water productivity (WP_{irr}), crop water productivity (WP_{ET}), water footprint (WF) and its three components, green, blue and grey WFs, were assessed under different irrigation management practices at two experimental sites cultivated with cotton, in northern and central Greece during the 2020 cultivation period. Three irrigation treatments were simulated for each experimental site with the implementation of the CropSyst model. The irrigation treatments involved different number of irrigation applications and doses (Treatments: T_1, T_2 and T_3) in relation to the applied irrigation (AI). The total amount of irrigation water applied was the same in all treatments and AI. The indicators of WUE_c, as well as the three WP indicators, increased (ranging from 0.6% to 21%) under the irrigation treatments compared to applied irrigation (AI) in both experimental sites. In both sites, the blue WF was the main component of total WF, indicating that cotton production in both locations mainly depends on blue water resources (irrigation water). The comparison between AI and the three treatments showed that in both sites, total WF and its three components decreased under the three treatments compared to applied irrigation (AI). The highest decreases in total WF were 10.6% in the case of Rizia and 6.9% concerning the location of Girtoni. Reducing the number of irrigation applications whilst increasing the irrigation dose during the critical phenological stages of cotton in heavy textured soils was shown as an irrigation management strategy to save water use due to the crop WF decrement. Finally, the time of application of the last irrigation should be estimated accordingly to the timing of the final crop growth stage in combination with the weather data of the area so the crop can exploit precipitation fulfilling its water requirements.

Key words: CropSyst; water use indicators; water use efficiency; water productivity; water footprint; cotton.

1. INTRODUCTION

The irrigators are under the increasing pressure of ensuring food security and long-term environmental and economic sustainability (Koech and Langat, 2018), targets that are increasingly threatened by both climate change and the growing population. Due to the imbalance between water demand and water supply in agriculture, the adoption of modern technologies and management tools to optimize irrigation water use is required (Pereira et al., 2009; Pereira, 2017; Jovanovic et al., 2020). On-farm sustainable water management assumes the adoption of adequate irrigation schedules that should lead to optimal yields and agricultural and irrigation practices that optimize water use, particularly the non-beneficial ones (Pereira et al., 2009, 2012; Jovanovic et al., 2020).

Water use indicators have been widely used to address the above issues for assessing on-farm water use and irrigation decision-making. The most common approaches are the water productivity and water use efficiency indicators and the recently introduced theoretical concept of water footprint for on-farm water management. The term efficiency accounts for a dimensionless ratio of the total amount of water used to the total amount of water applied. At the crop level, a correct definition of water use efficiency (WUE) is the crop evapotranspiration divided by the amount of water supplied by irrigation and precipitation (Perry et al., 2009; Heydari, 2014). Nowadays, there is a trend to call for increasing water productivity (WP) as an essential issue in irrigation (Molden et al., 2003; 2010; Oweis and Hachum, 2003; Clemmens and Molden, 2007). The attention formerly given to irrigation efficiency is now transferred to water productivity. However, this term is used with different meanings in relation to various scales as discussed by Molden et al. (2003; 2010) and, relative to biomass WP, by Steduto et al. (2007). 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. Nowadays, the WF tool is gaining increased applicability in determining the consumption of freshwater by crops (rain-fed or irrigated). For crop production, WF is the amount of freshwater used by a crop during the whole growing period (Xinchun et al., 2018).

Many studies have been conducted to explore the effect of varying agricultural management practices on different water use indicators concerning various crops in different countries. Fernández et al. (2020), in a case study of an olive orchard, studied the use of water use indicators to improve on-farm irrigation decision-making. The effect of varying agricultural management practices on crop water use efficiency (WUE) and green and blue water footprint (WF) was assessed at an experimental field in Northern China cultivated with winter wheat using the AquaCrop model (Zhuo and Hoekstra, 2017) Due to its increased merits, the WF approach has attracted the attention of many researchers over the past few years for a wide variety of applications (Xinchun et al., 2018), among which, its application for assessing freshwater use by crops (Mekonnen and Hoekstra, 2011; Herath et al., 2014; Chukalla et al., 2015; Morillo et al., 2015; Rodriguez et al., 2015; Madugundu et al., 2018; Geng et al., 2019). Many of these studies were focused on either global (Chapagain et al., 2006; Martinez-Aldaya et al., 2010) or national scale (Ahmed and Ribbe, 2011; Tsakmakis et al., 2018) utilizing conceptual/mathematical models to simulate the soil-plant-water interactions and assess the WF components (Cao et al., 2014; Chukalla et al., 2015). Zoidou et al. (2017) used CROPWAT and AquaCrop models to estimate the annual water footprint of cotton cultivation in Northern Greece for the period 2013 to 2016.

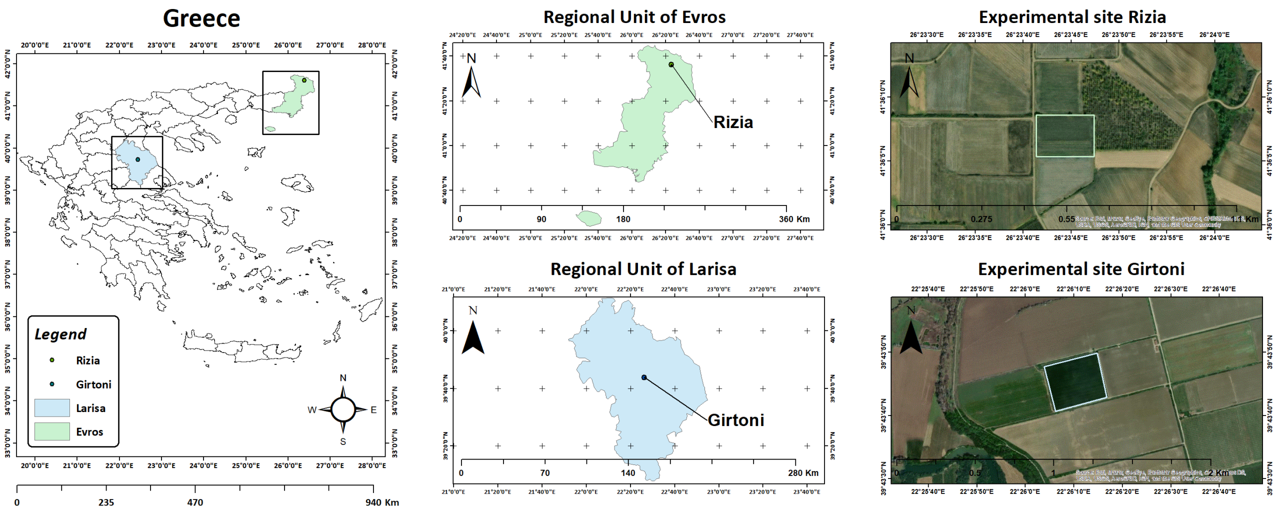
The objective of the study was to estimate the water use indicators for effective on-farm water management and to optimize on-farm irrigation. In this context, water use efficiency, water productivity and water footprint were studied under different irrigation management practices at two experimental sites cultivated with cotton, located in Northern and Central Greece during cultivation period 2020. Three irrigation treatments were simulated for each experimental site with the implementation of CropSyst crop growth simulation model. The irrigation practices involved different number of irrigation applications and doses (Treatments: T_1, T_2 and T_3) in relation to the applied irrigation (AI).

2. MATERIAL AND METHODS

2.1 Description of the study area

The study was undertaken in two fields cultivated with cotton (*Gossypium hirsutum*) in two different locations in Greece during cultivation period 2020. The first field (experimental site) was situated close to Rizia village (lat. 26°23', long. 41°36', 60 m a.s.l.), near Orestiada town, in the Regional Unit of Evros, Region of Eastern Macedonia & Thrace, Northern Greece. The location of the second experimental site was close to Girtoni village (lat. 22°26', long. 39°43', 62 m a.s.l.), near the city of Larisa, in the Regional Unit of Larisa, Region of Thessaly, Central Greece (Figure 1).

The climate of both areas is typical Mediterranean. The mean annual precipitation for 2020 was 711 mm for Rizia and 459 mm for Girtoni. The mean values of temperature for the same year were 14.39 °C and 16.11 °C for the above two experimental sites, respectively. The areas where the experimental sites are located are predominantly irrigated agricultural areas.



(a) (b)

Figure 1. (a) Map of the study area; (b) Experimental sites at the location of Rizia (Northern Greece) and Girtoni (Central Greece).

2.2 Crop simulation model - CropSyst

In the present work, for the estimation of the water use indicators of cotton at the two experimental sites under different water irrigation treatments, CropSyst model was used. CropSyst (Cropping Systems Simulation Model) (Stöckle et al., 2003) is a multi-year multi-crop, daily time step cropping systems simulation model developed to serve as an absorbency tool to study the effect of the weather, soil, and cropping systems management on crop productivity and the environment. This model has been used to simulate the growth and development of several crops such as maize, cotton, wheat, barley, soybean and sorghum with generally good results in many parts of the world, i.e., Mali, United Kingdom, Italy, Western USA, Southern France, Northern Syria, Northern Spain and Western Australia (Tingem et al., 2009; Koukouli and Georgiou, 2018). CropSyst has been evolving to give responses to new demands on agro-ecosystem simulation capabilities such as combined cycling of carbon and nitrogen, the carbon footprint of agricultural systems, improvements in the use of the water-use efficiency, and assessment of climate change impacts on agriculture (Stöckle et al., 2014). The model was selected for its robustness and relative ease of application, using commonly available data.

CropSyst model simulates the soil-water budget, soil-plant nitrogen budget, crop phenology, canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion, and salinity. The above processes are affected by weather, soil characteristics, crop characteristics, and cropping system management options, including crop rotation, cultivar selection, irrigation, nitrogen fertilization, water salinity, tillage operations, and residue management (Stöckle et al., 2003). The water budget in CropSyst includes precipitation, irrigation, runoff, interception, water infiltration and redistribution in the soil profile, crop transpiration, and evaporation. The nitrogen budget includes nitrogen application, nitrogen transport, nitrogen transformations, ammonium absorption, and crop nitrogen uptake.

2.2.1 Model data

The model's input data are *weather*, *soil*, *crop* and *management data*. The input files to run the CropSyst model for cotton simulation were prepared in its compatible format. The required meteorological data to run the CropSyst model are precipitation (Pr, mm), maximum and minimum temperature (T_{max} and T_{min}, °C), maximum and minimum relative humidity (RH_{max} and RH_{min}, %), solar radiation (R_s, MJ/m^{2}d) and wind speed (u^2, m/s). Meteorological data in hourly time intervals were gathered for the growing season 2020, from the meteorological stations at the experimental sites which were computed in a daily time step as required by the CropSyst model. Monthly values of the above parameters were calculated and are presented in Table 1. The mean temperature during 2020 ranged from 2.5 °C (January) to 24.9 °C (July) at the experimental site Rizia and from 4.1 °C (January) to 25.2 °C (July) at Girtoni. The highest amount of precipitation was observed in August regarding Rizia (137.4 mm) and during April concerning Girtoni (81.6 mm).

Soil samples were collected from both sites at three different depths: 0-30 cm, 30-60 cm, and 60-90 cm, and analyzed for the estimation of parameters such as soil texture, permanent wilt point, field capacity, bulk density, saturated hydraulic conductivity (K_{sat}), cation exchange capacity (CEC) and pH. The soil physicochemical properties of the experimental sites Rizia and Girtoni are presented in Table 2. The soil of the experimental site of Rizia is classified according to USDA Soil Conservation Service texture triangle as silty clay and the soil of Girtoni as clay soil (>50% clay) throughout the soil profile (heavy textured soils).

Table 1. Monthly meteorological data of Rizia and Girtoni in 2020.

Rizia	Monthly Meteorological Data												Year
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Pr (mm)	10.80	42.60	42.60	119.40	62.40	28.20	55.20	137.40	2.40	72.60	9.90	127.20	**710.70**
T_{mean} (°C)	2.49	6.16	9.47	11.28	17.27	21.33	24.94	24.66	21.74	16.54	8.57	6.60	**14.25**
T_{max} (°C)	9.60	13.46	16.64	19.33	24.72	29.30	33.38	33.21	30.63	24.76	14.75	10.37	**21.68**
T_{min} (°C)	-3.05	-0.42	2.82	3.48	10.58	14.02	15.93	16.07	13.55	9.75	3.61	3.39	**7.48**
RH_{mean} (%)	75.56	75.34	73.49	67.83	72.17	72.81	59.80	63.55	63.28	76.61	77.38	91.55	**72.45**
RH_{max} (%)	88.66	91.09	91.93	88.69	91.98	94.38	87.44	90.78	89.29	94.36	89.72	97.13	**91.29**
RH_{min} (%)	54.29	53.98	51.63	43.77	48.01	44.36	34.56	37.01	36.32	51.16	58.43	81.57	**49.59**
R_s (MJ/m^2d)	7.61	9.91	13.46	20.07	22.00	23.85	27.76	22.66	18.57	11.02	7.62	4.26	**15.73**
u_2 (m/s)	1.37	2.07	2.23	1.80	1.67	1.40	1.31	1.01	2.43	1.01	1.21	1.70	**1.60**
Girtoni	**Monthly Meteorological Data**												**Year**
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Pr (mm)	1.20	16.34	52.84	81.60	49.80	35.70	23.10	23.10	80.40	22.80	15.00	56.70	**458.58**
T_{mean} (°C)	4.14	8.04	10.54	13.47	20.12	23.72	25.24	25.24	22.12	17.04	11.02	9.95	**15.89**
T_{max} (°C)	11.92	15.22	17.39	20.11	28.20	30.36	32.31	32.31	29.23	24.67	16.72	13.04	**22.62**
T_{min} (°C)	-2.01	1.08	3.64	6.77	12.34	16.59	18.17	18.17	14.91	9.53	5.93	6.93	**9.34**
RH_{mean} (%)	75.44	70.77	72.81	67.71	62.12	58.60	65.47	65.47	67.03	74.35	80.93	91.03	**70.98**
RH_{max} (%)	89.89	89.39	92.89	90.13	88.95	81.98	89.46	89.46	88.90	96.49	95.83	97.97	**90.95**
RH_{min} (%)	53.24	50.78	50.05	43.62	35.55	37.05	41.23	41.23	43.10	45.41	60.07	78.32	**48.30**
R_s (MJ/m^2d)	9.05	12.08	15.06	19.62	24.02	26.78	23.45	23.45	18.13	13.43	7.98	4.81	**16.49**
u_2 (m/s)	0.83	1.28	1.74	1.75	1.72	1.79	0.84	0.84	1.11	0.50	0.59	0.50	**1.12**

Pr: Precipitation; T_{mean}: Mean Temperature; T_{max}: Maximum Temperature; T_{min}: Minimum Temperature; RH_{mean}: Mean Relative Humidity; RH_{max}: Maximum Relative Humidity; RH_{min}: Minimum Relative Humidity; R_s: Solar Radiation; u_2: Wind Speed.

In the current study, the values of the crop input parameters were either taken from the CropSyst manual (Stöckle and Nelson, 1994), other research works or set to the values observed in the experiment. A management file was prepared to represent the applied irrigation in the experimental sites and also management files were prepared to simulate the different irrigation treatments. Analytical information of the *management practices* regarding the planting and harvest dates, as well as total irrigation and N fertilization applications for both locations are summarized in Table 3.

The model was calibrated using the data obtained from the field experiment. The calibration consisted of fine-tuning adjustments of cotton input parameters to reflect reasonable simulations. These adjustments were around values that were typical for the crop species. Differences between the simulated by model and the measured data were minimized by applying a trial and error approach to mean daily temperature that limits early growth (°C), leaf area duration (degree days) and radiation use efficiency (g/MJ).

The simulated by CropSyst output data are presented in Figure 2, concerning the mean monthly values of actual crop evapotranspiration (Figure 2a) and the observed and simulated values of cotton production (Figure 2b) for the experimental sites Rizia and Girtoni in 2020. Cotton yield was satisfactorily simulated by the model for both experimental sites as the differences between simulated and observed values were less than 1%.

Table 2. Soil characteristics of Rizia and Girtoni in 2020.

Depth (cm)	Texture			Hydraulic Properties				Chemistry	
Rizia - Soil characteristics									
	Sand (%)	*Silt (%)*	*Clay (%)*	*Permanent wilt point (m^3/m^3)*	*Field capacity (m^3/m^3)*	*Bulk density (g/cm^3)*	*K_{sat} (m/day)*	*CEC ($cmol_c/kg$)*	*pH*
0-30 cm	34.0	37.2	28.8	0.163	0.303	1.342	0.099	41.10	7.6
30-60 cm	32.0	35.2	32.8	0.183	0.323	1.319	0.076	39.10	7.5
60-90 cm	26.0	37.2	36.8	0.204	0.352	1.291	0.066	38.60	7.6
Girtoni - Soil characteristics									
	Sand (%)	*Silt (%)*	*Clay (%)*	*Permanent wilt point (m^3/m^3)*	*Field capacity (m^3/m^3)*	*Bulk density (g/cm^3)*	*K_{sat} (m/day)*	*CEC ($cmol_c/kg$)*	*pH*
0-30 cm	8.1	36.5	55.4	0.327	0.478	1.196	0.059	35.70	7.9
30-60 cm	9.8	34.7	55.5	0.327	0.477	1.199	0.057	36.40	8.1
60-90 cm	11.3	32.5	56.2	0.331	0.478	1.200	0.055	35.60	8.3

K_{sat}: Saturated Hydraulic Conductivity; CEC: Cation Exchange Capacity.

Table 3. Management practices of Rizia and Girtoni for the growing season 2020.

Management Practices			
Rizia		***Girtoni***	
Planting Date	30 April	*Planting Date*	23 April
Total Irrigation (mm)	100.0	*Total Irrigation (mm)*	404.95
Total N fertilization (kg N/ha)	201.0	*Total N fertilization (kg N/ha)*	113.7
1st Harvest date	16 October	*1st Harvest date*	5 October
2nd Harvest date	26 October	*2nd Harvest date*	13 October

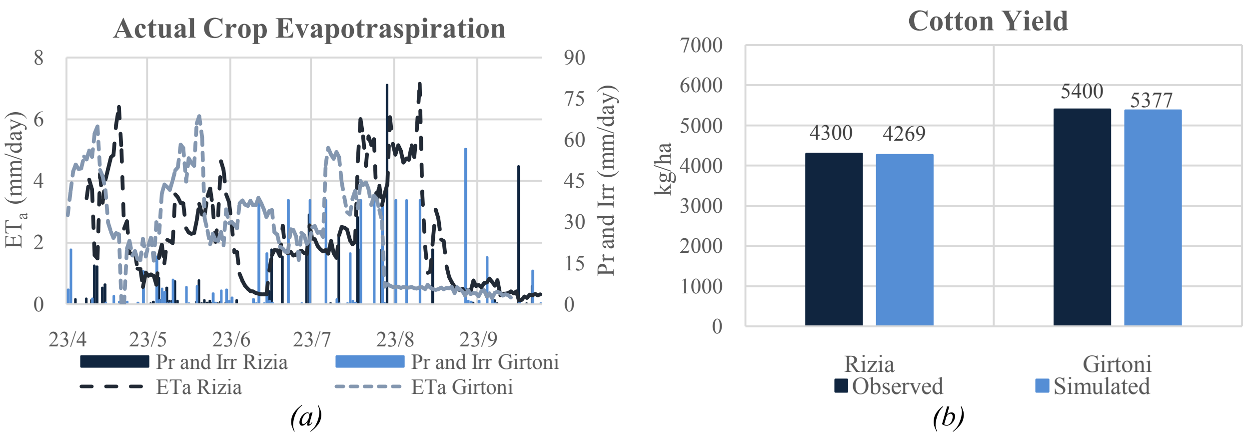


Figure 2. (a) Actual crop evapotranspiration (ET_a) and precipitation (Pr) with irrigation (Irr) for both case studies Rizia and Girtoni; (b) Observed (dark blue bar) and simulated (light blue bar) cotton production in Rizia and Girtoni.

2.2.2 Irrigation Regimes

Different irrigation regimes, including different treatments (T_1, T_2, and T_3), were applied to cotton cultivars for the two experimental sites on different growth stages with the use of the CropSyst model (Table 4). Applied irrigation (AI) was 100 mm of irrigation water at the experimental site Rizia (5 irrigation applications with equal amounts of irrigation doses of 20 mm) and 404.95 mm at Girtoni (12 irrigation applications).

The different irrigation treatments for the two experimental sites were the following:

- *Experimental site Rizia (S_1)* - S_1T_1: equal amounts of four irrigation doses (25 mm), S_1T_2: equal amounts of three irrigation doses (30 mm) and the fourth dose is reduced (10 mm) during the boll filling phase and S_1T_3: three irrigation applications with the two doses being equal (35 mm) the third dose is 30 mm during the beginning of the boll filling phase.
- *Experimental site Girtoni (S_2)* - S_2T_1: 12 irrigation applications with the 9 irrigation doses being increased in relation to the applied irrigation (from 38 mm to 40 mm) and the last application reduced (from 38 mm to 20 mm) during the boll filling phase, S_2T_2: 12 irrigation applications of which 11 doses are increased in relation to AI while the last irrigation dose is reduced at 10 mm during the boll filling phase and S_1T_3: 11 irrigation doses with the first two being equal with the AI and the rest increased at 42.22 mm.

2.3 Water use indicators

Water use indicators in agroecosystems can be calculated on small (e.g., field) or large scale (e.g., basin, globe) and generally focus on variables related to carbon uptake or plant production (e.g., yield, biomass, photosynthesis) (Hoover et. al., 2023). However, the chain of an agricultural product from the field to the dinner plate is large and complex using multiple water resources and increasing the total water use of the product. For a more holistic assessment of water use across the supply chain, there are approaches such as water productivity (Molden et al., 2010) and water footprint (Hoekstra et al., 2011) which refer to entire production systems.

2.3.1 Water Use Efficiency (WUE) and Water Productivity (WP)

The term efficiency accounts for a dimensionless ratio of the total amount of water used to the total amount of water applied (Fernández et al., 2020). At the crop level, a correct definition of crop *Water use efficiency* (WUE_c) is the actual crop evapotranspiration (ET_a) divided by the total amount of water supplied by irrigation and effective precipitation (Perry et al., 2009; Heydari, 2014):

$$WUE_c = ET_a / (Irr + P_{eff}) \tag{1}$$

where: ET_a is the actual crop evapotranspiration (m^3/ha), Irr is the applied irrigation (m^3/ha) and P_{eff} is the effective precipitation (m^3/ha).

Nowadays, there is a trend to call for increasing water productivity (WP) as an important issue in irrigation (Molden et al., 2003, 2010), with the attention formerly given to irrigation efficiency, now being transferred to water productivity. Water productivity is the closest of the supply chain-focused water use indicators to the standard definition of WUE because it calculates the ratio of net benefits of agriculture to water use ("physical water productivity") (Molden et al., 2010). Water productivity refers to the ratio of net benefits from agricultural systems (e.g., biomass, crop yields) to the amount of water used to produce the benefits (Molden et al., 2010).

Water productivity (WP, kg/m^3) is defined as the ratio between the crop yield (Y) and the corresponding water use, which refers to the total water use (TWU), to the total amount of irrigation water use (IWU), and to the actual crop evapotranspiration (ET_a). According to where the denominator refers different indicators derive to assess diverse irrigation scheduling scenarios.

In *Total water productivity* (WP_{Total}) (kg/m^3) the dominator refers to the total water use including effective precipitation where Y is the crop yield (kg/ha), observed or estimated and TWU is the total water use (m^3/ha), P_{eff} is the effective precipitation (m^3/ha), Irr is the amount of irrigation (m^3/ha), CR is the capillary rise or groundwater contribution, ΔSW is the variation in soil water storage in the root zone from planting to harvesting:

$$WP_{Total} = Y/TWU = Y/(P_{eff} + Irr + CR + \Delta SW) \tag{2}$$

As regards *Irrigation water productivity* (WP_{Irr}) (kg/m^3) the dominator refers just to the irrigation water use (IWU) where Y is the crop yield (kg/ha), observed or estimated and Irr is the irrigation water use (m^3/ha):

$$WP_{Irr} = Y/IWU = Y/Irr \tag{3}$$

Crop water productivity (WP_{ET}) (kg/m^3) where ET_a is the actual crop evapotranspiration (m^3/ha) estimated by the Equation 4. This ratio is often called water use efficiency as found in Pereira et al. (2012) where they discussed related terminology.

$$WP_{ET} = Y/ET_a \tag{4}$$

The meaning of the above indicators is necessarily different as the same amount of yield depends not only on the amount of irrigation water used but also on the amount of precipitation that the crop could use according to the precipitation distribution during the cultivation period (Pereira et al., 2012). Therefore, for improving WP which leads to water savings in irrigation, various different factors such as the contribution of precipitation to meet crop water requirements, the irrigation management and the agronomic practices should be considered.

2.3.2 Water Footprint - WF

The *Water Footprint* (WF, m^3/t) is a general tool that has gained interest after the introduction by Hoekstra and Hung (2002) for the assessment of the consumption of freshwater by different products along their supply chain. It is a multi-dimensional indicator, showing water consumption volumes by source and polluted volumes by type of pollution with all its components being specified geographically and temporally.

The three components of WF in crop production are the green, blue, and grey WF (Hoekstra, 2009). The green and blue footprints refer to consumptive use (evapotranspiration) of water by plants, whereas the grey WF refers to the amount of water used to assimilate the pollutants as a result of fertilization or the existing water quality standards. Blue Water Footprint (WF_{Blue}) refers to the consumption of blue water resources (surface and groundwater) along the supply chain of a product. 'Consumption' refers to the loss of water from the available ground-surface water body in a catchment area, which happens when water evaporates, returns to another catchment area or the sea or is incorporated into a product. The Green Water Footprint (WF_{Green}) refers to the consumption of green water resources (precipitation stored in the soil as soil moisture). The Grey Water Footprint (WF_{Grey}) refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards.

Total consumptive water footprint (WF_{Total}) (m^3/t) of a crop, is the sum of the blue (WF_{Blue}), green (WF_{Green}) and grey (WF_{Grey}) components of WF as shown in Equation 5 (Hoekstra et al., 2009, 2011):

$$WF_{Total} = WF_{Blue} + WF_{Green} + WF_{Grey} \tag{5}$$

where: WF_{Blue} is the blue WF (m^3/t), WF_{Green} is the green WF (m^3/t) and WF_{Grey} is the grey WF (m^3/t).

All the components of the total water footprint expressed per unit of product, viz. in water volume per mass as m^3/t, which is equivalent to litre/kg. The procedures followed to calculate the blue (WF_{Blue}), green (WF_{Green}) and grey (WF_{Grey}) WFs are presented as follows.

Green water evapotranspiration (ET_{Green}) is equated with the minimum of the actual crop evapotranspiration (ET_a, mm/day) (output from CropSyst model) and effective precipitation (P_{eff}, mm/day) (Equation 6).

$$ET_{Green} = \min\left(ET_a, P_{eff}\right) \tag{6}$$

Blue water evapotranspiration (ET_{Blue}) is equal to the actual crop evapotranspiration (ET_a, mm/day) minus effective precipitation (P_{eff}, mm/day), but zero when effective precipitation exceeds actual crop evapotranspiration (Equation 7).

$$ET_{Blue} = \max\left(0, ET_a - P_{eff}\right) \tag{7}$$

The effective precipitation (P_{eff}) (mm/day) was estimated using the Soil Conservation Service (SCS) method provided by the United States Department of Agriculture (USDA) (USDA Soil Conservation Service, 1972).

The green (CWU_{Green}) and blue (CWU_{Blue}) components in crop water use (m^3/ha) are calculated by accumulation of daily evapotranspiration (ET, mm/day) over the complete growing season (Equations 8 and 9) (Aldaya et al., 2012).

$$CWU_{Green} = 10\sum_{d=1}^{n} ET_{Green} \tag{8}$$

$$CWU_{Blue} = 10\sum_{d=1}^{n} ET_{Blue} \tag{9}$$

where: ET_{Green} is the green water evapotranspiration (mm/day) and ET_{Blue} is the blue water evapotranspiration (mm/day).

The green (WF_{Green}) and blue (WF_{Blue}) component (m^3/t) are calculated as the green and blue component in crop water use divided by the crop yield (t/ha), respectively (Equations 10 and 11).

$$WF_{Green} = CWU_{Green}/Y \tag{10}$$

$$WF_{Blue} = CWU_{Blue}/Y \tag{11}$$

where: CWU_{Green} is the green component in crop water use (m^3/ha), CWU_{Blue} is the blue component in crop water use (m^3/ha) and Y is the crop yield (t/ha).

The grey component (WF_{Grey}, m^3/t) in the water footprint is calculated as the chemical application rate per hectare (AR) times the leaching fraction (a) divided by maximum acceptable concentration (c_{max}) minus the natural concentration for the pollutant (c_{nat}) and then divided by the crop yield (Y) (Equation 12) (Hoekstra et al., 2009; Franke et al., 2013):

$$WF_{Grey} = \left[\left(a \times AR\right)/\left(c_{max} - c_{nat}\right)\right]/Y \tag{12}$$

where: a is the leaching-runoff fraction of applied chemical substances reaching to the water body (%), AR is the application of chemical substances on or into the soil (kg/ha), c_{max} is the maximum acceptable concentration for the pollutant in the receiving water body (kg/m^3), c_{nat} is the natural concentration for the pollutant in the receiving water body (kg/m^3) and Y is the crop yield (t/ha).

The leaching fraction (a) that receives the water body depends on soil infiltration and according to the literature ranges from 3%-10%. As regards the locations of Rizia and Girtoni, due to their low to medium soil infiltration, the value of the leaching fraction was considered 5.5% and 5%, respectively. In the present study, for the calculation of grey WF, only the fertilization in the form of nitrogen applied to the experimental sites was considered. The maximum acceptable concentration for the pollutant in the receiving water body (c_{max}), concerning Nitrogen as nitrate

(NO_3) was 50 mg/L and the natural concentration for the pollutant in the receiving water body (c_{nat}) was assumed to be zero.

3. RESULTS AND DISCUSSION

For the purpose of the study, water use efficiency and water productivity indicators as well as total water footprint and its three components, green, blue and grey WFs were estimated for cotton during the cultivation period 2020 for the experimental sites at the locations Rizia (S_1) and Girtoni (S_2).

Table 4 presents the cotton yield under applied irrigation (AI) and under the different irrigation treatments, as simulated by CropSyst model, for the locations Rizia and Girtoni. The yield differences under the different irrigation treatments are expressed as a percentage of the yield obtained under applied irrigation. Results showed that cotton yield increased under the different irrigation treatments for both experimental sites with the above increase being greater for treatments $T_3 > T_2 > T_1$. The simulated cotton yields for the growing season 2020 were 4269 kg/ha for the experimental field at Rizia and 5377 kg/ha at Girtoni. The increases in yields were by 2%, 9%, 16% regarding Rizia and by 5%, 8%, 11% under the irrigation treatments T_1, T_2 and T_3, respectively. The decrease in the number of irrigation applications from five to four or three at the location Rizia and from 12 to 11 at Girtoni seems not to have adverse impacts on yield production indicating that the phenological stages receiving irrigation are the key factors (Georgiou et al., 2020). Sustainable water management requires irrigation water application at the right time and in adequate quantities to meet different crop water requirements (Jensen, 2007).

Table 4. Cotton yield (kg/ha) and their differences in relation to applied irrigation (AI) under the three different simulated irrigation treatments T_1, T_2 and T_3 at the locations Rizia (S_1) and Girtoni (S_2).

Rizia	**Different Treatments - S_1**			
Dates	**AI**	**S_1T_1**	**S_1T_2**	**S_1T_3**
8 July	20	25	30	35
21 July	20	25	30	35
10 August	20	25	30	30
18 August	20	25	10	-
6 September	20	-	-	-
Total Irrigation (mm)		100		
Yield (kg/ha)	**4269**	**4341**	**4659**	**4940**
Increase (%)		***2%***	***9%***	***16%***

Girtoni	**Different Treatments - S_2**			
Dates	**AI**	**S_2T_1**	**S_2T_2**	**S_2T_3**
24 April	20	20	22.25	20
19 June	4.95	4.95	7.50	4.95
3 July	38	40	40.55	42.22
14 July	38	40	40.55	42.22
22 July	38	40	40.55	42.22
28 July	38	40	40.55	42.22
10 August	38	40	40.55	42.22
15 August	38	40	40.55	42.22
18 August	38	40	40.55	42.22
23 August	38	40	40.55	42.22
27 August	38	40	40.55	42.22
1 September	38	20	10	-
Total Irrigation (mm)		404.95		
Yield (kg/ha)	**5377**	**5652**	**5785**	**5969**
Increase (%)		***5%***	***8%***	***11%***

In general, higher crop yield increases were observed when greater irrigation water amounts were applied during the critical phenological stages of cotton from the beginning of flowering (first flower) to maturation (July-August) and when the last irrigation was not applied (late September irrigation). Under irrigation treatments where the last irrigation dose was missed out, probably precipitation (Rizia - August: 137 mm and Girtoni - September: 80 mm) fulfilled cotton water requirements. A general rule as regards the last irrigation is being applied until the end of August-beginning of September for Central Greece and until 15-20 August for Northern Greece.

Table 5 shows the water use efficiency (WUE) and water productivity (WP) indicators under the applied irrigation (AI) and the different irrigation treatments regarding the two experimental sites. The indicators of WUE_c as well as the three WP indicators increased under the irrigation treatments compared to applied irrigation (AI) for the experimental sites of Rizia and Girtoni with the increase being higher as $T_3 > T_2 > T_1$. Crop water use efficiency (WUE_c) increased by 0.6%, 2.3% and 3.7% for treatments T_1, T_2 and T_3 at the location Rizia and by 1.6%, 3.3% and 3.4% at Girtoni, respectively. Concerning the water productivity indicators WP_{Total}, WP_{Irr} and WP_{ET}, the increase was greater in the case of Rizia compared to Girtoni for most of the treatments, indicating the optimization of water use concerning Rizia. As regards WP_{Total}, the increase was 8%, 15% and 21% at Rizia and 5%, 7% and 11% at Girtoni for treatments T_1, T_2 and T_3, respectively. Among the three WP indicators, WP_{ET} showed the lowest increases being 1%, 7% and 12% for treatments T_1, T_2 and T_3 at the experimental site of Rizia and 3%, 4% and 7% (T_1, T_2 and T_3) as regards Girtoni. As far as WP_{Irr} is concerned, the percentages of increase were similar with that of WP_{Total} at the location of Girtoni and 2%, 9% and 16% (T_1, T_2 and T_3) regarding the location Rizia. Overall, the irrigation management practices favoured the water use of the crop and could be considered as irrigation strategies for on-farm water management.

Table 5. Water use efficiency (WUE_c) and water productivity (WP) (kg/m^3) indicators and their differences in relation to applied irrigation (AI) under three different simulated irrigation treatments T_1, T_2 and T_3 at the locations Rizia (S_1) and Girtoni (S_2).

Rizia	**Different Treatments - S_1**				**Girtoni**	**Different Treatments - S_2**			
	AI	**S_1T_1**	**S_1T_2**	**S_1T_3**		**AI**	**S_2T_1**	**S_2T_2**	**S_2T_3**
WUE_c	0.876	0.881	0.896	0.908	**WUE_c**	0.637	0.647	0.658	0.659
Increase (%)		***0.6%***	***2.3%***	***3.7%***	***Increase (%)***		***1.6%***	***3.3%***	***3.4%***
WP_{Total} (kg/m^3)	0.80	0.87	0.92	0.97	**WP_{Total}**	0.76	0.80	0.82	0.84
Increase (%)		***8%***	***15%***	***21%***	***Increase (%)***		***5%***	***7%***	***11%***
WP_{Irr} (kg/m^3)	4.27	4.34	4.66	4.94	**WP_{Irr}**	1.33	1.40	1.43	1.47
Increase (%)		***2%***	***9%***	***16%***	***Increase (%)***		***5%***	***8%***	***11%***
WP_{ET} (kg/m^3)	1.13	1.14	1.20	1.26	**WP_{ET}**	1.36	1.41	1.42	1.46
Increase (%)		***1%***	***7%***	***12%***	***Increase (%)***		***3%***	***4%***	***7%***

The values of the total water footprint, its components as well as the percentage distribution of total WF are different for the two experimental sites. Cotton total WF was equal to 940.24 m^3/t regarding Rizia while the value of total WF was 755.31 m^3/t as regards Girtoni. Accordingly, the three WF components had higher values at the location of Rizia compared to Girtoni. The above can be attributed to the different values of the parameters involved in the WF calculation at the two locations such as the weather parameters, the crop yields and the irrigation and fertilization amounts.

Figures 3 and 4 show the percentage distribution of cotton total WF (m^3/t) of the experimental sites at Rizia and Girtoni, respectively under the applied irrigation (AI) and the different irrigation management treatments. Blue WF constitutes the highest percentage, followed by the green WF while the grey WF shows the lowest percentage for both applied irrigation and the different treatments. The value of blue WF of cotton under AI at the location of Girtoni was lower (613.34 m^3/t) compared to that of Rizia (748.20 m^3/t), with the blue component constituting 81.2% and 79.58% of total WF. The percentage of blue WF was about 79%-82% concerning the irrigation treatments. Green WF was 140.24 m^3/t and 120.84 m^3/t for the experimental sites at Rizia and Girtoni, with the precipitation participating in the total water consumption by 14.92% and 16%, respectively, regarding AI. Green WF constitutes about 15%-16% of total WF regarding the irrigation management practices. As regards the grey WF, the crop cotton of the experimental site of Rizia requires a greater volume of water to assimilate the load of pollutants in relation to Girtoni. The values of grey WF under AI were 51.79 m^3/t and 21.14 m^3/t for Rizia and Girtoni, respectively. The above is attributed to the greater nitrogen fertilizer amounts applied to the crop of the experimental field at Rizia (201kg N/ha) compared to Girtoni (114kg N/ha).

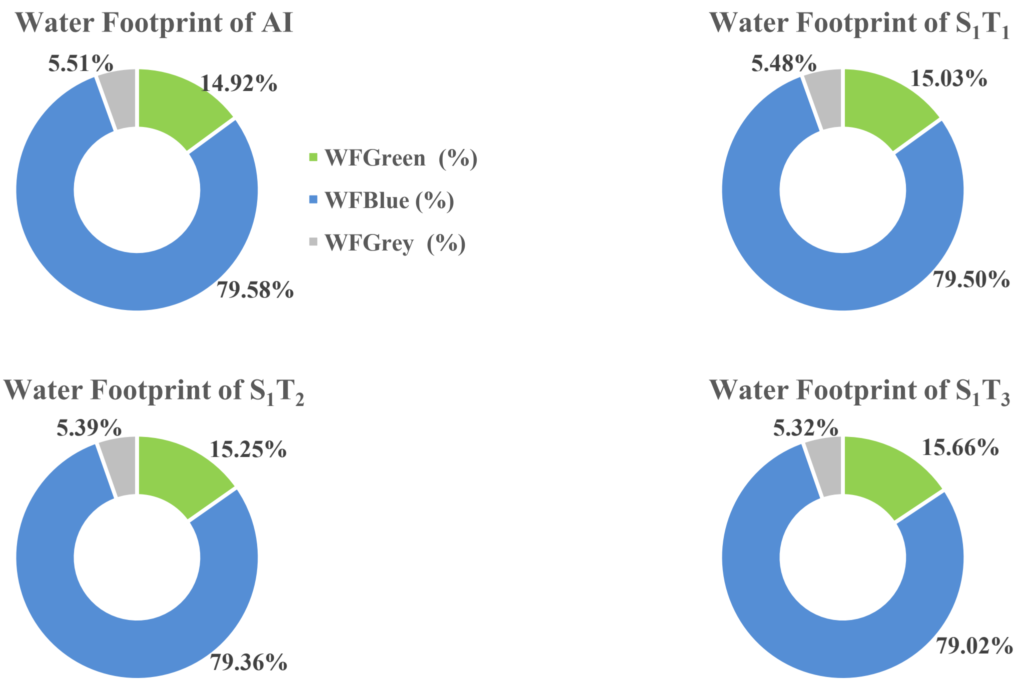


Figure 3. Percentage distribution of Water Footprint in Rizia (S_1) under applied irrigation (AI) and irrigation treatments T_1, T_2 and T_3.

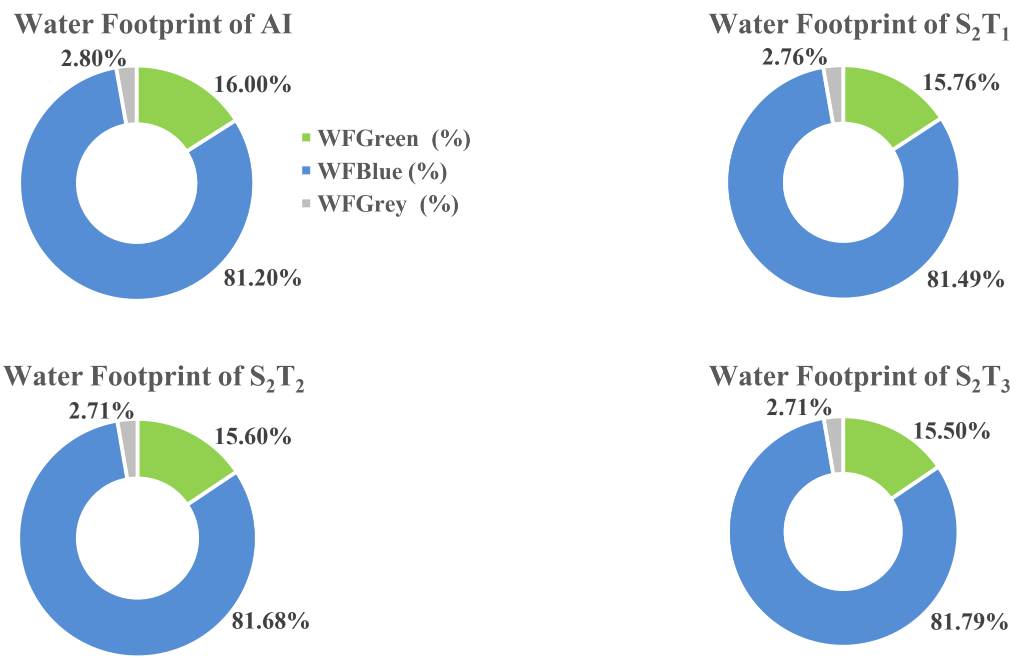


Figure 4. Percentage distribution of Water Footprint in Girtoni (S_2) under applied irrigation (AI) and irrigation treatments T_1, T_2 and T_3.

Our results show that cotton production in both locations in Northern and Central Greece mainly depends on blue water resources (irrigation water). These findings are in agreement with studies using the WF tool concluding that the blue WF of crop production accounted for the largest proportion in total water consumption (e.g., in irrigated cotton in Northern Ethiopia (Gebremariam et al., 2021), in an irrigation district of China (Sun et al., 2013)).

Table 6 and Figure 5 present the total water footprint and the three components (WF_{Green}, WF_{Blue} and WF_{Grey}) of cotton cultivar at the experimental sites Rizia and Girtoni under the applied irrigation (AI) and the different irrigation practices. Total WF, as well as its three components, decreased under the three irrigation treatments in relation to applied irrigation (AI) in both experimental sites. The decrease of total WF was higher for treatments T_3>T_2>T_1 concerning locations of Rizia and Girtoni. The green, blue and grey WFs followed a corresponding decrease under irrigation treatments with a reduced number of applications and increased amount of irrigation dose during the critical cotton growth stages in both experimental sites. As regards the experimental site Rizia, the decrease of total WF was 1.1%, 6.3% and 10.6% for treatments T_1, T_2 and T_3 while the decrease regarding Girtoni was 3.4%, 4.1% and 6.9%, respectively. Thus, reducing the number of irrigation applications as well as increasing the irrigation dose during the critical phenological stages of cotton, could be an irrigation management strategy to save water use due to the crop WF decrement. Furthermore, a key factor is the time of application of the last irrigation, which should be estimated according to the timing of the final crop growth stage in combination with the weather data of the area so that the crop can exploit precipitation, fulfilling its water requirements.

Table 6. Values of total Water Footprint (WF_{Total}) and, green (WF_{Green}), blue (WF_{Blue}) and grey (WF_{Grey}) components of WF of crop cotton at experimental sites Rizia and Girtoni under applied irrigation (AI) and three irrigation treatments T_1, T_2 and T_3.

Rizia	**Different Treatments - S_1**				**Girtoni**	**Different Treatments - S_2**			
WF (m³/t)	**AI**	**S_1T_1**	**S_1T_2**	**S_1T_3**	WF (m³/t)	**AI**	**S_2T_1**	**S_2T_2**	**S_2T_3**
WF_{Green}	140.24	139.68	134.30	131.64	**WF_{Green}**	120.84	115.00	113.04	108.98
Decrease (%)		***-0.4%***	***-4.2%***	***-6.1%***	***Decrease (%)***		***-4.8%***	***-6.4%***	***-9.8%***
WF_{Blue}	748.20	739.00	698.89	664.47	**WF_{Blue}**	613.34	594.77	591.78	574.93
Decrease (%)		***-1.2%***	***-6.6%***	***-11.2%***	***Decrease (%)***		***-3.0%***	***-3.5%***	***-6.3%***
WF_{Grey}	51.79	50.93	47.46	44.76	**WF_{Grey}**	21.14	20.11	19.65	19.05
Decrease (%)		***-1.7%***	***-8.4%***	***-13.6%***	***Decrease (%)***		***-4.9%***	***-7.1%***	***-9.9%***
WF_{Total}	940.24	929.62	880.64	840.87	**WF_{Total}**	755.31	729.88	724.47	702.96
Decrease (%)		***-1.1%***	***-6.3%***	***-10.6%***	***Decrease (%)***		***-3.4%***	***-4.1%***	***-6.9%***

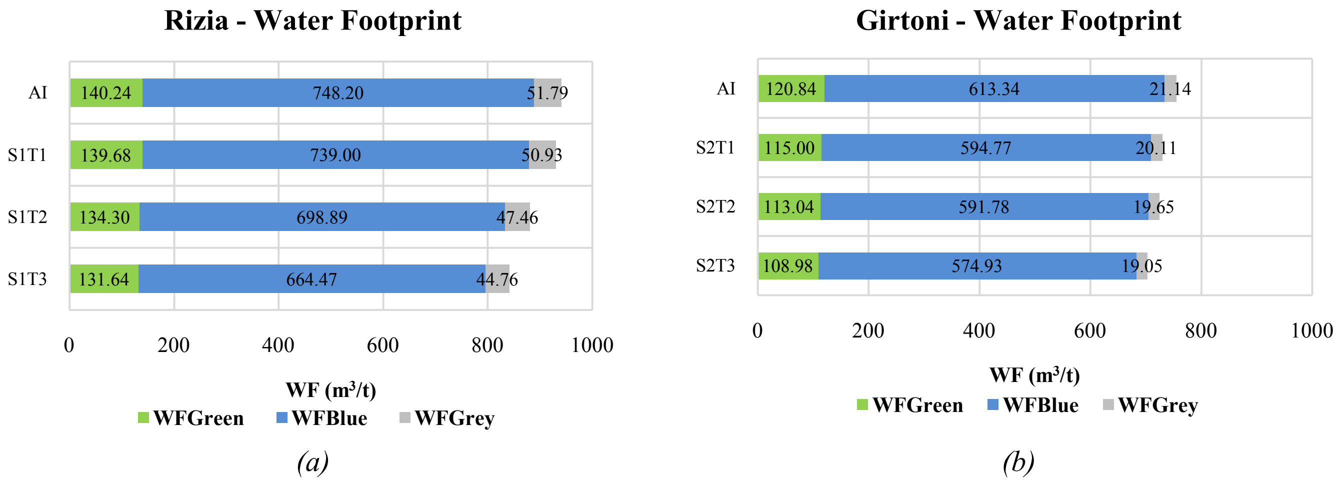


Figure 5. Green (WF_{Green}), blue (WF_{Blue}) and grey (WF_{Grey}) components of WF of crop cotton at experimental sites (a) Rizia and (b) Girtoni under applied irrigation (AI) and three irrigation treatments T_1, T_2 and T_3.

Many studies have used the WF to investigate the effects of different management practices involving water-saving irrigation technologies so as to reduce the WF from the agricultural sector (Jin et al., 2016). In a study by Zoidou et al. (2017) it was confirmed that precision irrigation could contribute significantly to the reduction of cotton water footprint in Northern Greece. Chukalla et al. (2015), which compared the effect of different irrigation techniques and strategies on green and blue water footprint in irrigated agriculture, also found diminished WF. Different irrigation strategies improved blue water use by reducing blue WF in a case study with winter wheat in Northern China (Zhuo and Hoekstra, 2017).

In the case of the experimental field at Rizia, the decrement in WF_{Blue} was higher compared to the decrease in $WF_{Green.}$ As green water generally has a lower opportunity cost than blue water (Martinez-Aldaya et al., 2010) because blue water resources are generally scarcer, determining how to reduce blue water consumption in agricultural production has become the target of countries and around the world (Martinez-Aldaya et al., 2010). Thus, the better use of precipitation when possible (increasing yields per drop of precipitation) would reduce the demand for blue water (Chapagain and Hoekstra, 2011).

In light of the findings presented in this paper, several promising avenues for future research emerge. Incorporating a quantitative comparison of different site conditions and their effects on results, along with a larger number of sites to parameterize these conditions, can also provide valuable insights and strengthen the research findings. Towards this direction, as a next step, a diverse set of sites representing a range of conditions could be selected with the aim of capturing variability and enabling statistical analyses. Additionally, the use of statistical methods such as regression analyses and multivariate analyses could effectively quantify the relationships between site conditions and outcomes and extract trends. Overall, addressing these aspects in future research can lead to a deeper understanding of effective on-farm water management, thereby contributing to the development of more efficient strategies for optimizing on-farm irrigation.

4. CONCLUSION

In this study, water use efficiency and water productivity indicators as well as total water footprint (WF) and its three components, green, blue and grey WFs were estimated for cotton crop, at two experimental sites in Northern and Central Greece (locations Rizia (S_1) and Girtoni (S_2), respectively), during the 2020 cultivation period. In both sites, irrigation management was carried out by the farmer (applied irrigation - AI). Different irrigation regimes (treatments: T_1, T_2 and T_3), were applied to cotton cultivar, on different growth stages, using CropSyst model. The total amount of irrigation water applied was the same in all three treatments and AI. According to simulation results, cotton yield increased under the different irrigation treatments in both experimental sites with the above increase being greater for treatments T_3>T_2>T_1. The indicators of WUE_c as well as the three WP indicators increased under the irrigation treatments compared to applied irrigation (AI) in both experimental sites with the increase being higher as T_3>T_2>T_1. The values of the total WF, and accordingly the three WF components were higher at S_1 compared to S_2, due to reasons predominantly related to different weather parameters, cotton yields, and irrigation and fertilization amounts applied. In both sites, the blue WF has the highest percentage, followed by the green WF while the grey WF has the lowest percentage. The comparison between AI and the three treatments showed that in both sites total WF, as well as its three components, decreased under the three treatments in relation to applied irrigation (AI). Our results showed that cotton production in both locations in northern and central Greece mainly depends on blue water resources (irrigation water). Reducing the number of irrigation applications as well as increasing the irrigation dose during the critical phenological stages of cotton, could be an irrigation management strategy to save water use due to the crop WF decrement. Another key factor to be considered is the time of application of the last irrigation which should be estimated according to the timing of the final crop growth stage in combination with the weather data of the area so that the crop can exploit precipitation fulfilling its water requirements. Based on the above results the water use indicators can be an efficient tool for the optimization of irrigation water management.

ACKNOWLEDGEMENTS

This research was part of the project with contract number LIFE17 ENV/GR000220 entitled "LIFE GAIA Sense: Innovative Smart Farming services supporting Circular Economy in Agriculture" which is co-funded by the LIFE Programme of the European Union.

An initial, shorter version of the paper has been presented at the 15th Conference of the Hellenic Hydrotechnical Association (Thessaloniki, Greece, June 2-3, 2022).

REFERENCES

Ahmed, S. M., Ribbe, L., 2011. Analysis of water footprints of rainfed and irrigated crops in Sudan. J. Nat. Res. Develop.; 1: 20-28.

Aldaya, M. M., Allan, J. A., Hoekstra, A. Y., 2010. Strategic importance of green water in international crop trade. Ecol. Econ.; 69: 887-94.

Aldaya, M. M., Chapagain, A. K., Hoekstra, A. Y., Mekonnen, Routledge, M. M., 2012. The Water Footprint Assessment Manual: Setting the Global Standard.

Cao, X., Wu, P., Wang, Y., Zhao, X., 2014. Water footprint of grain product in irrigated farmland of China. Water Resour. Manag.; 28(8): 2213-2227.

Chapagain, A. K., Hoekstra, A. Y., Savenije, H. H. G., Gautam, R., 2006. The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. Ecol. Econ.; 60(1): 186-203.

Chapagain, A. K., Hoekstra, A. Y., 2011. The water footprint of coffee and tea consumption in the Netherlands. Ecol. Econ.; 64: 109-18.

Chukalla, A. D., Krol, M. S., Hoekstra, A. Y., 2015. Green and blue water footprint reduction in irrigated agriculture: effect of irrigation techniques, irrigation strategies and mulching. Hydrol. Earth Syst. Sci.; 19(12): 4877-4891.

Clemmens, A. J., Molden, D. J., 2007. Water uses and productivity of irrigation systems. Irrig. Sci.; 25: 247-261.

Fernández, J. E., Alcon, F., Diaz-Espejo, A., Hernandez-Santana, V., Cuevas, M. V., 2020. Water use indicators and economic analysis for on-farm irrigation decision a case study of a super high density olive tree orchard. Agric. Water Manag.; 237: 106074.

Franke, N. A., Boyacioglu, H., Hoekstra, A. Y., 2013. Grey Water Footprint Assessment: Tier 1 - Supporting Guidelines. Water Footprint Network, Enschede, The Netherlands.

Gebremariam, F. T., Habtu, S., Yazew, E., Teklu, B., 2021. The water footprint of irrigation-supplemented cotton and mung-bean crops in Northern Ethiopia. Heliyon; 7: e06822.

Geng, Q., Ren, Q., Nolan, R. H., Wu, P., Yu, Q., 2019. Assessing China's agricultural water use efficiency in a green-blue water perspective: a study based on data envelopment analysis. Ecol. Indicat.; 96: 329-335.

Georgiou, P., Karpouzos, D., Koukouli, P., Katsifarakis, L., Gasparatos, D., 2020. Response of cotton yield to deficit irrigation using CropSyst model: a case study at Girtoni in Central Greece. Proceedings of International Conference Protection and Restoration of Environment XV. Patras, Greece, 35-44.

Herath, I., Green, S., Horne, D., Singh, R., Clothier, B., 2014. Quantifying and reducing the water footprint of rain-fed potato production part II: a hydrological assessment using modelling supported by measurements. J. Clean. Prod.; 81: 103-110.

Heydari, N., 2014. Water productivity in agriculture: challenges in concepts, terms and values. Irrig. and Drain.; 63: 22-28.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., Mekonnen, M. M., 2009. Water footprint manual: state of the art. The Netherlands: Enschede.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., Mekonnen, M. M., 2011. The water footprint assessment manual: setting the global standard. London: Earthscan.

Hoover, D. L., Abendroth, L. J., Browning, D. M., Saha, A., Snyder, K., Wagle, P., et al, 2023. Indicators of water use efficiency across diverse agroecosystems and spatiotemporal scales. Sci. Total Environ.; 864: 160992.

Jensen, M. E., 2007. Beyond irrigation efficiency. Irrig. Sci.; 25: 233-245.

Jhuo, L., Hoekstra, A. Y., 2017. The effect of different agricultural management practices on irrigation efficiency, water use efficiency and green and blue water footprint. Front. Agr. Sci. Eng.; 4(2): 185-194.

Jin, C., Huang, K., Yu, Y., Zhang, Y., 2016. Analysis of influencing factors of water footprint based on the STIRPAT model: evidence from the Beijing agricultural sector. Water; 8(11): 513.

Jovanovic, N., Pereira, L. S., Paredes, P., Pôças, I., Cantore, V., Todorovic, M., 2020. Methods, technologies and devices to reduce non-beneficial consumptive water use on farms with focus on the use of updated FAO56 methods. Agric. Water Manage.; 239: 106267.

Koech, R., Langat, P., 2018. Improving irrigation water use efficiency: a review of advances, challenges and opportunities in the australian context. Water; 10(1771): 17.

Koukouli, P., Georgiou, P., 2018. Evaluation of climate change impacts om cotton yield using CropSyst and regression models. J. Adv. Agric.; 8(1): 1433-1451.
Madugundu, R., Al-Gaadi, K. A., Tola, E., Hassaballa, A. A., Kayad, A. G., 2018. Utilization of Landsat-8 data for the estimation of carrot and maize crop water footprint under the arid climate of Saudi Arabia. PloS One; 13(2): e0192830.
Martinez-Aldaya, M., Munoz, G., Hoekstra, A. Y., 2010. Water footprint of cotton, wheat and rice production in Central Asia. Value of water research report 41; No. 41. Unesco-IHE Institute for Water Education.
Mekonnen, M. M., Hoekstra, A. Y., 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci.; 15(5): 1577-1600.
Molden, D., Murray-Rust, H., Sakthivadivel, R., Makin, I., 2003. A water-productivity framework for understanding and action. In: Kijne, J. W., Barker, R., Molden, D. (Eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement. IWMI and CABI Publ., Wallingford, pp. 1-18.
Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M.A., Kijne, J., 2010. Improving agricultural water productivity: between optimism and caution. Agric. Water Manage.; 97: 528-535.
Morillo, J., Rodríguez, D. J. A., Camacho, E., Montesinos, P., 2015. Linking water footprint accounting with irrigation management in high value crops. J. Clean. Prod.; 87: 594-602.
Oweis, T. Y., Hachum, A. Y., 2003. Improving water productivity in the dry areas of West Asia and North Africa. In: Kijne, J.W., Barker, R., Molden, D. (Eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement. IWMI and CABI Publ., Wallingford, pp. 179-198.
Pereira, L. S., 2017. Water, agriculture and food: challenges and issues. Water Resour. Manage.; 31: 2985-2999.
Pereira, L. S., Cordery, I., Iacovides, I., 2009. Coping with Water Scarcity. Addressing the Challenges. Springer, Dordrecht, 382 pp.
Pereira, L. S., Cordery, I., Iacovides, I., 2012. Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agric. Water Manage.; 108: 39-51.
Perry, C., Steduto, P., Allen, R. G., Burt, C. M., 2009. Increasing productivity in irrigated agriculture: agronomic constraints and hydrological realities. Agric. Water Manage.; 96(11): 1517-1524.
Rodriguez, C. I., Ruiz de Galarreta, V. A., Kruse, E. E., 2015. Analysis of water footprint of potato production in the pampean region of Argentina. J. Clean. Prod.; 90: 91-96.
Steduto, P., Hsiao, T. C., Fereres, E., 2007. On the conservative behavior of biomass water productivity. Irrig. Sci.; 25: 189-207.
Stöckle, C. O., Nelson, R., 1994. Cropping systems simulation: model user's manual (version 1.02.00). Biological Systems Engineering Department, Washington State University.
Stöckle, C. O., Donatelli, M., Nelson, R. L., 2003. CropSyst, a cropping systems simulation model. Eur. J. Agrono.; 18: 289-307.
Stöckle, C. O., Kemanian, A. R., Nelson, R. L., Adam, J. C., Sommer, R., Carlson, B., 2014. CropSyst model evolution: from field to regional to global scales and from research to decision support systems. Environ. Model. Softw.; 62: 361-369.
Sun, S., Wu, P., Wang, Y., Zhao, X., Liu, J., Zhang, X., 2013. The impacts of the interannual climate variability and agricultural inputs on water footprint of crop production in an irrigation district of China. Sci. Total Environ.; 444: 498-507.
Tingem, M., Rivington, M., Bellocchi, G., Colls, J., 2009. Crop yield model validation for Camerron. Theor. Appl. Climatol.; 96: 275-280.
Tsakmakis, I. D., Zoidou, M., Gikas, G. D., Sylaios, G. K. 2018. Impact of irrigation technologies and strategies on cotton water footprint using AquaCrop and CROPWAT models. Environ. Process.; 5: 181-199.
USDA Soil Conservation Service, 1972. National Engineering Handbook, Section 4, Hydrology. USDA Soil Conservation Service, Washington DC.
Xinchun, C., Mengyang, W., Rui, S., La, Z., Dan, C., Guangcheng, S., Shuhai, T., 2018. Water footprint assessment for crop production based on field measurements: a case study of irrigated paddy rice in East China. Sci. Total Environ.; 610-611: 84-93.
Zoidou, M., Tsakmakis, I., Gikas, G., Sylaios, G., 2017. Water Footprint for cotton irrigation scenarios utilizing CROPWAT and AquaCrop models. Eur. Water; 59: 285-290.