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Water Footprint for cotton irrigation scenarios utilizing CROPWAT and AquaCrop models

M. Zoidou, I.D. Tsakmakis, G.D. Gikas* and G. Sylaios
Laboratory of Ecological Engineering & Technology, Department of Environmental Engineering, School of Engineering, Democritus University of Thrace, 67100 Xanthi, Greece
* *e-mail: ggkikas@env.duth.gr*

Abstract: Water Footprint is a recently-introduced theoretical concept, estimating the amount of water needed to produce each of the goods and services we use. In agriculture, water footprint of a given cultivar is estimated by the water volume of plants' potential evapotranspiration per final crop yield unit. Many studies have been conducted to determine the Water Footprint of various crops in different countries, utilizing various models and datasets ranging from national to regional levels. In this study, we used two FAO agronomic models named CROPWAT and AquaCrop to estimate the annual water footprint of cotton cultivation in Northern Greece for the period 2013 to 2016. Field data obtained from a precision irrigation experiment at farm scale level were used. Both models were executed under full and deficit irrigation strategies. Results showed that there exist substantial differences between the estimations produced by the two models regarding the cotton potential evapotranspiration. Differences were also observed in the case of water footprint estimation by the two models. These differences (about 200 m^3/tn) were more evident under the full irrigation scenario and almost negligible (about 30 m^3/tn) when deficit irrigation was implemented. Lastly, it was confirmed that precision irrigation could contribute significantly to the reduction of cotton water footprint.

Key words: CROPWAT Model, AquaCrop model, Water footprint, Evapotranspiration

1. INTRODUCTION

Nowadays, the agricultural sector is responsible for the consumption of roughly 70% of the total global fresh water withdrawals annually (Tsakmakis et al., 2017). Climate change is expected to exacerbate the pressure in 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 overwhelms 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 irrigation water in a more sustainable way. 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 (Hoekstra, 2003). In agriculture, the water footprint of a given crop is the ratio of plants potential evapotranspiration divided by the final crop yield. This ratio can be used as an index of irrigation water rational use. The total volume of agricultural water consumed for crop production is the sum of the blue and green water footprints (Hoekstra, 2003; Zeng et al., 2012). Blue water footprint refers to the volume of surface and groundwater consumed during the production of a good or service; green water footprint refers to the rainwater consumed (Hoekstra, 2009). Many studies have been conducted to determine the water footprint of various crops in different countries, utilizing various models and datasets ranging from national to regional levels, providing estimates of the current status (Hoekstra and Mekonnen, 2012; Cao et al., 2014; Chukalla et al., 2015). In this paper two FAO agronomic models are used named CROPWAT and AquaCrop in order to estimate the annual water footprint of cotton in Northern Greece for the period 2013 to 2016, using data obtained from a precision irrigation experiment conducted in the area at farm scale. The models were run for full irrigation and deficit irrigation scenarios and the differences between the two models' estimates, as well as the potential improvement in the Water Footprint under deficit irrigation management, are presented.

2. METHOD AND MATERIALS

2.1 The agronomic models CROPWAT and AquaCrop

The CROPWAT model (FAO, 2009) utilizes the concepts of reference evapotranspiration (ET_o) and crop coefficient, introduced by Allen et al. (1998), in order to estimate the water requirements of a crop for different climate conditions and soil profiles. The model requires: (a) a soil file, where the saturated hydraulic conductivity (K_{sat}) and the available to root zone water content are defined; (b) a crop file, where the duration of the different cultivar development stages, the corresponding crop coefficients (K_c), the planting and harvest dates as well as the yield response factor (K_y) to potential water stresses are imported. Then, the model solves the water balance equation (Allen et al., 1998) utilizing daily ET_o, precipitation and irrigation data as inputs. The most substantial results obtained from CROPWAT simulations are the actual (ET_{cadj}) and potential (ET_c) crop evapotranspiration, effective rainfall and the total gross and net irrigation water. A drawback is that the model is incapable to estimate the final crop production, although it evaluates roughly the reduction in the cultivars potential yield when deficit irrigation is applied.

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). The data requirements are very similar to those of CROPWAT regarding the climate data, 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 except from the water balance data (evapotranspiration, irrigation, rainfall) include information regarding the crop's final dry aboveground biomass and yield.

A key difference between the two models is observed on the crop potential evapotranspiration (ET_c) calculation process. CROPWAT estimates ET_c by multiplying the daily ET_o values with a specific cultivar crop coefficient (K_c), as:

$$ET_c = K_c \times ET_o \quad (1)$$

On the other hand the AquaCrop model calculates the ET_c as the sum of crop potential evaporation (E_c) and crop potential transpiration (Tr_c)

$$ET_c = E_c + Tr_c \quad (2)$$

$$E_c = K_r \times K_e \times ET_o \quad (3)$$

$$Tr_c = K_S \times Kc_{Tr} \times ET_o \quad (4)$$

where: K_r is the evaporation reduction coefficient, fluctuating between 0 and 1, with lower values to occur when insufficient water is available in the soil to respond to the evaporative demand of the atmosphere; K_e is the soil evaporation coefficient being proportional to the fraction of the soil surface not covered by canopy, ranging between 0 – 1; K_s is the soil water stress coefficient (0 – 1); Kc_{Tr} is the crop transpiration coefficient (0 – 1).

The meteorological and soil data used for the models' simulations in the current work were obtained during a precision irrigation project, named FIGARO, carried out in a field located at

Xanthi coastal plain in Northern Greece (41.046º N; 24.892º E; 13 m altitude). The field was cultivated with cotton (*Gossypium hirsutum L.*) from 2013 to 2016 (Tsakmakis et al., 2017). The intensive rainfalls during 2014 cultivation period resulted in no cotton production and thus the data from this season were excluded.

Regarding the crop files, the AquaCrop was calibrated and validated under the deficit irrigation practices which were applied within the FIGARO project. In the case of CROPWAT, crop coefficients and yield response factors proposed by Allen et al. (1998) for the cotton different growing stages were utilized (initial stage K_c=0.15, K_y=0.20; mid-season K_c=1.15, K_y=0.5; harvest K_c=0.5, K_y=0.85), while the corresponding length of each stage was based on the observations of FIGARO project.

Initially the models were executed for deficit irrigation schedules. The amounts of irrigated water and the exact days for these schedules were obtained from FIGARO project. Consequently, an irrigation scenario corresponding to a full irrigation treatment was created. According to it every time the depletion level in the root zone dropped by 1% a theoretical irrigation event was triggered to refill the soil water content back to its field capacity. Then, the models were run again for the three cultivation periods. For both full and deficit irrigation schedules the total gross and total net irrigation amounts were considered to be equal, as the irrigation system utilized was a drip system with negligible losses.

Consequently, utilizing the models results, the green and blue component of crop water requirements (CWR) are calculated by accumulated data on daily crop evapotranspiration ET_c (mm/day) over the complete growing period.

$$CWR_{green} = 10 \times \sum_{d=1}^{lp} ET_{green} \tag{5}$$

$$CWR_{blue} = 10 \times \sum_{d=1}^{lp} ET_{blue} \tag{6}$$

where ET_{green} represents the rainwater lost by evapotranspiration (green water) (mm/d) and ET_{blue} the irrigated and soil water lost by evapotranspiration (blue water) (mm/d) during the cultivation period. The factor 10 is used to convert water depths in millimetres into water volumes per land surface in m^3/ha. 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).

2.2 Water footprint

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) against crop yield:

$$WF_{crop,green} = \frac{CWR_{green}}{Y} \tag{7}$$

$$WF_{crop,\text{blue}} = \frac{CWR_{blue}}{Y} \tag{8}$$

The green crop water requirement represents the total rainwater evaporated from the field during the growing period and the blue crop water requirement represents the total irrigation water evaporated from the field. In the case of deficit irrigation scenarios the yield was considered equal to the annual seed cotton yield measured each year during the FIGARO project. When the full irrigation scenario was implemented, the simulated cotton yield value produced by AquaCrop was 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 (Hoekstra et al., 2011):

$$WF_{crop} = WF_{crop,green} + WF_{crop,blue} \tag{9}$$

3. RESULTS

The simulation results obtained from the two models are presented in Table 1. For all seasons AquaCrop model estimated a significantly higher crop potential evapotranspiration for both full and deficit irrigation scenarios. This difference was found to be 81 ± 16.4 mm and 159 ± 45.9 mm under full irrigation and deficit irrigation scenarios, respectively. It is noteworthy that the ET_c was found to be the same through the same year in both irrigation scenarios by CROPWAT, while the ET_c under deficit irrigation was always higher according to AquaCrop. These discrepancies between the models are attributed to the different equations utilized by each model during evapotranspiration calculation process (equations 1 to 4). The difference observed between the two irrigation regimes within the same year from AquaCrop are ascribed to the soil evaporation coefficient K_e. The deficit irrigation resulted in lower canopy cover values and larger fractions of non-covered soil surface. As a result the difference between full and deficit irrigation schedule increases as the amount of irrigated water was reduced. In 2016 only 184 mm of irrigated water was applied, raising the difference between full and deficit strategies to 193 mm. In 2013 and 2015 when 227 mm and 303 mm were applied on the field these differences were lowered to 177 and 107 mm, respectively.

Table 1. CROPWAT and AquaCrop water-balance results for each cultivation period.

Year	Parameter	CROPWAT		AquaCrop	
		Full	Deficit	Full	Deficit
2013	Total Rainfall (mm)	142.6	142.6	142.6	142.6
	Effective Rainfall (mm)	3.7	140.9	121.2	141.7
	Efficiency Rain (%)	2.6	98.9	85.0	99.4
	Total Net Irrigation (mm)	720.1	227.0	682.7	227.0
	Potential crop evapotranspiration ET_c (mm)	719.2	719.2	781.5	896.4
	Actual crop evapotranspiration ET_{cadj} (mm)	719.2	508.2	795.7	513.2
2015	Total Rainfall (mm)	195	195.4	148.6	148.6
	Effective Rainfall (mm)	4.1	189.1	121.7	144.0
	Efficiency Rain (%)	2.1	96.8	81.9	96.9
	Total Net Irrigation (mm)	602.3	303.0	583.8	303.0
	Potential crop evapotranspiration ET_c (mm)	601.8	601.8	687.7	708.5
	Actual crop evapotranspiration ET_{cadj} (mm)	601.8	547.8	674.4	541.5
2016	Total Rainfall (mm)	164.8	164.8	164.8	164.8
	Effective Rainfall (mm)	4.0	100.8	135.0	160.0
	Efficiency Rain (%)	2.4	61.2	81.9	97.1
	Total Net Irrigation (mm)	670.2	184.0	649.7	184.0
	Potential crop evapotranspiration ET_c (mm)	669.5	669.5	763.4	862.5
	Actual crop evapotranspiration ET_{cadj} (mm)	669.5	453.4	749.1	491.7

The seed cotton yield at the end of the 2013, 2015 and 2016 cultivation periods was measured at 3.39, 3.97 and 3.55 tn/ha, respectively. The corresponding AquaCrop estimations for these three seasons were 3.28, 3.81 and 3.2 tn/ha. The model seems to perform satisfactorily under deficit irrigation, with a mean deviation from the measured yields equal to 0.21 ± 0.13 tn/ha. Taking into consideration this robust model performance, the simulated potential seed cotton yields in the full irrigation scenario were assumed as reasonable. The estimated yields for the three years were 4.7, 4.2 and 4.5 tn/ha, respectively. Comparing the potential with the measured yields, reductions equal to 27.8%, 5.5% and 27.9% for 2013, 2015 and 2016, respectively, were observed. The corresponding estimated yield reductions by CROPWAT were 30.4%, 6.5% and 32.6%.

The calculation of the blue, green and total water footprint of the two models are presented in Table 2. For all seasons CROPWAT model estimated a lower green WF for the full irrigation scenario. This mostly attributed to the fact that according to CROPWAT the crop firstly fulfills its water needs with irrigation water and then uses the rain water (Hoekstra et al., 2011). As a result almost 98% of rain water is lost as surface runoff or percolation. On the other hand, AquaCrop uses 98% of rain water for the crop needs, so the estimated green WF is higher than that of CROPWAT. For the full irrigation scenario, AquaCrop estimated lower blue WF values, while for deficit irrigation strategy both models estimated similar blue WF values.

Table 2. Cotton blue, green and total water footprint under full and deficit irrigation scenarios for the three cultivation years.

Year	Parameter (m^3/tn)	CROPWAT		AquaCrop	
		Full	Deficit	Full	Deficit
2013	WF_{green}	7.9	430.6	257.9	433.1
	WF_{blue}	1532.1	693.8	1452.6	693.8
	WF_{total}	1540.0	1124.4	1710.4	1126.8
2015	WF_{green}	9.7	477.8	287.4	363.8
	WF_{blue}	1422.5	763.0	1378.8	765.5
	WF_{total}	1432.2	1240.8	1666.3	1129.4
2016	WF_{green}	8.9	332.8	300.7	528.9
	WF_{blue}	1492.7	608.3	1447.0	608.3
	WF_{total}	1501.6	941.5	1747.7	1137.2

The mean WF_{total} under full irrigation scenario was estimated equal to 1,431 ± 54.6 m^3/tn and 1,708 ± 40.6 m^3/tn by CROPWAT and AquaCrop, respectively. This substantial difference of approximately 200 m^3/tn is a result of discrepancies introduced in the ET_c calculation. However, this difference was found to be considerably lower in the case of deficit irrigation (~ 30 m^3/tn). Moreover, according to AquaCrop, the deficit irrigation strategy has the potential to reduce cotton's WF_{total} more extensively than CROPWAT.

In a similar study, Chapagain and Hoekstra (2004) calculated cotton WF_{total} under full irrigation for different countries around the globe. They estimated values equal to 1,534 m^3/tn for Greece, 1,325 m^3/tn for Spain and 2,320 m^3/tn for Turkey. Their estimations for Greece and Spain were very similar to the findings of the current work.

The deficit irrigation strategy followed in 2015 highlighted its potential to reduce substantially cotton's WF_{total} by 191 m^3/tn and 536 m^3/tn (based on CROPWAT and AquaCrop, respectively). Deficit irrigation managed to save water with only a minor decrease in the seed cotton production (~ 6%).

4. CONCLUSION

In this study we evaluated the rational use of cotton irrigated water in Northern Greece, under full and deficit irrigation strategies, using two widely-used FAO agronomic models and applying the well-known water footprint concept. Under the full irrigation strategy, the CROPWAT model estimated lower Green WF than AquaCrop, but the opposite occurred in the case of blue WF. On the other hand, when deficit irrigation was implemented, the estimated by the two models blue WF was almost similar. As a result, AquaCrop estimated higher WF_{total} values under full irrigation and almost similar results under deficit irrigation strategy. CROPWAT's WF_{total} estimations under full irrigation were comparable to those of a previous study conducted for different countries around the world. The novelty of the present work lies in the fact that AquaCrop model has never been used as a tool to estimate the cotton water footprint.

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