# BENCHMARKING METHODOLOGIES FOR WATER FOOTPRINT CALCULATION IN AGRICULTURE

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**ABSTRACT**

In the present paper, the Water Footprint (WF) is used as a tool to evaluate the water resources management practices in Chania. The aim of this study is to explore and assess the potential of WF concept to be used as a reliable and convenient indicator for the development of an optimal agricultural policy in order to obtain an optimal water management of a region.

Based on this concept, the restructuring of cropland was studied in terms of water consumption and WF was calculated for different scenarios. Furthermore, the WF was calculated, by applying different methods to calculate evapotranspiration and effective rainfall, in order to determine whether the choice of a method applied may lead to different conclusions regarding water management outcomes.

The WF was proven to be a useful tool as it is a multidimensional indicator, by determining the volume and the type of water use. Furthermore, it was proved that the classification of crops (in terms of water consumption) varies slightly depending on the calculation method of different WF parameters. The actual evapotranspiration is the most accurate option, since it takes into account the frequency and amount of irrigation and the soil moisture used by the crop.

**KEYWORDS**

Water footprint, actual evapotranspiration (ET), CROPWAT, water resources management

## 1. INTRODUCTION

The increasing growth of global population combined with the accelerated rate of economic growth have evolved to a significant impact on agricultural and industrial needs. This, in turn, has had a number of far reaching consequences, one of which is the increased demand for large quantities of good quality freshwater. These pressures cause groundwater resources to be depleted and surface water resources to be consumed in ways that compromise freshwater ecosystems. As a result, freshwater is considered in many places to be a scarce and overexploited natural resource that needs to be properly managed. In order to achieve an optimum water resources management in a region is crucial to measure the level of human appropriation of fresh water capital. The Water Footprint (WF) of a crop is an empirical indicator introduced by A. Y. Hoekstra that estimates when, where and how much freshwater is consumed [1].

WF of a product or a service consists of three components: a) the blue WF which is the volume of freshwater that is consumed from the global blue water resources (surface water and ground water) to produce goods, b) the green WF which is the volume of water evaporated from the global green water resources (rainwater stored in the soil as soil moisture) and c) the grey WF which is the volume of polluted water that is associated with the production of goods. The latter can be estimated as the volume of water that is required to dilute pollutants to such an extent that the quality of water recipient remains at or above agreed water quality standards. With WF calculation the most water intensive crops (with the largest total WF), the most polluted (with the largest grey WF) and those that put extensive pressure on water resources of a region (with the largest blue WF) could be identified. The total WF of the process of growing crops or trees is the sum of the green, blue and grey components [1].

In the present paper, the WF is used as a tool to evaluate water resources management practices in Chania, which is considered one of the most developed agricultural areas in Greece. The aim of this study is to explore and assess the potential of the WF concept to be used as a reliable and convenient indicator for the development of an optimal agricultural policy focusing on an optimal water resources management of a region. Based on this concept, the restructuring of cropland is studied in terms of water consumption which was calculated for four different scenarios (dry-basic, average-basic, dry-future, average-future). Furthermore, the WF is calculated, for each crop, by applying different empirical methods to calculate evapotranspiration (eg. Blaney Criddle, Hargreaves, Penman-Monteith) and effective rainfall, in order to determine whether the choice of a method applied may lead to different conclusions regarding water resources management.

## 2. THE CHANIA PLAIN

The Chania plain is a relatively level landform spreading southward from the city of Chania on the island of Crete, as shown in Figure 1. This plain is considered to be one of the most developed agricultural areas of Greece but faces water scarcity due to the extention of irrigation networks. The expansion of tourism facilities and the intense construction of main residence leave no space for expansion of collaborative irrigation networks. However, some networks expansions will have been completed until 2016. In addition, restructuring of the irrigated land is in progress [2].

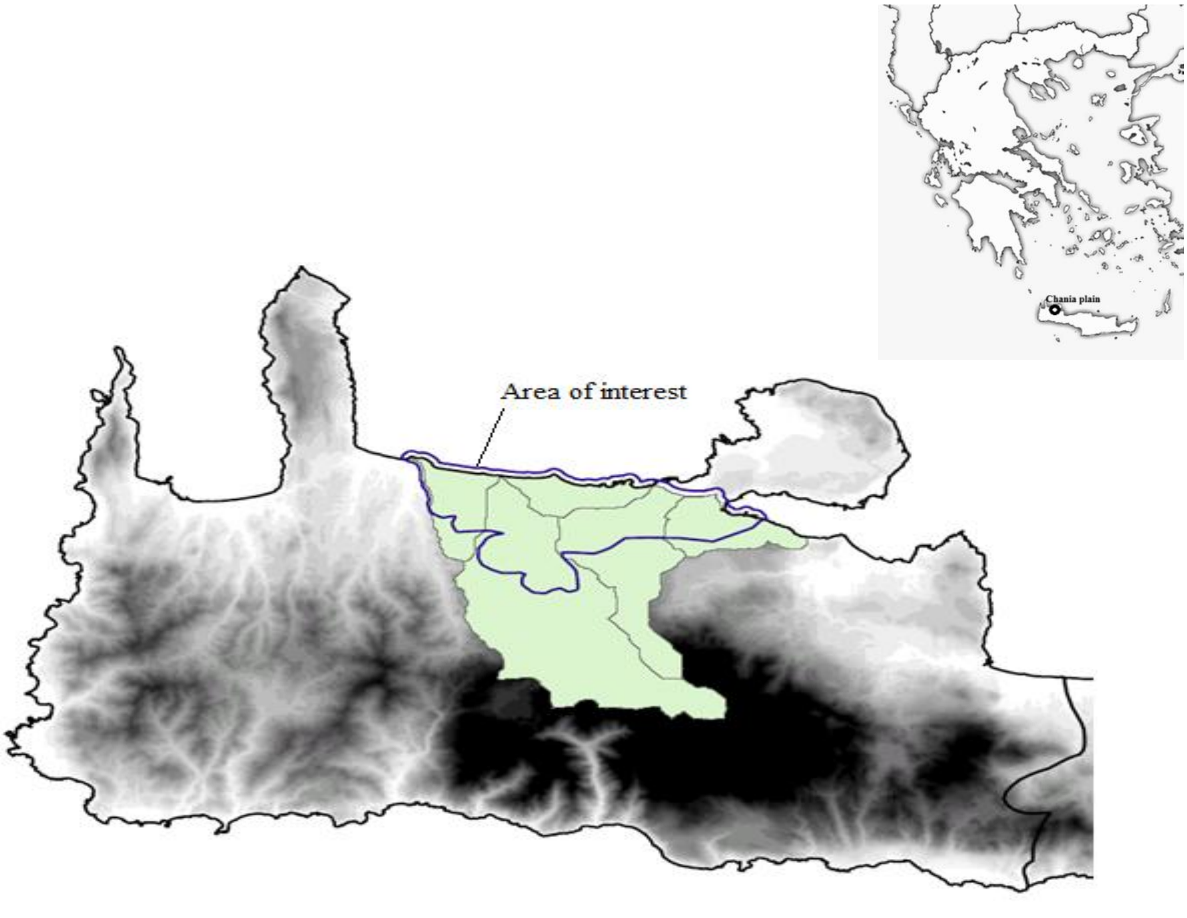


*Figure 1.* Area of interest [3]

The area of agricultural land in Chania plain according to National Statistical Service of Greece is about 165,000 acres. The crops mainly cultivated in the area are olives, citrus and grapes. According to the proposed restructuring of the irrigated land, citrus will be replaced by avocado crops and most of irrigated olive trees will be turned into rain-fed olive trees.

The present analysis compares the water consumption in agriculture for the currently applied agriculture policy (basic scenario) and the proposed one (future scenario when restructuring of irrigated land is completed) in order to determine if the proposed scenario leads to optimum water use. The water consumption is calculated based on the WF. Each scenario is studied for two different hydrological scenarios, a dry and an average one [4].

## 3. APPLIED METHODOLOGIES FOR EVAPOTRANSPIRATION AND RAINFALL

In order to calculate the volume of water consumed in agriculture in each scenario, the WF of each crop is calculated. The water consumption is calculated by multiplying the WF ($m^3$ $ton^{-1}$) by the weight of crops produced during the year (ton). There are two different approaches for calculating the WF based on: a) the irrigation requirements of the crop that should be fully met and b) the water consumption for each crop should consider equal to actual evapotranspiration (ET) [5]. In the present paper, the WF is calculated both ways, in order to determine the accuracy of each approach.

### 3.1 Estimation of the green water footprint

The green WF of a crop is calculated as the ratio of the volume of green water used for crop production, $CWU_g$ ($m^3$ $acre^{-1}$), to the weight of crop produced, Y (ton $acre^{-1}$).

$$WF_{\text{green}} = \text{CWU}_{\text{g}}/\text{Y} \quad (1)$$

The green water is calculated as the sum of green water use for each month, $u_g$ (mm $month^{-1}$), over the entire crop period. Assuming that the irrigation requirements of the crop are fully met, the monthly water use is equal to the minimum between effective rainfall, $P_{eff}$, and crop evapotranspiration, $ET_c$ [6].

$$\text{u}_{\text{g}} = \min\,(\text{P}_{\text{eff}}, \text{ET}_{\text{c}}) \quad (2)$$

In Chania plain, three different empirical methods to calculate evapotranspiration (Blaney-Criddle, Hargreaves, FAO Penman-Monteith) were applied, in order to determine whether the choice of the applied ET method may lead to different outcomes water consumption.

The Blaney-Criddle method, is based on an empirical equation and is the most common method for calculating evapotranspiration [7]. The evapotranspiration of a crop, $ET_c$ (mm $d^{-1}$), according to Blaney-Criddle equation [8], depends on the crop coefficient, $K_c$, the mean daily temperature, $T_\alpha$ ($^oC$) and the mean daily percentage of annual daytime hours, P.

$$\text{ET}_{\text{c}} = \text{K}_{\text{c}} \cdot (32 + 1.8\text{T}_{\alpha}) \cdot \text{P}/3.94 \quad (3)$$

The Hargreaves equation is also based on an empirical method that estimates the reference potential evapotranspiration of a crop, $ET_o$ (mm $d^{-1}$) and is a temperature-based method [9]. The evapotranspiration is a function of the extraterrestrial solar radiation, RA (mm $d^{-1}$), the maximum daily air temperature, $T_{max}$ (°C), the minimum daily air temperature, $T_{min}$ (°C) and the mean daily temperature, $T_\alpha$ ($^oC$).

$$\text{ET}_{\text{o}} = 0.0023 \cdot \text{RA} \cdot (\text{T}_{\alpha} + 17.8) \cdot \sqrt{(\text{T}_{\max} - \text{T}_{\min})} \quad (4)$$

The Penman-Monteith method is the method used by the CROPWAT model in order to calculate the evapotranspiration of crops. The method has been recommended as a combination method that determines evapotranspiration based on climatic data such as the mean temperature, $T_\alpha$ ($^oC$), humidity, U (%), sunshine, n (h/d), wind speed, u (m/s).

In this analysis, there are also applied different methods to estimate effective rainfall. The first method applied is based on equation (5), proposed by the USDA. According to this equation, the monthly effective rainfall depends on rainfall, $P_t$ (mm/month), and the monthly evapotranspiration. This method was chosen to be applied in combination with Blaney-Criddle and Hargreaves ET equations.

$$\text{P}_{\text{eff}} = \text{f(D)} \cdot [1.25 \cdot \text{P}_{\text{t}}^{0.824} - 2.93] \cdot [10^{0.000955 \cdot \text{ET}_{\text{c}}}] \quad (5)$$

The factor f(D) is considered to be equal to 1.

In case that the evapotranspiration method is the Penman-Monteith equation, the effective rainfall method applied is the one proposed by the USDA. According to this method, the effective rainfall depends only on the monthly rainfall.

$$P_{eff} = P_t \cdot \frac{125 - 0.2 \cdot P_t}{125}, P_t \leq 250 \text{ mm} \quad (6)$$

$$P_{eff} = 125 + 0.1 \cdot P_t, P_t > 250 \text{ mm} \quad (7)$$

**3.2 Estimation of the blue water footprint**

The blue WF ($m^3$ $ton^{-1}$) is similarly defined to the green WF [4].

$$WF_{blue} = CWU_b / Y \quad (8)$$

The blue water used for the production of a crop, $CWU_b$, represents the crop's irrigation requirement. The monthly blue water used for the production of a crop, assuming that the irrigation requirements of the crop are fully met, is considered zero, if the entire crop evapotranspiration requirement is met by the effective rainfall.

$$u_b = \max(0, ET_c - P_{eff}) \quad (9)$$

The estimated crop evapotranspiration in mm is converted to $m^3$/ha applying the factor 10 [5]. As a result, 1 mm/month is equal to 1 $m^3$/acre.

**3.3 Estimation of the blue and green WF, based on the actual evapotranspiration**

For irrigated agriculture, it is assumed that the irrigation requirements of the crop are fully met. However, farmers may apply less than the amount of water needed, in particular in those regions where water is scarce. The assumption that the irrigation water applied is sufficient enough to meet the irrigation requirements may lead to an overestimation of the blue water footprint [10].

The CROPWAT model can be used to calculate the green and blue water used in agriculture, taking into consideration the applied irrigation practices. In the area of study, the irrigation depth per month does not satisfy irrigation requirements of each crop. For this reason, the 'irrigation schedule CROPWAT option' is used to estimate green and blue water, in order to calculate the actual WF. The model does not work with the concept of effective precipitation. Instead, the model includes a soil water balance which keeps track of soil moisture content over time using a daily time step [5]. The input data to CROPWAT are related to climate, soil type, irrigation system, rainfall, crop and cropping pattern.

The green water evapotranspiration, $ET_{green}$, the blue water evapotranspiration, $ET_{blue}$, and the total evapotranspiration, $ET_a$, are estimated based on the CROPWAT's results. The total evapotranspiration, $ET_a$, is equal to what is called 'actual water use by crop' in the model output.

$$ET_a = \text{actual water use by crop} \quad (10)$$

Rain-fed conditions are simulated by the model by choosing the 'no irrigation' schedule option.

$$ET_{green} = ET_a \quad (11)$$

$$ET_{blue} = 0 \quad (12)$$

Irrigated conditions can be simulated by specifying the irrigation schedule. The blue and green water, consumed by the crop, can be calculated through equations (13) and (14). Total net irrigation and irrigation requirements are defined by CROPWAT model.

$$ET_{blue} = \min(\text{total net irrigation}, \text{actual irrigation requirement}) \quad (13)$$

$$ET_{green} = ET_a - ET_{blue} \quad (14)$$

### 3.4 Estimation of the grey water footprint

The grey WF ($m^3$ $ton^{-1}$) of a crop depends on fertilization rate applied to the field per acre, AR (kg/acre) where $\alpha$ is the leaching-run-off fraction, $c_{max}$ (mg $l^{-1}$) is the maximum acceptable concentration, $c_{nat}$ (mg $l^{-1}$) is the natural concentration for the pollutant considered in the receiving water body and Y is the crop yield [5].

$$WF_{grey} = (\alpha \cdot AR)/(c_{max} - c_{nat})/Y \quad (15)$$

## 4. RESULTS AND DISCUSSION

### 4.1 Evaluation of use of various ET methods

The WFs of nine crops were estimated for the two different hydrological scenarios: a) dry and b) average scenarios. The WF of each crop is calculated through the four different evapotranspiration methods, mentioned in Section 3. Benchmarking the WF of crops, the use of each evapotranspiration method leads to a different WF. Despite that fact, as shown in Figure 2, the olive trees proved to be the most water intensive crop and vegetables the less water intensive crop, irrespective the evapotranspiration method used, regarding the average hydrological conditions. The calculation of WFs in case of the dry hydrological scenario came to the same conclusion.

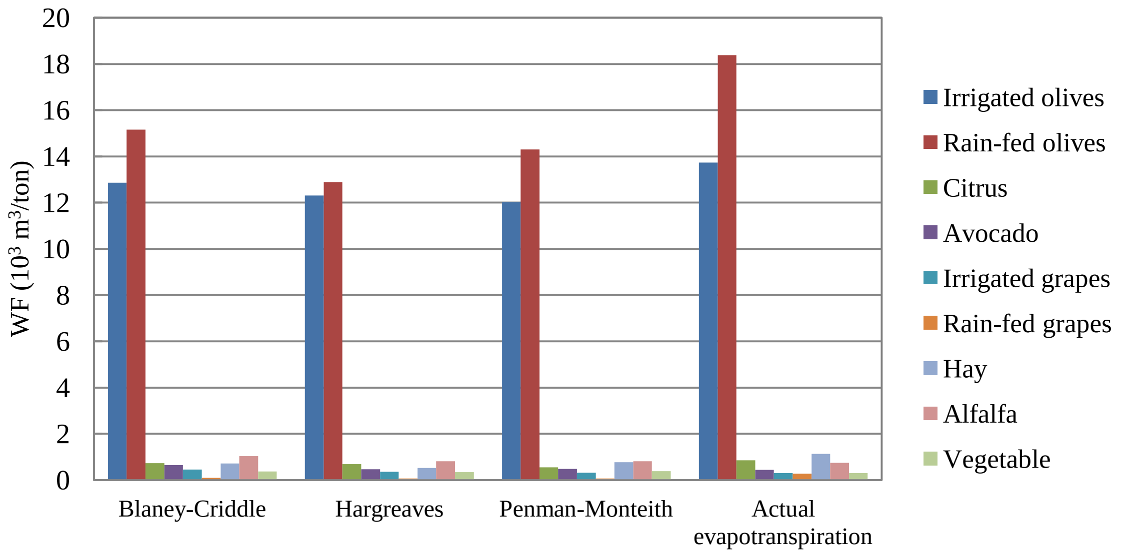


*Figure 2.* WF of crops ($10^3$ $m^3$/ton), calculated through different methods (average scenario) (after [2])

The aim of the present analysis, as mentioned, is to investigate whether the use of different evapotranspiration methods may lead to different conclusions regarding water resources management, in the area of study. The water consumption in agriculture is calculated for the scenarios: dry-basic (BD), average-basic (BA), dry-future (FD), average-future (FA) and through four different evapotranspiration methods: Blaney-Criddle (Blan.), Hargreaves (Harg.), Penman-Monteith (Pen.), actual evapotranspiration (actual). As shown in Figures 3 and 4, the water consumption in the future scenario (F) is slightly lower than the one in the basic scenario (B), both for average (A) and dry (D) scenario. The use of different evapotranspiration methods do not lead to a different conclusion concerning water consumption. However, comparing the water consumption in basic and future scenario, calculated based on the four different evapotranspiration methods (Blaney-Criddle, Hargreaves, Penman-Monteith, actual evapotranspiration), leads to a different percentage variation of each of the blue and green water components. In table 1, the percentage of variation in the present green, blue, grey and total water consumption is calculated, compared to the future water consumption.

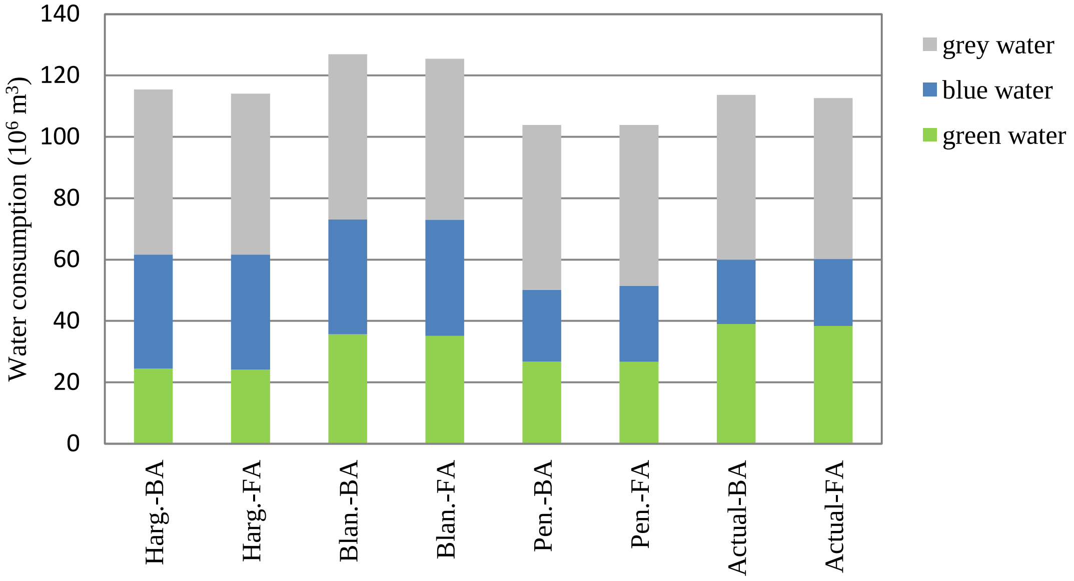


*Figure 3*. Water consumption ($10^6$ $m^3$) in agriculture - average scenario

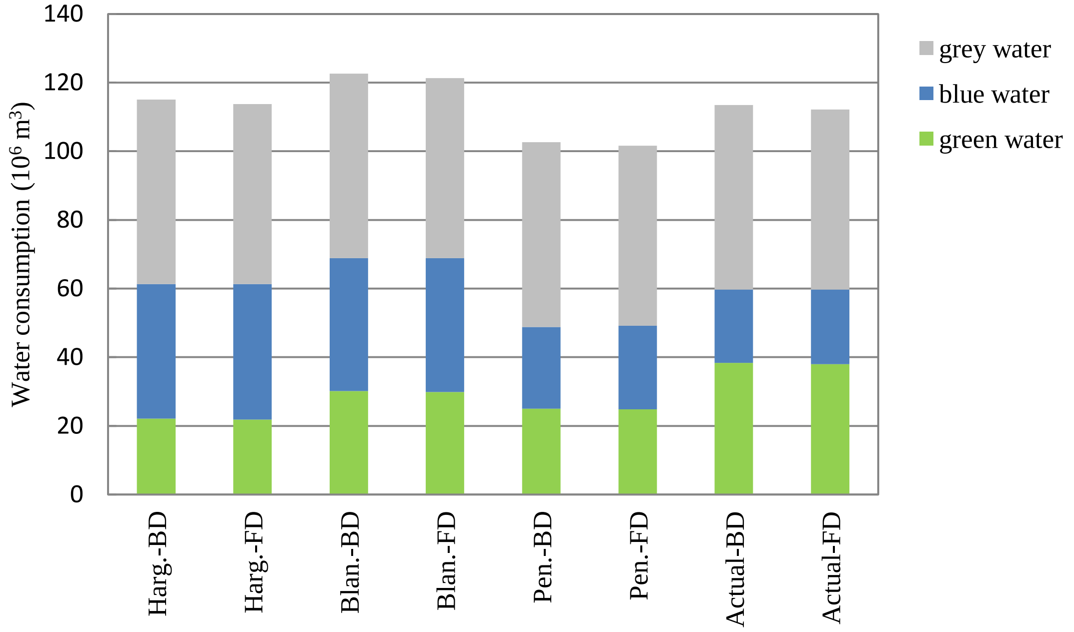


*Figure 4*. Water consumption ($10^6$ $m^3$) in agriculture - dry scenario

*Table 1*. Comparison between basic and future water consumption

| | Green water | Blue water | Grey water | Total water |
|---|---|---|---|---|
| Average scenario | | | | |
| Blaney-Criddle | -1,0% | +0,8% | -2,5% | -1,1% |
| Hargreaves | -1,2% | +0,7% | -2,5% | -1,2% |
| Penman-Monteith | -0,7% | +6,7% | -2,5% | ~0% |
| Actual evapotranspiration | -1,6% | +4,3% | -2,5% | -1,0% |
| Dry scenario | | | | |
| Blaney-Criddle | -1,0% | +0,9% | -2,5% | -1,1% |
| Hargreaves | -1,1% | +0,6% | -2,5% | -1,2% |
| Penman-Monteith | -0,7% | +2,4% | -2,5% | -1,0% |
| Actual evapotranspiration | -1,2% | +2,0% | -2,5% | -1,2% |

**4.2 Comparing WF of crops, cultivated in different regions**

Messara Plain is located in the southwest part of Crete's Heraklion Prefecture and is one of the most important Greek agricultural regions [11]. The climate in Messara Plain is similar to the Chania plain's climate. The average temperature in both areas is about 18 $^{o}$C. Olives and citrus are cultivated both in Messara Plain and in Chania plain. In Table 2 and Figure 5, WF of crops grown in Messara Plain [11] is compared to WF of crops grown in Chania. The evapotranspiration method used to calculate the WFs is the Blaney-Criddle equation and the rainfall equation used is equation (5).

*Table 2*. Comparison between WF of crops, grown in different regions

| WF ($m^3$/ton) | Messara Plain | Chania Plain |
|---|---|---|
| Rainfed olive trees (R_olive trees) | | |
| $WF_{green}$ ($m^3$/ton) | 6 123.28 | 5 985.26 |
| $WF_{blue}$ ($m^3$/ton) | - | - |
| $WF_{grey}$ ($m^3$/ton) | 5 057.34 | 9 174.31 |
| WF ($m^3$/ton) | 11 180.67 | 15 159.57 |
| Irrigated olive trees (Ir_olive trees) | | |
| $WF_{green}$ ($m^3$/ton) | 3 265.75 | 3 990.17 |
| $WF_{blue}$ ($m^3$/ton) | 5 635.52 | 2 751.01 |
| $WF_{grey}$ ($m^3$/ton) | 3 835.21 | 6 116.21 |
| WF ($m^3$/ton) | 12 737.48 | 12 857.39 |
| Citrus | | |
| $WF_{green}$ ($m^3$/ton) | 154.81 | 196.39 |
| $WF_{blue}$ ($m^3$/ton) | 411.82 | 246.37 |
| $WF_{grey}$ ($m^3$/ton) | 115.60 | 286.70 |
| WF ($m^3$/ton) | 682.23 | 729.46 |

As shown in Table 2, the WFs of the crops differ from region to region. This fact could be a result of different chemical application rate, in other words a result of the different grey WF. Another reason which can lead to WF variation is the choice of different method applied to calculate the blue WF. In Chania plain, the blue WF is calculated only for the period of year that the farmers have decided to irrigate the crops. On the other hand, in Messara Plain, the blue WF is calculated all over the growing period. Comparing the WF of the irrigated olive trees, there seems to be no significant difference concerning the water needs for the growing of the crop, cultivated in these areas. However, comparing each WF component, it is proved that olive trees which are cultivated in Messara valley put more pressure at the irrigation water, than the trees grown in Chania. In the other hand, the pollution caused by the fertilizers application is greater in Chania than in Messara.

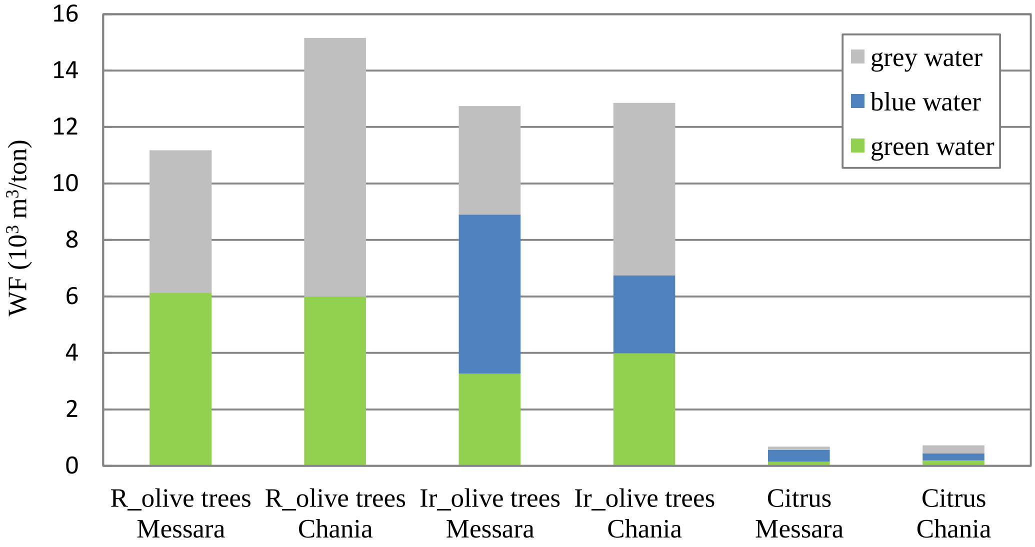


*Figure 5*. WF of crops ($10^3$ $m^3$/ton), grown in different regions (after [2], [11])

**5. CONCLUSIONS**

The comparison of WF of crops, as calculated through four different ET calculation methodologies for water consumption estimation (Blaney-Criddle, Hagreaves, Penman-Monteith, actual evapotranspiration via CROPWAT), led to the following results:

a) The agriculture ranking (based on water consumption) has slight deviations, depending on the calculation methodology. The ranking differences are not significant enough to lead to different conclusions on water policy.
b) Irrespective of the calculation methodology, the most water demanding crop is olives.
c) The calculation of WF based on the blue and green actual water usage, as extracted from CROPWAT, is the most accurate methodology, as the software calculates the actual evapotranspiration of agriculture, considering the method and frequency of irrigation, as well as the ground humidity. For this reason, the model requires input data on soil type and irrigation schedule. However, this methodology requires a lot of data, which is difficult to be collected.

Comparing the water consumption, that was estimated based on the WF as calculated through the four different methodologies for the current and the future situation, it was found that:

a) Irrespective of the calculation methodology, the grey water consumption is reduced in the future scenario about 2.5%, as well as the green, which it is reduced about 1%.
b) According the Blaney-Criddle and Hargreaves ET methodologies, the blue water consumption is slightly increased, as the increase percentage is lower than 1%. On the other hand, when using actual evapotranspiration and Penman-Monteith methodology, the increase percentage is more significant (4% and 7% respectively for the average scenario).

Therefore, the evaluation of the trend for restructuring agriculture should be performed using the same WF calculation methodology for both current and future scenarios. However, observing the trend of total water consumption in municipalities where the restructuring takes place, it is obvious that these actions lead to improved water resources management independent the applied calculation methodology.

Comparing water consumption for the dry and the average scenario, not considering the calculation methodology:

a) During the dry period, less green water is consumed in relation with the average scenario.
b) At the same time, significant increase of blue water usage.

Comparing the WF of Chania and Messara crops, significant differences were observed for both areas in:

a) grey WF, as the quantities of fertilizers applied were significantly different.
b) the calculation methodology, as for Chania Plain, the blue WF was limited to the irrigation period of the area, while for Messara Plain the WF calculation was based on a full cultivation season.

The WF was proven to be a useful tool as it is a multidimensional indicator of water use, showing the green, blue and grey water consumption as a function of space and time. Therefore, the total water footprint of a crop can be used as a rough indicator, in order to indentify the water intensive processes, but in fact, for developing sustainable water policies, each WF component should be studied separately [5].

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