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Assessment of the CROPWAT 8.0 software reliability for evapotranspiration and crop water requirements calculations

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Abstract

The results of the study devoted to assessment of accuracy and reliability of the CROPWAT 8.0 software application calculations of the evapotranspiration and crop water requirements are represented in the article.

The study was based on the results of the perennial field experiments, conducted during the period from 2012 to 2017 at the irrigated lands of the South of Ukraine with different crops, namely: sweet corn, grain corn, soybean, sorghum. We assessed accuracy of the CROPWAT 8.0 software application by the comparison of the calculated values with the real ones. We determined considerable differences between the calculated crops evapotranspiration values and crops irrigation requirements and the real ones obtained in the field experiments. The difference was the most essential in case of the drip-irrigated sweet corn crop and averaged to 46.05% for evapotranspiration and 89.20% for irrigation water requirements, correspondingly. Overhead sprinkler irrigated crops are likely to be more suitable for accurate evapotranspiration prediction by using the CROPWAT 8.0. The slightest discrepancy between the calculated and actual values of the studied parameters were determined on the overhead sprinkler irrigated grain corn crops, where the differences averaged just to 15.86% for evapotranspiration and 41.63% for irrigation norm. The results of the study gave us an opportunity to conclude that CROPWAT 8.0 software application should not be used without previous calibration and adjustment of the crop coefficients for the concrete agricultural production conditions.

Key words: *CROPWAT, evapotranspiration, grain corn, irrigation, sweet corn, soybean, sorghum, water requirements*

INTRODUCTION

Water is usually considered to be a renewable natural resource. But its improper distribution among the world and increasing demands can make a drastic effect on its availability and lead to significant freshwater scarcity in the nearest future [TARJUELO *et al.* 2010]. Recently conducted scientific studies have predicted increase in freshwater demands up to 80% by 2050 [FLÖRKE *et al.* 2018].

Agriculture is the main and biggest consumer of freshwater. About 70–80% (and in the arid zones up to 90%) of freshwater is used for agricultural purposes, particularly, for crop production at the irrigated lands [MOLDEN 2007]. Increasing demands for freshwater are highly likely to impact agricultural water supply. Proper agricultural water management is one of the most important issues that are on the table nowadays. Scientifically based and sensible water management is but the only way to provide crop production sustainability in the arid regions, which are very water-dependent ones. Rationale irrigation water use can significantly improve natural water resources use through preventing its pollution and improper application.

Precise evapotranspiration calculation is necessary for scientifically based irrigation water management. There are different methods for evapotranspiration calculation: mass-transfer based methods, radiation based methods and temperature-based methods [PENMAN 1956; USHKARENKO 1994; XU, SINGH 2002]. The Penman–Monteith method is considered to be one of the most reliable and comprehensive methods for estimation of evapotranspiration and crop water requirements, and it is actively used worldwide [ABEDINPOUR 2017; NORELDIN *et al.* 2016]. The CROPWAT 8.0 software application created by FAO specialists provides an opportunity of automation of all the necessary calculations for evapotranspiration determination. The application uses Penman–Monteith method as a base for further calculations, namely: evapotranspiration, irrigation water requirements for separate crops and crop-rotations, building of the irrigation schedules, etc. It is widely used for defining crops water requirements all over the world [FENG *et al.* 2007; STANCALIE *et al.* 2010; SURENDRAN *et al.* 2015]. It is likely to be one of the most popular tools for designing the irrigation schedule of crops [GEORGE *et al.* 2000]. At the same time recent studies established that there are better than Penman–Monteith models for evapotranspiration assessment now. For example, the Blaney–Criddle and Abtew models are the best ones for estimating the evapotranspiration (ET_o) in the arid and semiarid regions, respectively, and the modified Hargreaves−Samani 2 model represented the best performance in the Mediterranean and very humid regions [VALIPOUR *et al.* 2017]. Also, scientists mentioned that it is unlikely that the method of Penman–Monteith should be used in the world practice, because it has a number of potential restrictions and does not take into account some crucial points [CHEREMISINOV, CHEREMISINOV 2016]. The main goal of our study was to assess real accuracy and reliability of the CROPWAT 8.0 calculations both for sprinkler overhead and drip irrigated crops grown in different conditions of the South of Ukraine, so as to give substantiated recommendations for scientists and farmers on use of the application for practical purposes and to establish whether it is suitable for water management improvement in irrigated agriculture.

MATERIALS AND METHODS

All the field experiments were conducted in four replications by using the split plot design method at the irrigated lands of agricultural farms and research institutions.

1. Field experiments with sweet corn were conducted at the irrigated lands of the Agricultural Cooperative Farm "Radianska Zemlia" (Bilozerskiy district of Kherson region, Ukraine; coordinates of the experimental field: latitude 46°43'42" N, longitude 32°17'38" E, altitude 42 m). Size of the experimental plot was 30 m^2. The soil was represented by the dark-chestnut solonets soil with humus content in the 0–50 cm soil layer of 2.5%, lightly-hydrolized nitrogen content (determined by the Kornfield method) of 35 mg·kg^{-1} [SHKONDE 1971], mobile phosphorus content (determined by the methodology of Machygin) of 32 mg·kg^{-1}, exchangeable potassium content (determined by the methodology of Machygin) of 430 mg·kg^{-1} [ARINUSHKINA 1970]. The water-holding capacity of the soil in the 0–100 cm layer is 19.9%. The wilting point is 7.2% correspondingly. We used *Brusnytsia* (standard sweet *su* cultivar, originated at the Skvyrska research station of the Institute of Agroecology and Use of Environment – Ukr. Skvyrska doslidna stantsiia Instytutu Agroekologii ta Pryrodokorystuvanniia) crop cultivar in the field experiments. Sweet corn cultivation technology in the field experiments was common for growing under the irrigated conditions in the South of Ukraine. Soil moisture during the sweet corn vegetation was kept up at 80% of the field water-holding capacity by the means of drip irrigation. We placed drip tape in every row of sweet corn crops. We used Eurodrip 5 mil tape with spacing of drippers of 20 cm and discharge rate of 1.2 dm^3·h^{-1}. Water application doses were: in 2014 – 10 times at the rate of 5 mm until the stage of 7–8 leaves of crop and 12 times at the rate of 10 mm in the rest of the period; in 2015 – 6 times at the rate of 5 mm until the stage of 7–8 leaves of crop and 9 times at the rate of 10 mm in the rest of the period; in 2016 – 8 times at the rate of 5 mm until the stage of 7–8 leaves of crop and 12 times at the rate of 10 mm in the rest of the period.

2. Field experiments with grain corn, soybean and sorghum were conducted at the irrigated lands of the Institute of Irrigated Agriculture of the National Academy of Agrarian Sciences of Ukraine (coordinates of the experimental field: latitude 46°44'33" N, longitude 32°42'28" E, altitude 42 m). Size of the experimental plot was 300 m^2. The soil was represented by the dark-chestnut solonets middle-loamy soil with humus content in the 0–50 cm soil layer of 2.15%. The total nitrogen content (determined by the colorimeter method) averaged to 0.17%, mobile phosphorus content (determined by the methodology of Machygin) averaged to 30–40 mg·kg^{-1}, exchangeable potassium content (determined by the methodology of Machygin) averaged to 350–450 mg·kg^{-1} [ARINUSHKINA 1970]. The water-holding capacity of the soil in the 0–100 cm layer is 21.3%. The wilting point is 9.5% correspondingly. We used *Kahovskii* grain corn hybrid (FAO 380, originated at the Institute of Irrigated Agriculture – Ukr. Instytut zroshuvanoho zemlerobstva), *Apollon* soybean cultivar (originated at the Institute of Irrigated Agriculture) and *Sontsedar* sorghum hybrid (originated by the Nuseed company – Australia) in the field experiments. Cultivation technologies of all the studied crops in the field experiments were common for growing under the irrigated condi-

tions in the South of Ukraine. Soil moisture during the grain corn, soybean and sorghum crops vegetation was kept up at 70% of the field water-holding capacity. The irrigation was conducted by the means of overhead sprinkler irrigation machine DDA-100MA. Intensity of sprinkling of the irrigation machine was 2.5 mm·min^{-1}. Water application doses at the grain corn crops were: in 2012, 2014, 2015 – 7 times at the rate of 50 mm; in 2013 – once at the rate of 35 mm at the early stage and 5 times at the rate of 50 mm in the rest of the period; in 2017 – once at the rate of 30 mm at the early stage and 7 times at the rate of 50 mm in the rest of the period. Water application doses at the soybean crops were: in 2014 – 10 times at the rate of 40 mm; in 2017 – once at the rate of 30 mm at the early stage and 5 times at the rate of 50 mm in the rest of the period. Water application doses at the sorghum crops were 10 times at the rate of 40 mm.

The trials were carried out during the period from 2012 to 2017. Terms of sowing and harvesting of each crop are given in the Table 1.

Table 1. Terms of sowing and harvesting of the studied crops in the field experiments

Crops	Terms	
	of sowing	of harvesting
Sweet corn	1.05.2014	23.07.2014
	22.05.2015	8.08.2015
	21.05.2016	7.08.2016
Grain corn	30.04.2012	29.08.2012
	3.05.2013	10.09.2013
	5.05.2014	16.09.2014
	7.05.2015	23.09.2015
	10.05.2017	5.09.2017
Soybean	12.05.2014	25.09.2014
	11.05.2017	12.09.2017
Sorghum	21.04.2017	16.09.2017

Source: own elaboration.

The meteorological data was provided by the Kherson Hydro-Meteorological Center network stations which are situated close to the experimental fields. We used the monthly meteorological data for calculations. The Penman–Monteith method was used for calculation of the total evapotranspiration within the CROPWAT 8.0 software application [ALLEN *et al.* 1998; SMITH 1992]. We used key model parameters such as crops coefficients and climatic data assessment method recommended by FAO. All the mathematical calculations were conducted within CROPWAT 8.0 software application and no other calculation methodologies were used. The options used in CROPWAT 8.0 are represented in the Table 2.

Sweet corn root depth used in calculations was 30 cm at the initial stage and 50 cm in the rest of the growth period. Other crops' root depths used in calculations were 30 cm at the initial stage and 70 cm in the rest of the growth period.

Crop coefficients used in the trials are given in the Table 3.

Average duration of the main crop development periods used in calculations is given in the Table 4.

Table 2. CROPWAT 8.0 options used for determination of the evapotranspiration and crop water requirements calculations

Index or parameter	Option for calculations
ET_o Penman–Monteith	ET_o Penman calculated from temperature data (other data estimated)
Rainfall	dependable rain (FAO/AGLW formula)
Irrigation timing	irrigate at critical depletion
Irrigation application	refill soil to field capacity
Irrigation efficiency	70%

Source: own elaboration.

Table 3. Crop coefficients used in the calculations within CROPWAT 8.0

Crop	Stage of development	Crop coefficient
Sweet corn	initial	0.30
	mid-season	1.00
	late season	0.20
Grain corn	initial	0.30
	mid-season	1.00
	late season	0.20
Soybean	initial	0.30
	mid-season	1.00
	late season	0.40
Sorghum	initial	0.40
	mid-season	1.00
	late season	0.50

Source: own study.

Table 4. Duration of the main crop development periods used in calculations within CROPWAT 8.0

Crop	Period	Duration (days)
Sorghum	initial	20
	development	35
	mid-season	50
	late season	30
Soybean	initial	20
	development	30
	mid-season	50
	late season	20
Grain corn	initial	25
	development	35
	mid-season	30
	late season	30
Sweet corn	initial	20
	development	20
	mid-season	25
	late season	15

Source: own elaboration.

The real values of the above-mentioned indices were established by using the method of the field water balance as the sum of effective precipitation, available to plants soil moisture and applied irrigation water amounts. Precipitation amounts were established by using the pluviometers. Soil moisture was determined by the balance-drier method. The soil samples were collected from every 10 cm layer down to the depth of 100 cm at the sprouting stage and in the pre-harvesting period. The amounts of applied irrigation water were accounted by using the special water-counters [USHKARENKO *et al.* 2014].

Table 5. Total water consumption values for the studied crops (real and predicted by the CROPWAT 8.0 – CW 8.0)

Year	ET_o (mm)			*IWA* (mm)			*SM* plus *ER* (mm)		
	CW 8.0	real	CW 8.0 to real (%)	CW 8.0	real	CW 8.0 to real (%)	CW 8.0	real	CW 8.0 to real (%)
Sweet corn									
2014	427.7	287.2	148.92	317.8	170.0	186.94	109.9	117.2	93.77
2015	387.4	275.1	140.82	235.3	120.0	196.08	152.1	155.1	98.07
2016	398.9	269.1	148.23	298.4	160.0	186.50	100.5	109.1	92.12
Mean	404.7	277.1	146.05	283.8	150.0	189.20	120.8	127.1	95.04
Grain corn									
2012	623.3	545.1	114.35	462.7	350.0	132.20	160.6	195.1	82.32
2013	602.5	464.0	129.85	468.5	285.0	164.39	134.0	179.0	74.86
2014	652.5	557.4	117.06	505.9	350.0	144.54	146.6	207.4	70.68
2015	668.8	555.6	120.37	485.0	350.0	138.57	183.8	205.6	89.40
2017	572.6	570.2	100.10	506.8	380.0	144.80	67.0	190.2	35.23
Mean	623.9	538.5	115.86	485.8	343.0	141.63	138.4	195.5	70.79
Soybean									
2014	685.6	546.5	125.45	531.3	400.0	132.83	155.2	146.5	105.94
2017	611.5	464.6	131.62	545.7	280.0	194.89	65.8	184.6	35.64
Mean	648.6	505.6	128.28	538.5	340.0	158.38	110.5	165.6	66.73
Sorghum									
2017	736.0	570.5	129.00	638.2	400.0	159.55	97.8	170.5	57.36

Source: own study.

RESULTS AND DISCUSSION

Results of the study showed significant discrepancy between the calculated by the CROPWAT 8.0 software application and real evapotranspiration and irrigation water requirements of the drip and overhead sprinkler irrigated crops (Tab. 5).

In case of the drip irrigated sweet corn the difference averaged to the values of 112.3–140.5 mm for evapotranspiration and to 115.3–147.8 mm for the irrigation water amounts. The CROPWAT 8.0 model of the crop water requirements and use provided up to 140.82–148.92% higher values of evapotranspiration and up to 186.50–196.08% higher values of the required irrigation water amounts. It is obvious, that the main reason of the higher evapotranspiration values provided by the CROPWAT 8.0 is overestimation of the irrigation water requirements, while the values of the soil moisture and effective rainfall amounts were estimated by the software application with fairly high accuracy of 92.12–98.07%.

The evapotranspiration of the overhead sprinkler irrigated grain corn calculated by the means of the CROPWAT 8.0 software application was also considerably higher than the actual one. The difference averaged to 2.4–138.5 mm, greatly fluctuating in dependence on the climatic conditions of the year of study. The higher evapotranspiration rates were provided by the software application due to the overestimation of the irrigation water requirements (up to 32.20–64.39% overestimation rate) and underestimation of the available natural moisture (down to 10.60–64.77% underestimation rate). The same picture is observed on the other studied crops, viz., soybean and sorghum. Overestimation of the above-mentioned crops evapotranspiration was also connected with inaccuracy in the irrigation water requirements and natural moisture conditions assessment. The most crucial over-watering was suggested by the software in soybean crops in 2017, when predicted by the CROPWAT 8.0 irrigation water requirements were estimated as 194.89% to the real ones. The most inaccurate soil moisture and effective rainfall amounts calculation was provided by the CROPWAT 8.0 in 2017, when natural moisture conditions were underestimated to 64.36% on soybean crops and 42.64% on sorghum crops, comparatively to the actually fixed field values. The discrepancy in the evapotranspiration on soybean crops averaged to 139.1–146.9 mm, and to 165.5 mm on sorghum crops, respectively.

We consider several reasons of such a discrepancy in the evapotranspiration and irrigation water requirements estimation. We cannot put the obtained in our study differences down to imperfection of the CROPWAT 8.0 calculation algorithms. The fact that the differences depended on the climatic conditions of each year and crop biological features (the highest discrepancy was stated in dry years on the late-ripening sorghum and soybean crops) we suggest that the main problem lays in the crop coefficients, which are not actually adjusted for the certain climatic conditions. We conjecture that the crops coefficients by the stages of their development, which were provided by FAO and used in the CROPWAT 8.0 calculations, are not suitable for every agricultural production conditions and must be corrected with taking into account a number of specific parameters, for example, such as irrigation method used (drip irrigation, subsoil irrigation, furrow or overhead sprinkler irrigation, etc.), cultivation technology peculiarities, hybrid or variety morphological and biological features, climatic conditions of the zone, etc. Our conclusions are concordant with the results of some other scientific researches, reporting about the necessity of thorough adjustment of the crop coefficients for the drip-irrigated conditions of the concrete climatic zone for getting accurate crop water use predictions by the Penman–Monteith calculations within CROPWAT 8.0 software application [ROMASHCHENKO *et al.* 2016; ZHURAVLEV 2016]. That is why a number of studies, conducted in the non-typical agricultural conditions, a reports about evident inaccuracy (averaged to 8.3–13.5% depending on the irrigation method used) of the Penman–Monteith calculations in estimating evapotranspiration and irrigation water requirements for different crops [KHAMRAEV *et al.* 2016]. The results of scientific researches led to conclusion, that biological crop coefficient proposed by FAO for the calculations within the CROPWAT 8.0 software application are not suitable for every agricultural zone, and should be corrected due to the real crop requirements in certain soil and climatic conditions. Besides, natural humidification conditions also might be estimated by the software inaccurately, especially, when calculations are carried out for unusual, non-typical weather conditions [STULINA 2010]. Therefore we concluded that CROPWAT 8.0 software complex cannot be used "as it is" for precise irrigation scheduling as it has been earlier reported in some works [VOZHEHOV *et al.* 2016]. As a result, we recommend to use the CROPWAT 8.0 software application for the evapotranspiration and crops irrigation water requirements calculations only after previously conducted thorough adjustment of the crop coefficients.

CONCLUSIONS

The CROPWAT 8.0 software application is an interesting and modern tool for agricultural water management. It is easy in use, but it is not accurate enough and needs previous adjustments and thorough calibration of the crop coefficients for getting adequate predictions of the crop water requirements under the concrete conditions of agricultural production. We strongly recommend the CROPWAT 8.0 software application to be used in agricultural science and practice carefully and only after adjustment and carrying out field testing to guarantee efficient and rational agricultural water management.

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Ocena wiarygodności programu CROPWAT 8.0 do obliczania ewapotranspiracji i zapotrzebowania roślin na wodę

STRESZCZENIE

W artykule przedstawiono wyniki badań poświęconych ocenie dokładności i wiarygodności obliczeń ewapotranspiracji i zapotrzebowania roślin na wodę z zastosowaniem programu CROPWAT 8.0.

Podstawą badań były wyniki wieloletniego eksperymentu polowego prowadzonego od 2012 do 2017 r. na nawadnianych polach południowej Ukrainy z różnymi uprawami: kukurydzy cukrowej, kukurydzy zwykłej, soi i sorgo. Oceniono dokładność wyników uzyskanych za pomocą CROPWAT 8.0 przez porównanie wartości obliczonych z wartościami rzeczywistymi. Stwierdzono znaczne różnice między obliczonymi wartościami ewapotranspiracji upraw i ich zapotrzebowaniem na wodę a wartościami rzeczywistymi z eksperymentów polowych. Największe różnice stwierdzono w przypadku kroplowo nawadnianych upraw kukurydzy cukrowej i wynosiły one 46,05% w odniesieniu do ewapotranspiracji i 89,20% do zapotrzebowania na wodę do nawodnień. Obliczenia ewapotranspiracji za pomocą CROPWAT 8.0 były bardziej dokładne w odniesieniu do upraw nawadnianych deszczowniami. Najmniejszą rozbieżność między obliczonymi a rzeczywistymi wartościami badanych parametrów stwierdzono w przypadku deszczowanych upraw kukurydzy zwykłej, gdzie różnice wynosiły 15,86% w odniesieniu do ewapotranspiracji i 41,63% do norm nawadniania. Wyniki badań dają podstawy do wnioskowania, że CROPWAT 8.0 nie powinien być stosowany bez wstępnej kalibracji i dostosowania współczynników upraw do konkretnych warunków produkcji rolniczej.

Słowa kluczowe: *ewapotranspiracja, kukurydza cukrowa, kukurydza zwykła, nawadnianie, program CROPWAT, soja, sorgo*