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SIMULATION OF WINTER WHEAT WATER BALANCE WITH CROPWAT AND ISAREG MODELS

ABSTRACT

This paper presents the results of water balance simulations on winter wheat production in the area around Bijelo Polje. Winter wheat production over three years and on two soil types has been simulated with the CROPWAT and ISAREG models. The simulated results have proved variations between the two models and the measured yield. Crop evapotranspiration ranges between 304.5 to 463.3 mm. The relative yield obtained after the simulations is very similar to the relative yield obtained on a measured basis, except in the 2008/2009 season. Net irrigation requirements (NIR) to obtain the maximum yield are higher at 49-116 mm in the simulations with the CROPWAT model. The total NIR to maximize yield ranges between 84-300 mm depending on the season and model. Water use efficiency ranges from 0.82 to 1.28 kg/m^3. The obtained results verified both models as good tools for determining winter wheat water balance and indicated that winter wheat yields could be improved with irrigation.

Keywords: winter wheat, CROPWAT, ISAREG, water balance, water use efficiency, net irrigation requirements

INTRODUCTION

Continual improvement in agricultural production is essential to achieve the goals of national food security. Under Montenegrin mountain conditions rainfed wheat is planted in late autumn and completes its vegetative stage during mild winter conditions, when a water deficit is unusual. The stem elongation-anthesis stage takes place during late winter and early spring when the water supply is quite variable. The grain-filling period occurs during late spring and the beginning of the summer period when evaporative demands normally exceed rainfall. In these conditions mild to moderate water stress occurs in winter wheat vegetation, and reduces the final grain yield depending on the season.

Winter wheat has been grown in the area in Montenegro over the last four years, from around 846 ha in the year 2009 to 734 ha in 2010. The average yield for the same period was 3.21 t/ha. It ranged from 2.44 t/ha in the year 2007 to 3.60 t/ha in 2009. All production is under rainfed conditions. Winter wheat is

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grown around the town of Bijelo Polje, and arable land in this area is mainly restricted to the Lim River valley and to mountain plateaus.

The objectives of this research are: (1) to simulate water balance in winter wheat production during the 2007/2008, 2008/2009 and 2009/2010 seasons with the CROPWAT and ISAREG models and to compare them, (2) to compare the results of the simulations with the measured results and (3) to determine the net irrigation requirements and water use efficiency of winter wheat grown in the Bijelo Polje area.

MATERIALS AND METHODS

The study area of Bijelo Polje is located in the northern part of Montenegro, at 43°01′27" north latitude and 19°44′26" east longitude, and at the elevation of 720 m above sea level. It is located in the Lim River valley and it is the most important town in northern Montenegro representing administrative, economic, cultural and educational centres.

The climate in Bijelo Polje is typically mountainous. The average annual temperature is around 8.9 ^{0}C, while the mean annual precipitation is around 920 mm. The average monthly weather parameters during the vegetation period of winter wheat are presented in the Tables 1 - 3.

Table 1: Average monthly weather parameters during the vegetation period of winter wheat recorded at the Bijelo Polje meteo-station

Year	2007			2008			2009			2010		
Month	T_{min} (^{0}C)	T_{max} (^{0}C)	RH (%)	T_{min} (^{0}C)	T_{max} (^{0}C)	RH (%)	T_{min} (^{0}C)	T_{max} (^{0}C)	RH (%)	T_{min} (^{0}C)	T_{max} (^{0}C)	RH (%)
Jan				-3.1	5.0	84.8	-3.8	4.4	80.0	-1.6	5.7	84.0
Feb				-2.1	10.7	71.5	-2.3	6.7	77.0	-1.3	7.9	83.3
Mar				1.1	13.6	74.3	0.7	10.2	74.7	1.3	12.5	76.6
Apr				5.2	17.4	67.2	5.6	20.5	64.6	5.9	17.3	75.8
May				8.4	23.3	67.5	9.8	24.8	70.0	8.7	21.7	73.2
Jun				13.0	27.4	69.9	12.3	25.3	77.3	13.1	24.8	77.6
Jul				13.9	28.6	68.8	14.4	29.2	70.4	15.4	28.0	77.6
Aug				13.6	30.1	68.0	15.3	29.7	70.5			
Sep				9.7	21.6	76.4	11.8	24.5	75.5			
Oct	6.4	14.8	83.9	6.6	20.3	77.3	6.2	16.4	81.7			
Nov	-0.2	6.3	86.9	2.2	12.6	79.7	2.2	12.9	83.7			
Dec	-3.1	2.9	81.4	0.7	6.8	80.5	0.4	8.5	82.9			

RH - Mean relative humidity (%)
T_{min} – Average monthly minimal temperature (^{0}C)
T_{max}– Average monthly maximum temperature (^{0}C)

Two different soil types on which silage maize is grown were used for the simulations: a) soil with a medium total available water (130 mm/m) and b) soil with a high total available water (180 mm/m).

Eutric cambisol, known as brown eutric soil in the ex-Yugoslavian classification system, is very fertile and deep soil. It is a moderately permeable soil and has a high water holding capacity of 150-200 mm per meter depth. In this study this soil represents the most favourable production scenario, and the total available water adopted for the simulations in this study is 188 mm.

Dystric cambisol refers to brown soil on gravel and conglomerate. It is soil with a low to medium water holding capacity, higher in the top soil (30 cm), and significantly lower in the bottom soil. It is very shallow, up to 50 cm in depth, with a high content of gravel (up to 50%). The total available water for this soil, adopted for the simulations in this study, is 130 mm.

Table 2: Monthly precipitation (mm) and total precipitation in Bijelo Polje during the vegetation period of winter wheat

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Total
2007/ 2008	115.2	154.6	19.4	36.3	11.9	115.7	14.7	36.1	65.3	65.5	634.7
2008/ 2009	61.2	101	150.9	95.3	66.3	75.3	26.8	60	117.5	51.8	806.1
2009/ 2010	135.1	93.8	94.7	101.3	80	69.7	79.8	79.6	56.2	85.1	875.3

Table 3: Average monthly reference evapotranspiration (mm) in Bijelo Polje during the vegetation period of winter wheat

Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
2007/ 2008	1.27	0.52	0.38	0.44	1.13	1.81	2.86	4.28	4.87	4.87
2008/ 2009	1.58	0.72	0.43	0.45	0.82	1.50	3.22	4.33	4.39	4.94
2009/ 2010	1.37	0.65	0.44	0.46	0.81	1.71	2.67	3.79	4.27	4.54

Winter wheat (*Triticum durum)* was used as the crop material. The seeds were sown in the third week of October. Before sowing, 30 t/ha of cow manure was applied every year, and autumn tillage occurred each year before the sowing. Winter wheat is grown on several different parcels around the town of Bijelo Polje. In this analysis there was an assumption that the average sowing date on these parcels was 20 October for each growing season, however the sowing date actually varies among different plots. In the same manner, the length of the different vegetation stages was determined as the average value of all the particular plots. The date of harvesting was 26 July, and the total length of the vegetation season was 280 days for all of the growing years. These broad decisions were made because the measurement of the final yield was determined as the difference between the total measured yield from all the experimental plots and the total growing area. Regarding crop responses to water, the crop coefficients adopted for this work were those found in the literature. The Kc value for the initial stage was 0.4, mid-season the Kc was 1.15 and the late season Kc was 0.25. The maximum rooting depth was set at 1.00 m, while the critical depletion fraction was 0.55 during all of the seasons. The crop response to the water deficit was accounted for in the simulation by means of the yield response function, which was set at 1.05 for all of the seasons.

For the water balance, the crop evapotranspiration was estimated on a monthly basis as a product of the reference evapotranspiration (ET_o) and crop coefficient K_c:

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

The irrigation requirements were estimated by applying the soil water balance. The net irrigation requirements (NIR) were calculated by the following equation:

$$NIR = ET_c - P_{eff} \quad (2)$$

Where P_{eff} is the effective precipitation (mm), i.e. the amount of precipitation effectively used by the crop excluding the runoff and deep percolation losses. The USDA Soil Conservation Service empirical method (USDA, 1967) was applied for the estimate of the effective precipitation in both CROPWAT and ISAREG.

The water use efficiency (kg/m^3) was calculated by dividing the fresh grain yield (kg/ha) by the evapotranspiration (mm) (Howell et al., 1990; Scott, 2000).

The CROPWAT decision support tool was developed by the Land and Water Development Division of FAO. This computer software calculates crop water requirements and irrigation requirements on the basis of climate, soil, crop and management input parameters. The calculation procedures used in the software are explained in the FAO 56 Irrigation and drainage paper (Allen et al., 1998) and FAO 33 Irrigation and drainage paper (Doorenbos and Kassam, 1979). CROPWAT runs simulations in daily, ten-day and monthly time steps. It is a user friendly model and it offers various user-defined options for water supply and irrigation management. The output of the simulations is reference evapotranspiration (could be also input), crop water requirements under various management conditions defined by the user (full irrigation- optimum, deficit irrigation practices, or rainfed), net irrigation requirements and relative yield of the crops obtained with respect to the water deficit that the crops suffer.

The simulation model ISAREG (Teixeira and Pereira, 1992; Liu et al., 1998; Pereira et al., 2003) has been validated and is used in several regions and for various crops to develop improved irrigation scheduling practices leading to more efficient water use and water saving, and to predict the impacts of water stress on yields (Teixeira et al., 1995; Liu et al., 1998; Alba et al., 2003; Zairi et al., 2003; Cancela et al., 2006; Popova and Perreira, 2008). This model is based on the water balance approach developed by Doorenbos and Pruitt (1977) and updated by Allen et al. (1998), thus including the assessment of the impact of salinity on the yield and parametric functions to estimate the capillary rise and percolation through the bottom boundary of the soil root zone (Liu et al., 2006). The soil water balance simulation with ISAREG requires weather data on reference evapotranspiration and rainfall, soil data on soil depth, field capacity and wilting point for each horizon, crop data related to sowing and length of growing stages, crop coefficients, root depth, depletion fractions and response of crops to water deficits. The water stress effect on yield is based on the Stewart one-phase model when the yield response factor K_y is known (Stewart et al., 1977; Doorenbos and Kassam, 1979). This model offers many different irrigation scheduling options aiming for yield maximization at optimal or under water scarcity conditions, or simply under rainfed conditions.

As some of the weather variables required to estimate the ETo are missing for Bijelo Polje, the daily reference evapotranspiration was estimated by the modified Penman-Monteith method (Allen et al., 1998) and was an input parameter for both models. All the simulations in this study were run in a daily time step.

RESULTS AND DISCUSSION

The results of the winter wheat soil water balance for the 2007/2008, 2008/2009 and 2009/2010 seasons, with the CROPWAT and ISAREG models, on soil with medium and high water holding capacities are represented graphically in Figures 1 - 4.

Low to medium total available water

For the soil with a medium available water content (Figs. 1, 2) there are some differences among the simulations between the models.

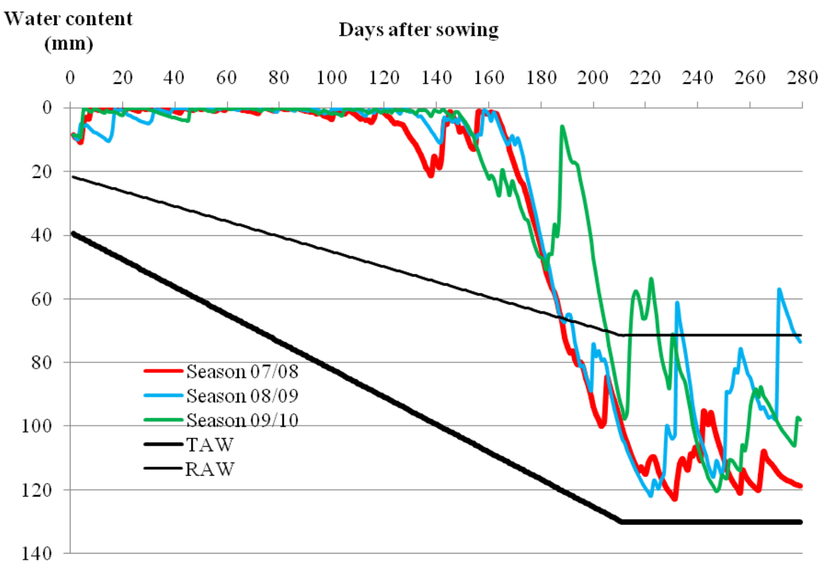

Figure 1: Water balance of winter wheat simulated with the CROPWAT model for the 2007/2008, 2008/2009 and 2009/2010 seasons, on soil with medium water holding characteristics (TAW – total available water, RAW – readily available water)

For the 2007/2008 season, the soil depletion in the ISAREG model approaches the lower limit of RAW 200 DAS, while the crop enters stress at DAS=213. The same behaviour is found in the 2008/2009 and 2009/2010 seasons, however the CROPWAT simulations enter stress at around DAS=180 in all three seasons. For the 2007/2008 season the crop enters water stress around 10 days earlier than in the other two seasons in the ISAREG simulation. In the simulation with CROPWAT the crop enters stress 20 days earlier in the 2007/2008 and 2008/2009 seasons, then in the 2009/2010 season. The shape of the depletion curves for both models is very similar and the distinction is related to the initial crop stage. The CROPWAT model directly calculates the root growth increase from the first day of vegetation, while the ISAREG model assumes 170 days of vegetation first without root growing.

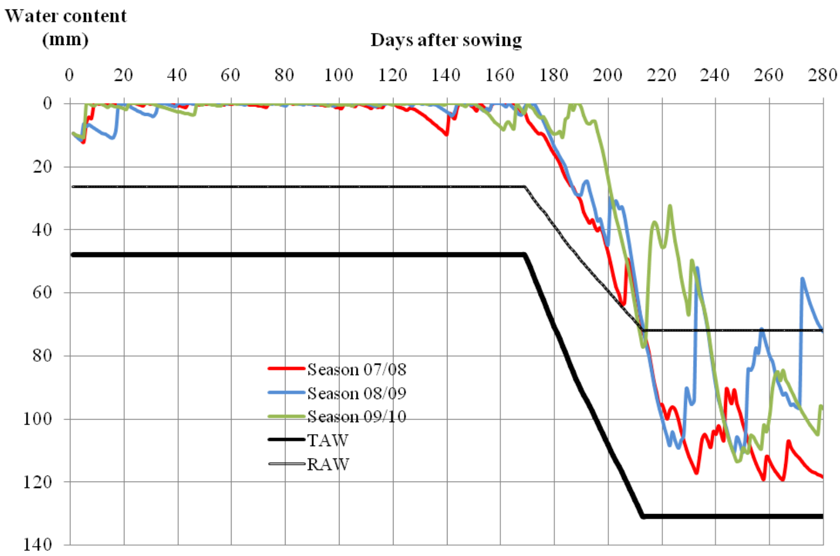

Figure 2: Water balance of winter wheat simulated with the ISAREG model for the 2007/2008, 2008/2009 and 2009/2010 seasons, on soil with medium water holding characteristics (TAW – total available water, RAW – readily available water)

High total available water

In the soil with a high total available water, both models behave in a similar way (Figs. 3, 4) to the soil with a medium TAW. In the 2009/2010 season, the ISAREG simulation enters stress 35 days after the CROPWAT simulation, while in the other seasons this difference is around 12 days. The main distinction between the models is related to the initial crop growth stage. The CROPWAT model directly calculates the root growth increase from the first day of vegetation, while the ISAREG model assumes 170 days of vegetation first, without root growing.

The maximum crop evapotranspiration with the CROPWAT model was estimated in the 2007/2008 season (598.6 mm), while the ET_m in the 2008/2009 and 2009/2010 seasons was 577.7 mm and 539.3 mm, respectively.

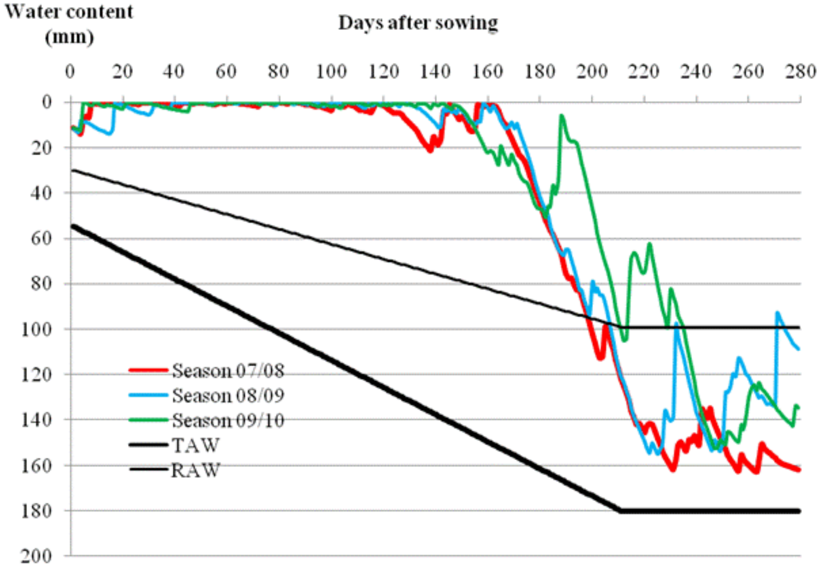

Figure 3: Water balance of winter wheat simulated with the CROPWAT model for the 2007/2008, 2008/2009 and 2009/2010 seasons, on soil with high water holding characteristics (TAW – total available water, RAW – readily available water)

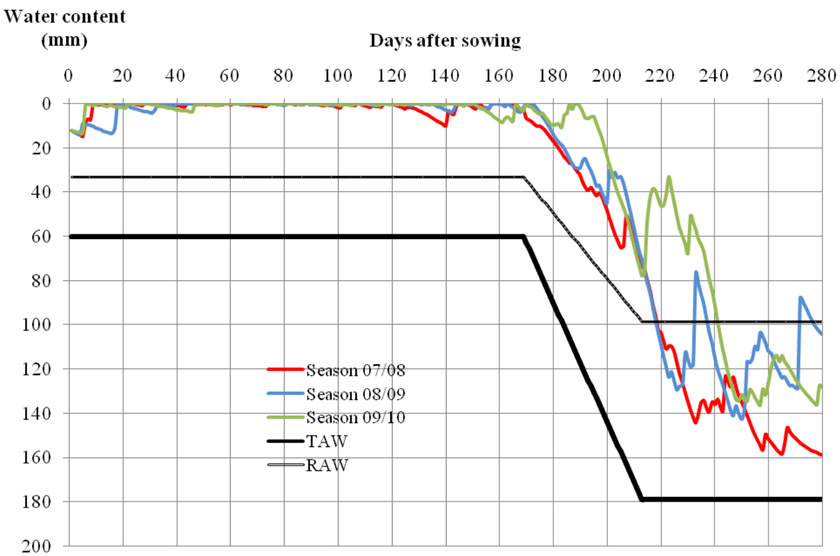

Figure 4: Water balance of winter wheat simulated with the ISAREG model for the 2007/2008, 2008/2009 and 2009/2010 seasons, on soil with high water holding characteristics (TAW – total available water, RAW – readily available water)

The actual crop evapotranspiration (ET_a) was the highest in 2009/2010 (463.3 mm on soil with a high TAW), while the lowest ET_a was estimated in the year 2008 (345.4 mm on the soil with a medium TAW). The highest relative yield was in 2009/2010 on soil with a high TAW (85.2%), while the lowest relative yield was estimated in 2007/2008 on soil with a medium TAW (55.6%). The water use efficiency varies over many years without any strict relationship.

Table 4: Crop maximum evapotranspiration (ET_m), actual evapotranspiration (ET_a), relative yield, net irrigation requirements and water use efficiency of winter wheat on soils with a medium and high TAW obtained with the CROPWAT model

Year	2007/2008		2008/2009		2009/2010	
Soil	medium	high	medium	high	medium	high
ET_m (mm)	598.6	598.6	577.7	577.7	539.3	539.3
ET_a (mm)	345.4	388.5	417.9	453.1	426.8	463.3
Relative yield (%)	55.6	63.1	71	77.4	78.1	85.2
NIR (mm)	300	274	192	208	159	160
Maximum yield (t/ha)	6.00					
Measured yield (t/ha)	3.62	3.62	3.70	3.70	4.60	4.60
Simulated yield (t/ha)	3.34	3.79	4.26	4.64	4.69	5.11
WUE (kg/m^3)	1.05	0.93	0.89	0.82	1.08	0.99

The yield ranges from 0.82 kg/m^3 on soil with a high TAW in the 2008/2009 season, to 1.08 kg/m^3 on soil with a medium TAW in 2009/2010. The relative yield obtained with the simulations can be expressed in absolute terms (kg/ha) and compared with the measured yield. In the 2008/2009 season there is a 15.1% difference in the results on soil with a medium TAW, and 25.5% difference in the results on soil with a high TAW. In all other years the results differ by around 10% or less. The results of the actual crop ET in the Bijelo Polje region, obtained under rainfed conditions, fit well with those obtained in other studies (Lopez-Bellido et al., 2007; Ilbeyi et al., 2006; Bouthiba et al., 2008).

The maximum crop evapotranspiration with the ISAREG model was estimated in the 2007/2008 season (492.5 mm), while the ET_m in the year 2009 and 2010 was 472.3 mm and 438.7 mm, respectively. The estimated values are around 100 mm lower than those found in the simulations with CROPWAT. The actual crop evapotranspiration (ET_a) was the highest in the 2008/2009 season (410.3 mm on soil with a high TAW), while the lowest ET_a was estimated in the 2007/2008 season (304.5 mm on soil with a medium TAW). The obtained ET_a values are around 40 mm lower than those obtained with CROPWAT. The highest relative yield was estimated in 2009/2010 on soil with a high TAW (88.8%), while the lowest relative yield was estimated in 2007/2008 on soil with a medium TAW (59.9%). The water use efficiency varies among many years without any strict relationship. It ranges from 0.90 kg/m^3 on soil with a high TAW in the 2008/2009 season, to 1.28 kg/m^3 on soil with a medium TAW in 2009/2010. The WUE values obtained after the ISAREG simulations are around 10% higher than those obtained with CROPWAT. In the 2008/2009 season there is a 22.1% difference in the relative yield in the results on soil with a medium TAW, and a 28.6% difference in the results on soil with a high TAW. In all other years the results differ by around 10% or less.

Table 5: Crop maximum evapotranspiration (ET_m), actual evapotranspiration (ET_a), relative yield, net irrigation requirements and water use efficiency of winter wheat on soils with a medium and high TAW obtained with the ISAREG model

Year	2007/2008		2008/2009		2009/2010	
Soil	medium	high	medium	high	medium	high
ET_m (mm)	492.5	492.5	472.3	472.3	438.7	438.7
ET_a (mm)	304.5	344.7	378.6	410.3	360.7	392.1
Ry (%)	59.9	68.5	79.2	86.4	81.3	88.8
NIR (mm)	235	209	119	92	110	84
Maximum yield (t/ha)	6.00					
Actual yield (t/ha)	3.62	3.62	3.70	3.70	4.60	4.60
Simulated yield (t/ha)	3.59	4.11	4.75	5.18	4.88	5.33
WUE (kg/m^3)	1.19	1.05	0.98	0.90	1.28	1.17

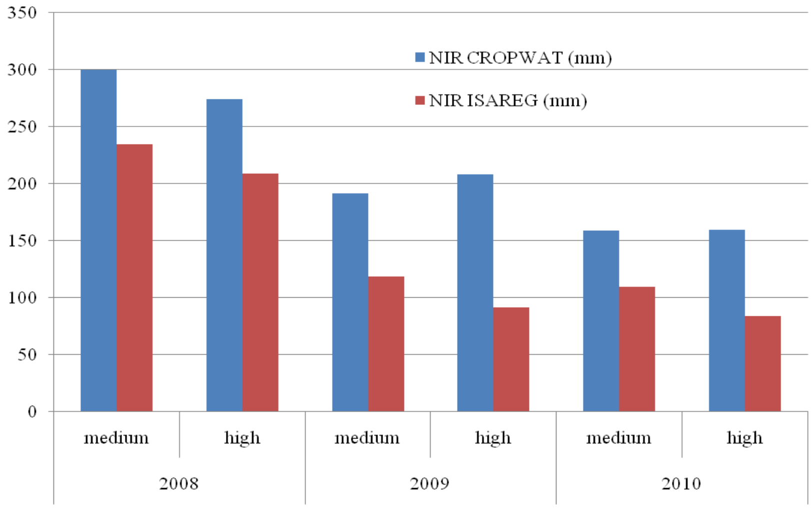

Figure 5: Net irrigation requirements in silage maize production obtained after simulations with two models, in three consecutive years and on two soil types

The results presented in Tables 4 and 5 indicate the huge difference in the measured and simulated results in the 2008/2009 season compared to the other two seasons. The main cause for these differences in the obtained results are the rainfall events that occurred from 29 May to 3 June, with a total of 72.3 mm recorded (45 mm recorded on 3 June), and on 12 July when a rainfall of 42.9 mm was recorded. These strong rainfall events were very intensive and effective precipitation and the effects were much lower than the ones calculated by the models.

In Figure 5 the NIR obtained after simulations with the CROPWAT and ISAREG models is graphically presented. The overall conclusion is that the ISAREG irrigation requirements are lower than those obtained after simulations with the CROPWAT. The differences are in the range of 49 mm to 116 mm.

CONCLUSION

According to the results of this 3-year study, winter wheat grain yields were decreased by water stress. The water balance of winter wheat grown in northern Montenegro was successfully simulated with the CROPWAT and ISAREG models. The obtained results have indicated that the difference between models related to the initial growth stage and root growth. The difference in crop evapotranspiration estimated with CROPWAT was around 100 mm higher than that simulated with ISAREG. Except in the 2008/2009 season, the relative yields obtained in the simulations were very close to the measured yields. The net irrigation requirements obtained with the CROPWAT were 49 to 116 mm higher than those found with the ISAREG. The maximum winter wheat yield in northern Montenegro could be obtained with 160-300 mm of irrigated water after the simulation with CROPWAT, or with 80-235 mm of irrigated water estimated with ISAREG, depending on the season. The water use efficiency obtained in northern Montenegro is in the range of values found globally (Musick et al., 1994; Jones and Popham, 1997; Xue et al., 2006; Wang et al., 2001; Zhang et al., 2005). The modelling of the water balance in winter wheat production in northern Montenegro could be applied under rainfed conditions, especially considering future climate change uncertainties.

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PRORAČUN VODNOG BILANSA U PROIZVODNJI PŠENICE SA MODELIMA CROPWAT I ISAREG

SAŽETAK

U ovom radu su prikazani rezultati proračuna vodnog bilansa u proizvodnji ozime pšenice na području Bijelog Polja. Gajenje ozime pšenice tokom tri godine i na dva tipa je simulirano sa CROPWAT i ISAREG modelima. Dobijeni rezultati proračuna su pokazali razlike između modela i mjerenog prinosa. Evapotranspiracija kulture iznosi od 304.5 do 463.3 mm. Relativni prinos koji je dobijen simulacijama je veoma blizak mjerenom prinosu, osim u slučaju sezone 2008/2009. Neto norme navodnjavanja za dobijanje optimalnog prinosa su za 49-116 mm veće u simulacijama sa CROPWAT modelom. Ukupne neto norme navodnjavanja za optimizaciju prinosa se kreću od 84-300 mm u zavisnosti od godine i moela. Efikasnost korišćenja vode od strane biljke iznosi od 0.82 do 1.28 kg/m^3. Dobijeni rezultati pokazuju oba modela kao efikasne alate za simulaciju vodnog bilansa u proizvodnji ozime pšenice i ukazuju na povećavnje prinosa primenom navodnjavanja.

Ključne riječi: Ozima pšenica, CROPWAT, ISAREG, vodni bilans, efiskansnost korišćenja vode, neto norme navodnjavanja