SIMULATING THE EFFECTS OF EXTREME DRY AND WET YEARS ON THE WATER USE OF FLOODING-IRRIGATED MAIZE IN A MEDITERRANEAN LANDPLANE.

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ABSTRACT

The effects of years of extreme rainfall events on maize water-use under traditional flooding irrigation in a Mediterranean landplane were estimated through a simulation assessment; combining a weather generator with an agrohydrological simulation model. Two options: “Fully Irrigation” and “Deficit Irrigation” were considered in the simulations as the extreme water-management situations. Besides, a 2-m depth shallow water table and Free Drainage were considered as the typical extreme situations that can be found at the bottom of the simulated soil layer. Thirty "Dry" (DY) and "Wet" (WY) years were randomly selected from the weather generator output. The model SWAP was used to simulate the Relative Transpiration (RT), i.e. ratio between actual and maximum maize transpiration, Actual Maize Evapotranspiration (ET_C), Percolated Water and Capillary Rising during wet and dry years and for each of the irrigation and bottom condition options. According to the modelling results, average mean RT is about 80% and 90% in dry and wet years, respectively. RT and ET_C variability are very high under dry conditions although such variability is notably reduced if a suitable irrigation option is considered. Capillary rising can play a very important role during dry years in those places where irrigation is not enough, but water table is relatively shallower. On the other hand, a shallower water table can carry out RT reductions during wet years, due to water excess, although these negative effects are comparatively lower than those produced by rain scarcity. Besides, percolated water during wet years is very high, particularly in well irrigated farms.

Keywords: flooding irrigation, climate variability, maize water-use, mechanistic modelling, weather generator

INTRODUCTION

Irrigation is needed to achieve reliable maize yields at the landplanes of Spain and other Mediterranean countries. Flooding irrigation has been traditionally conducted and it is still the most common irrigation method in the Mediterranean area. Due to environmental and water-constraint issues, a quite large irrigation modernisation is being conducted in Spain (Beceiro, 2003), aimed to replace flooding by sprinkler and other more-efficient techniques with governmental aids. However, it usually implies large investments and farmers need to be convinced that modernisation is worthy enough. Maize water-management in Spanish landplanes has been established by farmers through the historical experience (Farre, 1998). Flooding irrigation management depends on water-availability in some specific days, as well as on ancient "water rights" that are very inefficient under variable climate conditions (Neira et al., 2005).

However, global climate seems to be changing (IPCC, 2001). Olensen and Bindi (2002) predicted reduced cereal productivity in the Mediterranean countries, due to water-availability constraints in a future warmer and drier climate. On the other hand, climate variability and the frequency of extreme event could be incremented in the near future as a consequence of climate change (IPCC, 2001). Weather variability has been estimated as the most important climate-change risk in agriculture (Katz and Brown, 1992; Mearns et al., 1996; Riha et al., 1996; Rosenzweig et al., 2002).

Traditional flooding-irrigation management might be probably not enough to fulfil the crop-water requirements in the near future, particularly if droughts become more frequent. Besides, not only droughts but also heavy rainfalls might affect cropping systems. Rosenzweig et al. (2002) draw attention over the possible water-excess effects on crop yields, as result of extreme rainfall events associated to climate change. Modelling assessments could help to estimate how inefficient flooding irrigation could be under variable weather conditions, as well as to support the decision of where and how to invest in irrigation, taking in account climate variability. These assessments can be done combining climate scenarios and crop-growth simulation models (Sivakumar, 2000; Hoogenboom, 2000).

Several long-term assessments of global-change effects on Mediterranean agriculture appeared in the last years (Guereña et al., 2000; Wolf and Oijen, 2003; Villalobos and Fereres, 2004; Chartzoulakis and Psarras, 2005). Most of these predictive assessments considered the positive effects of the future atmospheric CO_2 rising (IPCC, 2001). Nevertheless, recent results point out that these CO_2-due positive effects have been overestimated in modelling approaches (Craft-Brandner & Salvucci, 2004; Aisnworth & Long., 2005), which reduces the reliability of such long-term assessment results for practical decisions concerning irrigation and other crop-management issues.

However, the same modelling tools can be used to estimate the effects of climate variability at a more short term. Agricultural impacts of climate variability rather than long-term climate change impacts have received more attention in the last years (Sivakumar, 2005).

The weather generators have been used in many of the assessments regarding climate effects on agriculture, as well as several other downscaling tools (Hoogenboom, 2000; Wilby and Wigley, 2001). A weather generator produces synthetic daily time series of climatic variables that can be used as input in crop models (Hoogenboom, 2000; Semenov and Jamieson, 2001). The weather generator usually mimics correctly the mean values of the climatic variables but underestimates their variability (Gregory et al., 1993; Mearns et al., 1996; Mavromatis and Jones, 1998; Semenov and Jamieson, 2001; Mavromatis and Hansen, 2001; Wilby and Wigley, 2001).

On the other hand, despite many crop-growth simulation models are currently available, only mechanistic models, i.e. those based on the physical laws of the soil-water-plant-atmosphere continuum, are able to account on all the possible weather, soil and crop management that can be found (Hoogenboom, 2000). According to Eatherall (1997), mechanistic models should be used for assessing climate variability impacts on crop yields, rather than non-mechanistic or statistically based models. Particularly, those models that simulate soil-water movement solving the Richards equation, produce better results than the model based on the "cascade approach" (Ritchie, 1998) since they are able to simulate capillary rising, fast and slow drainage and other processes that occur in nature (Gabrielle et al., 1995; Maraux et al., 1998; Mastrorilli et al., 2003).

Accordingly, this paper is aimed to assess the reliability of maize flooding-irrigation management under the extreme drought and heavy rainfall conditions. The assessment is based on extreme-weather scenarios obtained from a weather generator, used as input of a mechanistic water-use simulation model.

MATERIALS AND METHODS.

General experimental features

The simulations were conducted at Zaragoza (41º 43' N, 0º 48' W, 225 m altitude), which is located in the Ebro Valley, Northern Spain. The climate in the experimental site is Mediterranean semiarid, with mean annual maximum and minimum daily air temperatures of 21 and 8 ºC, precipitation of 353 mm, air relative humidity of 74% and average wind speed at 2m height of 2.4 m/s (Faci et al., 1994).

The soil is Typic Xerofluvent. Cavero et al. (2000) reported some physical and chemical soil properties of the experimental area which comprises texture, soil bulk density and organic matter content.

Although the sprinkler irrigated area has increased dramatically in the last 20 years (ANPC, 2003), flooding irrigation is the most common water-supply technique in the maize growing in the zone. The irrigation timing and water depths in such Mediterranean flooding-irrigation systems are quite variable (Neira et al., 2005). Farre (1998) evaluated ten flooding irrigation managements at different maize stages. A "Full Irrigated" (FI) option comprised nine irrigations with an average water depth of 65 mm at each 15 days. On the opposite, a "Deficit Irrigation" (DI) option comprised only 3 irrigation events with the same average depths. The Farre (1998) results were highly dependant on the yearly weather behaviour. However, significant differences between the "Fully Irrigated" and the "Deficit Irrigated" options were found at all the experimental years. Despite the variability in irrigation managements across the Mediterranean flooding-irrigation systems, most of them fall between these FI and DI options (Neira et al., 2005). Consequently, these two irrigation managements were chosen as the extreme representative alternatives to be evaluated under drought and heavy rainfall conditions.

The generated weather scenarios

A daily climate series of maximum and minimum temperatures, global soil radiation and precipitation were available from 1971 to 2002 at the experimental site. Since maize crop season is comprised between May and October (Farre, 1998), only accumulated rain during these months was considered as "effective precipitation" (EP). Table I shows the statistics of the local precipitation series considering both, the yearly accumulated and the effective precipitation. Table I shows also the 10th and 9th percentiles of both precipitation distributions, since rainfalls under or above these percentiles can be considered as extreme events (IPCC, 2001). Effective Precipitation is almost half the mean total yearly precipitation. However, it is more variable than considering the whole year. Besides, the absolute minimum EP and particularly the 10th percentile are considerably lower than the corresponding values considering the whole year. It means that droughts are more probable during the maize crop season, in the summer months, than during the winter.

Despite of two particular wet or dry years can show similar total rainfall, precipitation distribution within the year can yield to very different agricultural consequences. Therefore, the number of rainy days i.e. recorded rainfall higher than 0.1 mm, was considered in the analysis. Besides, the number of events with daily rainfall above the 90th percentile was used as another index of extreme precipitation conditions. This index was considered by Sanchez et al. (2004) while simulating future climate events in the Mediterranean area. The 90th percentile of the recorded rainfall data is 14.0.

The LARS-WG weather generator (Semenov and Barrow, 2002) was used in present study. LARS-WG is one of the two more frequently reported weather generators (Wilby and Wigley, 2001). LARS-WG results were as accurate as those obtained with WGEN and other weather generators (Mavromatis and Jones, 1998; Semenov et al., 1998; Mavromatis and Hansen, 2001). The available local series was used to obtain five hundred realizations of daily values of precipitation, temperatures and global radiation from LARS-WG.

Thirty droughts (DY) and severe rainfall (WY) years were randomly selected from the 500 realizations obtained from LARS-WG. Dry years were considered as those when EP was lower than the corresponding 10th percentile; whereas severe rainfall years were those when EP was higher than the 90th percentile. According to Hansen et al. (2005), constraining the weather generator outputs is a better approach than adjusting the generator input parameters in order to produce reliable weather data.

The mechanistic water-use simulation model.

The Maize water-use at each DY and WY was simulated through the physically-based model SWAP (Van Dam et al. 1997). SWAP is a functional combination of advanced soil water simulation models and a crop-growth simulation model. The Richards equation for soil-water movement is solved in SWAP by a numerical scheme, including several practical options for the initial and boundary conditions, as well as a “sink” term according to the Feddes et al. (1978) root-water uptake function. This function depends on soil water pressure head, h, and the maximum extraction rate, S_{max}.

$$S(h)=\alpha(h)\cdot S_{\max} \qquad [1.]$$

where α (h) is a coefficient which takes values from zero to one, according to the soil water potential.

Maximum uptake, S_{max}, is calculated for a homogeneously distributed rooted zone, according to:

$$S_{\max} = \frac{T_{pot}}{z_r} \qquad [2.]$$

where T_{pot} is the maximum possible transpiration rate and z_r is the rooting depth.

The Feddes et al. (1978) function has the advantage that accounts not only for the crop transpiration reductions due to lower soil-water contents, but also for the reductions related to soil-water excess conditions. Utset et al. (2000) reported values of the α (h) coefficient in the Feddes et al. (1978) function lower than one, immediately after heavy rainfalls and directly related to near-zero soil water potentials.

The soil hydraulic properties, as required in SWAP inputs, were estimated from the pedotransfer functions proposed by Rawls et al. (1982) and Rawls et al. (1998). Physical soil data needed for these estimations, i.e. mechanical composition, soil density, and soil organic matter content, were obtained from published data (Farré, 1998; Cavero et al., 2000). Table II shows the soil physical measured data and the corresponding estimated soil hydraulic properties at each soil layer. According to Cavero et al., 2000, the soil at the study site can be considered as well drained and representative of all the soils in the zone. Furthermore, the estimated Van Genuchten' coefficients also correspond to a well-drained loam soil (Carsel and Parrish, 1988).

The measured field capacity soil-water contents (Farré, 1998) were considered as the initial conditions for SWAP simulations. The maize crop function included in SWAP (Van Dam et al., 1997) was used for the crop water-uptake calculations. Maize seeding and harvest dates were assumed as May 15 and October 15, respectively, which agree with the traditional crop management in the zone (Farre, 1998). A 1-m soil depth was considered to simulate the soil-water balance, because it corresponds to the observed maximum maize root-length (Farre, 1998).

Since traditional maize cropping-areas are usually located nearby rivers and channels, a relatively shallower water-table could be expected. However, water-table depth is quite variable and it can be found between 1 and 30 m (ANPC, 2003). Therefore, two different bottom boundary conditions were considered: (i) A 2 m depth water-table, representative of the shallower extreme case and (ii) Free drainage at the bottom of the 1m-depth soil layer considered for simulations.

The Priestley and Taylor (1972) reference-evapotranspiration method, as well as the maize coefficients provided by Doorenbos and Pruitt (1977) were used for calculating the maize daily evapotranspiration, assumed as the top boundary condition in Richards-equation parameterization. Martínez-Cob (2002) pointed out that the Priestley and Taylor (1972) reference-evapotranspiration calculations under the semi-arid and windy Mediterranean-planes conditions, could be significantly lower than those obtained through the physically-based Penman-Monteith approach, presently considered as the state-of-the art in such calculations (Allen et al., 1998; Smith, 2000). However, if the Priestly and Taylor (1972) calculated evapotranspirations are used as SWAP input, the model yields statistically equivalent results than those obtained considering the evapotranspirations calculated by the Penman-Monteith approach (Utset et al., 2004).

SWAP simulations were conducted at each of the thirty dry and wet years, considering each of the two extreme irrigation-management options described above, FI and DI, as well as each of the two different bottom boundary conditions, corresponding to shallower or deeper water-tables. Simulation results comprised maximum and actual maize transpiration, maximum and actual soil evaporation, runoff, capillary rising and percolated water. Effective precipitation and Total Water Supply (TWS), i.e. effective precipitation plus irrigation, were estimated at each case. Maximum and actual maize evapotranspiration were calculated from the simulated results, as well as the Relative transpiration (RT), i.e. the ratio between actual and maximum transpiration. Relative Transpiration is directly related to crop yields and to the fulfilment measure of crop-water requirements (Smith, 1992). Therefore, RT was assumed as an irrigation-efficiency index in our assessment.

RESULTS AND DISCUSSION

Figure 1 depicts the effective precipitation during the dry and wet years. The corresponding 10th and 90th percentiles are drawn in the figure as broken lines. Besides, Table I shows the EP summary statistics during DY and WY. Despite standard deviations in WY is higher than that found in DY, the corresponding coefficient of variation is considerably low. LARS-WG and other weather generators usually underestimate the inter-annual variability (Wilby and Wigley, 2001). However, the results shown in Table I clearly indicate that rainfall variability during dry years is higher than during wet years.

The number of rainy days in dry years (NRDY) is much lower than in extreme wet years, as expected. Variability in number of rainy days is also higher during dry years. Furthermore, the average number of heavy rainfall days during the simulated extremely wet years is 9.8, four times greater than the corresponding average number in dry years.

Considering both extremely wet and dry years in the statistical analysis, the RT mean is still relatively good. However, the RT absolute minimum in both cases is quite unacceptable, indicating that simulation results comprise also significant yield-losses years. The RT median is higher than mean and the RT distribution shows a negative skewness in both cases. Hence lower RT values are less probable, particularly in wet years. A relatively high coefficient of variation was found, pointing out that extreme wet and dry years will carry mainly an important yield variation. The CV of Relative transpiration is much higher during dry years.

The RT mean in dry years is lesser than that obtained considering extremely wet years. Particularly, RT kurtosis coefficient in dry years is quite different than the corresponding coefficient in wet years, indicating that RT distribution significantly departs from normality as compared to RT distribution in wet years.

The simulated maize actual evapotranspiration follows the same behaviour than RT during dry and wet years. Maximum evapotranspiration (ET_0) also follows the same behaviour, although differences between dry and wet years are much lower than in the RT case.

Figure 2 depicts the Box and Whisker plots of the Relative Transpiration, as grouped according to the weather (extremely wet or dry years), irrigation management (deficit or full irrigated option) and conditions at the bottom of the 1-m depth simulated soil layer, i.e. free drainage (FD) or shallower water-table at 2-m depth (2m). Dry years yield to smaller RT means and higher standard deviations. Full irrigation option and a relatively shallow water table give raise also to higher RT. Particularly, these factors are associated to very low RT variability, which is quite small in the FI option.

The RT mean is particularly low if a deficit irrigation management is chosen during a dry year in a field where free drainage can be assumed as the most probable condition at the bottom of the 1-m depth simulated soil layer. RT mean is also lower during wet years, keeping the same irrigation management and bottom conditions.

Actual evapotranspiration follows similar behaviour than RT during dry and wet years regarding bottom condition and irrigation management. Mean Percolated Water is null during dry years, in a maize field with shallower water table and irrigated with the DI option. On the other hand, average percolated water is very high during wet years, particularly in the FI case: 314.8 mm if a shallower water table is considered and 296.6 mm if free drainage at the bottom of the simulated soil layer is assumed. The simulated average Capillary Rising is different from zero only in fields where water table is shallow and irrigation is clearly short. The CR average is 53.9 mm in wet years and it reaches 220.4 mm in dry years.

According to a performed Duncan test, almost all the evaluated factors affect the simulated maize actual evapotranspiration. The presence of a shallow water table has no influence in the studied variables during dry years if full irrigation is considered. However, the bottom condition option significantly affects the Relative Transpiration, Capillary Rising and Maize Evapotranspiration in the case of deficit irrigation during dry years. Besides, the bottom conditions yield to significant differences in all the considered variables during wet years in the deficit irrigation option. Furthermore, Relative transpirations remain similar in both irrigation options and weather behaviours if a shallow water table is found, despite that maize evapotranspirations are significantly different. These results indicate that capillary rising and water-table depth can play a very important role under extreme weather conditions, although they are largely ignored and infrequently measured. Percolated Water depends only on irrigation option during dry years. However, it is significantly higher in wet years if water table at the bottom of the maize root zone is not very deep.

Figure 3 depicts the simulated RT during dry years as a function of TWS, considering a water table at a 2-m depth. The line shows the obtained regression. As can be seen in the figure, higher TWS give raise to a reduction in RT rather than to further increments. These negative effects of extreme precipitation values were already noticed (Rosenzweig et al., 2002) but not yet simulated. Since the Feddes et al. (1978) root water-uptake function is able to account on water-excess effects on crop water use, our simulation approach can estimate the extreme rainfall effect also, whereas other models are unable to evaluate that consequence. Simulations indicate that precipitation excess could bring a negative effect in flooded irrigated maize, if relatively shallow water tables are found. However, this effect is lower in the well-drained soils of the zone, compared to the yield reductions associated to dry conditions or an incorrect irrigation management.

CONCLUSIONS

Extremely dry years yield to an average reduction of maize relative transpiration and hence to the flooding-irrigation efficiency, although average values are still satisfactory. The flooding irrigation efficiency during these extreme dry years seems to be quite variable. Nevertheless, reliable results can be achieved in most of the cases if suitable irrigation management options are considered. Wet years would carry an important amount of percolated water. Besides, relative transpiration and therefore irrigation efficiency is lower during extremely rainy years if a shallow water table is found. This negative effect, however, is comparatively lower than the relative transpiration reduction associated to rainfall scarcity, which can be due to the well soil drainage conditions. Water capillary rising from relatively shallower water-tables can partially supply the maize water-requirements under dry years, even in the case of irrigation-water shortage.

The obtained results could considerably change according to soil conditions, because physically-based agrohydrological models as SWAP are highly dependant on the soil hydraulic properties. However, similar outcomes could be achieved for other well drained soils of the zone.

The use of weather generators, to provide the weather scenarios, combined with an agrohydrological model, to simulate all the components of the water balance; seems to be a practical approach to support agricultural decision-making under variable weather conditions. Furthermore, the Feddes et al. (1978) function for root water-uptake, as considered in SWAP, could help to estimate the effects of water excess in crop growth, particularly in the case of heavy rains.

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Table I. Mean, standard deviation (SD), Coefficients of Variation (CV), maximum (Max) and minimum (Min) values and the 10th and 90th percentiles of the recorded yearly accumulated precipitation and effective precipitation (EP), during the maize crop season from May to October, as well as the generated EP for dry (EPDY) and wet (EPWY) years and the corresponding numbers of heavy rain days (NRDY), (NRWY).

	Mean	SD	CV	Max	Min	10th P	90th P
Year	324.6	78.9	24.3	466.7	184.1	246.2	445.8
EP	155.2	58.9	38.0	263.0	47.3	85.2	249.7
EPDY	58.6	15.6	26.7	74.8	26.1	-	-
EPWY	270.0	24.8	9.2	329.9	249.9	-	-
NRDY	47.6	8.8	18.4	69.0	34.0	-	-
NRWY	67.8	10.8	16.0	88.0	46.0	-	-

Table II. Soil properties at each measured layer: pH, Carbon (C), Nitrogen (N) and $CaCO_3$ contents; soil mechanical composition, soil density (D), Field capacity (FC); wilting point (WP); as well the coefficients of the Van Genuchten´s model[*], i.e. residual (θ_{res}) and saturated (θ_{sat}) water contents, and alpha (α) and n parameters as well as the saturated hydraulic conductivity (Ks).

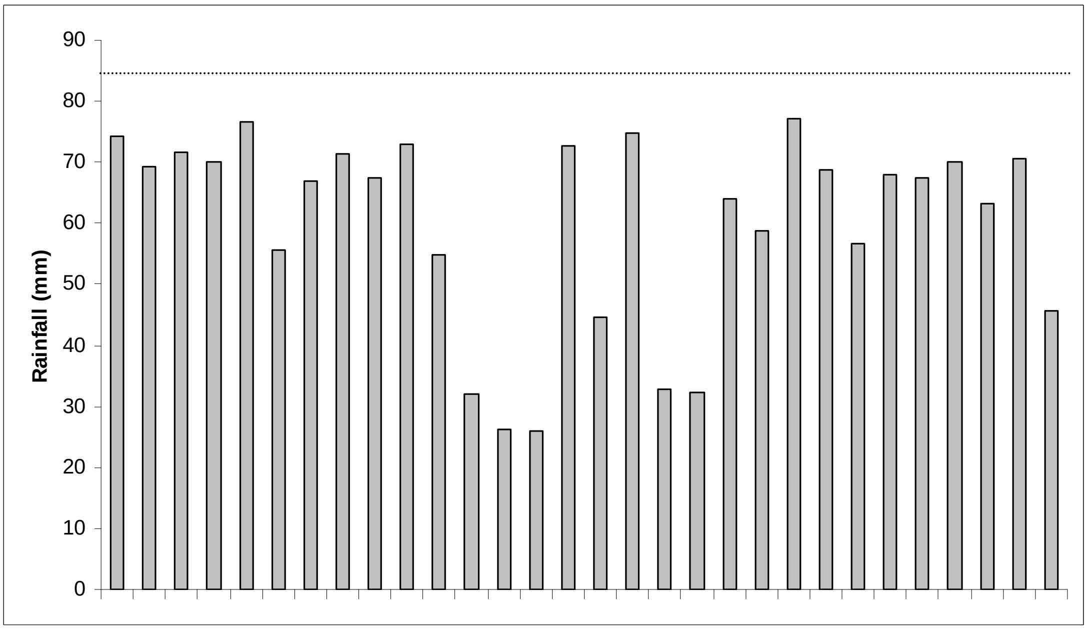
Layer Depth	(cm)	0-30	30-60	60-90	90-150
pH		8.3	8.3	8.4	8.5
C	(%)	0.95	0.49	0.43	0.45
N	(%)	0.102	0.052	0.045	0.047
$CaCO_3$	(%)	36.5	37.1	37.8	37.3
Sand	(%)	43.3	62.3	57	51.8
Silt	(%)	40.1	26.4	30.6	34.6
Clay	(%)	16.6	11.3	12.4	13.6
D	(Mg m^{-3})	1.32	1.38	1.38	1.41
FC	(m^3 m^{-3})	0.267	0.275	0.271	0.283
WP	(m^3 m^{-3})	0.103	0.091	0.08	0.078
θ_{res}	(m^3 m^{-3})	0.17	0.14	0.15	0.16
θ_{sat}	(m^3 m^{-3})	0.76	0.84	0.85	0.80
α	cm^{-1}	0.3284	0.3525	0.4911	0.4286
n		1 264	1 396	1 341	1 317
Ks	(cm/day)	25.61	79.51	58.64	34.62

[*] the Van Genuchten' coefficients and the hydraulic conductivity were estimated from pedotransfer function, using the measured soil physical data.

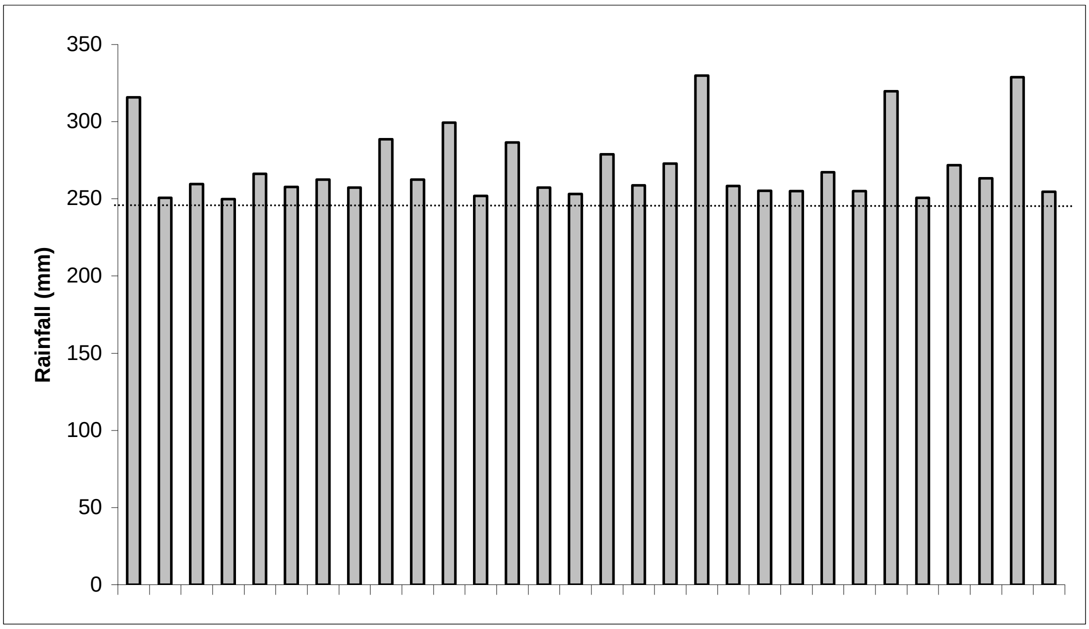
Table III. Means, standard deviations (std), coefficients of variation (CV), medians, maximum (max) and minimum (min) values, as well as the skewness and kurtosis coefficients of the Relative Transpiration (RT), actual (ET_C) and maximum (ET_0) maize Evapotranspiration, Percolated Water (PW), Capillary Rising (CR) and Total Water Supply (TWS) considering all data, as well as dry and wet years, separately.

A. All data analysis.

		RT	ET_C	PW	CR	TWS
Dry years	mean	0.795	564.7	58.7	55.1	570.2
	std	0.314	123.9	62.3	99.8	204.8
	CV	39.5	21.9	106.2	181.1	35.9
	median	0.967	614.8	42.8	0.0	599.0
	max	0.995	709.6	296.7	293.2	896.5
	min	0.121	291.6	0.0	0.0	301.4
	skewness	-1.282	-1.061	0.840	1.334	0.014
	kurtosis	-0.234	-0.375	0.377	-0.082	-1.764
Wet years	mean	0.900	643.9	163.8	13.5	810.6
	std	0.140	68.9	149.8	32.3	210.6
	CV	15.5	10.7	91.4	239.8	26.0
	median	0.967	652.0	163.2	0.0	782.5
	max	0.992	763.3	418.0	166.1	1114.8
	min	0.266	397.8	0.0	0.0	450.2
	skewness	-2.165	-0.964	0.144	2.761	-0.010
	kurtosis	4.749	1.607	-1.767	7.507	-1.583

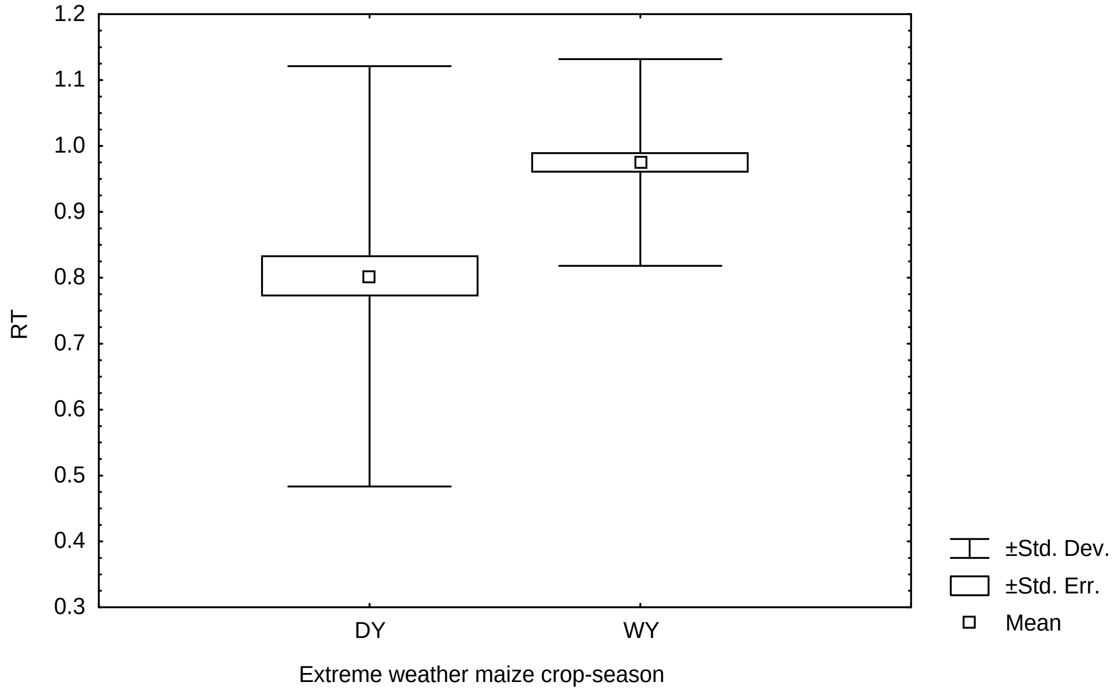


A. Extremely dry years (DY).

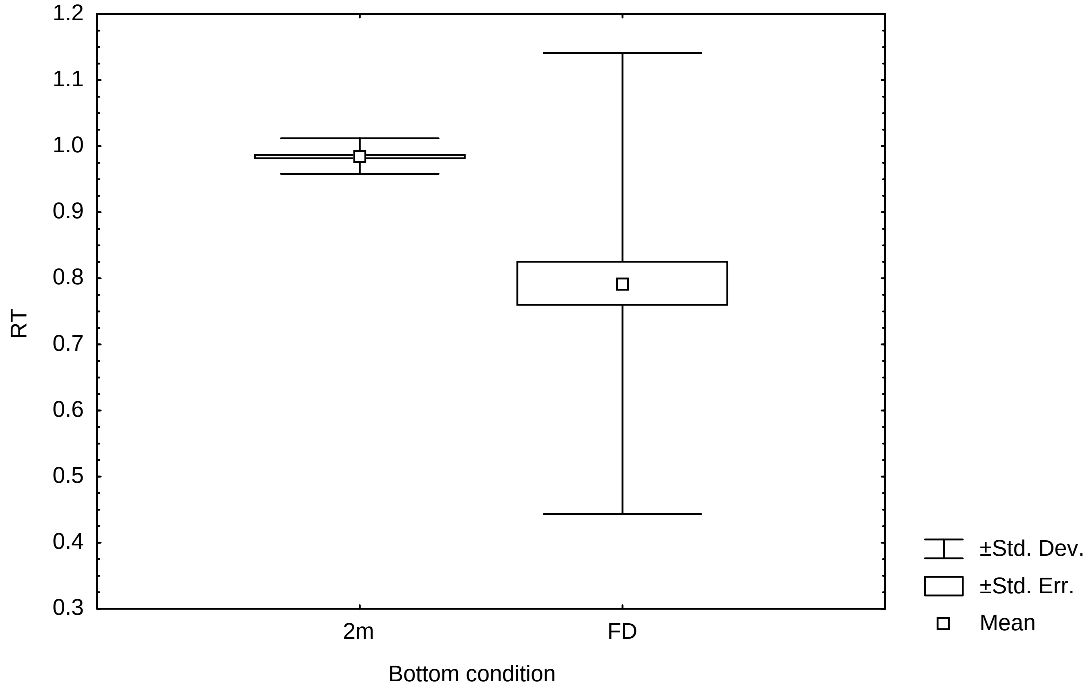


B. Extremely wet years (WY).

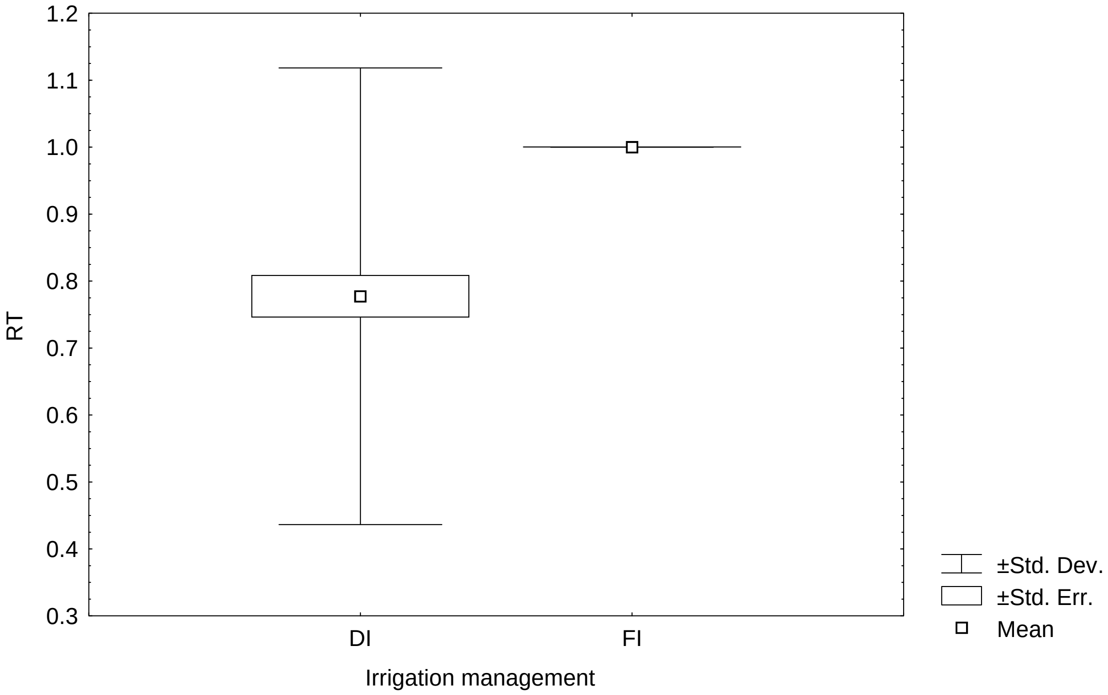
Fig. 1. Thirty realizations of Effective Precipitation (EP) from May to October during dry (DY) and wet (WY) years as obtained from the LARS-WG generator. The broken lines depict the 10% (Fig. 1A) and 90% (Fig. 1B) percentiles.



A. Analysis respecting wet or dry years



B. Analysis respecting soil-water movement condition at the bottom of the 1-m depth soil layer.



C. Analysis respecting irrigation management..

Fig. 2. Box and Wilcox graphs of simulated Relative Transpirations, according to weather behaviour during dry (DY) and wet (WY) years, the condition at the bottom of the 1-m soil layer considered for simulations, as well as the water management option i.e. deficit of full irrigation.

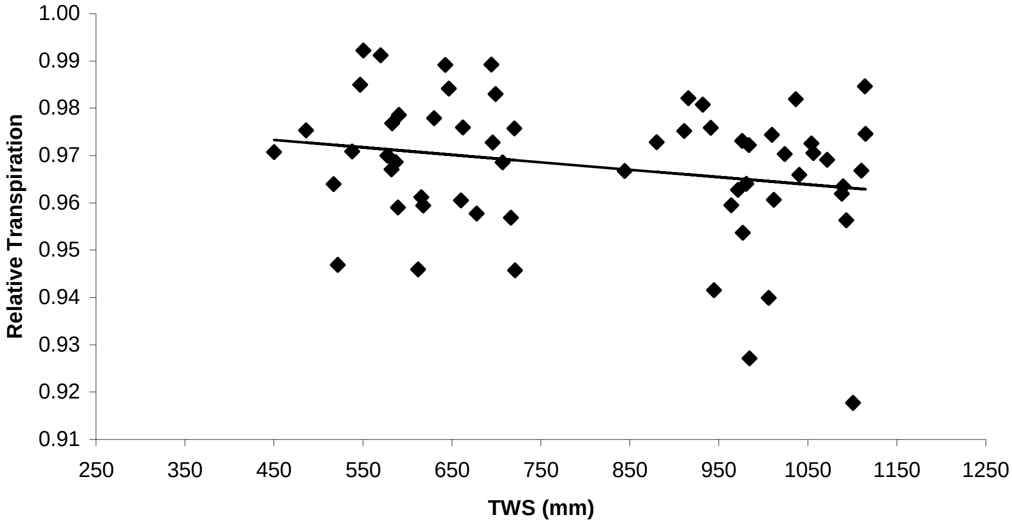


Fig. 3. Relative transpirations as a function of Total Water Supply in dry years, considering a shallower water-table at 2-m depth.