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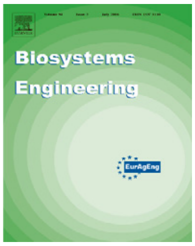

Research Paper: SW—Soil and Water

Irrigation scheduling for furrow-irrigated maize under climate uncertainties in the Thrace plain, Bulgaria

Zornitsa Popova[a], *Luis S. Pereira*[b,*]

[a]*N. Poushkarov Institute of Soil Science, 7, Shosse Bankya Str., Sofia 1080, Bulgaria*
[b]*Agricultural Engineering Research Center, Institute of Agronomy, Technical University of Lisbon, Tapada da Ajuda, 1349-017 Lisboa, Portugal*

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Climate change creates uncertainties for irrigation management. To cope with them, simulations were performed for the present and scenario-built weather conditions that include a pessimistic scenario of precipitation decrease in the next 25 years. In a former study, the irrigation scheduling simulation model ISAREG was calibrated for two maize varieties: the water stress-resistant hybrid *Kn-2L-611* and the water stress-sensitive hybrid *H708*. Both are subjects of this study, which compares four irrigation scheduling alternatives: (1) refilling the soil reservoir and adopting a management-allowed depletion fraction (MAD) of 0.47; (2) refilling the soil reservoir and adopting MAD = 0.33; (3) partially refilling the soil reservoir and adopting MAD = 0.47; and (4) crop without irrigation. For the very dry year and the present climate all alternative irrigation schedules behave similarly but for the average year, alternatives 1 and 3, allowing a larger soil water depletion with MAD = 0.47, require less water than the alternative with MAD = 0.33. However, analysis of impact on yields using simulations relative to every year during 1970–1992 shows that alternative 2 leads to less impact on yields. The results of simulations were compared with irrigation schedules presently advised in the region and show that the latter do not fully cover crop requirements in dry seasons, when some yield decrease occurs. Simulations for the pessimistic scenario show that all three irrigation scheduling alternatives can easily accommodate the foreseen changes mainly by selecting suitable irrigation dates. The results of simulations do not allow selecting one among the three alternatives as the best irrigation scheduling strategy but are useful for later building an information system for farmers using actual weather data. Relative to the rainfed crop, the results indicate that yield impacts highly increase for the pessimistic scenario, particularly for the water stress-sensitive hybrid *H708*. The results indicate that vulnerability to climate change is higher for non-irrigated crops and that coping with possible rainfall decreases requires adopting less sensitive crop varieties, including when deficit irrigation would be applied for water saving.

1. Introduction

The development of technologies for reduced irrigation demand and water saving is important for the sustainability of water use in agriculture, namely considering climate uncertainties. Well-calibrated water balance models are practical, precise and efficient tools to compute irrigation requirements and estimate their probabilities, to support

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*Corresponding author. Tel.: +351 213653339; fax: +351 213621575.
E-mail addresses: zornitsa@techno-link.com, zornitsa_popova@yahoo.com (Z. Popova), lspereira@isa.utl.pt (L.S. Pereira).

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Nomenclature

ASW	available soil water, mm
D	application depths, mm
ET_a	actual crop evapotranspiration, mm
ET_c	potential crop evapotranspiration, mm
ET_o	reference evapotranspiration, mm
K_c	crop coefficient, dimensionless
K_y	yield response factor, dimensionless
MAD	management allowed depletion, dimensionless
NIR	net irrigation requirement, mm
p	depletion fraction for no stress, dimensionless
P_I	probability of exceedance, %
TAW	total available water, mm

irrigation management practices and to evaluate water stress impacts on yields. Such models are then useful for scenario analyses aiming at optimal water saving and environmentally oriented irrigation practices for efficient water use in agriculture (Pereira et al., 1995; Sepaskhah & Akbari, 2005; Cancela et al., 2006).

Various studies have been carried out in Bulgaria to develop improved irrigation scheduling considering impacts on yields and water-saving issues (Varlev et al., 1994, 1996; Varlev & Popova, 1999; Popova & Kercheva, 2004). Long-term experiments were conducted in Thrace with the objective of recognising the water relations of maize under deficit and full irrigation, as well as rainfed conditions (Eneva, 1993, 1997). These data was later analysed with the water balance simulation model ISAREG, which was then calibrated and validated for two maize hybrids cropped in vertisols of the Thrace plain (Popova et al., 2006a). The calibration consisted in deriving crop coefficients (K_c), the ratio between crop and reference evapotranspiration, depletion fractions for no stress (p), i.e. the soil water fraction that may be extracted by the crop without causing water stress, and yield response factors (K_y), which relate relative yield decreases due to water management with the relative evapotranspiration deficits (Allen et al., 1998). The validation proved that the ISAREG model and the calibrated parameters could be further used to generate and select irrigation scheduling alternatives for maize in the study area.

Aimed at improved water use and saving, as well as controlling environmental impacts of irrigation, various studies were developed at Pustren experimental station, in Thrace region, to develop improved furrow irrigation practices applied to vertisol cracking soils cropped with maize (Popova et al., 1994, 1998; Popova & Kuncheva, 1996; Varlev et al., 1998). Field research was developed with furrows with a length of 300 m, with a uniform slope of 1% and furrow distances of 0.7 m. Inflow rates ranged from 1.02 to 1.10 l s^{-1}. Irrigations were performed for various soil moisture conditions, generally between 0.33 and 0.42 cm^3 cm^{-3}. It was observed that high deep percolation occurred for low soil moisture at the time of irrigation due to preferential flow when cracks are formed; in contrast, percolation was controlled when irrigating at higher soil moisture before soil cracking. These studies led to the development and validation of a furrow irrigation model that was used to define the best soil water content at the time of irrigation that could avoid soil cracking and the application depths that could both complete the furrow advance and control percolation. Conditions are therefore created to explore the ISAREG irrigation scheduling model for furrow-irrigated maize in Thrace vertisols, with alternatives built in agreement with the constraints imposed by the irrigation method.

The objectives of this study are to assess the impacts of several irrigation scheduling alternatives for two maize hybrids that were subjects of a former study (Popova et al., 2006a), and to predict the impact of climate uncertainties on irrigation requirements and scheduling and maize yields in a vertisol soil of the Thrace plain by application of the validated ISAREG model to a 36-year data series (1970–2005). Numerical simulation modelling and data from furrow irrigation experiments are used to define the irrigation scheduling strategies aimed at improved water use and water-saving practices in the region. Climate uncertainties were simulated by considering two precipitation scenarios for the period 2005–2030, which were built from precipitation data relative to 1970–2005 referring to the maize irrigation season (July and August).

2. Materials and methods

2.1. *The study area*

The paper reports the results of a study carried out with maize in the representative Pustren experimental site (42°16′ latitude, 25°39′ longitude and 167 m altitude), which is located near Stara Zagora, in the Thrace plain, which is one of the driest agricultural areas in Bulgaria.

Its climate is typical for the East-Central Bulgaria. Rainfall is higher in spring and lower in July and August, when the average monthly precipitation is 48 and 45 mm, respectively. The variability of precipitation is large, as shown in Fig. 1 where precipitation is plotted for the maize crop season. The reference evapotranspiration ET_o follows a regular seasonal trend with maxima in July and August, averaging 4.7 and 4.5 mm day^{-1}, respectively, when the average monthly precipitation is lower. In contrast to rainfall, ET_o variability is relatively small in those months, when the 80% confidence interval of the mean is 0.4 and 0.7 mm day^{-1}, respectively, for July and August.

The soil is a vertisol with one of the highest total available water (TAW) in Bulgaria (175 mm m^{-1}). It is mainly constituted of clay, which is about 54–58% in the top layers (0–50 cm) and nearly 65% in the lower horizons (50–130 cm). The content of coarse sand is only 11% and 6%, respectively. The soil hydraulic parameters used in this study are given in Table 1.

The maize crop considered for this study was parameterised as described by Popova et al. (2006a). The main characteristics relative to crop growth stages are given in Table 2. The maximum root depth considered was 1.10 m. The two maize varieties used have different sensitivity to water stress as indicated by the respective yield response factors, $K_y = 1.0$ for the water stress-resistant hybrid *Kn-2L-611*, and

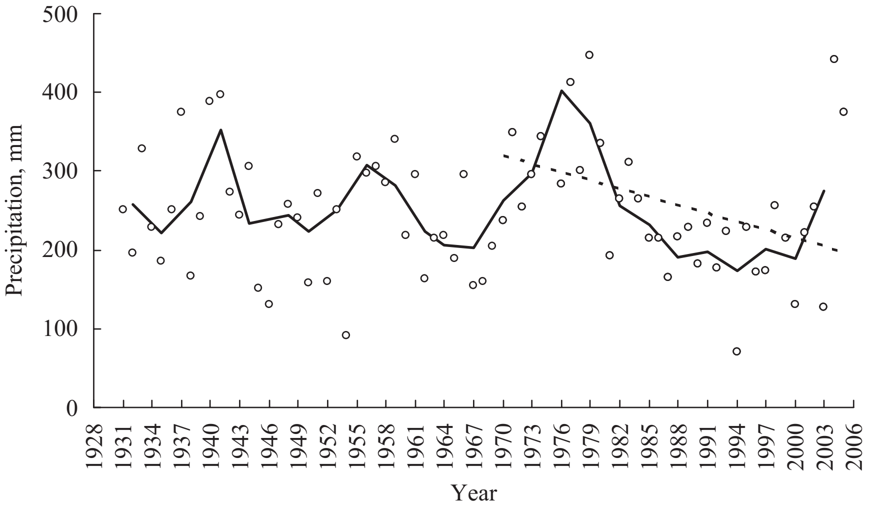

Fig. 1 – Seasonal precipitation at Pustren (○) during the maize cropping season (May to September) for the period 1929–2005, respective 3-year average (▬▬) and an approximate trend line (- - - -) relative to the period 1970–2005.

Table 1 – Main soil hydraulic properties of a Vertisol at Pustren experimental site

Horizon	Depth, cm	Hydraulic conductivity at saturation, K_s, cm d^{-1}	Soil moisture (θ), cm^3 cm^{-3}	
			Field capacity	Wilting point
A1	0–26	7.9	0.42	0.25
A2	26–50	3.3	0.50	0.33
A3B1	50–80	0.8	0.51	0.34
B2C1	80–130	1.1	0.46	0.27

Table 2 – Dates of maize development stages and respective crop coefficients (K_c) and soil water depletion fractions for no stress (p) for maize at Pustren (from Popova *et al.*, 2006a)

Growth phases	Initial period	Mid-season period	End-season period
Dates	26/04 to 19/05	15/07 to 09/08	30/09 (harvest)
K_c	0.28	1.28	0.23
p	0.45–0.75	0.60	0.78

$K_y = 1.5$ for the water stress-sensitive hybrid *H708* (Popova et al., 2006a).

2.2. *Simulation model*

The ISAREG model (Teixeira & Pereira, 1992; Liu et al., 1998) is used in this study following previous calibration (Popova et al., 2006a). It is a simulation tool for computing the soil water balance, generating alternative irrigation schedules and evaluating the respective impacts on crop yields. It is based on the water balance approach adopted by Doorenbos and Pruitt (1977).

The data required to perform the soil water balance with ISAREG are: (1) weather data on precipitation and reference evapotranspiration (ET_o); (2) soil data referring to a multi-layered soil including, for each layer, the respective depth, field capacity and wilting point (data in Table 1); and (3) crop data relative to the crop development stages and corresponding dates, crop coefficients, root depths and the soil water depletion fractions for no stress (data in Table 2).

The later version of the model (Pereira et al., 2003) adopts the updated methodology to compute crop evapotranspiration and irrigation requirements proposed by Allen et al. (1998) and includes functionalities to assess the impact of salinity and parametric functions to estimate the capillary rise and percolation through the bottom boundary of the soil root zone (Liu et al., 2006). Two auxiliary programmes are used, one to compute the reference evapotranspiration (ET_o), including alternative methods when some weather variables are missing, and the other to support crop parameterisation. Yield impacts of water stress are assessed with the Stewart one-phase model when the yield response factor K_y is known (Stewart et al., 1977; Doorenbos & Kassam, 1979).

Simulation options include: (a) to schedule irrigation aiming at maximum yields; (b) to simulate an irrigation schedule using selected irrigation thresholds, including under conditions of limited water supply and constant or variable irrigation depths; (c) to evaluate an irrigation schedule when water is applied at given dates; (d) to execute the water balance without irrigation; and (e) to compute the net crop water requirements for irrigation. Options (a) and (b) were used in this study.

The ISAREG model 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 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).

For computing the soil water balance a main input variable is reference evapotranspiration (ET_o), which is commonly estimated with the FAO Penman–Monteith method proposed by Allen et al. (1998). Some of the weather variables required to calculate ET_o are often missing in the irrigation practice in Bulgaria, especially solar radiation (Davidov et al., 1998; Varlev & Popova, 1999; Kercheva & Etropolsky, 2003). To overcome this problem and estimate ET_o with missing climate data, the related methodology proposed by Allen et al. (1998) was validated using data relative to five meteorological stations in the Thrace (Popova et al., 2006b). This study has demonstrated that estimating solar radiation from maximum and minimum daily temperatures allows to estimate ET_o, with small standard errors of estimates, ranging from 0.17 to 0.22 mm day^{-1}. Daily ET_o was therefore calculated with the methodology validated by Popova et al. (2006b).

As mentioned above, the crop coefficients (K_c) and depletion fractions for no stress (p) were obtained with the ISAREG model using data collected through long-term maize experiments (Eneva, 1993, 1997; Varlev & Eneva, 1990) relative to various irrigation regimes in a vertisol soil (Popova et al., 2006a). Particular attention was paid to the derivation of yield response factors (K_y) for two maize hybrids with different responses to water stress, *Kn-2L-611*, that has $K_y = 1$, which indicates that it is highly tolerant to drought conditions, and the hybrid *H708*, that has $K_y = 1.5$ and is highly sensitive to water stress.

2.3. Scenarios for simulation of alternative irrigation schedules

The ISAREG model is applied to develop more appropriate irrigation scheduling alternatives for vertisol soil (Table 1) and to evaluate irrigation requirements and yield decrease due to water deficit for both maize hybrids *Kn-2L-611* and *H708*. Crop parameters (Table 2) are those obtained when calibrating the model (Popova et al., 2006a).

Simulations with the ISAREG model were performed adopting soil water thresholds and application depths defined from previous experiments of furrow irrigation for the same soils. Net irrigation requirements (NIRs) calculated with the model using weather data relative to 1970–1992 were used to identify the years of average and extreme irrigation demand. The alternative irrigation schedules simulated for these years are presented in this paper.

Past studies on continuous and surge-flow furrow irrigation carried out at Pustren field (Popova et al., 1994, 1998; Popova & Kuncheva, 1996; Varlev et al., 1998) have shown that the distribution uniformity is high and deep percolation might be practically avoided when the soil water content is maintained above the cracking level, which is about 80–82% of the field capacity. Results of inflow–outflow measurements under such conditions show that the average infiltrated depth in a furrow set is within the range of 80–100 mm for continuous furrow irrigation. Results for surge irrigation have shown that further improvements on the distribution uniformity could be achieved and the application depths could be reduced by 18–25%. Irrigation scheduling alternatives were based on these results and are as follows:

1. *Alternative 1*: relates to furrow irrigation with a continuous flow and consists of refilling the soil reservoir and adopting a management-allowed depletion fraction (MAD) of 0.47, thus with application depths of 90 mm. The TAW, defined from the difference between the stored soil water at field capacity and the wilting point considering 1.10 m soil root depth, is 193 mm.
2. *Alternative 2*: refers to furrow surge flow and consists of refilling the soil reservoir to TAW adopting MAD = 0.33 and application depths of 60 mm.
3. *Alternative 3*: aims at better storage and use of precipitation and irrigation water; thus, it consists of refilling up to 84% of TAW (162 mm) adopting MAD = 0.47 and application depths of 60 mm. About 30 mm of the soil reservoir are not refilled to better accommodate for any precipitation occurring after the irrigation event.
4. *Alternative 4*: crop without irrigation.

According to irrigation practice in Thrace region and previous studies (Zahariev et al., 1986), the last irrigation should not be scheduled after 15 August. This condition is considered for all irrigation scheduling alternatives in addition to a free definition of the irrigation timings.

2.4. Scenarios for climate uncertainty

Precipitation during the maize crop season shows a variability marked by “wet” and “dry” cycles of variable length as observed over the last 77 years (Fig. 1). Dry periods result in increased demand for irrigation. The period of the last 36 years (1970–2005) refers to a dry cycle although some years of high season rainfall were observed. The trend line in Fig. 1 is used to build the irrigation demand scenarios but it cannot be interpreted as a real trend in precipitation. In fact, the 3-year moving average in Fig. 1 shows that a cyclic variation with variable amplitude is occurring since 1929 to the present and not a definitive trend for precipitation decrease.

The seasonal precipitation during the maize crop season, May to September, for the period 1929–2005 (Fig. 1), shows that “dry” periods tend to be longer than “wet” ones and that the last 36 years are dryer than similar periods in the past, but the length of records is not long enough to provide for an appropriate analysis. However, trends for increased dryness in the last few years can be found from records of several climatic stations in Bulgaria (Alexandrov, 2002; Slavov & Moteva, 2002, 2006). This fact allows establishing scenarios for possible variation of precipitation, particularly relative to the July–August period, when the demand for irrigation is higher. Fig. 2 shows that for 1970–2005, which may be assumed to represent the contemporary climate in the region, there is a “trend” for precipitation decrease. This decrease is of 72 mm during the maize crop season and 54 mm in the peak irrigation period. The average year representing the contemporary climate (1970–2005) is 1980, when the precipitation sum in July and August (92 mm) equals the average value for that period.

Uncertainty in precipitation is considered through building a pessimistic and an optimistic scenario. The first builds upon the assumption that the trend of precipitation decrease in July and August would be the same as for the last 36 years (1970–2005). It is therefore built by extending for the following 25 years the same “trend” as for 1970–2005 (full line in Fig. 2). The seasonal rainfall (May–September) would then reduce by 50 mm until 2030, while during July–August the rainfall decrease is 37 mm. The optimistic scenario assumes a reversing trend for the period 2005–2030 (dashed straight line in Fig. 2), thus an increase of precipitation during July and August of 37 mm from 2006 until 2030. These scenarios do not result from predictions but are just built to assess possible consequences of climate variations on the maize irrigation demand and to check how the considered irrigation scheduling alternatives would behave if rainfall during July–August did or did not decrease, then increasing or maintaining the demand of water for irrigation.

3. Results and discussion

3.1. *Assessing the alternative irrigation schedules*

The probability curve of NIRs for maize at Pustren for the period 1970–1992 is presented in Fig. 3. NIRs range 60–100 mm in wet seasons having a probability of exceedance $P_I > 95\%$, 180–230 mm in moderate demand seasons ($40\% < P_I < 75\%$) and reaching 300–350 mm in extremely dry years ($P_I < 5\%$). The NIR is 234 mm for the average year (1980) of the contemporary climate (1970–2005) defined through the precipitation trend represented in Fig. 2.

The results of the simulations over the period 1970–1992 relative to the maize irrigation scheduling alternatives 1, 2 and 3 are shown in Fig. 3. It shows that related irrigation thresholds and depths produce demands that may be lower or higher than NIR and that are different among them. The seasonal irrigation demand relative to the alternative 2, because it refers to application depths $D = 60$ mm applied at high soil moisture (MAD = 0.33), is the highest among the

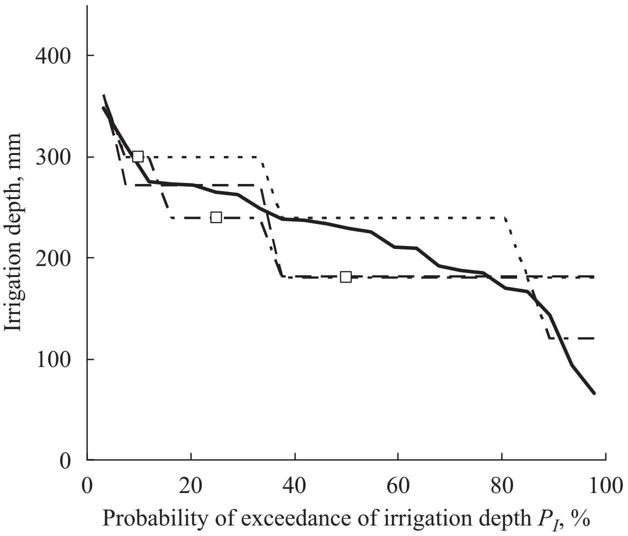

Fig. 3 – Probability curves of net irrigation requirements, NIR (▬), and net season irrigation demand, ID, for the irrigation scheduling alternatives 1 (– –), 2 (– – –) and 3 (- - -) compared to ID for currently adopted scheduling in the region (□).

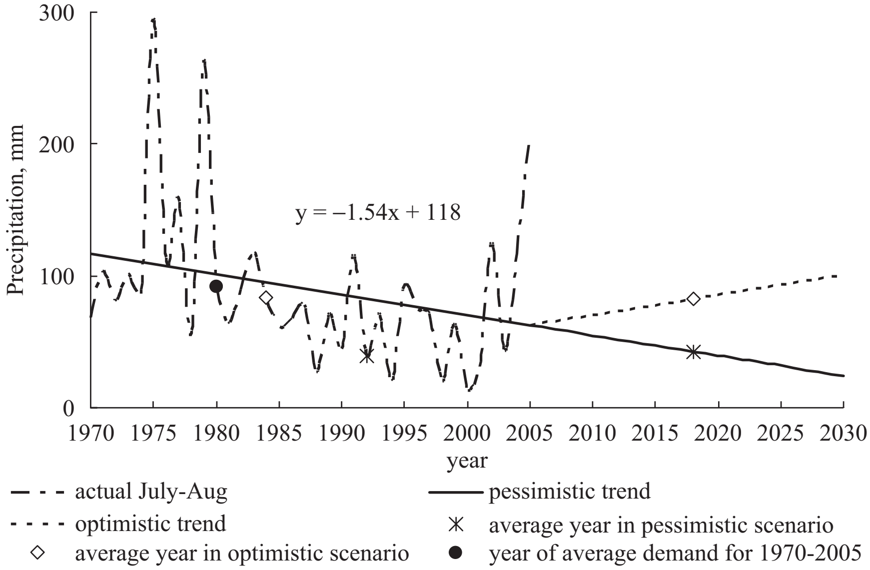

Fig. 2 – Cumulative rainfall in July and August over the last 36 years (1970–2005) and hypothetical scenarios for precipitation trends for the period 2005–2030 with identification of the average (AVG) years of the pessimistic and optimistic scenarios.

three alternatives and is often larger than NIR. Alternative 3, despite having the same $D = 60$ mm, because it is scheduled with a lower threshold (MAD = 0.47) and refills the soil reservoir to only 84% of TAW, produces the smaller seasonal irrigation demand, often smaller than NIR. In general, this alternative 3 leads to saving of about 60 mm net irrigation water when compared with alternative 2. The seasonal irrigation demand of alternative 1, which refers to MAD = 0.47 and application depths of 90 mm, is similar to that of alternative 3 in moderately wet and average crop seasons ($P_I = 40$–90%), and is between the irrigation demand values of alternatives 2 and 3 for dry crop seasons. These results show that allowing a higher soil water depletion, i.e. a larger MAD, favours water saving. However, for a vertisol, MAD is constrained by the critical soil water content to avoid soil cracking.

The results of simulations of the available soil water (ASW) for the three irrigation scheduling alternatives are presented in Fig. 4 for 1981, which was an extremely dry year ($P_I = 3\%$) in the period 1970–1992. It shows that alternative 1 requires 4 irrigation events of 90 mm each before 15/08 and alternatives 2 and 3 require 6 events of 60 mm, thus the same irrigation demand of 360 mm for all three alternatives. The full line in Fig. 4 refers to the ASW simulation when the last irrigation is applied before 15/08 and the dashed line refers to the last irrigation before 31/08. The results indicate that an irrigation event could be saved for alternatives 1 and 2 when not irrigating after 15/08. In fact, ASW is kept above the non-stress threshold until the end of the season for all three cases when the last irrigation is practiced before this date.

The results of ASW simulations of the 3 alternatives for 1980, the average demand year in the last 36 years, are shown in Fig. 5. Relative to the dry year (1981), the number of irrigation events reduces to 3, 5 and 4 for, respectively, alternatives 1, 2 and 3; the last irrigation event is for all cases anticipated relative to the corresponding dates for the dry year. Hence, the irrigation demand reduces, to 270, 300 and 240 mm, respectively. These results agree with the analysis performed earlier when comparing NIR with the irrigation demand: alternative 3 produces the smallest demand and alternative 2 the highest, exceeding the former by 60 mm. For all 3 cases, ASW remains above the non-stress threshold when the last irrigation is applied before 15/08.

A summary of results for all alternatives including the rainfed one is presented in Table 3. For all irrigation alternatives, the actual evapotranspiration (ET_a) equals the potential crop ET (ET_c); thus, no yield decrease is produced. In contrast, for the rainfed crop $ET_a < ET_c$ originating high yield decreases, particularly when the water stress-sensitive hybrid is considered. The rainfall is not fully utilised for crop growth, particularly in the average year, because it falls during the earlier stages of the crop, when the demand is low and the soil water content is high. The referred difference in water demand among the 3 alternatives in the average year is well visible through the ASW at harvesting: with alternative 3 it reduces to 50 mm while with alternative 2 a higher value of 110 mm is obtained. These results are in argument with the fact that alternative 3 allows a higher soil water depletion than alternative 2 (MAD = 0.47 vs. MAD = 0.33). Comparing alternatives 1 and 3, which have the same MAD, the higher ASW at harvesting and the corresponding higher irrigation demand for alternative 1 result from the fact that application depths for this one are larger than for the former ($D = 90$ mm vs. $D = 60$ mm).

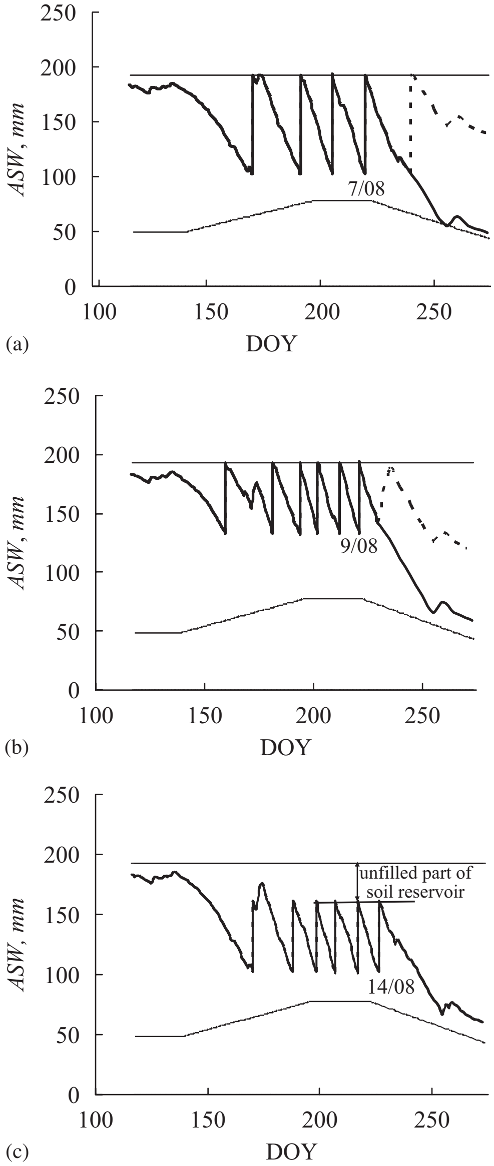

Fig. 4 – Simulation of the available soil water (ASW, mm) for the three irrigation scheduling alternatives in the year of extreme irrigation demand (1981): (a) alternative 1; (b) alternative 2; and (c) alternative 3, with identification of the date of the last irrigation. The horizontal line, above, corresponds to TAW and the broken line, below, to the non-stress threshold.

The currently adopted irrigation scheduling in the Thrace (Zahariev et al., 1986) is different from the schedules evaluated above and generally exceeds the irrigation demand proposed herein in moderately dry ($P_I = 25\%$) and average years ($P_I = 50\%$). The overestimation is 60 mm when compared with alternative 2, which adopts application depths similar to those proposed by Zahariev et al. (1986). Considering the currently proposed schedules, all 3 alternatives

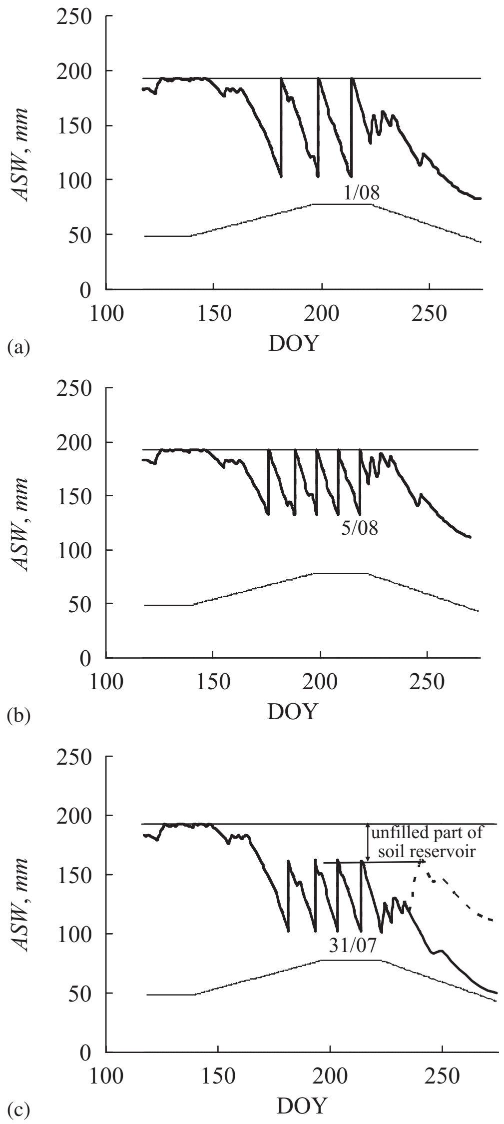

Fig. 5 – Simulation of the available soil water (ASW, mm) for the three irrigation scheduling alternatives in the year of average irrigation demand (1980): (a) alternative 1; (b) alternative 2; and (c) alternative 3, with identification of the date of the last irrigation. The horizontal line above corresponds to TAW and the broken line below to the non-stress threshold.

analysed above could lead to appreciable water savings in moderately dry to moderately wet years ($75\% > P_I > 25\%$), particularly alternative 3.

Alternative 3 could therefore be selected as the one producing higher water savings and good irrigation performances. It is easier to apply if surge flow is adopted because then advance times are shorter than for continuous flow. If the latter is adopted, then furrows may have to be reduced to ensure adequate uniformity of distribution, particularly for the first irrigation. However, the experiments referred to before (Popova et al., 1998; Popova & Kuncheva, 1996) show that net application depths of 60 mm can be applied with continuous flow and achievement of good irrigation performances when soil moisture at the time of irrigation is above the cracking threshold.

3.2. *Yield impacts*

The impacts on yields produced by the irrigation alternatives for both maize hybrids *Kn-2L-611* ($K_y = 1$) and *H708* ($K_y = 1.5$) are compared in Fig. 6. The results indicate that for the years when the adopted application depths do not fully cover the crop requirements (about 30% of the years), alternatives 1 and 3 produce an evapotranspiration deficit and therefore a yield decrease proportional to the yield response factor K_y that characterizes those hybrids. The relative yield decrease may attain a maximum of 16% in case of hybrid *H708* and 11% for hybrid *Kn-2L-611* with both alternatives 1 and 3. These alternatives have similar impacts on yields, except for moderately wet years, which relates to the respective application depths. Yield decreases produced with alternative 2 are negligible in practice.

According to these results, if irrigation is scheduled for maximising yields without considering the need for improved water saving, alternative 2 is the best. Further studies considering the economic impacts of water saving and yield decreases are then required to adequately base decisions. However, the results show that a water stress-sensitive maize hybrid such as *H708* is less appropriate to be cultivated when irrigation is scheduled for water saving and water stress is allowed.

The relative yield decreases for both maize varieties referring to the rainfed crop (alternative 4) over the period 1970–1992 are plotted *vs.* the probability P_I of exceedance of NIRs (Fig. 7). Simulations relative to the drought-resistant hybrid *Kn-2L-611* ($K_y = 1$) show that the relative yield decrease averages 21% in wet years ($P_I > 75\%$), 47% in dry years ($P_I < 25\%$) and 37% in years of average demand ($40 < P_I < 60\%$). For the hybrid *H708* ($K_y = 1.5$), the relative yield decrease averages 30% in wet years, 70% in dry years and 50% for average demand years. These results indicate that the hybrid *H708*, as well as other hybrids highly sensitive to water stress, should not be cultivated under rainfed conditions; differently, the hybrid *Kn-2L-611* and other hybrids tolerant to water deficits would experience excessive yield decreases only in very dry years.

3.3. *Future scenarios*

Hypothetical climate scenarios for 2005–2030 were developed on the basis of trends of contemporary precipitation (Figs. 1 and 2) as described before. The pessimistic scenario refers to a decrease of precipitation in July and August of 37 mm from 2005 to 2030 and to a reduction of 50 mm in seasonal rainfall (May–September) for the same period. Conversely, the optimistic scenario assumes that the precipitation would increase by the same amounts in the same period.

The average precipitation of the pessimistic scenario in July and August (40 mm) is similar to that observed for 1992 (⁎ in Fig. 2); thus, the year 1992 is used in this analysis to represent the average demand relative to the pessimistic scenario. It should be noted that 1992 is labelled as a dry year ($P_I = 16\%$) in the contemporary climate data set. NIR for 1992 (273 mm) are

Table 3 – Summary water balance and yield decrease results of maize irrigation scheduling alternatives 1, 2 and 3 and rainfed alternative 4 for the average and the very dry years

Climate	Average year				Very dry year			
Year	1980				1981			
Precipitation May–Sep, mm	251				139			
Precipitation Jul–Aug, mm	92				63			
Net irrigation requirements, mm	234				348			
Irrigation alternatives	1	2	3	4	1	2	3	4
Irrigation depths, mm	270	300	240	0	360	360	360	0
Number of irrigation events	3	5	4	0	4	6	6	0
Crop evapotranspiration (ET_a), mm	538	538	538	330	590	590	590	284
Non-used precipitation, mm	74	74	74	83	14	0	0	2
ASW at harvest, mm	82	110	50	18	49	59	60	15
Relative yield decrease when $K_y = 1$, %	0	0	0	40	0	0	0	55
Relative yield decrease when $K_y = 1.5$, %	0	0	0	58	0	0	0	80

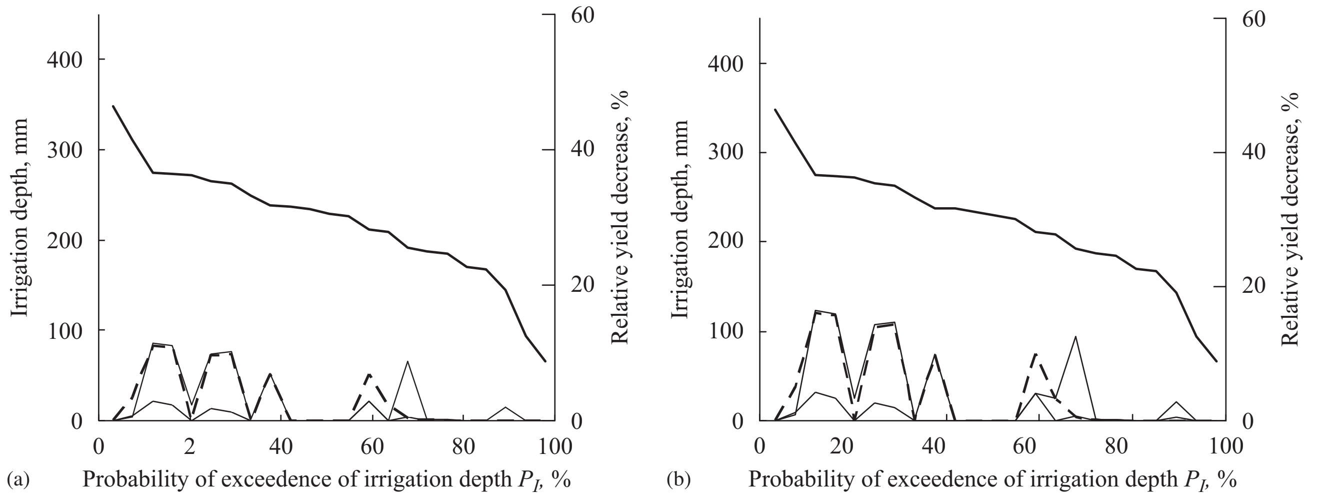

Fig. 6 – Relative yield decrease for hybrids (a) *Kn-2L-611* ($K_y = 1$) and (b) *H708* ($K_y = 1.5$) in relation to the probability curve of net irrigation requirements (▬▬) and depending on the adopted irrigation scheduling alternatives 1 (––), 2 (· · · · · · ·) and 3 (—). Pustren, 1970–1992.

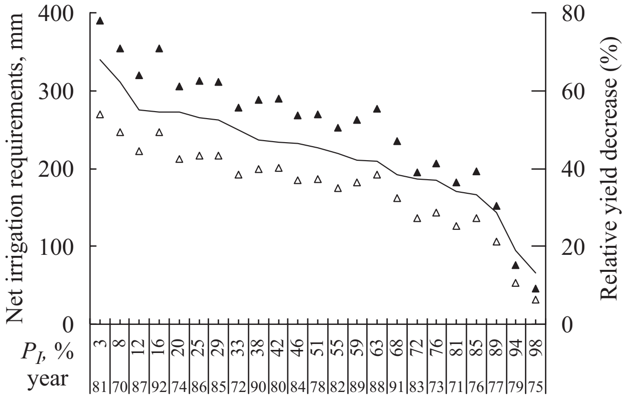

Fig. 7 – Relative yield decrease of rainfed maize comparing the hybrids *Kn-2L-611* (△), with $K_y = 1$, and *H708* (▲), with $K_y = 1.5$, plotted against the NIR probability curve (—), 1970–1992.

40 mm higher than those of the average year, 1980, which is the subject of the precedent analysis.

The simulation results for the three irrigation alternatives for 1992 are presented in Fig. 8 and Table 4. Comparing them with the corresponding results for 1980 (Fig. 5 and Table 3) it may be observed that for alternatives 1 and 2 the same number of irrigation events and season application depths are required. However, an additional irrigation event is needed for alternative 3, which would not save water relative to alternatives 1 and 2. Also different from the present average year, the last irrigation event should be applied after 15 August, i.e. by 19th, 23th and 28th August, for alternatives 1, 2 and 3, respectively. If the rule for not applying any irrigation after that date is enforced the ASW would be depleted below the non-stress threshold for the end crop season (see the dashed line in Fig. 8), hence affecting

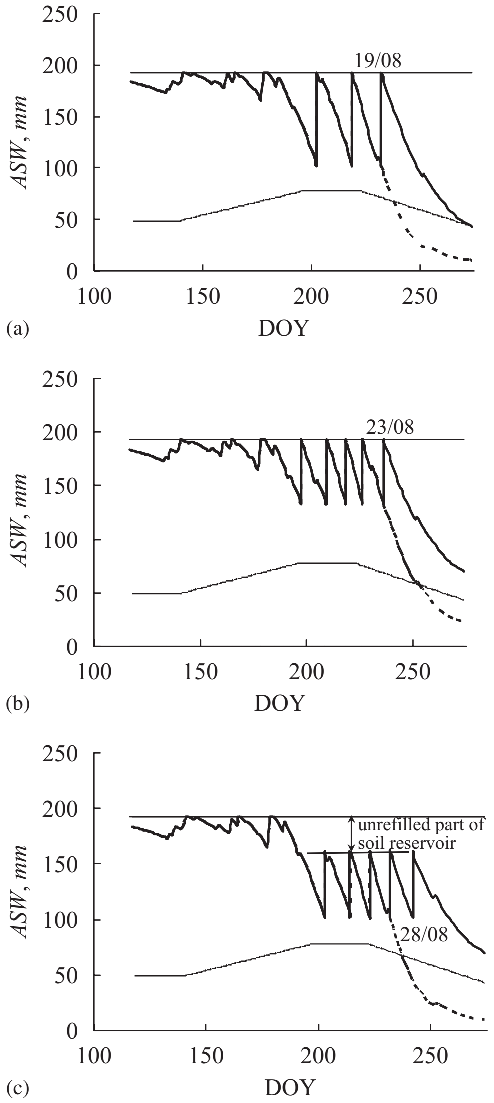

Fig. 8 – Simulation of the available soil water (ASW, mm) for the three irrigation scheduling alternatives in the average demand year (1992) of the pessimistic scenario: (a) alternative 1; (b) alternative 2; and (c) alternative 3, with identification of the date of the last irrigation. The horizontal line above indicates TAW, and the broken line below the non-stress threshold.

evapotranspiration and impacting yields. The results indicate that alternative 1 would save 30 mm water compared with alternatives 2 and 3.

Comparing the average demand year of the pessimistic scenario with the contemporary dry year 1981 (Fig. 4 and Table 3) it may be observed that the first requires, for all alternatives, one less irrigation event than the last.

The average year relative to the optimistic scenario is represented by the year 1984 (◇ in Fig. 2), when the precipitation in July and August (83 mm) is practically the same as the average value of this scenario. NIRs totalise 238 mm, which is practically the same as for the average year of the contemporary climate (1980); related simulations for the 3 alternatives yield results similar to those for 1980 (Fig. 5) and therefore are not presented herein.

A summary of the results for both the pessimistic and the optimistic future scenarios is presented in Table 4. Comparing the average demand years (Tables 3 and 4), the irrigation demand in the pessimistic scenario is higher than that for current climate only for alternative 3; thus, alternative 3 does not produce larger water savings anymore. In case of alternatives 1 and 2, ASW at the end of the season are lower than for the average year 1980 and the non-used rainfall is also lower, but an additional irrigation event is not required. This indicates that foreseen changes in climate could be accommodated for these two irrigation scheduling alternatives by only changing the last irrigation date. The results for the optimistic scenario show that present irrigation and cropping conditions would remain as at present.

Due to increased climatic demand for the pessimistic scenario, the relative yield decrease for the rainfed crop (alternative 4) is significantly higher than those for the average year of the contemporary climate (Tables 3 and 4), 50% and 70%, respectively, for the maize hybrids having $K_y = 1$ and $K_y = 1.5$, compared with 40% and 58% for 1980. Hence, a main adaptation required to face climate uncertainty is to adopt crop varieties that could be less sensitive to water stress, including when crops are irrigated and deficit irrigation would need to be applied.

4. Conclusions

To assess how future climate scenarios could affect irrigated agriculture, irrigation scheduling simulations were performed for two maize hybrids with different sensitivities to water stress. Various irrigation scheduling alternatives were compared in terms of yield impacts under different precipitation scenarios. For the present climate, NIRs vary widely, from less than 100 mm in extremely wet crop seasons up to 360 mm in extremely dry years. Simulations for the very dry year have shown that all alternative irrigation schedules behave similarly when non-stress conditions are aimed at. For the average year, the alternatives allowing a larger soil water depletion (MAD = 0.47) require less water than the one having MAD = 0.33. The lowest demand corresponds to the alternative 3 that adopts smaller irrigation depths and refills the soil reservoir 30 mm below the TAW to better accommodate for any rain falling during the season. However, analysis of the impact on yields from simulations relative to every year during 1970–1992 shows that alternative 2 leads to less impact on yields.

For the average demand year of the pessimistic scenario, it is observed that the last irrigation should be applied after the conventional date (15/08). The ASW at harvest is reduced and an additional irrigation for alternative 3 is then required. For the optimistic scenario, simulation results are similar to those for the average demand year of the present climate. Therefore, the results show that all irrigation scheduling alternatives can easily accommodate the foreseen changes and none of the three alternatives may be selected as the best irrigation scheduling strategy. All three adapt well to the present and scenario conditions and respond to constraints of the furrow irrigation method. The next step is to create an information system for farmers that helps them to better

Table 4 – Summary water balance and yield decrease results of maize irrigation scheduling alternatives 1, 2 and 3 and rainfed alternative 4 for the average years of the pessimistic and optimistic scenarios for 2005–2030

	Pessimistic scenario				Optimistic scenario			
Representative years	1992				1984			
Precipitation May–Sept, mm	177				237			
Precipitation Jul–Aug, mm	40				83			
Net irrigation requirements, mm	273				238			
Irrigation alternatives	1	2	3	4	1	2	3	4
Season irrigation depths, mm	270	300	300	0	270	300	240	0
Number of irrigation events	3	5	5	0	3	5	4	0
Crop evapotranspiration (ET_a), mm	557	557	557	310	548	548	548	354
Non-used rainfall, mm	32	32	32	42	0	0	0	0
ASW at harvesting, mm	42	69	70	3	118	138	146	47
Relative yield decrease when $K_y = 1\%$	0	0	0	50	0	0	0	37
Relative yield decrease when $K_y = 1.5\%$	0	0	0	70	0	0	0	53

schedule irrigations, namely using a simulation model similar to the one adopted in this study and current weather data. Building such an information system is the next challenge to help cope with climate uncertainties. Considering alternative maize varieties and alternative crops is also foreseen.

Relative to the rainfed crop, the results indicate that yield impacts highly increase for the pessimistic scenario, particularly for the water stress-sensitive hybrid *H708*. The results indicate that vulnerability to climate change is higher for non-irrigated crops and that coping with possible rainfall decreases requires adopting less sensitive crop varieties and alternative crop patterns. This is also important if deficit irrigation is applied aimed at water saving.

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