A COUPLED CROP AND SOLID SET SPRINKLER SIMULATION MODEL:

II. MODEL APPLICATION

by

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ABSTRACT

In this work, applications of the coupled solid set sprinkler irrigation and crop model AdorSim introduced in the companion paper are presented. The sprinkler irrigation model is based on ballistic theory, while the crop model is based on CropWat. AdorSim was used to evaluate the effect of sprinkler spacing on seasonal irrigation water use (*WU*) and crop yield. The most relevant results were related to the characterization of advanced irrigation scheduling strategies. The differences in crop yield and *WU* derived from irrigating at different times of the day were estimated for two locations strongly differing in wind speed. Irrigation guidelines were established in these locations to relate gross water use and water stress induced yield reductions. Simulations were also applied to estimate adequate wind speed thresholds for irrigation operation. In the experimental conditions, thresholds of $2.0 - 2.5 \text{ m s}^{-1}$ proved effective to control yield reductions and to minimize *WU*.

INTRODUCTION

In arid and semi-arid areas, agricultural production depends upon effective irrigation. In a context of increasing water costs and water scarcity, developing adequate irrigation scheduling procedures requires knowledge of soil water properties, crop water requirements, meteorology, and yield response to irrigation water. In sprinkler systems, irrigation scheduling can be effectively used by farmers, since the irrigation depth can be easily adjusted. At the same time, pressurized distribution systems are often operated with a high degree of flexibility. A number of techniques can be applied to establish optimum management strategies leading to a minimization of water inputs, the control of potentially unfavorable meteorological conditions and the optimization of crop yields. These

techniques can be used to improve the design and/or the management of on-farm irrigation equipment.

In the middle Ebro valley of northeastern Spain, wind is the major environmental factor affecting sprinkler irrigation performance. In this area, sprinkler irrigation management is primarily determined by the wind. Farmers concentrate irrigation operations in calm days in order to conserve water and maintain an acceptable level of uniformity. When windy conditions prevail, farmers are forced to irrigate under moderate and high wind conditions, therefore accepting poor irrigation performance and less than potential yields.

In the last decades, several studies have been performed to identify design and management problems of irrigated areas equipped with modern sprinkler irrigation systems in the Ebro Basin (Faci, 1988; Faci and Bercero, 1991; Dechmi et al., 2003a; Dechmi et al., 2003b). The purpose of these studies was to improve irrigation performance in the area. In a companion paper, the computer model AdorSim has been presented. The model constitutes a decision support tool in solid set sprinkler-irrigated agriculture. AdorSim consists on the combination of a ballistic sprinkler irrigation simulation model (Ador-Sprinkler) and a crop model (Ador-Crop). The irrigation routine is based on similar models in the literature (Fukui et al., 1980; Seginer et al., 1991; Carrión et al., 2001; Montero et al., 2001), and incorporates a drop size distribution curve (Kincaid et al., 1996), along with a locally calibrated predictive equation for wind drift and evaporation losses. The most innovative aspect of the model is that crop yield simulation, as affected by water availability and water demand by the crop, is performed at a number of points within the sprinkler spacing. Therefore, the spatial distribution of irrigation water is converted to a

spatial distribution of crop yield reduction, and the effects of irrigation uniformity on crop yield spatial variability can be properly assessed. Model validation was performed on a corn crop (*Zea mays* L. cv. Dracma). The experimental solid set was designed to represent a typical setup of the new irrigation developments in the Ebro basin. In the companion paper, the model was validated reproducing the experimental irrigation dates and times.

The objectives of this work included: 1) Determine the effect of the sprinkler spacing and the azimuth of the sprinkler lines on irrigation performance and crop yield in the conditions of the field experiment used for validation of AdorSim; 2) Characterize wind speed and other meteorological variables in two locations in the Ebro valley, and use the resulting meteorological database in conjunction with AdorSim; 3) Assess the effect of the critical stress level on irrigation performance and crop yield; and 4) Evaluate the effect of wind-related irrigation scheduling strategies on crop yield, seasonal irrigation water use (*WU*) and irrigation performance. In the fourth objective, the irrigation starting time (closely related to the wind speed in the Ebro Valley), the establishment of wind thresholds, and the variability of meteorological conditions among irrigation seasons, were explored.

MODEL PARAMETERS

The simulations reported in this work reproduced the experimental conditions (soil characteristics, crop and cultivar characteristics, sowing date) reported in the companion paper (Dechmi et al., 2004). Unless otherwise stated, the characteristics of the simulated solid set were:

- Triangular sprinkler spacing, 18 by 15 m;

- Sprinkler head VYR 70 (manufactured by VYRSA, Briviesca, Burgos, Spain), with principal and auxiliary nozzles of 4.4 and 2.4 mm, respectively;
- Nozzle height of 2.30 m over the soil surface;
- Operating pressure of 300 kPa.

Different wind drift and evaporation losses (*WDEL*) equations were used in different periods of the day. Between 4 h and 20 h GMT, the predictive equation developed by Dechmi et al. (2003c) was used:

$$WDEL = 5.29W + 7.48 \quad [1]$$

Where W is the wind speed (m s^{-1}). Between 20 h and 4 h GMT, $WDEL = 7.48 \%$ was used, following the findings of Salvador (2003), who reported that during these hours the *WDEL* of solid set sprinkler irrigation were statistically independent of wind speed and other meteorological variables, and that the *WDEL* were similar to the intercept of the equation used for the rest of the day. Both day and night time expressions for *WDEL* should only be considered valid for the local conditions of the middle Ebro Valley of Spain, since factors other than wind speed have been reported to affect *WDEL* (Tarjuelo et al., 2000).

EFFECT OF DESIGN PARAMETERS ON IRRIGATION PERFORMANCE AND CROP YIELD

Two design parameters were selected for this study: the sprinkler spacing and the azimuth of the sprinkler lines. Both parameters have been identified as relevant to irrigation uniformity and crop yield in the Ebro Valley (Dechmi et al., 2003a, Dechmi et

al., 2003b). In this simulation study, AdorSim was applied to the validation conditions. Therefore the soil and crop characteristics, and the experimental irrigation dates and amounts were reproduced. Changes were only introduced in the analysed variables.

Sprinkler spacing

Simulations were performed to analyse the effect of sprinkler spacing on irrigation uniformity, crop yield and deep percolation losses. AdorSim was run to simulate the following triangular (T) and rectangular (R) sprinkler spacings: 15 x 12 m, 15 x 15 m, 15 x 18 m, and 18 x 18 m. The only required adjustment on the input data was the duration of the irrigation events, which was corrected in each spacing to maintain constant the gross irrigation depth per irrigation event. The negative effect of wind speed on crop yield was alleviated by the use of narrow, triangular sprinkler spacings (Table 1). In the experimental conditions, the differences between the studied spacings attained a relevant 10.5 % of crop yield. In each sprinkler spacing (except for 18x18) the model detected an improvement in crop yield for triangular layouts. The variation of deep percolation losses among sprinkler spacings was not very relevant, although narrow spacings resulted in smaller losses. The most relevant differences were in the average value of the Christiansen coefficient of uniformity ($\overline{CU}$), which varied from 63.9 % to 83.5 %. These differences in uniformity were the main cause of the differences in crop yield. Keller and Bliesner (1990) reported design CU for different sprinkler spacings and wind speeds, and the relationship between CU and yield reduction. No direct comparison is possible between their results and ours because in our case the CU of each irrigation event is used to calculate the yield reduction, instead of using an average value for all the irrigation events of the crop season. At the same time, Keller and Bliesner (1990) presented general relationships, while our results are

representative of our choice of irrigation hardware, operating conditions and crop characteristics.

Azimuth of the sprinkler line

According to Keller and Bliesner (1990), one of the design-time defenses against the negative effect of wind on solid set sprinkler irrigation performance is the alignment of the sprinkler lines with respect to the dominant wind direction. Dechmi et al. (2003a) analyzed the effect of wind direction on triangular and rectangular spacings, and applied their findings to the evaluation of the Loma de Quinto District (Northeastern Spain).

In this work, two simulation experiments are presented, exploring the effect of sprinkler line alignment on irrigation performance and crop yield. In the first experiment, the solid set field experiment reported in the companion paper (with a spacing of T18x15) was simulated with sprinkler line azimuths ranging between 0 and 60° (in equilateral triangular layouts two azimuths differing in multiples of 60° are equivalent). In the second experiment, the same simulation was performed using a R18x18 spacing, adjusting the irrigation time to maintain the same seasonal gross irrigation depth. Sprinkler line azimuths were simulated from 0 to 90° (in square layouts two azimuths differing in multiples of 90° are equivalent). Simulation results for both experiments indicate that the azimuth of the sprinkler lines does not have a relevant effect on simulated crop yield, deep percolation losses and irrigation uniformity. The differences in simulated yield reduction for each sprinkler spacing due to the change in the line azimuth amounted to only 0.6 %. The reasons for this limited effect can be attributed to the natural variability in wind speed and

direction throughout the season, and/or to limitations in the model predictive capability. Additional research will be required to obtain solid conclusions on this issue.

CLIMATIC CHARACTERIZATION OF TWO LOCATIONS IN THE EBRO RIVER VALLEY IN RELATION TO SPRINKLER IRRIGATION

In the following simulation experiments, the meteorological data used for model input (wind speed and direction, global solar radiation, and air temperature and relative humidity) were recorded in two automated meteorological stations (Campbell Scientific, Logan, Utah) installed on grass in Zaragoza (41° 43'N, 0°49'W, 225 m of altitude) and Tamarite (41° 46'N, 0° 22'E, 218 m of altitude), located at north-eastern Spain (Figure 1). Reference evapotranspiration (ET_0) was estimated using the meteorological data and the FAO version of the Penman-Monteith equation (Allen et al., 1998). In Zaragoza, the mean annual maximum and minimum daily air temperatures for the period 1995-2002 were 21.4°C and 8.3 °C, respectively, while the annual average precipitation and ET_0 were 353 mm and 1,197 mm, respectively. In Tamarite, the mean annual maximum and minimum daily air temperatures for the period 1997-2002 were 20.8 °C and 7.0 °C, respectively, while the annual average precipitation and ET_0 were 375 mm and 1,003 mm, respectively.

Zaragoza and Tamarite were considered in this study because of the relevant differences in wind speed recorded at both locations, and because of the availability of adequate 30 min wind speed and direction data series (from 1996 to 2002 – seven years – in Zaragoza and from 1998 to 2002 – five years – in Tamarite). Zaragoza climate is characterized by the presence of an intense wind from the NW-W, locally called “*cierzo*”. In Tamarite, *cierzo* is less intense than in Zaragoza. In Tamarite the maximum monthly

average wind speed was 1.5 m s^{-1} , while in Zaragoza monthly average wind speeds ranged from 1.9 m s^{-1} to 3.0 m s^{-1} (Figure 2). Thus, the annual average wind speed in Zaragoza was approximately double than in Tamarite (Table 2). The inter-annual wind speed variability was also larger in Zaragoza than in Tamarite, being the respective CV's of 9.8 % and 3.8 %. Seasonal maximum corn evapotranspiration (ET_m) and seasonal corn net irrigation requirement (NIR) were larger in Zaragoza than Tamarite. For each day, ET_m was computed following the methodology described by Allen et al. (1998), by multiplying the reference evapotranspiration (ET_0) by the corresponding crop coefficient. Crop coefficients were obtained from tabulated values (Allen et al., 1998) adapted to the phenological local conditions. NIR was calculated as the difference between ET_m and effective precipitation (Cuenca, 1989). The inter-annual differences were 60 and 57 mm for ET_m and NIR , respectively (Table 2).

Figure 3 presents the daily evolution of the averages of half-hour wind speed (W) in Zaragoza and Tamarite for the months of April to September. Values for May to July were combined in a single curve, as well as values for August and September, because of similar monthly wind speed averages (Figure 2) and similar general traits observed within those months in the daily pattern of long-term average half-hour W . At both stations, the daily patterns of long-term averages of half-hour W were similar, with the highest values observed in April and the lowest in August-September. In Zaragoza, long-term averages of half-hour W were less than 2.0 m s^{-1} for the 2:30-6:30 periods in April, for the 1:00-6:30 periods in May to July, and for the 21:30 to 8:00 periods in August and September. In Tamarite, half-hour W less than 2.0 m s^{-1} occurred for the 18:00 to 10:30 periods in April, the 18:00 to 13:00 periods in May to July, and for all half-hour periods in August and September.

In both Zaragoza and Tamarite, daily patterns of relative frequencies of half-hour W above 2.0 m s^{-1} were similar (Figure 3), with the highest values observed in April and the lowest in August-September. In Zaragoza, relative frequencies of half-hour W above 2.0 m s^{-1} were higher than 50 % for the periods 8:00 to 19:30 in April, 8:00 to 20:30 in May to July, and 10:00 to 18:00 in August to September. In April, a maxima plateau of frequencies about 80 % was observed for the periods 13:30 to 17:30; in May to July, a maxima plateau of frequencies about 70 % was observed for the periods 15:30 to 17:30; finally, in August to September, a maxima plateau of frequencies about 70 % was observed for the periods 15:30 and 16:00. In Tamarite, relative frequencies of half-hour W above 2.0 m s^{-1} were higher than 50 % for the periods 12:00 to 17:00 in April, while all frequencies were lower than 50 % in the other months. In April, a maxima plateau of frequencies about 60 % was observed for the periods 15:00 to 16:30; in May to July, a maxima plateau of frequencies about 50 % was observed for the periods 17:00 to 17:30; finally, in August to September, a maximum frequency of 35 % was observed for the period 16:30.

It is clear from Figure 3 that in Zaragoza it is important to avoid daytime irrigations. In the case of Tamarite, this recommendation can be somewhat relaxed, and just restricted to the midday hours, particularly in spring. The consideration of the frequency of high winds (above the 2.0 m s^{-1} threshold) leads to the conclusion that throughout the irrigation season, 51 % of the time in Zaragoza and 79 % of the time in Tamarite can be used for sprinkler irrigation without compromising its performance. The analysis of the wind patterns in both locations leads to design and management consequences. In the following sections, management consequences will be explored.

Future research will be required to identify design rules providing enough flexibility to avoid irrigation in windy periods. Such designs will undoubtedly represent an increase in the investment costs. Fortunately nighttime irrigation will benefit from reduced electric energy costs, partly compensating the additional investment.

EFFECT OF THE CRITICAL STRESS LEVEL ON IRRIGATION PERFORMANCE AND CROP YIELD

In this simulation experiment, AdorSim schedules an irrigation event when a critical percentage of the solid set area is under water stress. This critical stress parameter is an additional model variable, acting as an index of deficit irrigation. Merriam and Keller (1978) proposed irrigation adequacy criteria based on the low quarter distribution. Following this concept, an irrigation must be performed when the soil available water is depleted in 25 % of the field area. If the soil water follows a normal distribution, at that time 12.5 % of the field area will be water stressed. Therefore, the adequacy criterion corresponds to a critical stress level of 12.5 % of the area. Using AdorSim, simulations can be performed with the critical stress ranging from 4 % to 48 % (between 1 and 12 stressed subplots, out of the total number of 25). The particular irrigation scheduling criteria of each simulation determines the model reaction to an irrigation demand. When the irrigation is finally performed, AdorSim searches the meteorological database to identify the average meteorological conditions during the irrigation event. The model determines the weighted average wind direction corresponding to the class in which the recorded wind direction during the irrigation event is most frequent, as described in the companion paper.

Simulations were performed to explore the effect of the critical stress level on irrigation performance and crop yield. On-demand 4 h irrigation events starting at 8 h GMT and ending at 12 h GMT were simulated, using the meteorological data for Zaragoza in 2000. The twelve above-mentioned levels of critical stress (from 4 to 48 %) were used. Results indicate that yield reduction increased linearly with critical stress, from 0.86 % to 13.39 % (data not presented). At the highest critical stress the number of irrigation events was reduced from 40 to 30 as compared to the lowest critical stress level. Differences in the average *CU* or in the average wind speed during the irrigation events were not relevant.

The comparison of the cumulative irrigation depth resulting from this simulation experiment with the field experimental data presented in the companion paper, for different values of critical stress is presented in Figure 4. This comparison seems adequate since the irrigation events in the field experiment lasted for four hours on the average and were applied at approximately the same morning hours. In terms of irrigation depth, the experimental field conditions were equivalent to a critical stress value of 28 % (subfigure c). The corresponding yield reduction in the simulation experiment was 7 %, while AdorSim results for the irrigation scheduling of the field experiment conditions (which consisted on making the average irrigation depth in the plot for each irrigation equal to the crop water requirements) indicated a simulated *YR* of 17 %. These results suggest that an additional 10 % yield could be obtained just improving irrigation scheduling by considering the spatial variability of soil water depletion (resulting mainly from non uniform irrigation). A similar finding was reported by Dechmi et al. (2003b) for commercial corn plots in the Loma de Quinto District.

These results underline the limitations of using irrigation uniformity alone to explain water stress induced yield reductions. The irrigation CU is important in determining the average yield of a plot, but the irrigation scheduling criteria (Keller and Bliesner, 1990), based on the average depth applied to the plot or on the depth applied in a certain percentage of subplots within the plot, can be even more important. This could also be the reason why different relationships between CU and yield reductions have been found in different works.

ANALYSIS OF IRRIGATION SCHEDULING STRATEGIES

Three irrigation scheduling strategies were simulated to explore opportunities to conserve water and improve crop yield in solid set sprinkler irrigated corn. The purpose was to determine the inter-annual effect of the variability in the meteorological variables and irrigation starting time on sprinkler irrigation performance, corn yield reduction (*YR*), seasonal irrigation water use (*WU*) and deep percolation losses (*Dp*). The day was divided in 6 periods of 4 hours starting at 0 h GMT. Irrigations starting at 8, 12 and 16 GMT were considered as daytime, while the remaining three periods were considered as nighttime. Following the model validation data set, a total available water of 170 mm m^{-1} and a soil depth of 0.9 m were considered. The soil was initially considered at field capacity.

Fixed irrigation starting time

Under this scheduling option, simulations were performed for each irrigation starting time, each year of the data set in Zaragoza and Tamarite, and at the 12 levels of critical stress. The case corresponding to a critical stress level of 12 % in Zaragoza and

Tamarite is presented in Figure 5. Regarding *WU* in Zaragoza (Fig. 5a), results show a clear variability between years and between irrigation times. The difference between the six irrigation starting times was 195 mm on the yearly average. The minimum *WU* corresponds to the nighttime (starting times 0, 4 and 20 h GMT). In most cases, the maximum *WU* was applied when irrigation started at 12 h GMT. The yearly average *WU* ranged from 527 to 897 mm. This high variability was not only due to inter-year variation in evapotranspiration (Table 2). In fact, most of the *WU* variability was due to inter-year wind speed variability. The inter-year pattern of *YR* variability reproduces the variability in *WU* (data not presented). The *YR* variability between irrigation times does not follow any trend and cannot be considered relevant (between 2.16 % and 2.98 % in the average). Simulation results for Tamarite show lower inter-year and inter-time variability in *WU* than in Zaragoza (Fig. 5b). Also, much less water was required to complete the crop cycle (183 mm less than in Zaragoza on the average). In Tamarite the difference between the six irrigation starting times was 96 mm on average. Regarding *YR*, results were similar to those obtained for Zaragoza.

Figure 6 presents contour line maps for the yearly average values of *YR*, *WU* and *Dp* depending on the irrigation starting time and on the critical stress for Zaragoza and Tamarite. In both locations *YR* does not show a clear variation with the irrigation time, but increases linearly with the critical stress. As for *WU*, more water is required in both locations to obtain the same *YR* as the irrigation time approaches midday. In fact, *WU* shows the same daily pattern as the wind speed (Figure 3). Regarding deep percolation, losses were higher when irrigation was applied during the nighttime period. This seems to be due to the fact that *WDEL* are smaller during the night. Consequently, during the night the net irrigation depth is larger and so are the chances of deep percolation losses. As

previously observed, more water is required in Zaragoza to obtain the same yield as in Tamarite. Since the average difference in *NIR* between both locations is just 57 mm and irrigation uniformity is lower in Zaragoza, the irrigation scheduling led to more frequent irrigation events, more irrigation water and higher deep percolation losses in Zaragoza.

The inter-time average reproduces the case in which a farm is divided in irrigation sectors irrigated sequentially (with each sector irrigated at the same time throughout the season). In such a case, a direct relationship could be obtained between *WU* and *YR*, without explicit consideration of the critical stress level or the irrigation starting time. Such relationship is presented in Figure 7 for the conditions of Zaragoza and Tamarite. These regression equations can be used for irrigation management and design, since each point in the curve is an average containing relevant variability associated to the irrigation time and the meteorological conditions, primarily *W* and *ET_m*. Regarding irrigation management, one particular application of such a curve could be the determination of the optimum yield respect to the water cost. The curve can also be used to plan continuous deficit irrigation schedules in response to water scarcity. Regarding irrigation design, consideration was given to the critical month, August in this case. The crop water requirements for August in Zaragoza and Tamarite amount to one third and one quarter of the seasonal crop water requirements, respectively. Using this rule, the design capacity of the irrigation network can be established for any level of design yield reduction. For instance, if an irrigation network in both zones was designed to operate 24 hours a day and a 5 % yield reduction was assumed, the critical monthly capacity would be 265 mm and 226 mm for Zaragoza and Tamarite respectively. Under this particular hypothesis farmers would irrigate all day and with any wind condition.

Variable irrigation starting time

The previous section confirmed that nighttime irrigation can be useful to minimize *WU*, and the difference between daytime and nighttime irrigation was quantified. Unfortunately, exclusive nighttime irrigation cannot be performed in many collective irrigation networks due to simultaneity constraints. Therefore, it is important to identify irrigation scheduling options including daytime operation leading to moderate yield reductions and minimum *WU*. Three scheduling options were considered based on different treatments of the irrigation starting time: random (chosen from the six above mentioned starting times), alternative (daytime operation at 12 h GMT and nighttime operation at 0 h GMT) and sequential (from 0 to 20 h GMT in cycles). The selected operation times for the alternative scheme are just one realization of the strategy, and two other similar schemes would be available (8/20 h GMT and 4/16 h GMT).

Simulations were performed considering each year of the data set in Zaragoza and the critical stress level of 12 %. The *YR*, *WU* and *Dp* resulting for each scheduling option in all simulated years were averaged and the standard deviation was calculated. A comparison in terms of *WU* between the six irrigation starting times considered in the previous section and the three schedules with variable starting irrigation time is presented in Figure 8. The random, alternative and sequential irrigation schedules resulted in very similar *WU*, with random irrigation producing minimum *WU*. The yearly variability of *WU* was minimum for the sequential schedule. No relevant difference was observed between the three options regarding deep percolation and yield reduction (data not presented). The average *WU* for the three variable irrigation starting time schedules was 759 mm. This figure is bracketed by the average daytime *WU* (834 mm) and the average nighttime

irrigation water use (698 mm). The average *WU* in all six fixed irrigation starting time schedules was 766 mm.

Irrigation Efficiency (*IE*) can be determined for all treatments in Fig. 8 as the ratio between the yearly average seasonal net irrigation requirements (*NIR*) and the *WU*. Results showed that *IE* varied from 64 % to 67 % in the daytime treatments (8h, 12h and 16h GMT). The nighttime treatments showed *IE*'s ranging from 76 % to 80 %. Finally, in the variable irrigation starting time schedules *IE* ranged from 71 % to 73 %. These values show correspondence with the Potential Application Efficiency values presented by Clemmens and Dedrick (1994) for well-designed and managed solid set sprinkler systems (between 70 and 85 %). However, these values are the result of combining particular irrigation materials, a given irrigation set up and local environmental conditions. Therefore, these *IE* estimates should only serve the purpose of comparison among treatments.

As previously discussed, when planning the irrigation of a solid set farm, the common procedure is to divide the farm in sectors. There are many feasible options for dividing the farm in sectors, but at this point we would like to explore options based on the use of six sectors. This is an illustrative option, since the considered irrigation time was 4 hours, and therefore all six sectors could be irrigated in just one day (this would not be a real practical option, since a number of hours should be set aside for maintenance and repairs). In order to irrigate these six sectors, the farmer can either use a fixed irrigation starting time in each of them, or a variable irrigation starting time schedule. In the simulated case, moderate water conservation can be obtained if a variable schedule is used. Conservation can be estimated as $766 - 759 = 7$ mm per season. However, from the

agronomic point of view, the variable irrigation starting time option seems more interesting and practical, since all sectors will require the same irrigation water to attain the target crop yield. Additionally, if a variable irrigation starting time schedule is used, irrigation uniformity will reach 68 % all over the farm, while in fixed irrigation starting time options uniformity will fluctuate among sectors between 65 % and 75 %. As a consequence, deep percolation losses will range between 120 and 173 mm per season in the farm. Therefore, nutrient leaching may be a problem in some sectors, while maintaining an adequate salt balance will be difficult in others.

Fixed irrigation starting time, limited wind irrigation

In this irrigation scheduling strategy, an additional variable is introduced: the wind threshold. Irrigation is performed the first day after the critical stress level is attained if the wind speed is below a threshold at the selected irrigation starting time. If during the 4 h irrigation event the wind speed exceeds the threshold, irrigation is interrupted. Consequently, irrigation events have a maximum duration of 4 h. The magnitude of the threshold poses an additional threat to the crop: yield can also be reduced because of generalized water stress during a number of consecutive days with intense wind speeds and therefore no irrigation. However, it is interesting to explore this type of management because new irrigation automation devices permit the application of such irrigation scheduling rules and could play a relevant role in *WU* optimization in windy areas.

Simulations were performed for the year 2000 in Zaragoza and Tamarite using wind speed thresholds varying from 1 to 5 m s⁻¹ (with an increment of 0.5 m s⁻¹) for each irrigation starting time (0 h GMT to 20 h GMT). Figure 9 presents inter-time averages of

YR, *WU* and *Dp* for a) Zaragoza, and b) Tamarite, with a critical stress level of 12 %. In Zaragoza the adoption of low wind thresholds results in deficit irrigation, with the consequent reductions in crop yield and *WU* (Figure 9a). A moderate threshold of 2.5 m s^{-1} in Zaragoza seems adequate to minimize *WU* and maintain moderate *YR* at the considered critical stress level. According to the reported analysis of the wind in Zaragoza, more than half of the time would be available for irrigation under these conditions. Larger thresholds would not significantly increase yield, but would result in a large *WU* and therefore abundant *Dp* losses.

Finally, the comparison of subfigures 9a and 9b permits to draw conclusions about the site-specificity of the wind threshold. Since wind is not such a relevant issue in Tamarite, the threshold is not so necessary as it is in Zaragoza. If irrigation is performed 24 h a day, a threshold of 2.0 m s^{-1} is enough to grant almost full yield in Tamarite. However, according to the results of the previous sections, in both locations, if 12 h nighttime operation is possible, the threshold strategy is not required and irrigation can proceed regardless of wind speed without relevant damage to crop yield.

SUMMARY AND CONCLUSIONS

This paper presents the application of the AdorSim simulation model to the analysis of several irrigation design and management issues. Although AdorSim was systematically calibrated and validated in the companion paper, all simulations presented in this work should be considered exploratory in nature, and subjected to proper field verification.

In the experimental conditions, the effect of the sprinkler spacing is clear, and follows the expected trends. In this work we have been able to quantify the effect of the sprinkler spacing on crop yield. The sprinkler spacings currently used in the Ebro Valley resulted in corn yield differences of up to 10.5 %, favouring the narrower, triangular spacings. The model predicted an average 1.6 % yield increase when a given spacing was switched from a rectangular to a triangular layout.

The most relevant conclusions are related to irrigation scheduling. When AdorSim is run in automatic schedule mode, irrigation is programmed when a given percentage of the solid set spacing area is water stressed, according to the soil water balance performed in the crop simulation module. This percentage is referred to in the model as the critical stress level. As the critical stress level grows, the number of irrigation events decreases, the crop yield is reduced by water stress, and seasonal irrigation water use decreases. In a simulation experiment reproducing the field experiment reported by Dechmi et al. (2003c) and used for model validation and calibration in the companion paper, yield reduction increased with the increase in the critical stress level from 0.86 % to 13.39 %, while *WU* decreased from 1,011 to 758 mm.

Three irrigation scheduling strategies were explored and tested in two locations representative of irrigated agriculture in the central Ebro Valley of Spain: Zaragoza and Tamarite. The average wind speed for both locations was 2.4 and 1.2 m s⁻¹, respectively. In the first case of irrigation scheduling, AdorSim allowed to quantify the effect of the irrigation starting time on *WU*. In both locations, daytime irrigation starting time used more water than nighttime irrigation starting time to obtain similar yield reductions. This difference was more marked in Zaragoza (834 mm vs. 698 mm), where nighttime irrigation

is strongly recommended to minimise *WU*. When complete nighttime irrigation is not possible, the second irrigation schedule, variable irrigation starting time (using random, alternative or sequential procedures), has proven satisfactory to limit yield reduction and minimize *WU*. In the third irrigation scheduling strategy, an additional variable, the wind threshold, was introduced. If irrigation is to be performed, AdorSim checks on the current wind speed and delays the irrigation event until the day in which the wind speed is lower than the threshold. This strategy has shown potential to conserve irrigation water. In the conditions of Zaragoza, a threshold of 2.5 m s^{-1} seems adequate, while in Tamarite the threshold can be reduced to 2.0 m s^{-1} . The application of wind thresholds only seems necessary when daytime irrigation is required, since nighttime irrigations were not severely affected by the wind in any of the two considered locations.

Current developments in on-farm irrigation controllers are offering new possibilities for advanced irrigation scheduling routines. New products offer a wide range of possibilities in on-farm irrigation decision making. Irrigation controllers can gather wind measurements and respond to wind in a programmable way. Research efforts will have to be applied to the assessment of adequate on-farm irrigation scheduling rules for such devices.

In a larger scale, remote control systems for pressurized networks offer the possibility of managing large farms or collective irrigation systems (serving thousands of hectares) from just one control point. In such systems, the central commander can schedule the irrigation of each sector in each farm. In this way, the remote control system permits to operate the irrigation network even without the farmer's intervention. If on-farm irrigation decisions are centralized, the remote control system will have the responsibility of

responding to environmental factors like wind speed in such a way that the farmers' revenues are optimised. In this context, the use of wind thresholds can be very useful. However, adequate thresholds should be developed for each area, water cost and crop type. If the irrigation network covers a large, heterogeneous area, a number of wind sensors will be required. Alternatively, maps of wind exposure could be developed and used for irrigation scheduling in combination with just one wind sensor.

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APPENDIX I: REFERENCES

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APPENDIX II: NOTATION

The following symbols are used in this paper:

- CU = Christiensen coefficient of uniformity (%);
- Dp = deep percolation loses (mm);
- ET_0 = Reference evapotranspiration (mm);
- ET_m = maximum seasonal evapotranspiration (mm);
- NIR = seasonal net irrigation requirements (mm);
- R = rectangular sprinkler spacing;
- T = triangular sprinkler spacing;
- W = wind speed ($m\ s^{-1}$);
- $WDEL$ = wind drift and evaporation loses (%);
- WU = Seasonal irrigation water use (mm);
- YR = yield reduction (%).

APPENDIX III: TABLES

Table 1. Yield reduction (YR), average deep percolation losses (Dp), and average Christiansen coefficient of uniformity ($\overline{CU}$) obtained within four sprinkler spacings arranged in triangular (T) and rectangular (R) layouts.

Table 2. Inter-annual variation of the annual average wind speed (W), seasonal maximum corn evapotranspiration (ET_m) and seasonal corn net irrigation requirements (NIR) in the Zaragoza and Tamarite meteorological stations.

Table 1. *Yield reduction (YR), average deep percolation losses (Dp), and average Christiansen coefficient of uniformity ($\overline{CU}$) obtained within four sprinkler spacings arranged in triangular (T) and rectangular (R) layouts.*

Sprinkler spacing	YR (%)	Dp (%)	$\overline{CU}$ (%)
T12x15	17.2	3.3	83.5
R12x15	18.9	3.3	81.8
T15x15	17.6	3.2	83.7
R15x15	18.3	3.4	80.3
T18x15	20.4	3.5	79.7
R18x15	24.5	4.8	71.2
T18x18	27.8	5.6	65.5
R18x18	27.7	5.8	63.9

Table 2. *Inter-annual variation of the annual average wind speed (W), seasonal maximum corn evapotranspiration (ET_m) and seasonal corn net irrigation requirements (NIR) in the Zaragoza and Tamarite meteorological stations.*

Years	Zaragoza			Tamarite			Difference	
	W (m s ⁻¹)	ET_m (mm)	NIR (mm)	W (m s ⁻¹)	ET_m (mm)	NIR (mm)	ET_m (mm)	NIR (mm)
1996	2.3	643	561	-	-	-	-	-
1997	2.1	587	434	-	-	-	-	-
1998	2.7	681	568	1.2	605	517	76	51
1999	2.7	585	488	1.2	567	441	19	47
2000	2.3	702	652	1.2	613	522	89	130
2001	2.2	658	590	1.1	573	480	85	110
2002	2.4	686	530	1.2	589	486	96	44
Average	2.4	649	546	1.2	589	489	60	57

APPENDIX IV: FIGURES

Figure 1. Localisation of the Zaragoza and Tamarite meteorological stations within Spain, the Ebro Basin and the Aragón Department.

Figure 2. Monthly average wind speed for the average year at the Zaragoza and Tamarite meteorological stations.

Figure 3. Daily evolution of long-term averages of half-hour wind speed and relative frequencies of half-hour wind speeds above 2.0 m s^{-1} for the months of April to September in Zaragoza and Tamarite. (A) and (B), averages; (C) and (D), relative frequencies. GMT, Greenwich Meridian Time.

Figure 4. Time evolution of the Cumulative simulated (grey line) and experimental (black line) irrigation depth for critical stress levels of 4 % (a), 12 % (b), 28 % (c) and 48 % (d).

Figure 5. Seasonal irrigation water use (WU) for each year and each irrigation time considering a critical stress of 12 % and using Zaragoza (a) and Tamarite (b) meteorological data.

Figure 6. Contour line maps of yield reduction (YR), seasonal irrigation water use (WU) and deep percolation (Dp) losses resulting from combinations of irrigation time and critical stress. Results are presented for Zaragoza and Tamarite.

Figure 7. Irrigation system design and planning curves for Zaragoza and Tamarite. Seasonal Irrigation water use (WU) is presented as a function of corn yield reduction (YR). Black and gray lines correspond to regression lines between WU and YR in both locations.

Figure 8. Seasonal irrigation water use (WU) and irrigation Efficiency values (IE) of the three irrigation schedules performed with variable starting irrigation time [random (R),

alternative (A) and sequential (S)] and the six fixed irrigation starting times (0, 4, 8, 12, 16 and 20 h GMT). The irrigation efficiency (*IE*) of each case is presented at the top of the figure.

Figure 9. Limited wind irrigation schedule. Inter-time averages of yield reduction (*YR*) and seasonal irrigation water use (*WU*) for a) Zaragoza, critical stress level of 12 %; and b) Tamarite, critical stress level of 12 %. Time averages are presented for the 24 h of the day.

Figure 1. Localisation of the Zaragoza and Tamarite meteorological stations within Spain, the Ebro Basin and the Aragón Department.

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