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From on-farm solid-set sprinkler irrigation design to collective irrigation network design in windy areas

by

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Abstract

In this paper, a contribution to the design of collective pressurized irrigation networks in solid-set sprinkler irrigated windy areas is presented. The methodology is based on guaranteeing minimum on-farm performance, using a historical hourly wind speed database and a ballistic solid-set irrigation simulation model. The proposed method was applied to the Montesnegros Irrigation District (central Ebro basin, Spain). The district irrigates an area of 3,493 ha using an on-demand schedule. The average wind speed in the area is 2,8 m s^{-1}. An analysis of district water records showed that farmers often reduce water demand when the wind speed is high, but their irrigation

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decision making is limited by the capacity of the irrigation network and by the unpredictable character of local winds. Simulations were performed for eleven irrigation seasons, two triangular sprinkler spacings (18x18 and 18x15 m), and two sprinkler models. The percentage of monthly suitable time for irrigation was determined for four management strategies. The first one was based on a wind speed threshold (3 m s^{-1}), while the other three were based on three levels (standard, relaxed and restrictive) of two irrigation performance parameters: the Christiansen Uniformity Coefficient (*CU*) and the Wind Drift and Evaporation Losses (*WDEL*). The thresholds for the standard strategy were *CU* ≥ 84% and *WDEL* ≤ 20%. The suitable time for the first strategy (56%) was always lower than for the standard and the relaxed strategies (with respective average values of 75 and 86%), and higher than for the restrictive strategy (30%). In order to design the collective network, the hydrant operating time was equalled to the suitable time for irrigation. The differences in the cost of the collective network plus the on-farm equipment were particularly relevant between the restrictive strategy and the other three. Differences in suitable operating time were clear between sprinkler spacings, and less evident between sprinkler models. The application of the proposed methodology may be limited by the availability of historical wind speed records and *CU* estimates for different combinations of sprinkler models, sprinkler spacings and wind speed.

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Introduction

The design of collective pressurized water distribution networks has been the subject of a number of research works, due to the relevance of its economic, environmental and social aspects (Alperovits and Shamir, 1977; Goulter and Morgan, 1985; Savic and Walters, 1997; Lansey et al., 1989). The design objective is to obtain networks which are flexible enough to permit efficient on-farm irrigation, leading to high crop yields at moderate investment and operational costs.

Among the different types of irrigation delivery schemes, the on-demand scheme offers the greatest potential (Lamaddalena and Sagardoy, 2000). This scheme provides farmers with great flexibility, allowing them to adjust water application to crop water requirements. On-demand design of collective irrigation networks must meet the discharge requirements during the peak period. A minimum hydrant pressure must also be guaranteed to ensure appropriate on-farm performance.

One of the main design problems of large, collective water supply and distribution systems lies in the estimation of hydrant discharge during the peak period. Since the probability of having all the network hydrants simultaneously open is very low, probabilistic criteria have been widely used to determine flow rates at the design stage (Clément, 1966; Clément and Galand, 1979; Lamaddalena and Sagardoy, 2000). This classical approach uses only one flow regime (corresponding to the peak period) to design the network. One of the key parameters of this approach is the hydrant available operating time (as a percent of the total time). The uncertainty of water demand has been widely researched in the context of urban water networks (Lansey et al., 1989; Lansey, 2000; Babayan et al., 2004; Farmani et al., 2005).

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Several authors have argued that farmers' application criteria and preferences are not included in the probabilistic approach (D´Urso et al., 1995; Pulido-Calvo et al, 2003), while these issues have a relevant effect on network performance. Pulido-Calvo et al. (2003) presented a method in which different working probabilities were assigned to each hydrant depending on energy costs (these costs may vary during the day). Monserrat et al. (2004), presented an analysis of the Clèment´s first formula, comparing it to real data from two irrigation networks. These authors found that differences between the demand simulated by Clément and the real demand were smaller than 9.4% for a wide range of operating conditions. Planells et al. (2005) presented a process of daily random generation of demand curves applied to the problem of pumping requirements in on-demand irrigation networks.

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In windy solid-set sprinkler-irrigated areas, the farmers' application criteria greatly influence the working probability of the hydrants. Farmers frequently avoid irrigation under windy conditions because of higher wind drift and evaporation losses (Frost and Schwalen, 1955; Tarjuelo et al., 2000; Playán et al., 2005) and lower irrigation uniformity (Dechmi et al., 2003b; Dechmi et al., 2004). Neglecting wind-induced farmers' criteria could lead to a severe underestimation of the peak flow and therefore of the system capacity. As a consequence, wind-wise, efficient irrigation management would be greatly difficulted. Although wind speed is the most important meteorological variable affecting sprinkler irrigation performance (Playán el al., 2005), its effect is conditioned by other technical variables such as sprinkler spacing, operating pressure, nozzle diameter and sprinkler type (Keller and Bliesner, 1990, Tarjuelo et al., 1992).

According to Vories et al. (1987), wind effects should be considered when designing a solid-set sprinkler irrigation system in an area subjected to nearly constant wind speed and direction. While in some areas the wind direction shows a clear pattern, Dechmi et al. (2003b) reported that wind direction and, particularly, wind speed are often subjected to a large variability within a given day and among days. These same authors concluded that this time variability poses a serious limitation to the adequate design of sprinkler irrigation systems and makes water management a difficult task.

Solid-set sprinkler irrigation simulation models based on ballistic theory have been developed in the last decades (Fukui et al, 1980; Carrión el al., 2001; Montero et al., 2001; Dechmi et al., 2004; Lorenzini, 2004). Since an intense process of calibration and validation is required for each combination of sprinkler, nozzle and operation conditions, only a few applications of ballistic models have been reported (Montero et al, 2001; Playán et al, 200Xb). Modelling techniques permit to reproduce a given on-farm irrigation event subjected to different technical and meteorological conditions. As a consequence, simulation models can be used to improve on farm and network irrigation design in windy areas.

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This paper presents a contribution to the design of collective pressurized irrigation networks in solid-set sprinkler irrigated windy areas. A methodology to characterise the combined effects of wind speed and on-farm irrigation design variables is presented. This methodology was applied to determine the suitable time for irrigation in a windy district, using a meteorological data series of eleven years in combination with a ballistic simulation model. The methodology is based on adopting minimum thresholds for irrigation performance parameters and establishing the available operating time as the time when those thresholds are exceeded.

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Materials and Methods

Solid-set sprinkler Irrigation District description

The Montesnegros Irrigation District is located near Bujaraloz (Aragón region, central Ebro valley, Spain). The district, with an irrigated area of 3,493 ha, is solid-set sprinkler irrigated with an on-demand schedule. The irrigation network has 405 hydrants. The total network discharge is recorded at the pumping station SCADA every five minutes. The maximum network capacity is 241,920 m^3 d^{-1}. The district area is classified as windy (Puicercús et al., 1994), since the average daily wind speed (2.8 m s^{-1}) exceeds 2 m s^{-1}. The district shows a clear pattern for wind direction, particularly when the average daily speed is exceeded. Water allocation data for the 2001 and 2002 irrigation seasons were available at the Irrigation District database. The Ador software (Playán et al., 200Xa) was used at the district office to store and process water meter readings and the crops associated to each plot, among other variables.

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Meteorological data

Meteorological data were recorded using an automatic meteorological station located within the Irrigation District area (41°31′25′′ N, 0°10′24′′ W). Hourly averages of wind speed (*U*, m s^{-1}), air temperature (*T*, ºC), and relative humidity (*RH*, %) were recorded for 11 years (from 1993 to 2003). Only the hourly data belonging to the irrigation season (April to September) were analysed. Reference crop evapotranspiration was determined at the study area for the 2001 and 2002 irrigation seasons using the Hargreaves equation (Hargreaves and Samani, 1985). Local crop coefficients (Tejero, 2003) were combined with reference crop evapotranspiration and effective precipitation to estimate crop water requirements.

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Description of the solid-set simulation model

A sprinkler irrigation simulation model based on ballistic theory was used to simulate irrigation events in the Montesnegros Irrigation District. In ballistic models, a sprinkler is simulated as a device emitting drops of different diameters. It is assumed that drops are formed at the sprinkler nozzle, and travel independently until reaching the soil surface (or the crop canopy). In the absence of wind, and for a given sprinkler configuration, the horizontal distance between the drop landing point and the sprinkler nozzle is a function of the drop diameter. Ballistic theory is used to determine the trajectory of each drop diameter subjected to an initial velocity vector and a wind vector. The action of gravity (acting in the vertical direction) and the resistance force (opposite to the drop trajectory) complete the analysis of forces acting on the water drop. General details about the construction and testing of ballistic models can be found in Fukui et al. (1980) and Carrión et al. (2001).

The model used in this work was presented by Playán et al. (200Xb) and has been calibrated and validated for two sprinkler types: "VYR-70", manufactured by VYRSA (Briviesca, Burgos, Spain) and "RC-130H" manufactured by Riegos Costa S.L. (Lleida, Spain) (the citation of commercial trademarks does not imply endorsement). Both sprinkler models are frequently installed in the central Ebro valley of Spain. Two principal nozzle diameters (4.0 and 4.4 mm) plus an auxiliary 2.4 mm nozzle were used in the calibration and validation process, operating in a wide range of pressures (200-400 kPa) and wind speeds.

Model application

The model requires a combination of meteorological and operational conditions in order to simulate an irrigation event. Meteorological conditions were derived from

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the eleven seasonal data sets. The total number of hours in each data set represents the potential available time for irrigation. Two sprinkler spacings were simulated: a triangular spacing with a distance of 18 m among irrigation lines and 18 m between sprinklers within the same irrigation line (T18x18), and a triangular spacing with a distance of 15 m among irrigation lines and 18 m between sprinklers within the same irrigation line (T18x15). The selected spacings are the two common choices for new solid-sets in the area. The two calibrated sprinklers, "VYR-70" and "RC-130H", were considered in this application. In both cases the diameter of the principal nozzle was 4.4 mm, the usual choice for the selected sprinkler spacings. The simulated pressure at the sprinkler nozzle was 300 kPa, a common local target. Simulations were performed for each hourly meteorological record, for both sprinklers and for the two selected sprinkler spacings.

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Data analysis

Six intervals were used to characterize wind speed in the study area (Dechmi et al., 2004). The frequency corresponding to each interval was calculated on a monthly basis for the eleven irrigation seasons. Daily district water delivery for the seasons 2001 and 2002 was contrasted with wind speed in order to assess the current irrigation management practices. Relationships between water delivery and different wind conditions were established. Monthly day and night water deliveries were also characterised for the two seasons. Water delivery from 7:00 GMT to 19:00 GMT was considered as day time delivery. The remaining daily water allocation was considered as night time delivery.

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The suitable time for irrigation (%) was determined following four irrigation management strategies. The first strategy was established taking into consideration the wind speed limit for sprinkler irrigation operation reported by Tarjuelo et al. (1992). These authors proposed a threshold of 3 m s^{-1} for irrigation operation in a triangular 18 m x 18 m sprinkler spacing. For this first irrigation management strategy, the hours with a wind speed exceeding 3 m s^{-1} were classified as non suitable for irrigation. The three remaining strategies were established taking into account two irrigation performance parameters: the Christiansen Uniformity Coefficient (*CU*) (Burt et al., 1997) and the Wind Drift and Evaporation Losses (*WDEL*), expressed as a percentage of the emitted discharge. The following equation, developed for day and night operation (Playán et al., 2005), was implemented in the model to estimate *WDEL* from meteorological data:

$$WDEL = 24.1 + 1.41\,U - 0.216\,RH \qquad [1]$$

The second management strategy was based on threshold values for *CU* and *WDEL*: irrigation can only be performed if $CU \geq 84\%$ and $WDEL \leq 20\%$. The threshold value of *CU* was selected following the recommendation by Keller and Bliesner (1990). The threshold value of *WDEL* was taken from Martinez-Cob et al. (2005), who presented values of *WDEL* averaging about 20% in local windy areas. This management strategy was considered as “standard”, and the remaining two strategies include threshold values deviating from the standard. The third management strategy, denoted “restrictive”, was characterised by $CU \geq 90\%$ and $WDEL \leq 15\%$. This criterion could be adequate in irrigation districts with high water costs and/or high crop values and/or water scarcity. The fourth management strategy, denoted as “relaxed” was characterised by $CU \geq 80\%$ and $WDEL \leq 25\%$.

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The four abovementioned management strategies were compared in terms of suitable time for irrigation (average and 20% return probability). Comparisons between the different on-farm technical configurations (two sprinklers x two spacings) were also established. The four strategies and the different on-farm configurations were also compared in economic terms for the conditions of the central Ebro Valley. The comparison was only established in terms of the irrigation investment costs, considering the collective network and the on-farm equipment. Investment was expressed in terms of total cost (€ ha^{-1}) and yearly payback cost (€ ha^{-1} yr^{-1}).

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The construction cost (€ ha^{-1}) of a new irrigation network designed for different values of hydrant operating time (determined in this paper as the suitable time for irrigation) was estimated for the conditions of the Callén Irrigation District. This district is located in the vicinity of the Montesnegros district, and its pressurized network is currently being designed as part of an irrigation modernization project. Having similar extension, meteorology and irrigation layout, the network construction costs (€ ha^{-1}) of both districts are expected to be similar. The investment cost of on-farm irrigation equipment was estimated for the T18x18 and T18x15 solid-set spacings. The cost of the solid-set did not depend on the choice of sprinkler model, since their prices are similar. The yearly irrigation investment payback was determined considering a lifespan of 50 years, and following the current financing conditions set-out by the local banks.

Finally, the time distribution of the non suitable hours for irrigation was analysed. The monthly number of groups of 1/3, 1, 2, 3 and 4 days non suitable for irrigation was established for the four management strategies and for the four on-farm

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technical configurations. Average, maximum, minimum and 20% return probability statistics were determined for each case.

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Results and discussion

Field crops are grown in the wide majority of the district area, with corn and alfalfa being the most frequent. For the two analysed irrigation seasons, a decrease in percent corn area was observed: from 64% to 55%. An increase of the same order was observed for alfalfa: from 24% to 32%. Horticultural crops follow in this ranking, and are characterised by a slight increment in time: from 4% to 6%. The area devoted to winter cereals (4%) and fallow (4%) remained constant during the two seasons.

Figure 1 presents the daily net irrigation requirements and water deliveries for the Montesnegros Irrigation District during the 2001 and 2002 seasons. Adequate agreement between both variables was generally observed. Figure 1 shows that the irrigation network operated at maximum capacity (241,920 m^3 d^{-1}), and even slightly beyond this limit, throughout the peak period of crop irrigation requirements, around July. A limited network capacity resulted in relatively stable maximum values of daily water deliveries during the peak of the season.

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Meteorological data

The characterization of wind speed at the study area for the eleven year data set is presented in Figure 2. April is the month most affected by high wind speeds (in 45% of the time the wind speed exceeds 3 $m\ s^{-1}$), followed by July (in 38% of the time the wind speed exceeds 3 $m\ s^{-1}$). April is the windiest month, while July shows the highest monthly crop water requirements (Figure 1).

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Figure 3 presents the evolution of water delivery and wind speed for April and July, and for the two analysed irrigation seasons (2001 and 2002). Wind speed peaks generally result in reduced water delivery (e.g., the two windy periods of mid July

2001). A regression analysis revealed that wind speed can explain 8,2% and14,1% of the variability in water delivery in April and July, respectively. The difference between both months is partly due to the fact that crop water requirements increase during the month of April, and remain fairly stable during July (Figure 1). Although both regressions are highly significant ($P < 0.001$ in both cases), the predictive capacity of the resulting models is very low, suggesting that wind speed can only explain the variability of water delivery under certain circumstances. Further to this analysis, Table 1 presents the water deliveries (L s^{-1}) for April and July, for the two seasons. Average values are presented for periods over and below wind speed thresholds of 3.0 and 4.5 m s^{-1}. Day and night water deliveries are also presented in Table 1. In April of both irrigation seasons, the water delivery pattern showed a clear response to wind speed. The April ratio between average daily water delivery over and below 3.0 m s^{-1} was computed as 0.67 and 0.62 for 2001 and 2002, respectively. In July, this ratio adopted values of 0.87 and 0.95 for 2001 and 2002, respectively. Similar results were found for the 4.5 m s^{-1} threshold, although farmers were more effective avoiding wind speeds over 4.5 m s^{-1} than they were for 3.0 m s^{-1}.

Farmers' selection of low winds was not particularly effective in April, when the network capacity permits to select the adequate irrigation timing. In July, farmers tended to avoid large winds, but seemed to be constrained by the network capacity. In many areas of the world, wind speeds are much lower during the night time than during the day time. As a consequence, night irrigation is frequently advised to optimise irrigation efficiency. In the Montesnegros District, day and night water delivery are very similar in April and July. The day/night delivery ratio was computed as 0.93 for both April and July, for 2001, and as 0.87 and 0.93 for April and July, respectively, for 2002. These small differences are supported by intense night winds in the area, with average day/night wind speed ratios of 1.25 and 1.18 for April and July,

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respectively. In the absence of a clear day/night wind pattern, attaining high irrigation efficiency will depend more on reacting to the actual wind conditions than on applying preset irrigation rules.

The Montesnegros District water delivery pattern seems to unveil relevant network capacity restrictions. As a consequence, farmers could not successfully deal with high wind speeds and high crop water requirements at the same time, and saw themselves forced to irrigate under unsuitable environmental conditions. The fact that in April farmers only moderately succeed to select adequate winds could be due to the absenteeism promoted by the generalised use of on-farm irrigation programmers. In July, when crop water requirements reach peak values and the network operates at full capacity, farmers often use a fixed irrigation schedule in their programmers, regardless of wind speed.

The relationship between yield and irrigation uniformity in solid-set sprinkler irrigation has been described in the literature (Li, 1998; Dechmi et al., 2004). In the case of corn, this relationship is particularly significant during the month of July. The combination of peak water requirements and drought sensitivity makes this month a critical period for the analysis of the suitable time for irrigation in the study area.

Suitable time for irrigation

Table 2 presents the results for the first irrigation strategy ($U < 3 \text{ m s}^{-1}$), which does not depend on farm design variables. The monthly percentage of suitable hours is presented for each year and month of the irrigation season. Results are also presented for the average year and for the 20% return probability. Differences between years are relevant, with coefficients of variation of 20% for April and 14% for July. When it comes to comparing design oriented strategies, the season with a 20% return probability is more adequate than the average season. Following this criterion, April is the most restrictive month in terms of suitable hours (48%). As previously discussed, July is the most restrictive in terms of crop water requirements, and is characterised by a percentage of suitable hours of 56%. For the whole irrigation season, 62% of the irrigation time is suitable for sprinkler irrigation (20% return probability).

Table 3 presents the monthly percentage of suitable hours for the standard management strategy. Results are presented for the two sprinkler types (VYR-70 and RC-130H) and for the two triangular sprinkler spacings (T18x18 and T18x15). Overall, April is the most restrictive month, while August is the least restrictive. There is a clear difference on suitable time between sprinkler spacings, with the ample spacing resulting in lower suitable time than the narrow spacing (19% difference in seasonal terms for the 20% return probability). Comparing sprinkler types, in the ample spacing VYR-70 performs better than RC-130H. In the narrow spacing the performance of both sprinklers is similar, with VYR-70 showing a small advantage. Focusing on July, the highest suitable time is obtained with a VYR-70 sprinkler installed in a T18x15 spacing. This configuration is characterised by 85% of suitable hours (with a 20% return probability). The opposite choice for July (RC-130H and T18x18) is characterised by 63% of suitable hours. In this particular case, the choice of sprinkler model and a small difference in sprinkler spacing results in 22% difference in suitable time. Such a difference can play a major role in water use and/or crop yield.

The percentage of monthly suitable hours for irrigation for the restrictive strategy is presented in Table 4. Restrictions on irrigation performance parameters drastically decrease the suitable time for irrigation. For the 20% return probability, the percentage of suitable hours in July ranges from 22 to 35%, depending on the irrigation hardware. Between months, April is always the most restrictive. The difference between sprinkler spacings is not as clear as in the standard strategy. For VYR-70 the narrow spacing (T18x15) performs better than the ample spacing (T18x18), with a difference of 4% on July, and of 2% in seasonal terms. In the case of RC-130H the results do not follow the usual trend, and the ample spacing outperforms the narrow spacing by a seasonal difference of 11%. The difference between sprinkler types is not clear for the ample spacing, while for the narrow spacing VYR-70 performs better than RC-130H (with a seasonal difference of 15%).

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Table 5 presents the monthly percentage of suitable hours for irrigation for the relaxed strategy. The decrease on the irrigation performance thresholds results in a general increase of the suitable irrigation time, as compared with the two abovementioned strategies. The choice of sprinkler spacing greatly affects the time availability, with the narrow spacing presenting 21% more suitable time than the ample spacing (20% return probability). The differences between sprinkler models are larger for the ample spacing than for the narrow spacing, with VYR-70 showing better performance than RC-130H.

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Figure 4 presents the percentage of suitable hours for irrigation in July for the four analysed strategies. For the strategies based on simulation results, Figure 4 presents data for the four analysed combinations of sprinkler models and spacings. The suitable time for irrigation for the first strategy (56%) is comparable to the standard strategy for the RC-130H sprinkler model at a T18x18 spacing (63%). The other three on-farm hardware combinations present larger suitable time percentages. The suitable time for the first strategy (U < 3 m s^{-1}) is always lower than for the standard and the relaxed strategies (with respective average values of 75 and 86%), and higher than for the restrictive strategy (average suitable time of 30%). The difference between the standard and the relaxed strategies is moderate (11%), while the difference

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between the standard and the restrictive strategies is very important (45%). Table 6 presents the average values for *U*, *CU* and *WDEL* for each combination of management strategy and on-farm equipment. In the case of the first management strategy ($U < 3$ m s^{-1}), different values of *CU* are presented for each on-farm configuration, as obtained with the simulation model. Differences between strategies for average *U*, *CU* and *WDEL* are not particularly important, since the thresholds of all strategies were exceeded in a large part of the total number of irrigation hours.

The standard strategy reveals relevant differences between sprinkler spacings, and moderate differences between sprinkler types. On the average, the T18x15 spacing permits to irrigate in 83% of the time, while the T18x18 spacing reduces the suitable time to 67%. This 16% difference can be very relevant in terms of irrigation design and management. It is worth noting that the difference in sprinkler irrigated area between both spacings also amounts to 16%. Regarding sprinkler models, they show a moderate difference of 6%, with absolute values of 78 and 72% for VYR-70 and RC-130H, respectively.

A low suitable time for irrigation implies that crop water requirements must be fulfilled in a short period of time. As a consequence, the capacity of the irrigation network (pipeline diameters and hydrant capacities) must be enlarged, resulting in increased investment costs. Irrigation Districts combining meteorological constrains (high wind speeds), high crop water requirements and low water productivity (derived from low income crops) will not be able to afford the high performance provided by the restrictive management strategy. Montesnegros and a number of other Irrigation Districts in the central Ebro Valley of Spain combine all the abovementioned constrains.

The analysis above reveals that the choice of a management strategy is linked to the choice on-farm irrigation hardware (i. e., the sprinkler model and spacing). The suitable time for irrigation (the hydrant operating time) is one of the main input variables in collective irrigation network design. In parallel, all these decisions influence crop agronomy, yield and water use. A complete economic analysis is required to determine the most convenient management strategy in each particular case. The analysis used in this paper does not permit to draw conclusions on crop yield differences among strategies, thus restricting the possibility of applying a complete economic analysis. In order to illustrate the economic implications of the management strategies, one relevant economic variable will be discussed: the construction cost of the irrigation district.

Construction costs: irrigation network and on-farm equipment

An approximation to the construction cost of an irrigation district in the study area is presented in Table 6 for each management strategy and on-farm hardware configuration. Differences in network investment resulted important, particularly between the restrictive strategy (averaging 7,444 € ha^{-1}) and the other three (averaging 5,145, 4,675 and 4,456 € ha^{-1} for the $U < 3$ m s^{-1}, standard and relaxed strategies, respectively). The network investment cost was inversely proportional to the operating time. When all investment costs were considered, the strategies could be ranked as: relaxed < standard < ($U < 3$ m s^{-1}) < restrictive (with average values of 8,003, 8,222, 8,692 and 10,990 € ha^{-1}, respectively). The analysis of the yearly investment payback produced the same ranking. For the standard management strategy, installing a T18x15 spacing resulted 135 € ha^{-1} more expensive than installing a T18x18, while installing RC-130H sprinklers resulted in an extra investment of 144 € ha^{-1}, as compared to VYR-

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70 sprinklers. For this particular strategy, the choice of on-farm irrigation hardware did not seem particularly relevant in terms of overall investment cost (less than 2%).

Distribution of the non suitable time for irrigation

The distribution of non suitable time for irrigation is not homogeneous in time. In the local conditions, windy periods can last for several days, seriously affecting irrigation management. Consideration of suitable time for sprinkler irrigation at the design phase will facilitate irrigation management when these events arise. However, the coincidence of critical crop water requirements and long periods of high wind speed will cause severe management problems.

Table 7 presents some statistics about the number of groups of 1/3, 1, 2, 3 and 4 contiguous days of unsuitable time for sprinkler irrigation. These data are presented for the two sprinkler types, the two sprinkler spacings, the two months (April and July) and the four management strategies. Data are presented in average, maximum, minimum and 20% return probability terms. Although the discussion below focuses on the 20% return probability, all four statistics are presented to illustrate the variability in windy periods.

For the four analysed strategies, April is the most critical month in terms of contiguous non adequate days for irrigation. These data confirm the previous discussion abut wind in April (see Tables 2 to 5). Although evapotranspiration is low in April, water application in the area is relevant in many crops due to emergence irrigations and soil water recharge at the beginning of the season (Figure 1). This is why the analysis of this month is conducted in parallel to July, the month showing critical water requirements.

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The wind speed threshold strategy (U < 3 m s^{-1}) does not depend on on-farm design. As a consequence, the results of this analysis are the same for the four on-farm design configurations. Using the 20% return probability statistic, 30 groups of 1/3 day (8 contiguous hours), 4 groups of 1 day, and 1 group of 2 days of non suitable irrigation time were detected in July. Since the network design criterion for this strategy is 56% suitable hours (13.4 hours of average daily operation), short windy periods (1/3 day) should be easy to accommodate in the irrigation schedule. However, 1 and 2 days of non-irrigation will induce a delay in the farm irrigation schedule that can result in sustained water stress and yield reduction.

The standard strategy shows clear differences between on-farm configurations. The narrow sprinkler spacing (T18x15) results in shorter and less numerous groups of non adequate irrigation periods than the ample sprinkler spacing (for both sprinkler types). The best performing on-farm configuration, sprinkler VYR-70 arranged at T18x15, presents nine periods of 1/3 days and one period of 1 day in July, using the 20% return probability statistic (Table 7). This distribution of non suitable periods does not seem to impose severe limitations to irrigation scheduling. However, since this combination of strategy and hardware is characterised by a network design criterion of 85% suitable hours (20.4 hours of average daily operation), overcoming the unsuitable periods may be challenging at some points during the season. The ample spacing configuration can impose limitations to irrigation scheduling, since 4 or 3 groups of 1 day and 1 group of 2 days of non suitable time for irrigation with 20% of return probability will arise in July.

The restrictive strategy presents the largest and most numerous groups of unsuitable periods for irrigation. Differences between on-farm hardware options are not very clear in this case. In general, RC-130H presents the non suitable hours for irrigation arranged in shorter groups than VYR-70. The narrow spacing results more advantageous than the ample spacing in terms of size and number of non suitable irrigation periods (for both sprinkler types). As previously discussed, the implementation of this strategy in the study area will be very costly and difficult to manage.

The relaxed strategy presents less and shorter groups of contiguous non suitable hours for irrigation than the other analysed strategies. The design criterion for this strategy is based on 5% to 31% non suitable time (depending on on-farm hardware). Considering the best case, corresponding to a T18x15 spacing and a VYR-70 sprinkler, groups of more than 3 contiguous non-suitable hours can already result in management problems. Data not presented reveal that 5 groups of 3 hours will be present in July with a 20% return probability. The number of groups is reduced to 2 when considering periods of 1/3 day (Table 7).

In practical terms, a farmer can implement two management policies to cope with long windy periods. The first policy is to maintain soil water content high, particularly during the peak of the season, when the irrigation systems are working close to full capacity. In the central Ebro valley (and many other semiarid areas) this policy will not represent a significant contribution to the solution of the problem, since soil water retention is typically low (Cavero et al., 2003; Dechmi et al., 2003a). Additionally, this policy could result in deep percolation losses if a heavy rainfall occurred. The second policy is to adapt irrigation scheduling to the actual evolution of wind speed. This will require a very labour intensive irrigation scheduling. As presented in Figure 3, local farmers modify their irrigation schedule in response to

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extreme wind events, and their modifications may result in 50% decrease in water delivery. In our opinion, wind-sensitive irrigation programmers are required in the study area to perform these scheduling adaptations in an automatic fashion.

Since these management policies will not work to perfection in many practical situations, designers should further decrease the percentage of suitable time for irrigation presented in Figure 4. This reduction will provide the slack required to deal with long windy periods. Additionally, a minimum time for network maintenance and repairs must be considered at the design phase. If the percentage of suitable time is low, these operations can be performed during windy periods. The combination of these design and management rules with an adequate on-farm irrigation scheduling will guarantee uniform and efficient irrigation.

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Conclusions

The following can be concluded from this paper:

1. Farmers in the Montesnegros Irrigation District respond to very high wind speeds by reducing water demand. However, they often irrigate under high winds (even exceeding 4.5 m s^{-1}) due to limitations in the collective network capacity and to the difficulty of continuously adjusting their irrigation schedule to an unpredictable wind event.
2. A methodology has been proposed to link on-farm irrigation performance (*CU* and *WDEL*) to hydrant operating time in windy irrigation districts. Three strategies based on irrigation performance were compared with a strategy based on a wind speed threshold.
3. Under the local conditions (meteorology and on-farm equipment), the strategy based on wind speed proved to be too restrictive, leading to low suitable time for irrigation (56%). The standard strategy showed an average percentage of suitable time of 75%. The different choices of sprinkler model and spacing resulted in a range of 63 to 85% suitable time for this strategy. The restrictive strategy resulted technically and economically unfeasible for the local conditions.
4. The applicability of the proposed method is subjected to the availability of wind speed records and *U-CU* relationships for the local on-farm irrigation spacings and sprinklers. This information is not available in most sprinkler irrigated areas in our environment. Our results suggest that wind speed is the most important factor, followed by the choice of sprinkler spacing, and finally by the sprinkler model.
5. The proposed design methodology could be improved by linking irrigation performance to crop performance, using a crop model. In this way, the irrigation structures could be designed to meet crop yield or water productivity targets.

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6. Sustainable sprinkler irrigated agriculture in windy areas will require proper design and management. Flexible networks, designed to apply crop water requirements in periods of low wind, will not result in high efficiency unless farmers apply wind-wise irrigation scheduling. New irrigation programmers are required that incorporate wind sensors and produce real-time irrigation schedules optimizing irrigation performance, crop yield or water productivity.

Acknowledgement

This research was funded by the CICYT of the Government of Spain through grant AGL2004-06675-C03-03/AGR and by the Government of Aragón through grant PIP090/2005 . We are very grateful to the Montesnegros Irrigation District (Bujaraloz, Zaragoza, Spain) for their co-operation in data retrieval and for their support in the field work. Thanks are particularly due to the district manager, Carmelo Lorente.

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Table 5. *Monthly percentage of suitable hours for sprinkler irrigation for the eleven season data set at the Montesnegros Irrigation District. Data are presented for two sprinkler types (VYR-70 and RC-130H) and two triangular sprinkler spacings (T18x18 and T18x15) for the relaxed management strategy. The monthly average and the 20% return probability (20% RP) are also presented.*

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Table 6. *Average wind speed (U) Coefficient of Uniformity (CU), Wind Drift and Evaporation Losses (WDEL) irrigation investment (network, on-farm and total), and yearly investment payback determined for the four discussed management strategies and their combinations of sprinkler type and spacing.*

Table 7. *Number of groups of 1/3, 1, 2, 3 and 4 days non suitable for sprinkler irrigation for two sprinkler types and two sprinkler spacings. The average, maximum, minimum and 20%*

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return probability (20% RP) statistics are presented for April and July for the four management strategies.

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Table 1. *Average daily water deliveries (L s^{-1}) and ratios for periods with wind speeds below or over thresholds of 3.0 and 4.5 m s^{-1} and for day and night time. Data are presented for April and July of the 2001 and 2002 irrigation seasons.*

	April			**July**		
	2001	**2002**	**Average**	**2001**	**2002**	**Average**
U $\leq$ 3 m s^{-1}	1,681	1,032	1,262	2,852	2,748	2,807
U > 3 m s^{-1}	1,128	638	945	2,485	2,599	2,557
U$\geq$3/U$\leq$3	0.67	0.62	0.75	0.87	0.95	0.91
U $\leq$ 4.5 m s^{-1}	1,510	985	1,208	2,822	2,722	2,349
U > 4.5 m s^{-1}	1,022	438	828	2,092	2,539	2,290
U$\geq$4.5/U$\leq$4.5	0.68	0.44	0.69	0.74	0.93	0.87
Day	1,273	823	1,328	2,662	2,543	2,240
Night	1,369	945	884	2,863	2,830	2,446
Day/Night	0.93	0.87	0.90	0.93	0.89	0.91
Average	1,323	884	1,100	2,762	2,686	2,724

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Table 2. *Monthly percentage of suitable hours for sprinkler irrigation for the eleven season data set at the Montesnegros Irrigation District, calculated as the number of hours with average wind speed lower than 3 m* s^{-1}*. The monthly average and the 20% return probability are also presented.*

Year	APR (%)	MAY (%)	JUN (%)	JUL (%)	AUG (%)	SEPT (%)
1993	53	66	60	58	87	80
1994	38	63	47	56	45	74
1995	65	73	71	65	61	51
1996	59	69	65	64	69	58
1997	66	73	64	63	85	86
1998	48	63	62	48	60	61
1999	51	64	70	66	83	85
2000	56	75	64	53	68	76
2001	37	80	67	76	73	60
2002	63	49	61	58	65	78
2003	68	60	79	74	93	80
Average	55	67	65	62	72	72
20% RP	48	63	61	56	61	60

Table 3. *Monthly percentage of suitable hours for sprinkler irrigation for the eleven season data set at the Montesnegros Irrigation District. Data are presented for two sprinkler types (VYR-70 and RC-130H) and two triangular sprinkler spacings (T18x18 and T18x15) for the standard management strategy. The monthly average and the 20% return probability (20% RP) are also presented.*

Spacing	Year	VYR-70						RC-130H					
		APR (%)	MAY (%)	JUN (%)	JUL (%)	AUG (%)	SEP (%)	APR (%)	MAY (%)	JUN (%)	JUL (%)	AUG (%)	SEP (%)
T 18X18	1993	61	80	73	83	96	86	53	70	66	73	94	82
	1994	42	74	61	77	62	79	39	66	52	65	50	76
	1995	72	82	81	81	78	64	67	77	75	73	68	56
	1996	69	79	76	80	82	70	62	72	69	69	75	62
	1997	74	84	77	75	94	93	70	77	69	67	90	89
	1998	55	73	74	68	71	70	49	67	67	56	64	64
	1999	56	74	85	83	94	91	52	67	77	72	89	88
	2000	64	83	85	67	84	82	58	78	81	59	76	79
	2001	45	85	78	86	85	71	39	82	73	81	79	64
	2002	68	57	74	70	76	85	64	51	68	63	68	80
	2003	73	72	92	89	98	88	69	66	85	78	96	83
	Average	62	77	78	78	84	80	57	70	71	69	77	75
	20% RP	55	73	74	70	76	70	49	66	67	63	68	64
T 18X15	1993	84	92	84	87	99	94	81	92	81	86	99	93
	1994	56	86	76	91	84	87	51	85	73	88	77	85
	1995	89	91	89	92	90	80	85	89	87	90	87	78
	1996	84	90	88	91	93	83	81	88	85	89	90	81
	1997	87	94	89	86	97	98	83	92	86	84	96	97
	1998	72	89	88	80	88	81	70	87	85	77	85	77
	1999	72	88	96	92	99	96	69	85	95	90	99	96
	2000	85	93	93	77	94	90	82	92	91	74	92	88
	2001	66	93	87	92	94	83	62	91	86	92	91	81
	2002	84	77	82	85	87	93	81	73	81	81	84	92
	2003	85	88	98	98	100	96	82	84	98	96	100	95
	Average	78	89	88	88	93	89	75	87	86	86	91	88
	20% RP	72	88	84	85	88	83	69	85	81	81	85	81

Table 4. *Monthly percentage of suitable hours for sprinkler irrigation for the eleven season data set at the Montesnegros Irrigation District. Data are presented for two sprinkler types (VYR-70 and RC-130H)and two triangular sprinkler spacings (T18x18 and T18x15) for the restrictive management strategy. The monthly average and the 20% return probability (20% RP) are also presented.*

Spacing	Year	VYR-70						RC-130H					
		APR (%)	MAY (%)	JUN (%)	JUL (%)	AUG (%)	SEP (%)	APR (%)	MAY (%)	JUN (%)	JUL (%)	AUG (%)	SEP (%)
T 18X18	1993	25	43	39	10	15	60	26	41	31	22	62	42
	1994	26	38	30	31	28	63	21	35	26	31	25	33
	1995	45	44	52	41	38	28	35	43	42	37	31	30
	1996	35	47	40	41	46	41	29	39	38	32	35	29
	1997	49	51	43	43	67	62	27	40	31	32	36	52
	1998	28	39	42	24	42	41	28	34	35	25	33	39
	1999	34	44	45	45	62	71	26	34	34	33	47	41
	2000	33	53	15	34	33	56	31	44	32	33	41	45
	2001	22	60	49	57	54	40	20	45	39	44	43	28
	2002	42	30	40	39	45	58	35	32	37	32	37	37
	2003	52	37	57	56	79	60	36	34	44	38	46	42
	Average	35	44	41	38	46	53	29	38	35	33	40	38
	20% RP	26	37	39	31	33	41	26	34	31	32	33	30
T 18X15	1993	26	45	42	11	30	62	31	30	24	39	61	24
	1994	27	40	32	35	31	64	15	30	23	30	21	21
	1995	46	49	55	46	40	30	24	30	23	29	27	31
	1996	36	49	43	45	49	42	25	25	28	27	25	23
	1997	51	53	45	46	71	66	18	23	23	25	19	24
	1998	29	41	44	27	45	43	26	29	25	29	24	22
	1999	35	45	48	48	65	72	19	23	28	28	23	15
	2000	34	55	21	38	40	59	30	26	39	21	37	24
	2001	23	62	52	61	58	43	19	23	25	21	21	23
	2002	43	31	43	41	48	60	23	24	27	22	23	22
	2003	53	40	61	59	82	62	21	26	25	24	17	22
	Average	37	46	44	42	51	55	23	26	26	27	27	23
	20% RP	27	40	42	35	40	43	19	23	23	22	21	22

Table 5. *Monthly percentage of suitable hours for sprinkler irrigation for the eleven season data set at the Montesnegros Irrigation District. Data are presented for two sprinkler types (VYR-70 and RC-130H) and two triangular sprinkler spacings (T18x18 and T18x15) for the relaxed management strategy. The monthly average and the 20% return probability (20% RP) are also presented.*

Spacing	Year	VYR-70						RC-130H					
		APR	MAY	JUN	JUL	AUG	SEP	APR	MAY	JUN	JUL	AUG	SEP
T 18X18	1993	85	95	88	89	99	96	63	79	72	84	97	86
	1994	56	90	80	94	89	88	42	74	61	74	61	79
	1995	89	92	91	94	92	84	72	82	81	81	76	63
	1996	86	91	90	93	96	86	70	80	75	78	81	71
	1997	88	94	92	90	97	98	75	83	76	75	93	92
	1998	75	90	90	82	92	83	56	73	73	67	70	69
	1999	74	90	97	94	100	97	58	74	84	81	93	91
	2000	87	96	95	80	96	92	66	83	85	66	84	83
	2001	70	93	89	93	96	86	46	85	77	86	84	72
	2002	85	80	85	88	89	94	69	58	73	69	76	86
	2003	86	90	99	99	100	96	74	72	92	88	99	86
	Average	80	91	91	91	95	91	63	77	77	77	83	80
	20% RP	74	90	88	88	92	86	56	73	73	69	70	71
T 18X15	1993	92	98	94	95	99	99	86	98	91	91	99	96
	1994	70	95	92	100	97	94	55	90	83	97	95	90
	1995	95	97	98	98	98	92	89	93	94	96	94	87
	1996	91	96	96	96	99	93	86	91	92	95	97	88
	1997	93	97	97	95	98	100	87	94	95	92	97	99
	1998	86	97	95	93	98	90	76	92	92	85	95	84
	1999	85	94	99	99	100	98	74	90	97	97	100	97
	2000	94	98	98	88	98	96	88	97	95	82	97	94
	2001	83	97	95	96	98	95	70	93	91	94	97	88
	2002	93	89	90	95	93	98	85	80	84	91	88	95
	2003	93	95	100	100	100	99	88	90	100	100	100	97
	Average	89	96	96	96	98	96	80	92	92	93	96	92
	20% RP	85	95	94	95	98	93	74	90	91	91	95	88

Table 6. *Average wind speed (U) Coefficient of Uniformity (CU), Wind Drift and Evaporation Losses (WDEL) irrigation investment (network, on-farm and total), and yearly investment payback determined for the four discussed management strategies and their combinations of sprinkler type and spacing.*

Strategy	Sprinkler model	Sprinkler Spacing	Average U (m s^{-1})	Average CU (%)	Average WDEL (%)	Investment			Investment Payback (€ ha^{-1} yr^{-1})
						Network (€ ha^{-1})	On-farm (€ ha^{-1})	Total (€ ha^{-1})	
U < 3	VYR-70	T18x18	1.8	90.6	13.8	5,145	3,306	8,451	393.4
		T18x15	1.8	91.0	13.8	5,145	3,787	8,932	415.8
	RC-130H	T18x18	1.8	90.5	13.8	5,145	3,306	8,451	393.4
		T18x15	1.8	89.8	13.8	5,145	3,787	8,932	415.8
Standard	VYR-70	T18x18	2.0	89.9	13.6	4,756	3,306	8,062	375.3
		T18x15	2.3	89.9	13.7	4,450	3,787	8,237	383.4
	RC-130H	T18x18	1.8	90.2	13.4	4,940	3,306	8,246	383.8
		T18x15	2.2	89.8	13.7	4,554	3,787	8,341	388.3
Restrictive	VYR-70	T18x18	1.5	91.4	11.3	7,309	3,306	10,615	494.1
		T18x15	1.6	91.5	11.4	7,012	3,787	10,799	502.7
	RC-130H	T18x18	1.9	91.8	11.0	7,250	3,306	10,556	491.4
		T18x15	2.6	91.8	11.5	8,204	3,787	11,991	558.2
Relaxed	VYR-70	T18x18	2.2	89.3	14.1	4,401	3,306	7,707	358.7
		T18x15	2.3	89.6	14.5	4,362	3,787	8,149	379.3
	RC-130H	T18x18	2.0	89.5	14.4	4,763	3,306	8,069	375.6
		T18x15	2.4	89.4	15.1	4,299	3,787	8,086	376.4

Table 7. *Number of groups of 1/3, 1, 2, 3 and 4 days non suitable for sprinkler irrigation for two sprinkler types and two sprinkler spacings. The average, maximum, minimum and 20% return probability (20% RP) statistics are presented for April and July for the four management strategies.*

Strategy	Month		VYR-70										RC-130H									
			T18X18					T18X15					T18X18					T18X15				
		Statistics	1/3	1	2	3	4	1/3	1	2	3	4	1/3	1	2	3	4	1/3	1	2	3	4
$U < 3\ m\ s^{-1}$	APRIL	Average	28	5	1	0	0	28	5	1	0	0	28	5	1	0	0	28	5	1	0	0
		Max	47	12	4	2	1	47	12	4	2	1	47	12	4	2	1	47	12	4	2	1
		Min	18	2	0	0	0	18	2	0	0	0	18	2	0	0	0	18	2	0	0	0
		20% RP	41	7	2	1	0	41	7	2	1	0	41	7	2	1	0	41	7	2	1	0
	JULY	Average	22	3	1	0	0	22	3	1	0	0	22	3	1	0	0	22	3	1	0	0
		Max	35	7	3	1	0	35	7	3	1	0	35	7	3	1	0	35	7	3	1	0
		Min	9	1	0	0	0	9	1	0	0	0	9	1	0	0	0	9	1	0	0	0
		20% RP	30	4	1	0	0	30	4	1	0	0	30	4	1	0	0	30	4	1	0	0
Restrictive Strategy	APRIL	Average	55	10	3	1	0	53	10	3	1	0	55	9	3	1	0	55	8	2	0	0
		Max	63	14	8	2	2	60	12	5	2	1	65	12	6	2	1	64	12	4	0	0
		Min	41	4	1	0	0	39	4	1	0	0	41	5	1	0	0	47	3	0	0	0
		20% RP	62	12	5	2	1	58	12	4	2	1	60	11	4	2	1	59	10	3	0	0
	JULY	Average	39	5	1	0	0	35	7	2	1	0	35	5	1	0	0	43	3	0	0	0
		Max	59	8	3	2	1	54	15	6	3	0	57	8	3	2	1	49	7	2	1	0
		Min	23	2	0	0	0	19	2	0	0	0	20	2	0	0	0	38	1	0	0	0
		20% RP	45	9	3	1	0	41	9	3	1	0	40	6	1	1	0	46	5	1	0	0
Standard Strategy	APRIL	Average	23	5	1	0	0	12	2	0	0	0	27	5	1	0	0	15	3	0	0	0
		Max	45	10	4	2	1	30	5	1	0	0	46	10	4	2	1	34	6	2	0	0
		Min	14	2	0	0	0	5	0	0	0	0	17	3	0	0	0	7	1	0	0	0
		20% RP	27	6	1	0	0	18	4	1	0	0	33	7	2	1	0	20	4	1	0	0
	JULY	Average	12	2	0	0	0	6	1	0	0	0	16	3	1	0	0	7	1	0	0	0
		Max	23	5	2	0	0	15	3	1	0	0	28	7	3	1	0	17	4	1	0	0
		Min	4	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0
		20% RP	18	3	1	0	0	9	1	0	0	0	24	4	1	0	0	11	1	0	0	0
Relaxed Strategy	APRIL	Average	12	2	0	0	0	5	0	0	0	0	23	4	1	0	0	11	2	0	0	0
		Max	31	5	1	0	0	15	0	0	0	0	45	10	4	2	1	28	5	1	0	0
		Min	4	0	0	0	0	1	0	0	0	0	14	2	0	0	0	5	0	0	0	0
		20% RP	17	3	1	0	0	6	0	0	0	0	27	6	1	0	0	18	4	0	0	0
	JULY	Average	5	0	0	0	0	1	0	0	0	0	12	2	0	0	0	4	1	0	0	0
		Max	13	2	0	0	0	6	0	0	0	0	24	6	3	0	0	12	3	1	0	0
		Min	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
		20% RP	7	1	0	0	0	2	0	0	0	0	19	3	1	0	0	7	1	0	0	0

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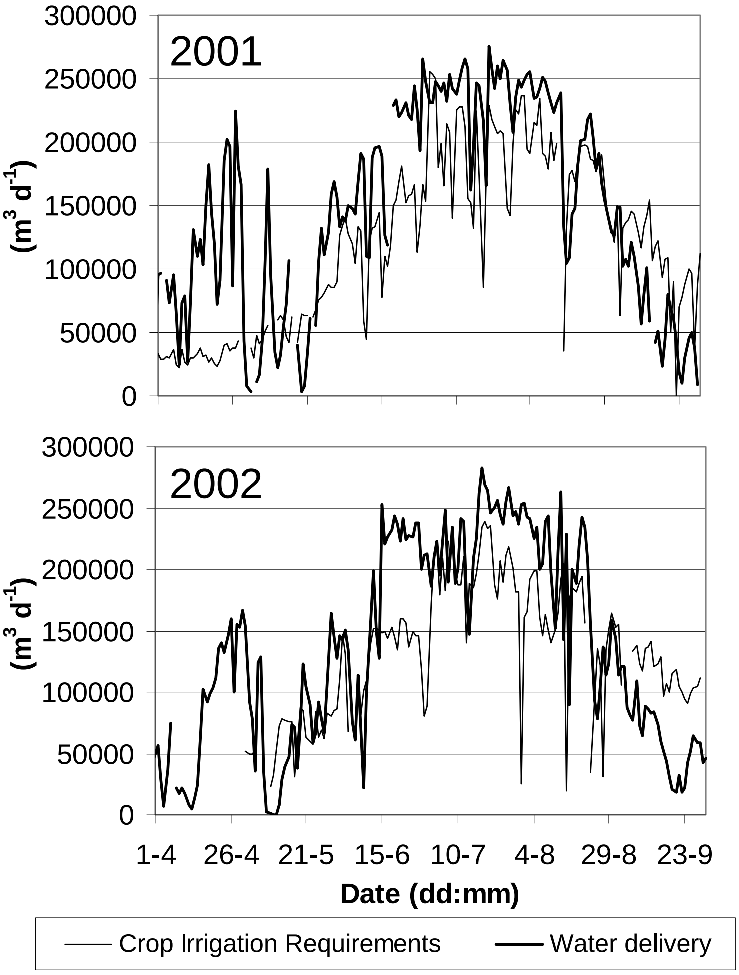

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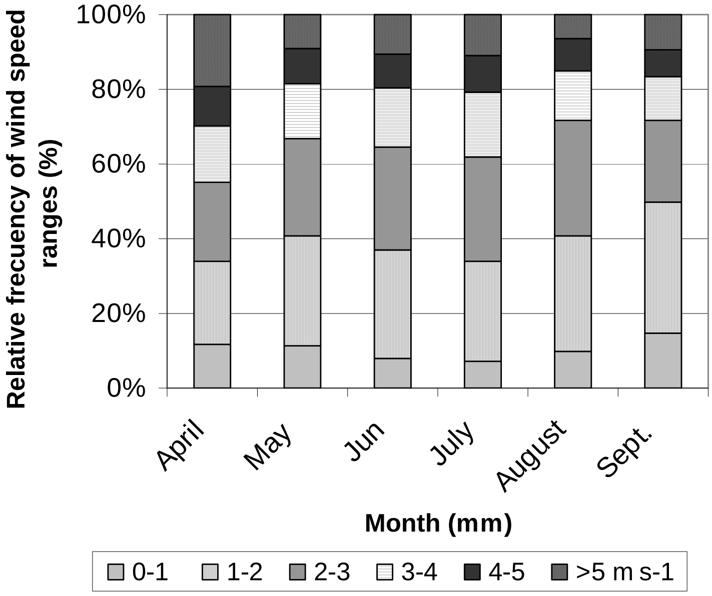

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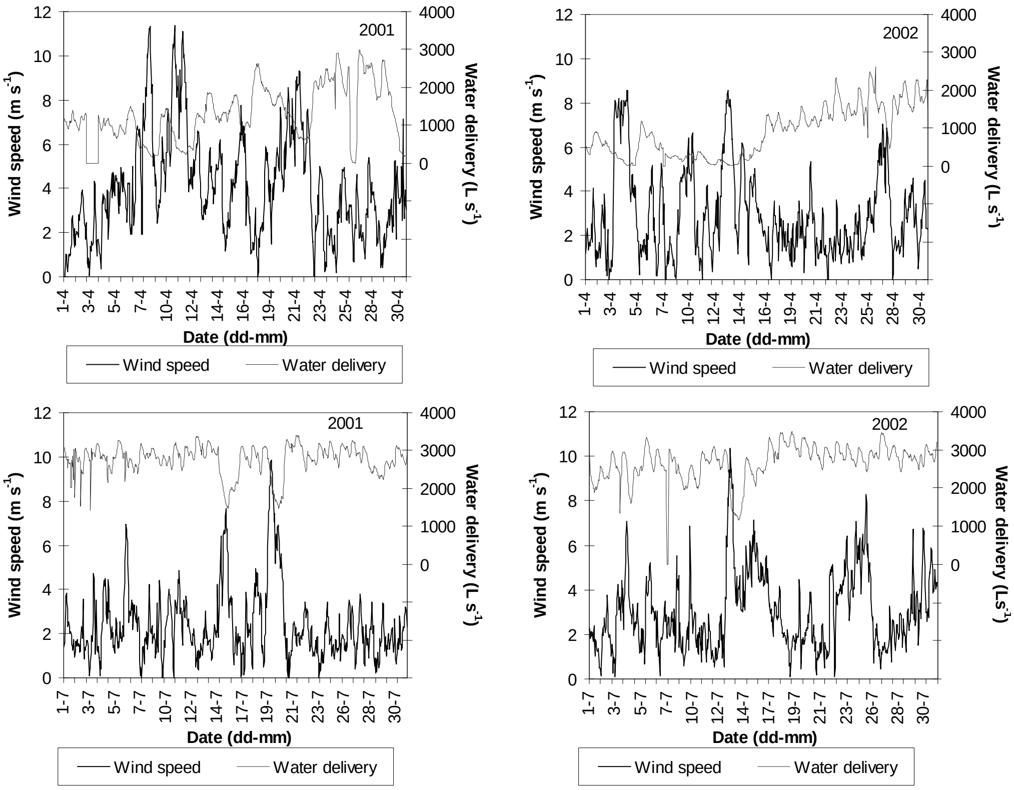

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