The spatial variability of the wind in a sprinkler irrigated district: implications for irrigation management.

by

Sanchez I. [a1], Zapata N. [b], Faci J.M.[a] and Martínez-Cob A. [b]

[a] Unidad de Suelos y Riegos (asociada al CSIC), Centro de Investigación y Tecnología Agroalimentaria (CITA), Gobierno de Aragón. Avenida Montañana 930, 50059, Zaragoza, (Spain).

[b] Dept. Suelo y Agua, Estación Experimental de Aula Dei (EEAD), CSIC, Apdo. 13034, 50080 Zaragoza (Spain).

Corresponding Author**:**

Sanchez Marcos I.
Unidad de Suelos y Riegos (asociada al CSIC), Centro de Investigación y Tecnología Agroalimentaria (CITA), Gobierno de Aragón. Avenida Montañana 930, 50059, Zaragoza, España.
Phone: +34 976 71 6324.
Fax: + 34 976 71 6335.
Email: isanchezm@aragon.es; ingancio@gmail.com

---

[1] Present address: Agrosystèmes et développement territorial (AGIR). Centre de Recherches INRA Toulouse. Chemin de Borde Rouge. Auzeville. 31320 Castanet Tolosan (France).

Abstract

The spatial variability of the wind in the Montesnegros Irrigation District (*MID*), in Spain, has been analysed. From a wind series (2004-2007) registered by the reference weather station, a windspeed > 2 m s^{-1} was observed about 50% of the time. During these periods about 70% of the time it blew from the northwest (known as the *Cierzo*).

Wind was monitored at the reference site and at 17 sites throughout the *MID*. Using regression a series of the local wind velocities for the irrigation seasons 2004 to 2007 were estimated from the reference station data. Wind exposure for 39% of the *MID* area was found to be similar to that of the reference site; 25% were less exposed and 36% considerably more exposed.

The spatial variability of the wind was used to calculate the suitable time for irrigation (*STI*, %) using *Ador-Sprinkler* software. *STI* was simulated for different irrigation systems and strategies: *standard* - Christiansen's uniformity coefficient (*CUC)* > 84% and wind drift and evaporation losses (*WDEL)* ≤ 20%), *restrictive - CUC* ≥ 90% and *WDEL* ≤ 15% *and relaxed - CUC* > 80% and *WDEL* ≤ 25%. At the reference site, *STI* varied from 50 to 56% of the total time during the irrigation season time for *standard strategy*, from 68 to 77% for the *relaxed strategy* and 8 to 30% for the *restrictive strategy*. Excluding the *restrictive strategy*, the least exposed sites averaged 14% greater *STI* than the most exposed sites.

Keywords

Sprinkler; wind; uniformity; water losses; management.

Nomenclature

a.g.l.: Above the ground level.

CUC: Christiansen's uniformity coefficient (%).

GMT: Greenwich meridian time (h).

INM: Spanish Meteorology State Agency.

MCP: Measure-correlate-predict.

MID: Montesnegros irrigation district.

R^2: Coefficient of determination.

RH: Relative humidity of the air (%).

SIAR: Agro-climatic information service for irrigation.

STI: Suitable time for irrigation (%).

WD_z: Wind direction (°) at height z (m) where used.

WDEL: Wind drift and evaporation losses (%).

WV_z: Windspeed (m s^{-1}) at height z (m) where used.

Introduction

The distribution uniformity and application efficiency of sprinkler irrigation systems are potentially high, but these parameters are highly dependent on the weather conditions, especially on wind (Cuenca, 1989; Keller & Bliesner, 1990). Wind strongly affects the sprinkler irrigation performance since it lowers the uniformity and the efficiency of the water distribution (Seginer, Nir, von Bernuth, 1991; Seginer, Kantz, Nir, 1991; Tarjuelo, Carrión, Valiente, 1994; Kincaid, 1996; Dechmi, Playán, Cavero, Faci, Martínez-Cob, 2003; Dechmi, Playán, Cavero, Martínez-Cob, Faci, 2004; Playán et al., 2005; Zapata et al., 2007). Consequently, it is necessary to increase technical knowledge and develop tools that can improve sprinkler irrigation performance in windy conditions.

Wind monitoring is essential to manage sprinkler irrigation districts where moderate or high winds are frequent and extensive. Usually one reference weather station, located close to the irrigation district, is used to assess the water needs of crops for the whole of the area. The information provided by these stations is useful to assess the water needs of crops and to schedule irrigation. However, both can be improved by accounting for the spatial variability of the wind within the irrigation district, a topic commonly disregarded.

The estimation of the wind conditions at sites with no or few records can be performed by linking a location to a nearby place for which a wind series is available. This is based on the idea that within a certain distance, given by the local meso-scale conditions, overall wind conditions are the same (Landberg & Mortensen, 1994). The suitability of the data provided by a meteorological station may vary since its representativeness depends on the complexity of the terrain and nearby obstacles (Troen & Petersen, 1989). Wind close to the

Earth's surface is strongly influenced by the nature of the terrain surface (Petersen, Mortensen, Landberg, Hojstrup, Frank, 1998). The components that cause variation are changes in the land surface and hills (Kaimal & Finnigan, 1994). Wind exposure can vary within an irrigation district, and specific irrigation management may be advisable depending on the degree of exposure. Nevertheless, the problem is complex and scale-dependent (Achberger, Ekström, Bärring, 2002).

Among the methods used to predict the wind resources at target sites, *empirical methods* are based on statistical correlations between the time series from different sites. However, these methods are usually applied to describe general and average conditions rather than to find relationships for short periods such as irrigation events. The Measure–Correlate–Predict (*MCP*) technique is an empirical method often used to estimate the wind parameters at a site (Landberg et al., 2003). It relates the wind measurements at two different sites by means of a regression analysis. Over the last fifteen years, a number of the *MCP* techniques have been proposed. *MCP* algorithms differ in terms of overall approach, model definition, use of direction sectors, data used for the validation and their length, criteria to evaluate the length of concurrent data required and criteria to evaluate the effectiveness of the approach (Rogers, Rogers, Manwell, 1994).

Knowledge of the local wind conditions is an important topic in many applications such as sitting of wind turbines and estimating the environmental impact of air pollution from a point source (Achberger et al. 2002). Important advances have been achieved in the description and modelling of the spatial and temporal variation of the wind within an area. They present a great opportunity to improve the quantification of the crop water needs and scheduling of sprinkler irrigation towards a more efficient use of water.

When farmers are forced to irrigate under unfavourable and prolonged windy conditions, and when the period with low wind is not sufficient to irrigate the whole irrigation district, then average irrigation performance of the district can be improved by including the wind exposure of each zone as a management factor. In addition, the crop rotation schedule needs to be improved by observing the sensitivity of the crops to the irrigation uniformity together with the local wind exposure. The spatial variability of the wind is also a criterion to be included in designing the sprinkler spacings and arrangements adopted in new sprinkler installations. Nevertheless, despite the close relationship between the spatial variability of the wind and sprinkler irrigation performance and scheduling, it is a subject that has not been deeply studied.

During the last two decades, national and regional policies in Spain have encouraged the modernisation of irrigation districts. Recent projects have installed pressurised sprinkler irrigation systems incorporating, in many cases, automation and monitoring systems (MAPA, 2001; Forteza del Rey, 2002; Carrión, Tarjuelo, Montero, 2001). From 2003 onwards, a network of weather stations designated *SIAR* has been deployed in representative Spanish irrigation districts to specifically provide the water needs data for each irrigated zone. These stations provide, amongst other meteorological variables, wind conditions.

Sprinkler irrigation models have been developed in the last decades in Spain (Dechmi et al. 2004; Carrión et al. 2001; Montero, Tarjuelo, Carrión, 2001; Playán et al., 2006). The family of programs *Ador* provides tools for multicriteria decision making in irrigation management including economic, agronomical, technical, environmental and social criteria (Dechmi et al. 2004; Carrión et al. 2001; Montero et al. 2001; Playán et al., 2006; Shkiri, 2007; Playán et al., 2007). These models are valuable tools to simulate the irrigation performance according to meteorological conditions.

The present work was performed in the Montesnegros irrigation district (*MID*), located in the central part of the Ebro river valley (Fig. 1). The *MID* represents an average irrigation district in this windy region. The windspeed at 2 m above the ground level (a.g.l.) (WV_2) in the *MID* is, on average, 2.8 m s^{-1} (Zapata et al., 2007). Several studies have analysed the implications of wind for sprinkler irrigation management in different irrigation districts of the Ebro river valley (Faci & Bercero, 1991; Dechmi et al. 2003; Playán et al. 2005; Playán et al., 2006; Zapata et al., 2007)

The Ebro basin, in the northeast corner of the Iberian Peninsula (Fig. 1), includes 347 rivers, 12000 km in total length, and comprising an area of 85362 km^2, almost 99% of which are in Spain; the remainder being in Andorra and France. It is the largest river basin in Spain (17.3% of the Spanish territory in the Iberian Peninsula). In many irrigation districts throughout the Ebro Valley it is difficult to achieve uniform and efficient sprinkler irrigation because the wind is strong and persistent along the valley. The connection between the regional wind conditions and the Ebro Valley orography have been thoroughly described (Masson & Bougeault, 1996; Frangi & Richard, 2000; Gomes et al., 2003). Common winds in the region are named the *Cierzo* and the *Bochorno*. They are, respectively, winds from the northwest and the southeast. The *Cierzo* is the most frequent and strongest wind in the Ebro Valley. In this area, in terms of daily averages, WV_2 exceeds 2 m s^{-1} (Puicercús et al., 1994; Hernández Navarro, 2002; Martínez-Cob & Tejero-Juste, 2004). At 50 m a.g.l. (i.e. WV_{50}), the *Cierzo* exceeds 6.5 m s^{-1} over open plains; even more over a high proportion of the territory along the axis of the valley (Troen & Petersen, 1989).

In this work, the spatial variability of the wind in the *MID* will be analysed. The windspeed measured at several locations in the *MID* is correlated with that simultaneously recorded at the reference meteorological station. The implications of the spatial variability of wind in the sprinkler irrigation performance and management will be analysed by calculating the suitable time for irrigation (*STI*) at these locations and at the reference site over several years.

1. Material and methods

The MID is an illustrative example of a current sprinkler irrigation district in the windy Ebro Valley. It is located along the limits of Zaragoza and Huesca provinces in the Northeast of Spain and has an area of 7352 ha, 3456 ha of which are sprinkler irrigated. This study is based on the irrigated area (Fig. 1). The *MID* was set up in 1995 and at present, 247 farmers have joined the district.

In the *MID*, farmers irrigate using an on-demand scheme. This procedure offers the greatest potential and provides farmers with great flexibility, allowing them to adjust water application to crop water requirements (Lamaddalena & Sagardoy, 2000). Water is pumped from a local reservoir using electric pumps powered by diesel generators. Consequently, water use in the district is expensive (0.048 € m^{-3} in 2004) and the cost is not varied whether the pumps work during day or night (Skhiri, 2007). The maximum network capacity is

241920 m^3 d^{-1} and the average theoretical continuous flowrate is 0.8 l s^{-1} ha^{-1} (Zapata et al., 2007). Also, many hydrants are shared among various plots. Thus, the flexibility in the irrigation scheduling is restricted because limitations in the irrigation network.

The manager of the *MID* must place an order for the farmers' water needs to the Ebro River Basin Agency two days before the water is released in the district system. The reservoir capacity of the *MID* is limited, hence if farmers fail to irrigate because of strong winds or rain, the water previously requested has to be returned through the spillways to the basin system. The authorities of the Ebro River Basin punish this practice with a financial penalty. This is particularly important in the *MID* since windy conditions are common.

The average wind conditions in the *MID* were first characterised according to the wind series recorded over eleven years by a meteorological station which is the property of the *Spanish Meteorology State Agency* (*INM*) located in Bujaraloz (Fig. 1 and Table 1). This is the longest time series available for this area. The *INM* station recorded WV_{10} and WD_{10} every 10 min. These variables were averaged every 30 min. WV_{10} was transformed into WV_2 using the conversion factor reported in Table 2.9 of Annex 2 published by (Allen, Pereira, Raes, Smith, 1998), i.e., [WV_2 = 0.748 * WV_{10}]. After these transformations, the format of the data matched those registered by the *SIAR* reference station. The *INM* station used 3-cuprotoranemometer model SV.5 and wind direction sensor model SD.5 (Seac S.A., Madrid, Spain), connected to a data-logger from the same manufacturer.

Despite the *INM* weather station providing the longest data series in the area, the reference weather station of the *SIAR* network located at Valfarta (

Table 1, Fig. 1) is the reference agro-meteorological station for irrigation scheduling purposes in the *MID*. The wind series from the *SIAR* reference station between 2004 and 2007 was used. The distance between the *SIAR* reference and the *INM* weather stations is 2455 m.

The *SIAR* reference station monitors WV_2 and WD_2 using a propeller-type anemometer (Young's wind monitor Model 05103, Campbell Scientific, Inc., Shepshed, Leicestershire, UK). According to the manufacturer's specifications, the starting windspeed threshold and accuracy were 1.0 m s^{-1} and ± 0.3 m s^{-1}, respectively. For wind direction, its accuracy was ± 3º and the starting threshold at 10° displacement is 1.1 m s^{-1}. Data were averaged every 30 min.

Sixteen sectors of wind direction were defined and analysed, clockwise: *North* (*N*), from 348.75 to 11.24º, *North-North-East* (*NNE*) from 11.25 to 33.75º, and so on up to *North-North-West* (*NNW*) from 325.25 to 348.74 º. Winds from direction between 236.25º and 326.24º were considered as *Cierzo* and winds between 56.25º and 146.24º were considered as *Bochorno* winds*.*

1.1.1. Characterisation of the spatial variability of the wind

To analyse the spatial variability of the wind, the windspeed was measured in situ at seventeen sites uniformly distributed throughout the (Table 1, Fig. 1) between February and March in 2005*,* resulting in approximately one monitoring point every 200 ha. Four set of measurements were carried out. During each set, the *SIAR* reference site and four of these points (five during the third set) were monitored simultaneously. *Cierzo* wind conditions prevailed during the monitoring period. The monitoring period for each set of measurements lasted enough to register an ample range of windspeeds, approximately one day; the fourth period was extended to about three days.

Local WV_2 was monitored using A100R 3-cup-rotors anemometers (Vector Instruments^{TM}, Rhyl, UK) and recorded every minute using a CR10X data logger (Campbell Scientific Ltd, UK). The records were later averaged every 30 min to match the format of the *SIAR* reference station records. The devices were powered by solar panels.

The local measurements were carried out during the period when fields were without crops because during this period the differences in the roughness conditions amongst sites were reduced. The advection term was considered small enough because the monitoring period was very cold (average temperature of the air was 0.4 ºC) and differences in soil moisture amongst locations were reduced because of the regular rainfalls during autumn and winter. Thus, we could expect most of the spatial variability of the wind to occur because of terrain features.

Simultaneous records of local and reference windspeeds were related using linear regressions. Afterwards the local windspeeds were assessed during the irrigation seasons (i.e. from April to September) between 2004 and 2007 for each of the seventeen sites. When the *WD* was a *Cierzo* and WV_2 at the reference weather site was > 2 m s^{-1}, local WV_2 was calculated from the reference WV_2 through the regression models. When the WV_2 at the reference site was < 2 m s^{-1} or the *WD* was not a *Cierzo*, the WV_2 was considered to be the same at the local and reference sites. This is because at *MID* we focus on *Cierzo* and because windspeeds < 2 m s^{-1} are not considered to be detrimental for sprinkler irrigation (Faci & Bercero, 1991).

From the local windspeed series from 2004 to 2007, the ratio of the local to the reference windspeeds was computed for reference windspeeds greater than 2 m s^{-1} and *Cierzo* conditions. The average ratios for each of the seventeen sites were interpolated throughout the irrigated area of the *MID* using kriging in order to produce a contour map that illustrates the spatial variability.

The quality of the measurements has been reported as one of the most likely sources of uncertainty comparing wind records among sites (Schaudt, 1998). To analyse the differences between sensors, local and reference windspeeds were measured simultaneously at the reference site by installing a 3-cuprotor anemometer with its logger at the *SIAR* site from February 16th to March 4th, 2005.

1.1.2. Implications of the spatial variability of the wind in the sprinkler irrigation performance

The ballistic model in the *Ador-sprinkler* software (Dechmi et al. 2004; Playán et al., 2006) was used to analyse the variation in irrigation performance with weather conditions. The model requires a combination of meteorological and operational inputs. The operational parameters include the solid-set arrangement, sprinkler height and model, the number and diameter of the nozzles, the operating pressure and the sprinkler-bearing lines azimuth. The meteorological parameters windspeed, wind direction and relative humidity of the air (*RH)* must be defined.

Two triangular sprinkler arrangements were simulated: 18 m between sprinklers along the lateral; 18 and 15 m between the laterals; they were designated T18x18 and T18x15, respectively. An azimuth angle of 105° between North and the sprinkler-bearing line was fixed. The performance of two calibrated sprinklers, *VYR-70* (VYRSA, Burgos, Spain) and *RC-130H* (Riegos Costa, Lleida, Spain) with principal and auxiliary nozzles of 4.4 and 2.4 mm in diameter mounted at 2 m a.g.l. was examined. An operating pressure of 300 kPa was set for the sprinkler nozzle. These combinations are widely used in the area.

From these data, the *Ador-sprinkler* software yielded the *Christiansen's Uniformity Coefficient* (*CUC*, %) (Christiansen, 1942) and the *Wind Drift and Evaporation Losses* (*WDEL*, %). One value of *CUC* and one value of *WDEL* were computed for each 30 min interval for the series of local windspeeds found between 2004 and 2007. The wind direction and *RH* monitored by the *SIAR* reference station were considered the same throughout the *MID*.

WDEL was computed according to the equation proposed for day and night operation conditions by Playán et al. (2005):

$$WDEL = 24.1 + 1.41\,WV - 0.216\,RH \qquad (1)$$

where *WV* will be WV_2 in m s^{-1} and *RH* in %.

The suitable time for irrigation (*STI*, %) was defined as the percentage of the time for which irrigation can be performed above a specific *CUC* threshold and below a specific *WDEL* threshold. *STI* was calculated as the percentage of records observing this condition with respect to the total 30 min records for the 2004-2007 irrigation seasons. Thus, *STI* depended on the distribution of the windspeed and on the spatial variability of the wind.

Four different management strategies were established (Zapata et al., 2007):

Standard strategy: *CUC* > 84% and *WDEL* ≤ 20%.

Restrictive strategy: *CUC* ≥ 90% and *WDEL* ≤ 15%.

Relaxed strategy: *CUC* > 80% and *WDEL* ≤ 25%.

WV < 3 m s^{-1}.

STI was calculated for the *SIAR* reference station and local sites for each sprinkler combination and strategy.

2. Results and discussion

2.1. General wind conditions in the *MID*

Fig. 2 shows that, in terms of daily averages, WV_2, i.e., at the level of the sprinklers nozzles, was > 2 m s^{-1} for almost all of the year. Windspeed varies both during the day and during the year. It is strongest for February, March and April. For these months, WV_2 was > 3 m s^{-1} during most of the daytime. The irrigation season for alfalfa and maize, two crops extensively cultivated in the *MID*, is from April to September, with the greatest water demand occurring during July and August. During these months, the daily variation of the windspeed differs from the rest of the year, both in profile and the time at which the maximum windspeed occurs (Fig. 2).

Sprinkler irrigation can be improved in terms of uniformity and efficiency by irrigating during the night since windspeed decreases considerably during the night (Martínez-Cob, Zapata, Sanchez, Playán, 2005). However, farmers' water demands in the *MID* cannot be met completely during the night since the water conveying system is limited in section and water demands are high and concentrated (Zapata et al., 2007). For this reason, farmers are forced to irrigate during the day, facing windy conditions.

General wind conditions in the area were also analysed using the wind series monitored between 2004 and 2007 by the *SIAR* reference station.

Wind direction mostly follows the contours of the Ebro Valley, particularly during the *Cierzo* (Fig. 3). In the *MID*, the *Cierzo* slightly veered from *WNW* to *W*. Considering the whole series, *Cierzo* winds blew half of the time, almost twice as much as *Bochorno*. During the irrigation season, *Bochorno* increased moderately (5 units in %) at the expense of *Cierzo*. Light winds (WV_2 < 2 m s^{-1}) occurred around half of the time (Table 2). The frequency of *Cierzo* greatly increased when WV_2 > 2 m s^{-1} only were considered (Fig. 3).

Winds other than *Cierzo* or *Bochorno* were less than 30% (Fig. 3) and were mostly light winds (Table 2). Consequently, they were not especially detrimental for the sprinkler irrigation performance in the *MID*. *Bochorno* involves a high frequency of light winds (about 60%), more than twice as much as the *Cierzo* (Table 2). Considering WV_2 > 2 m s^{-1}, *Bochorno* and *Cierzo* winds noticeable differed too: under *Bochorno* conditions, *WV* ranges mostly between 2 and 4 m s^{-1} whereas under *Cierzo* conditions, winds > 5 m s^{-1} were as frequent as light winds.

2.2. Analysis of the spatial variability of the wind

2.2.1. Comparison between sensors in wind measurements

Fig. 4 illustrates the differences in the windspeed monitoring data between the sensors gauging *local WV* (3-cuprotor anemometers) and the *SIAR* reference weather station (propeller type anemometer). The distribution of the records was bimodal, with one peak between 0.5 and 2 m s^{-1} (30% of the records) and other between 4.5 and 6 m s^{-1} (25% of the records). According to a linear regression, the slope and intercept coefficients were statistically significant. The 3-cuprotor anemometers measured greater windspeeds than the propeller-type. The deviation was greater for low winds and decreased with windspeed. The mismatch was probably related to the differences in the starting threshold windspeed which was 0.25 m s^{-1} for the 3-cuprotor anemometer and 1 m s^{-1} for the propeller-type (according to the manufacturer's specifications). The scattering of the data around the line 1:1 in Fig. 4 is appreciable. The standard error was 0.68 m s^{-1} and it was particularly greater between 3 and 4 m s^{-1} (0.96 m s^{-1}). Bias was not observed in the distribution of the residuals but they increased (in absolute terms) for $WV > 3$ m s^{-1}. According to these results, differences among sites < 0.3 m s^{-1} were carefully considered.

2.2.2. Linear Regression Models

Local windspeed was related to the reference *SIAR* windspeed using regression analysis on data from the seventeen sites (Fig. 1, Table 1). *Local* windspeed was recorded from February 16th to March 4th , 2005 (Fig. 1, Table 1). During this time, the wind was strong and mainly classified as *Cierzo*. Between February 16th and 17th, the average windspeed at *SIAR* reference site was 5.2 m s^{-1} and 93% of the time the wind direction was *Cierzo*. Between February 17th and 18th , between February 28th and March 1st, and between March 1st and 4th, these figures were 4.9 m s^{-1} and 95%, 3.2 m s^{-1} and 87%, and 2.7 m s^{-1} and 54%, respectively.

The linear regression models between local and reference windspeeds under *Cierzo* conditions differed among sites illustrating the spatial variability of the wind (Fig. 5). *Local windspeeds* were greater than the reference *SIAR* windspeed for the sites 14, 19, 13 and 52 (where the data was almost parallel to the line 1:1) and for the sites 35 and 43 (where the differences decreased with windspeed). At the sites 25, 6 and 33, the local windspeed was greater than the reference windspeed up to the limit beyond which the trend was reversed. *Local* *windspeed* was lower than the *SIAR* reference windspeed for the sites 45, 30 and 49 (the differences increased with windspeed). Site 49 [*local WV* = 0.50 + 0.7156 x *SIAR WV* (R^2 = 0.90)], monitored during the third period, is not presented in Fig. 5 in the interests of clarity. At the sites 7 and 36, local windspeed was lower than the *SIAR* windspeed up to a limit beyond which the opposite was true. Both local and reference windspeeds were similar for the sites 9, 23 and 21 (site 21 was the closest to the *SIAR* reference site). Several regressions differed despite their close proximity revealing that the spatial variability of the wind was important even for distances of about 1 km (Figs. 1 and 5).

From the analysis of the local windspeed series under *Cierzo* conditions for the irrigation seasons between 2004 and 2007 (light winds excluded), important differences were found among sites (Fig. 6). The cumulative frequency for windspeeds < 4 m s^{-1} was less than 50% for the most of the sites except for sites 33, 45, 30 and 49. Windspeeds > 5 m s^{-1} had a cumulative frequency greater than 60% at sites 19, 35, 43 and 7, but about 30% or less at the sites 23, 33, 45, 30 and 49.

Figure 7 illustrates the average windspeed throughout the irrigated area of the *MID* expressed relative to that at the *SIAR* reference site. The spatial variability of the wind was quantified in terms of % area in four categories (Table 3). For 39% of the *MID* territory, the wind was similar to that for the *SIAR* reference site, 25% of the area was less exposed and 36% was more exposed. The results show that wind monitored at the *SIAR* reference station could underestimate the windspeed found in more than one third of the *MID* area.

2.3. Implications of the spatial variability of the wind on the sprinkler irrigation performance

The spatial variability of the wind within an irrigation district affects irrigation performance in terms of uniformity and water losses since both depend on the wind velocity at the irrigated site, i.e., the local windspeed. Simulations with *Ador-sprinkler* software revealed that *STI* greatly varies depending on the irrigation strategy, the sprinkler system and the wind exposure (Table 4).

The *restrictive strategy* can be hardly followed in the *MID* as it implies extremely low *STI* irrespective of the sprinkler system and site (Table 4). It requires very low windspeeds combined with high *RH*, conditions which are infrequent in the *MID*. The choice of the sprinkler model is significant for this strategy. Playán et al. (2006) showed that *VYR-70* sprinklers yielded higher values of the CUC than *RC-130H* sprinklers for windspeeds < 2 m s^{-1}, while the *RC-130H* sprinklers had greater CUC than *VYR-70* for windspeeds in the range of 2 to 5 m s^{-1}. Since this strategy requires very low windspeed, the *VYR-70* sprinklers gave noticeably greater *STI* than the *RC-130H* sprinklers. For the *restrictive strategy*, the choice of the irrigation layout (T18x15 or T18x18) was less important than the selection of the sprinkler model in terms of the *STI* (Table 4).

The *relaxed strategy* was found to be more suitable in the *MID* as *STI* greatly increases with respect to the *restrictive strategy*. For the *relaxed strategy*, the *STI* increases when the narrowest layout was selected: the increase is 8 units in the case of the *RC-130H* model and 4 units in the case of the *VYR-70* sprinklers (results for the *SIAR* reference site). Similar trends are found for the *relaxed* and *standard* strategies, although the *STI* is lower for the latter.

Predicted *STI* noticeably increased for the least exposed areas (sites 30, 45 and 49) when compared to the most exposed areas (sites 43 and 35) (Table 4, Fig. 7). For the *standard* and *relaxed strategies*, farmers with plots at the least exposed sites (90th percentile) have between 10 and 20% greater *STI* than the farmers at the most exposed sites (10th percentile), between 5 and 10 units (%) calculated as differences (penultimate and last rows in Table 4, respectively). The differences increased with sprinkler spacing. For the *restrictive strategy*, the *STI* was too low even for the least exposed sites and it was concluded that this strategy is unaffordable in the *MID*.

The average water needs for a maize crop (crop evapotranspiration, ET_c) in the area during the most demanding month (July) are 215 mm (Martínez-Cob, Faci, Bercero, 1998). The irrigation network of the *MID* was designed with an average theoretical continuous flow rate of 0.8 $l\ s^{-1}\ ha^{-1}$ (Zapata et al., 2007) which is equivalent to 214 $mm\ month^{-1}$. Accordingly, farmers in the *MID* can hardly meet the water requirements for maize during July. The network investment cost is inversely proportional to the operating time and this is connected with the local wind conditions. *STI* values lower than 55-60% result in important increases on the investment cost (Zapata et al., 2007). Consequently, irrigation districts located in semiarid and windy areas, subject to high evapotranspiration and with low values of the *STI*, must devote significant investments in water conveyancing systems in order to provide the volume of water required for a short period of time. The assessment of the *STI,* together with the following analysis of the investment cost, illustrates the unusual characteristics of irrigation network designs for windy areas.

Zapata et al. (2007) related the network construction cost, including both the collective and the on-farm irrigation structures, to the *STI* (considered as a % of the hydrant operating time). The function presented next was assessed from those values and considering the results obtained during the year 2007 in the Callén Irrigation District, a new irrigation network similar to the *MID* but about 70 km to the north. The function provides the network construction cost (€ ha^{-1}) as a function of the *STI* (%). The function is valid for the combinations of solid-set arrangement and sprinkler model included in the present study. The equation is:

$$\text{Cost} = 1.1116\ \text{STI}^2 - 181.43\ \text{STI} + 15390 \qquad (R^2 = 0.98) \quad (2)$$

Construction costs vary significantly depending on the irrigation management regime adopted (Fig. 8). Also, the cost associated with each irrigation management depends on the solid-set arrangement, the sprinkler model and exposure to the wind.

Figure 8 shows that the *restrictive* strategy implies construction costs between 11000 and 14000 € ha^{-1} and, as previously stated, it is unaffordable at *MID* (the form of Eq. 2 stresses the differences in the *STI* between sprinkler models). The differences in the cost between the *standard* and the *relaxed* strategies is about 500 € ha^{-1}; in all, for a district such as the *MID*, to shift from the *relaxed* to the *standard* strategy would involve more than 1700000 € in terms of the construction cost. It is noteworthy the effect of the spatial variability of the wind, especially for the *standard* strategy. For this strategy, the differences in the network construction cost associated with the wind exposure exceed the differences due to the arrangement and model of the sprinklers.

The characterisation of the spatial variability of the wind in windy areas is a valuable tool for sprinkler irrigation. Irrigating the least exposed zones to the wind during the most unfavourable periods may improve the management of sprinkler irrigation. Furthermore, accounting for the differences in wind exposure improves the estimation of the crop water requirements.

Since the wind conditions depends on the roughness conditions, the resulting relationships (Fig.5) may vary from the non-vegetative period to the irrigation season, and among irrigation seasons, depending on the farmers' decisions about cropping. This is inherent in the nature of the wind in the surface layer. When economically viable, the implementation of real-time irrigation programmers by wind velocity monitored locally is advisable.

3. Conclusions

Wind monitoring is essential for the management of sprinkler irrigation districts. In windy irrigation districts, the spatial variability of the wind can be important and it can be a rough simplification to assume the wind velocity (*WV*) monitored at only one point (the *SIAR* reference weather station in this study) represents the whole irrigation district. The characterisation of the wind exposure can improve the design and management of sprinkler irrigation systems where moderate or high winds are frequently found such as in the MID.

The analysis of the *SIAR* wind data series for the 2004-2007 irrigation seasons reveals that *Cierzo* blows 45% of the time during the irrigation season. Considering the winds that jeopardize sprinkler irrigation exclusively (*WV* > 2 m s^{-1} at 2 m above the ground) this rises to 69%. Under *Cierzo* wind conditions, because of the spatial variability of the wind, 25% of the *MID* territory was less exposed to the wind than the *SIAR* site, 39% was equally exposed, and 36% more exposed.

The *Ador-Sprinkler* simulation model can convert the differences in the wind exposure into predicted differences for the suitable time for irrigation (*STI*, %). Depending on the local exposure and the sprinkler system, *STI* ranges in the *MID* between 42 and 58% for a *standard strategy* (CUC > 84% and WDEL ≤ 20%) and between 57 and 79% for a *relaxed strategy* (CUC > 80% and WDEL ≤ 25%). For these strategies, the ratio of *STI* for the least exposed sites (90th percentile) to *STI* for the most exposed sites (10th percentile) ranges between 108% and 118%. This means a between 6 and 10 units greater *STI* for the least exposed sites. For a *restrictive strategy* (CUC ≥ 90% and WDEL ≤ 15%) the differences between sites and sprinkler systems increase but *STI* was too low for any system to be affordable in the *MID* (*STI* between 6 and 32%). For the *standard strategy*, the differences in the network construction costs associated with the wind exposure exceed the differences due to the arrangement and model of the sprinklers.

Because of the strong and frequent winds in the region and the limited water conveying system in the *MID*, the time needed to supply the irrigation water needs exceeds the hours of the day with low winds. Consequently, farmers have important limitations for their irrigation schedule. Characterisation according to the wind exposure provides new tools to improve the sprinkler irrigation management and provide new criteria to design irrigation systems. The methodology presented in this study is valid for windy irrigation districts that present significant spatial variability of the wind. This methodology could be very useful to improve sprinkler irrigation management using data from meteorological stations in the area.

This study is a simplification of the characterisation of spatial variability of the wind since it is restricted to a specific wind conditions (i.e. *Cierzo*). Further studies extending the periods of simultaneous measurements are required to assess the relationships between the local and reference meteorological sites.

4. Acknowledgements

We applied the sequence-determines-credit approach for the sequence of authors in this paper. This research was funded by the CICYT of the Government of Spain through grants AGL2004-06675-C03-03/AGR and AGL2007- 66716-C03, by the Government of Aragón through grant PIP090/2005, and by the INIA and CITA through the PhD grants program. We are very grateful to the colleagues and friends of the Department of Soils and Irrigation (CITA-DGA) and of the Department of Soil and Water (EEAD-CSIC), for their support and co-operation in the fieldwork and weather monitoring and retrieval. We specially thank to Carmelo Lorente, secretary of the Montesnegros Irrigation District, for all his cooperation and help.

5. References

Achberger, C. Ekström, M., & Bärring, L. (2002). Estimation of local near-surface wind conditions: a comparison of WASP and regression based techniques. Meteorological Applications, 9, 211–221.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration – Guidelines for computing crop water requirements. Irrigation and drainage paper 56. Rome: FAO.

Carrión, P., Tarjuelo, J. M., & Montero, J. (2001). SIRIAS: a simulation model for sprinkler irrigation: I. Description of the model. Irrigation Science, 20 (2), 73-84.

Christiansen, J. E. (1942). Irrigation by sprinkling. California Agriculture Experiment Station Bulletin 670. Berkeley: University of California.

Cuenca, R. H. (1989). Irrigation system design: an engineering approach, Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1989.

Dechmi, F., Playán, E., Cavero, J., Faci, J. M., & Martínez-Cob, A. (2003). Wind effects on solid set sprinkler irrigation depth and yield of maize (Zea mays). Irrigation Science, 22, 67-77.

Dechmi, F., Playán, E., Cavero, J., Martínez-Cob, A., & Faci, J. M. (2004). A coupled crop and solid ser sprinkler simulation model: II. Model application. Journal of Irrigation and Drainage Engineering, 130 (6), 511-519.

Faci, J. M. & Bercero, A. (1991). Efecto del viento en la uniformidad y en las pérdidas por evaporación y arrastre en el riego por aspersión. Investigación Agraria, Producción y Protección Vegetal, 6 (2). (In Spanish).

Forteza del Rey, V. (2002). El plan nacional de regadíos. Agricultura, 842, 554-556. (In Spanish).

Frangi, J. P. & Richard, D. C. (2000). The WELSONS experiment: overview and presentation of first results on the surface atmospheric boundary-layer in semiarid Spain. Annales Geophysicae-Atmospheres Hydrospheres and Space Sciences, 18 (3), 365-384.

Gomes, L., Arrúe, J.L., López, M. V., Sterk, G., Richard, D., Gracia, R., Sabre, M., Gaudichet, A., & Frangi, J. P. (2003). Wind erosion in a semiarid agricultural area of Spain: the WELSONS project. Catena, 52 (3-4), 235-256.

Hernández Navarro, M. L. (2002). Frecuencia e intensidad del viento en Zaragoza. Geographicalia (2ª época), 27, 63-75. (In Spanish).

Kaimal, J. C. & Finnigan, J. J. (1994). Atmospheric Boundary Layer Flows, Their Structure and Measurement. New York, Oxford: Oxford University Press.

Keller, J. & Bliesner, R. D. (1990). Sprinkler and trickle irrigation. Van Nostrand Reinhold, New York.

Kincaid, D. C. (1996). Spraydrop kinetic energy from irrigation sprinklers. Transactions of the ASAE, 39 (3), 847-853.

Lamaddalena, N. & Sagardoy, J. A. (2000). Performance analysis of on-demand pressurized irrigation systems. Irrigation and Drainage Paper 59. Rome: FAO.

Landberg, L. & Mortensen, N. G. (1994). A Comparison of physical and statistical methods for estimating the wind resource at a site, in: K.F. Pitcher (Eds.), Proceedings of the Fifteenth BWEA Wind Energy Conference (pp. 119–125). London. BWEA.

Landberg, L., Myllerup, L., Rathmann, O., Petersen, E.L., Jørgensen, B.H., Badger, J., & Mortensen, N.G. (2003). Wind Resource Estimation - An Overview, Wind Energy, 6 (3), 261-271.

MAPA. (2001). Plan Nacional de Regadíos: Horizonte 2008. Ministerio de Agricultura Pesca y Alimentación (MAPA). Madrid: Dirección General de Desarrollo Rural. (In Spanish).

Martínez-Cob, A., Faci, J. M., & Bercero, A. (1998). Evapotranspiración y necesidades de riego de los principales cultivos en las comarcas de Aragón. Publicación 1882. Zaragoza: Institución Fernando el Católico. (In Spanish).

Martínez-Cob, A. & Tejero-Juste, M. (2004). A wind-based qualitative calibration of the Hargreaves ET_0 estimation equation in semiarid regions. Agricultural Water Management, 64 (3), 251-264.

Martínez-Cob, A., Zapata, N., Sanchez, I., & Playán, E. (2005). Variabilidad espacio-temporal de las pérdidas potenciales por evaporación y arrastre en el Valle Medio del Ebro. XXIII Congreso Nacional de Riegos y Drenajes (pp. 113-118). Elche: Asociación Española de Riegos y Drenajes (AERYD). (In Spanish).

Masson, V. & Bougeault, P. (1996). Numerical simulation of a low-level wind created by complex orography: A Cierzo case study. Monthly Weather Review, 124 (4), 701-715.

Montero, J. Tarjuelo, J. M., & Carrión, P. (2001). SIRIAS: a simulation model for sprinkler irrigation: II. Calibration and validation of the model. Irrigation Science, 20 (2), 85-98.

Petersen, E. L., Mortensen, N. G., Landberg, L., Hojstrup, J., & Frank, H. P. (1998). Wind power meteorology. Part II: Sitting and models. Wind Energy, 1 (2), 55-72.

Playán, E., Salvador, R., Faci, J. M., Zapata, N., Martínez-Cob, A., & Sanchez, I. (2005). Day and night wind drift and evaporation losses in sprinkler solid-sets and moving laterals. Agricultural Water Management, 76 (3), 139-159.

Playán, E., Zapata, N., Faci, J. M., Tolosa, D., Lacueva J. L., Pelegrin, J., Salvador, R., Sanchez, I., & Lafita, A. (2006) Assessing sprinkler irrigation uniformity using a ballistic simulation model. Agricultural Water Management, 84 (1-2), 89-100.

Playán, E., Cavero, J., Mantero, I., Salvador, R., Lecina, S., Faci, J. M., Andrés, J., Salvador, V., Cardena, G. Ramón, S., Lacueva, J. L., Tejero, M., Ferri, J., & Martínez-Cob, A. (2007) A database program for enhancing irrigation district management in the Ebro Valley (Spain). Agricultural Water Management, 87 (2), 209-216.

Puicercús, J. A., Valero, A., Navarro, J., Terren, R., Zubiaur, R., Martin, F., & Iniesta, G. (1994). Atlas Eólico de Aragón. Departamento de Industria, Comercio y Turismo, Zaragoza: Diputación General de Aragón. (In Spanish).

Rogers, A. L., Rogers, J. W., & Manwell, J. F. (1994). Comparison of the performance of four measure-correlate-predict algorithms. Journal of Wind Engineering and Industrial Aerodynamics, 93, 243-264.

Schaudt, K. J. (1998). A new method for estimating roughness parameters and evaluating the quality of observations. Journal of Applied Meteorology, 37 (5), 470-476.

Seginer, I., Kantz, D., & Nir, D. (1991). The distortion by wind of the distribution patterns of single sprinklers. Agricultural Water Management, 19 (4), 341-359.

Seginer, I., Nir, D., & von Bernuth, R. D. (1991). Simulation of wind-distorted sprinkler patterns. Journal of Irrigation and Drainage Engineering, 117, 285-305.

Skhiri, A. (2007). Mejora de la productividad del agua en comunidades de riego por aspersión. M.S. Thesis. Zaragoza: Instituto Agronómico Mediterráneo de Zaragoza (CIHEAM-IAMZ). (In Spanish).

Tarjuelo, J. M., Carrión, P., & Valiente, M. (1994). Simulación de la distribución del riego por aspersión en condiciones de viento. Investigación Agraria, Producción y Protección Vegetal, 9, 255-271.

Troen, I. & Petersen, E. L. (1989). European Wind Atlas. Roskilde: Risoe National Laboratory.

Zapata, N., Playán, E., Martínez-Cob, A., Sanchez, I., Faci, J.M., & Lecina, S. (2007). From on-farm solid-set sprinkler irrigation design to collective irrigation network design in windy areas. Agricultural Water Management, 87 (2), 187-199.

List of Tables

Table 1. Location (UTM coordinates) and monitoring periods for each selected site for wind measurement in the Montesnegros Irrigation District in Northeast of Spain.

Site	X	Y	Z	Period
SIAR	738048	4601902	354	January 1, 2004 to December 31, 2007
INM	735850	4600809	357	July 6, 1992 to July 5, 2003
14	737056	4601995	358	February 16 (12:35[a]) to February 17, 2005 (9:05)
19	738056	4599995	327	
35	741056	4597995	310	
43	743056	4595995	320	
7	736056	4599995	360	February 17 (12:35) to February 18, 2005 (7:05)
9	736056	4601995	360	
25	739056	4600995	361	
36	741056	4598995	316	
6	736056	4598995	340	February 28 (14:39) to March 1, 2005 (9:38)
23	739056	4598995	320	
33	740056	4596995	320	
45	743056	4597995	300	
49	744056	4596995	320	
13	737056	4599995	339	March 1 (19:16) to March 4, 2005 (10:08)
21	738056	4601995	355	
30	740056	4599995	320	
52	745056	4595995	320	

[a] *Greenwich Mean Time (GMT) indicated within brackets.*

Table 2. Distribution of the windspeed frequencies (%) according to the wind direction (Bochorno, Cierzo winds and Others) and calculated from the wind series monitored at the SIAR reference meteorological station between 2004 and 2007 (data registered every 30 min). Values are shown for the whole year (Year) and for the irrigation season (IS).

(m s^{-1})	Wind direction						Total	
	Bochorno		Cierzo		Others			
	Year	IS	Year	IS	Year	IS	Year	IS
< 2	58.9	57.2	26.3	24.2	87.8	84.9	50.7	50.0
2 - 3	22.0	24.3	16.9	18.5	8.9	10.3	15.7	17.8
3 – 4	11.8	12.2	15.7	18.9	2.0	2.9	11.0	12.6
4 – 5	4.9	4.5	13.1	15.0	0.7	1.2	7.9	8.3
> 5	2.3	1.7	28.0	23.4	0.6	0.7	14.8	11.3
Total	100	100	100	100	100	100	100	100

Table 3. Spatial variability of the windspeed within the Montesnegros Irrigation District (MID) calculated from the Fig. 7 and expressed as the percentage of the area corresponding to each range of ratios.

Ratio	*0.7- 0.9*	*0.9 – 1.1*	*1.1 - 1.3*	*> 1.3*
Area (%)	25	39	30	6

Table 4. Suitable Time for Irrigation (STI) calculated as percentage of the irrigation season for two sprinkler models, two irrigation layouts and four management strategies. Values calculated from the wind series between 2004 and 2007. The bottom two lines of the table show the ratio (%) and the differences between the 90th and 10th STI percentiles for the sites in the table.

Strategy	Standard				Restrictive				Relaxed				< 3 m s^{-1}
Spacing	T18x18		T18x15		T18x18		T18x15		T18x18		T18x15		
Sprinkler	RC	VYR	RC	VYR	RC	VYR	RC	VYR	RC	VYR	RC	VYR	
Site													
43	42	44	51	49	9	25	6	27	57	65	71	73	57
35	42	45	51	49	9	25	6	27	58	65	70	72	57
19	45	47	52	51	9	25	8	27	61	68	72	73	60
7	47	49	53	52	11	26	8	28	63	68	72	73	63
52	47	49	54	53	11	26	8	28	64	70	73	75	63
6	47	50	55	54	10	25	9	27	65	72	76	77	62
13	48	50	54	53	12	26	8	29	65	70	74	75	64
25	48	50	55	54	11	26	9	28	65	71	75	76	64
14	48	50	54	54	12	27	8	29	65	71	74	75	65
9	49	51	55	54	12	27	8	29	66	72	75	76	68
21	50	52	55	55	12	28	7	30	67	72	75	76	67
SIAR	50	52	56	55	12	28	8	30	68	73	76	77	68
36	50	52	55	55	11	28	8	30	67	72	75	76	69
23	50	53	57	56	13	28	8	30	68	74	77	78	68
33	50	53	57	56	13	27	9	30	68	75	77	78	68
45	52	54	58	57	13	28	8	31	70	76	78	79	70
30	52	54	58	57	12	29	8	32	70	76	78	79	71
49	52	55	58	58	13	28	9	31	71	77	79	79	63
$\frac{k_{0.9}}{k_{0.1}} \times 100$	*118*	*116*	*112*	*113*	*144*	*112*	*134*	*115*	*116*	*113*	*109*	*108*	*117*
$k_{0.9} - k_{0.1}$	*8*	*8*	*6*	*7*	*4*	*3*	*2*	*4*	*10*	*9*	*6*	*6*	*10*

List of Figures

Fig. 1. Situation of the Montesnegros Irrigation District (MID) within the Ebro basin in the Iberian Peninsula (in the upper row). Detailed map of the MID irrigated area (axes show UTM units) including the SIAR reference station, the INM meteorological station and seventeen sites at which windspeed was measured (in the bottom row).

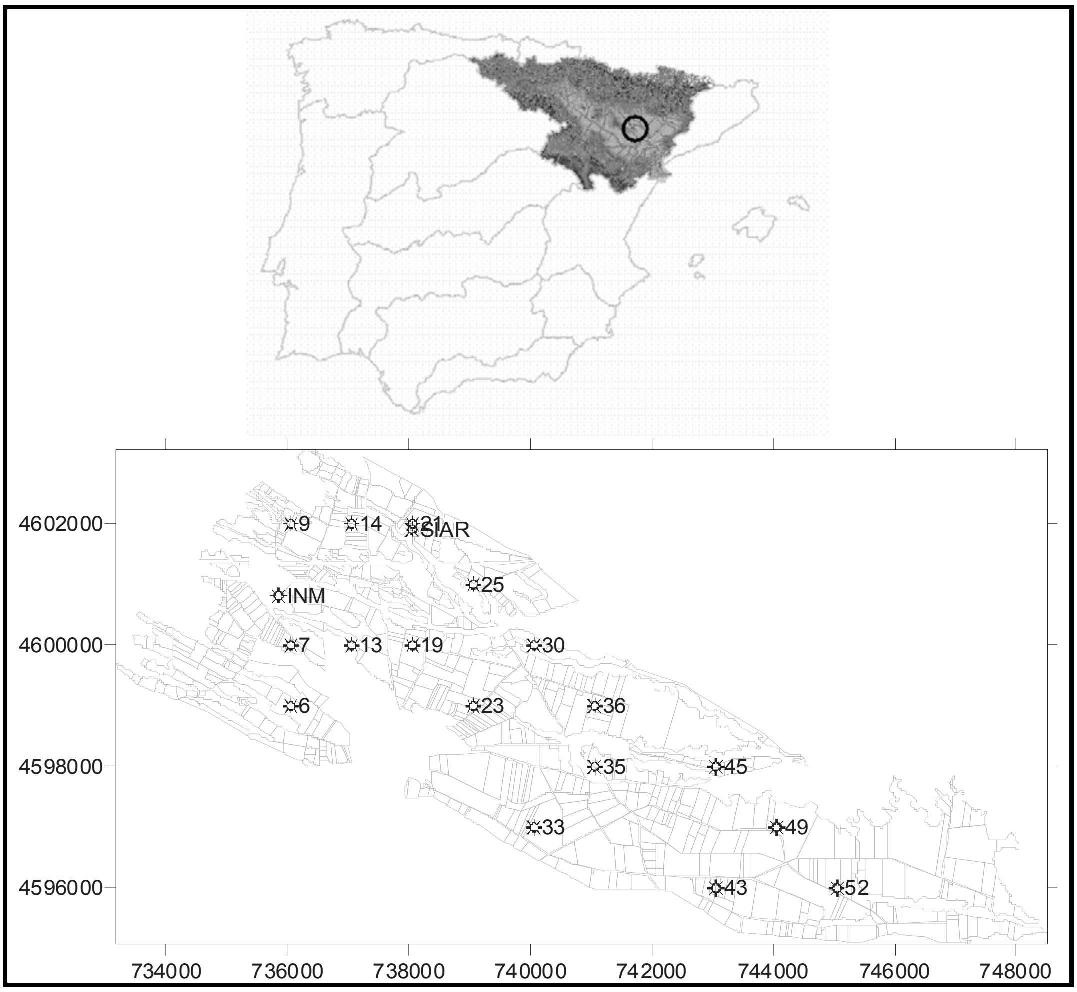

Fig. 2. Average windspeed at 2 m above the ground level from the 1992 – 2003 series at the Bujaraloz INM weather station. Results calculated in terms of the average day from records every 30 min. Wind directions are not noted. The time is expressed as Greenwich Mean Time (GMT).

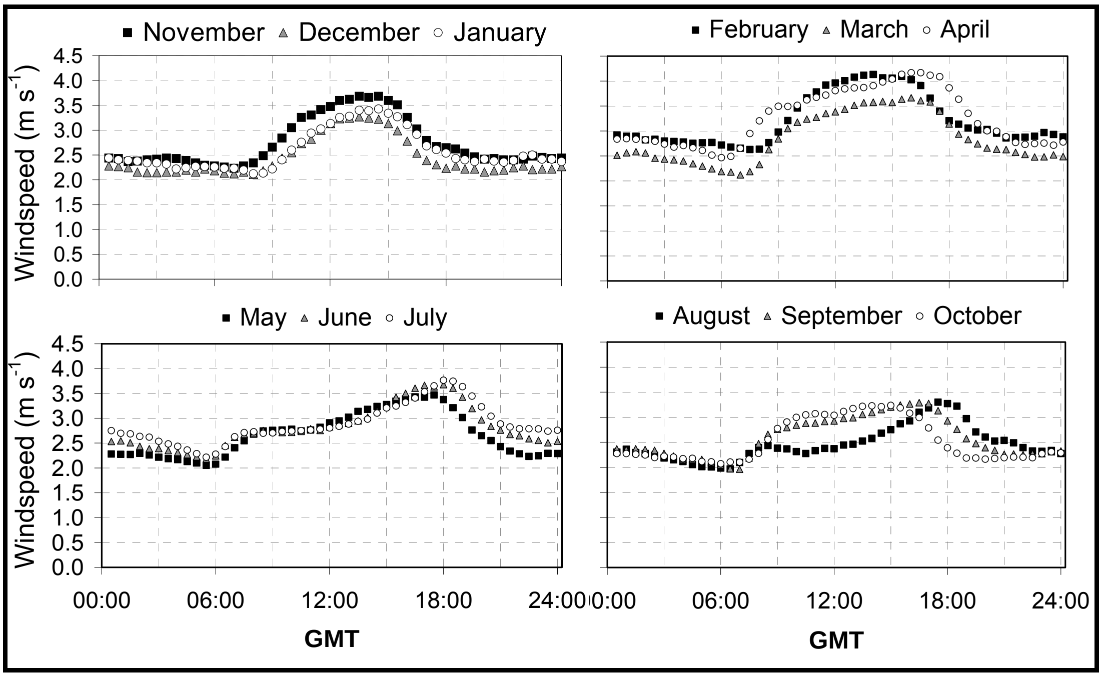

Fig. 3. Distribution of the frequencies (%) of the wind direction at the SIAR reference site between 2004 and 2007 (records every 30 min). In the upper row, all data are included; in the bottom row only data for windspeeds > 2 m s^{-1} are plotted; in the left column data for the whole year are plotted; in the right column data for the irrigation season (April to October) are plotted. The Bochorno wind directions are ENE, E, ESE and SE. The Cierzo wind directions are WSW, W, WNW and NW.

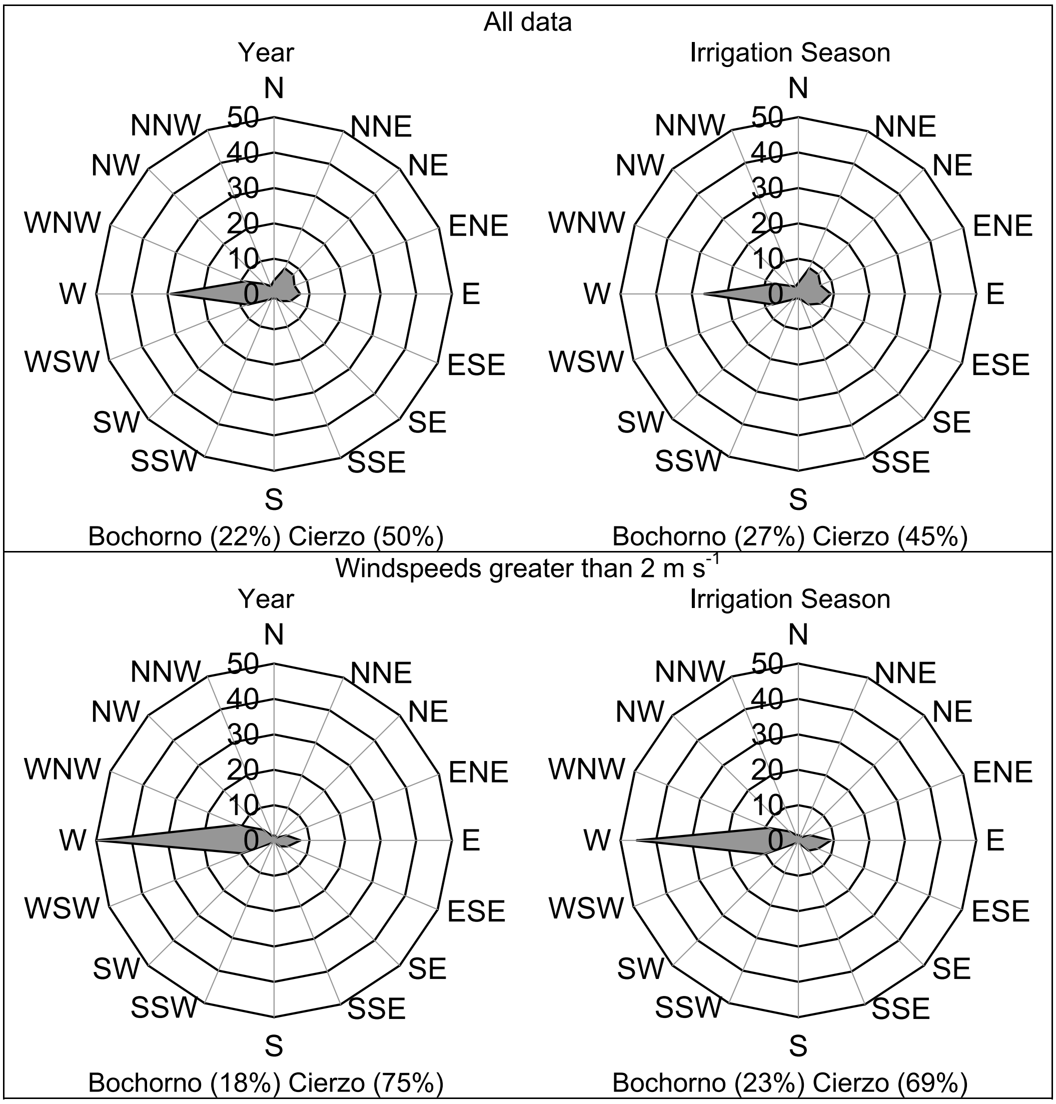

Fig. 4. Comparison between the measurements of the windspeed made with 3-cup-rotor and propeller-type anemometers. The measurements were recorded simultaneously every 30 minutes at the same site (the SIAR reference station) from February 16 to March 4, 2005. Dashed line illustrates the 1:1 ratio.

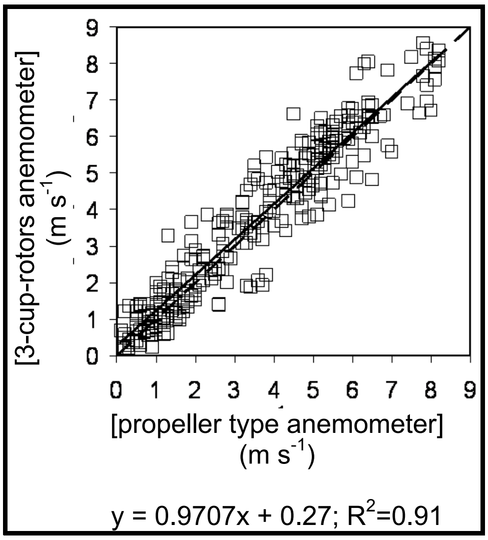

Fig. 5. Linear regression models between the local windspeeds and the windspeeds at the SIAR reference site. Values measured under Cierzo wind conditions. Each row shows sites monitored simultaneously.

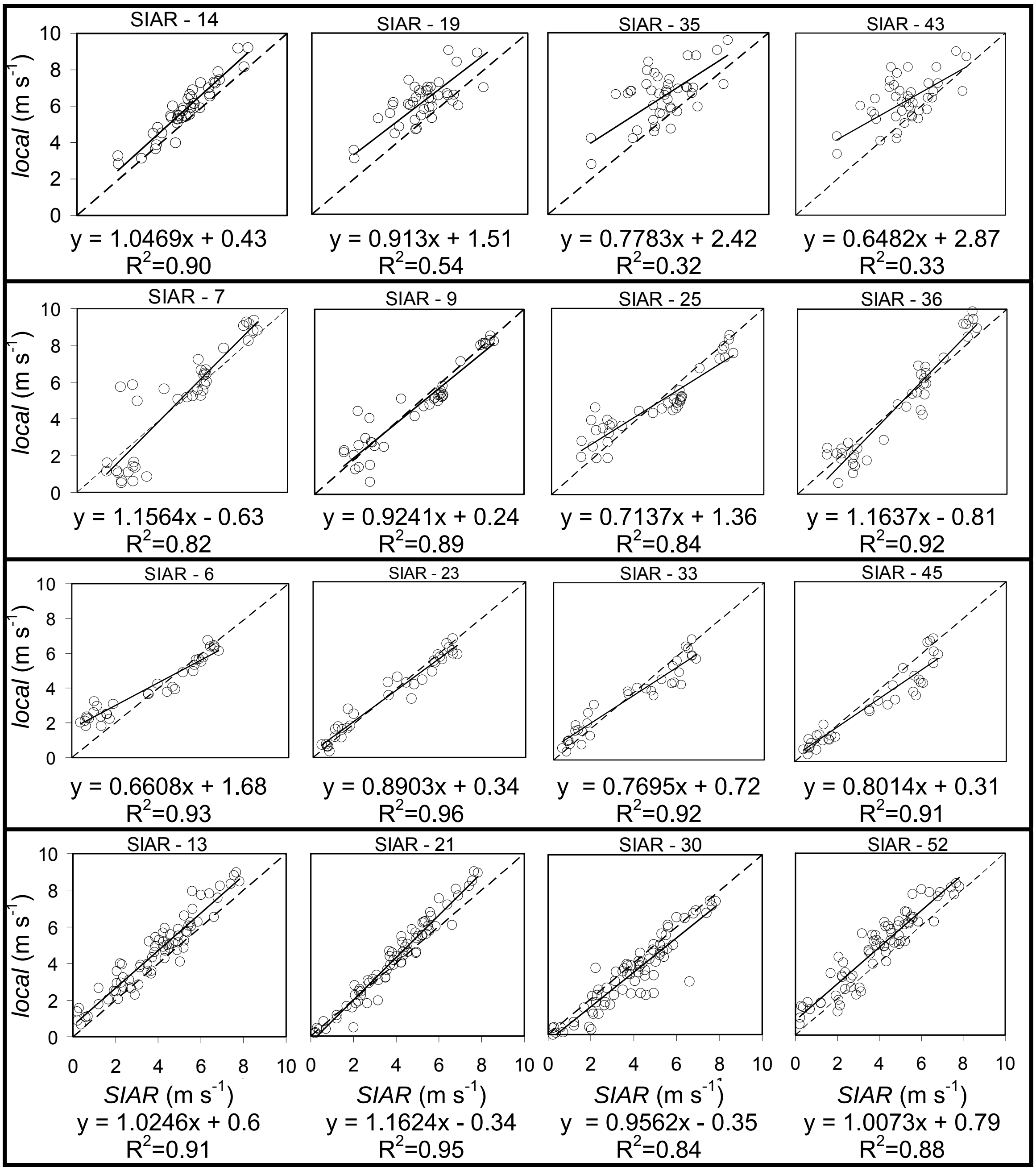

Fig. 6. Cumulative frequency (%) of the windspeed under Cierzo wind conditions ranked by levels. The values at the seventeen sites are estimated from the values measured at the SIAR reference site during the irrigation seasons between 2004 and 2007 according to the equations in the Fig. 5. Values at the SIAR reference site < 2 m s^{-1} are excluded.

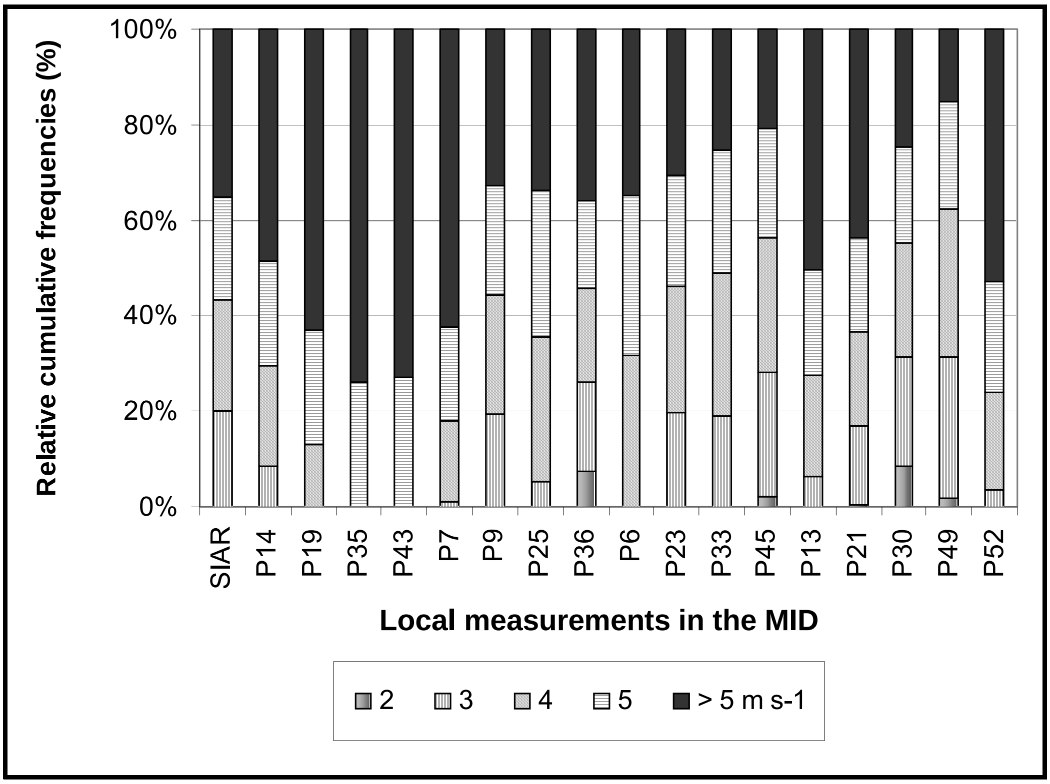

Fig. 7. Contour map of the average ratio of the local windspeed (estimated) to the windspeed at the SIAR reference site (measured) calculated for the irrigation seasons between 2004 and 2007 under Cierzo wind conditions. Values at the SIAR reference site < 2 m s^{-1} *are excluded.*

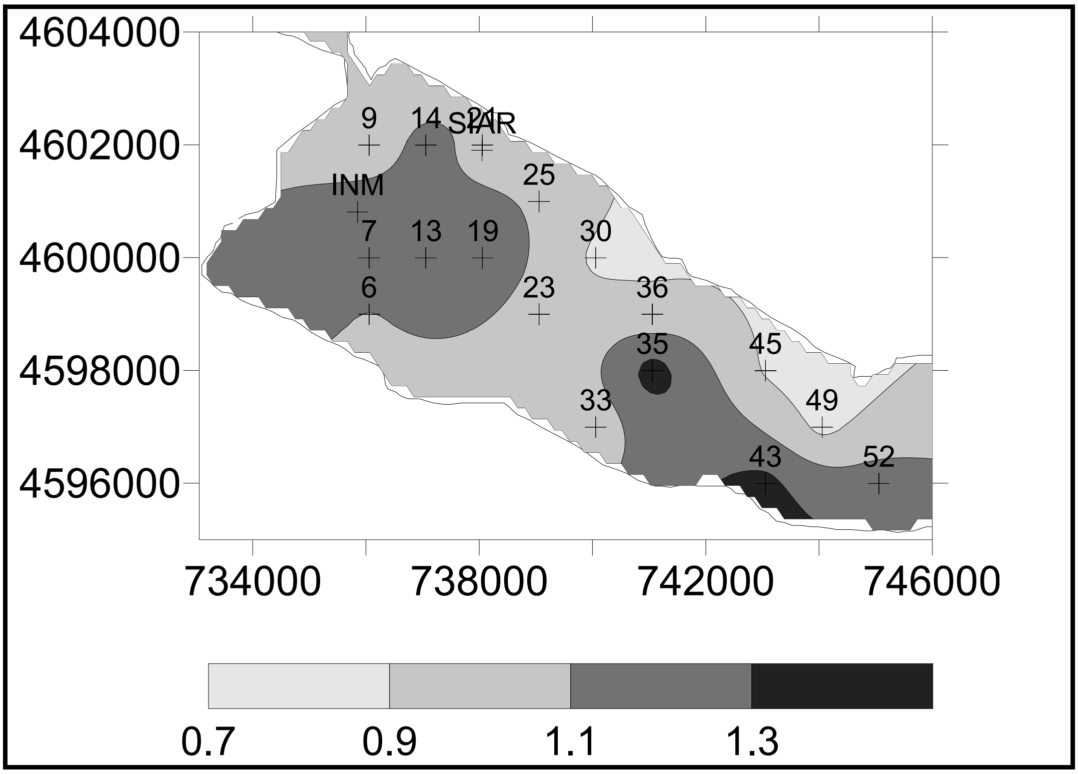

Fig. 8. Relationship between the irrigation network construction cost and the suitable time for irrigation (STI) according to three irrigation management strategies, two triangular sprinkler spacings (T18x18 and T18x15) and two sprinkler models (RC 130 and VYR 70). Symbols correspond to the values calculated at the SIAR site. Bars illustrate the influence of the spatial variability of the windspeed: the upper limit corresponds to the most exposed site and the lower limit to the least exposed site (according to the Eq. 2 and to the values in the Table 4).