WIND SPATIAL VARIABILITY IN AN IRRIGATION DISTRICT OF ARAGÓN (SPAIN)

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ABSTRACT

Irrigation management in sprinkler irrigated districts, where wind events are frequent and extended, should be carried out considering the wind speed due to its important effects on sprinkler uniformity and efficiency. This study surveys the spatial variability of wind speed and its influence on the sprinkler irrigation results at the Irrigation District of Montesnegros, located in the NE of Spain, in the provinces of Zaragoza and Huesca (Aragon), and classified as windy. At the moment, only one meteorological station of the SIAR net (Irrigating Agriculture-Weather Information System of the Spanish Agriculture Ministry) located in the irrigation district supplies the weather reports. This paper will attempt to study if these reports are representative for all the district area, according to irrigation performance indexes. WAsP model was used to estimate the wind distribution at 13 different points within the Irrigation District. Wind data from the SIAR station for the period August 13th 2003 to August 13th 2005 were used to this estimation. To check the WAsP results, using cup anemometers, continuous measurements during at least 24 h were recorded at those 13 sites.

To determine whether the SIAR met reports are representative in the district territory, four irrigation designs, two sprinklers and two triangular spacings, and the pressure at sprinkler nozzle, were pre-defined. Using ADOR-Sprinkler, a solid-set model based on ballistic theory, the wind speeds modelled at these 13 sites for the 2003-2005 period were translated into parameters of uniformity and efficiency that were compared. A second aim was to calculate the percentage of suitable time for irrigation. It was compared the number of suitable hours whether 13 different wind distributions were considered or only that from the SIAR station. The suitable time for irrigation was determined according to four management strategies: One based on a wind threshold (<3 m/s) and three others based on the irrigation performance parameters Christiansen Uniformity Coefficient *CUC* and Wind Drift Evaporation Losses *WDEL* (CUC≥84% and WDEL≤20% for the *standard*, CUC≥90% and WDEL≤15% for the *restrictive* and CUC≥80% and WDEL≤25% for the *relaxed*).

Key words: Sprinkler, wind, spatial variability, modelling.

1. INTRODUCTION

Sprinkler irrigation is the second most important system in the irrigated areas of Aragón. During the last years, national and regional policies have encouraged the modernization of the irrigation districts of Spain and pressurized irrigation systems are commonly installed in the new irrigation projects. Nowadays the irrigating land in Aragón is distributed as follows: 20 % *sprinkler irrigation*, 70% *surface irrigation* and 10% *drip irrigation*. Sprinkler and drip irrigation systems in these new modernized projects incorporate high technical control and monitoring systems to improve the regional farming according to the XXI century level needs (M.A.P.A., 2001).

In various applications, such as sitting of a wind turbine, assessment of the environmental impact of air pollution from a point source, or in agriculture and forestry, knowledge of the local wind climate is needed (Achberger, 2002). Sprinkler irrigation is

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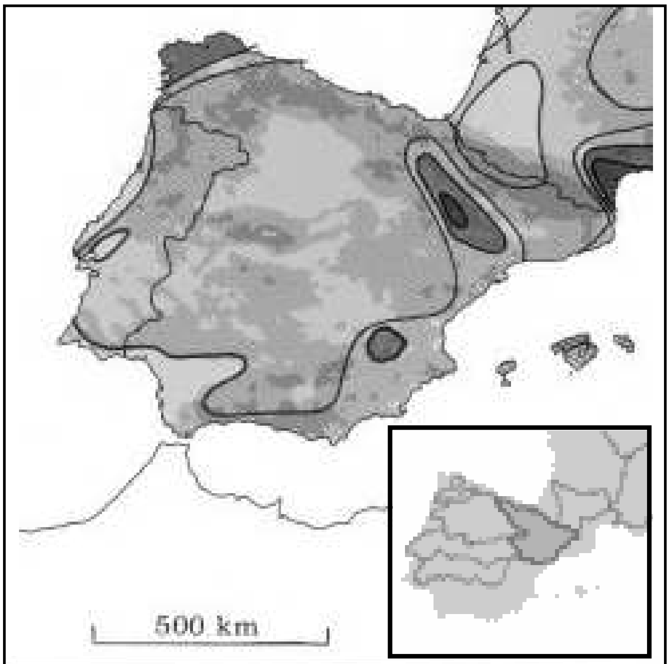
affected by technical and meteorological conditions. Wind velocity, among the meteorological variables, is the most related with the sprinkler irrigation performance because of its influence on uniformity and wind drift and evaporation losses (Dechmi et al., 2004; Playán et al., 2005).

A high percentage of the irrigation districts of Aragón, especially along the Middle Ebro Valley, are located in windy areas. The average daily wind velocity at 2 m a.g.l. over these zones is higher than 2 m/s (Puicercús et al., 1994; Hernández Navarro, 2002; Martínez-Cob y Tejero-Juste, 2004). Within most of the territory of the Middle Ebro Valley the mean wind speed at 50 m a.g.l. is higher than 5,0 m/s over sheltered terrain, higher than 6,5 m/s over open plain and higher than 10,0 m/s over hills and ridges. (Figure 1) (Troen & Petersen, 1989).



Wind resources[1] at 50 metres above ground level for five different topographic conditions										
	Sheltered terrain[2]		Open plain[3]		At a sea coast[4]		Open sea[5]		Hills and ridges[6]	
	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$	$m s^{-1}$	$W m^{-2}$
	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
	5.0-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0- 8.5	400- 700
	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Figure 1: European Wind Atlas by Risø National Laboratory in Roskilde, Denmark (Ebro river basin detail).

A network of agro-meteorological stations (SIAR) has been installed during the last years at a large number of Spanish irrigation districts. Its main goal is to assist the estimation of crop water needs. Wind speed and direction data are collected at these stations. The regional representativeness of the wind records at a given meteorological station depends on the complexity of topography and obstacles surrounding the station (Troen & Petersen, 1989).

To plan an efficient sprinkler irrigation management in a windy zone, where an important spatial variability could be found, the wind data supplied by only one station could not be enough. Wind close to the Earth's surface is strongly influenced by the nature of the terrain surface (Petersen et. al 1998). The local effects, specific only to the site are, namely: 1) shelter from near-by obstacles; 2) effects of roughness and changes in roughness; 3) effects of the orography on scales less than 10 km; and 4) thermally driven flow (Landberg et al. 2003).

When one wants to estimate the wind conditions at a site with no or few measurements, one has to link these measurements to measurements of a long duration from another (near-by) site. The idea behind this being that within a certain distance –given by the local meso-scale conditions- the overall wind climate is the same (Landberg and Mortensen, 1994). When measurements are lacking, data form a nearby meteorological station, gridded data from operational forecast models or large scale climate data sets are often used to derive a site's wind climate. This problem is complex and scale-dependent (Achberger et al., 2002). To predict the wind resource at target sites two methods, or families of methods, are mainly used: a) A physical method, i.e., a method based on a physical model of effects affecting the two sets of measurements b) A statistical method, i.e., a method based on statistical correlations between the two time series (Landberg and Mortensen, 1994).

Among the statistical methods, a method often used in estimating the resource at a site is the measure–correlate–predict (MCP) (Derrick, 1993). Over the last 15 years well over a half of dozen variations of the MCP technique have been proposed. Derrick used linear regression to characterize the relationships between the reference and target site wind speeds. He concluded that, at least, 8 months of data was needed to minimize uncertainties in the results. Landberg and Mortensen (1993) showed that concurrent data lengths should be at least 9 months long, with little improvement using longer data lengths. Nielsen et al (2001) concluded that estimated long-term statistics based on regression models and a long record from the reference site become uncertain for data-overlap periods shorter than a year.

About the physical methods, during the last half a dozen years numerical flow models and other advanced computational tools have become widespread in the wind energy community. One of these is the Wind Atlas Analysis and Application Program-WAsP (Troen and Petersen 1989). Its major advantage is that it can generalise a long term meteorological data series to be valid not only at the site where it has been measured, but in an area around this site. A disadvantage is that it is not possible, beforehand, to give a solid estimate of the size of the region where the calculated wind climate is valid (Landberg and Mortensen, 1993). In contrast to the regression models, the WAsP model does not need wind data from the predictive site (Achberger et al. 2002). Because of this worthy benefit, the topic approached in this study could be solved.

This work was focused on the spatial variability of the wind within the Montesnegros district. Three were the main objectives: 1) to validate the WAsP 8 model (Mortensen et. al, 2005) to simulate the spatial variability of wind speed and direction at the study area; 2) to characterize the differences in wind velocity recorded at the SIAR station located at the Montesnegros district, and those modelled by WAsP at different points within the district; and 3) to analyze the consequences of the wind variability on sprinkler-irrigation management for different on-farm designs using the ADOR-Sprinkler simulation model (Playán et. al 200X).

2. MATERIAL AND METHODS

The Montesnegros irrigation district is located along the limits of Zaragoza and Huesca provinces, stretched within La Almolda, Bujaraloz, Peñalba and Valfarta municipal districts. The Montesnegros irrigation district covers 7.352 ha, consisting of 3.492 irrigated ha. This study has been based on the irrigated land.

WAsP model

WAsP version 8.03.0015 model (Mortensen et. al, 2005) has been used in this study to predict wind at different sites within the irrigation district. Site predictions were calculated at thirteen locations spread over the area (Table 1, Figure 2).

The program is mainly used for a) Establishing of regional wind climatologies, i.e., wind atlases and b) Micro-sitting, i.e. determination of wind turbine sites in specific areas. The European Community Wind Atlas was produced using WAsP and published in 1989. Wind Atlases have been produced and published in Algeria, Jordan, Finland, Sweden, Switzerland and Western Australia (Mortensen et al. 1993).

It is an integrated model including parameterised physical-based submodels for moderately complex topography, landscape roughness and flow around obstacles. Following the WAsP methodology, a map of roughness and topographic conditions, one describing the obstacles and the observed wind data were formatted to be input and to generate the wind atlas for this area.

Wind data used in this work were recorded at two sites (Table 1, Figure 2): 1) the SIAR station located at Valfarta, from August 13th, 2003 to August 13th, 2005; and 2) the Spanish Meteorological Service (INM) station located at Bujaraloz, from July 6th, 1992 to July 6th, 2003. It must be noticed that these series are not overlapped. The reference site used in this paper is the Valfarta SIAR station. The met data for this site are free available by courtesy of *Oficina del Regante, SIRASA (Spain).* It provides different met data but only wind speed (m/s) and direction (°) were collected. These records are collected at 2 m a.g.l. Measurements are stored as 30 min averages. The station located at Bujaraloz collects data at 10 m a.g.l. and measurements are stored as 10 min averages. The distance between these stations is 2455 m.

For the topographical description the DEM (grid size 25x25 m), property of the *MIMAM- Dirección General de Conservacion de la Naturaleza,* was used and height contour lines (equidistance 20 m) were calculated. The roughness was derived at first from the Corine land cover 2000 (CLC2000) 250 m - version 8/2005 map of land uses. It was used the roughness classification proposed by Troen & Petersen (1989). Around the reference station and/or predictive sites (about 2 Km around), the roughness was digitised and detailed by hand with the help of the orthophotos and software from the SigPac (MAPA). These ortophotos were also used to detect and define the obstacles nearby the reference and/or predictive sites.

Basically, the model transforms a wind speed and direction series at a reference site to a regionally representative wind climatology representing a theoretical wind over a flat and featureless landscape of homogeneous roughness. The wind climatology is expressed as a set of sector-wise Weibull parameters describing the wind speed distribution in sectors (sixteen 25° sectors for this study):

$$f(M) = \frac{k}{A}\left(\frac{M}{A}\right)^{k-1} \exp\left(-\frac{M}{A}\right)^{k} \qquad (1)$$

where f(M) represents the relative frequency of occurrence of wind speed with magnitude M, A is the scale parameter related to mean wind speed and the shape the parameter k describes the form of the distribution function.

For the application it was assumed that a) the geographical region is very flat and complex topography is not a major problem, b) approximately neutrally stable conditions prevail when winds are strong.

The representativeness of the calculated regional wind climate depends on the complexity of the landscape and decreases when the orography becomes more rugged (Achberger et al. 2002). To check the model results, wind speed were recorded, at least for 24 h, at thirteen sites within the irrigation district. Measurements were not simultaneous at the thirteen sites but were taken at 3 different time periods (Table 1). For the validation the wind mean velocities predicted were compared with the observed values. The proceeding to collect these measurements is explained next at the Meteorological Measurements Section.

Wind data for two years at the Valfarta SIAR station were used for the WAsP prediction. A different wind atlas was performed with data at the Valfarta SIAR station for each continuous recording period (more or less 24 h) (Table1). Therefore, three different wind atlases were calculated to check the WAsP representativeness. It must be noticed that these three periods are overlapped within the two years period recorded at the SIAR station. Finally, a wind atlas was calculated using the 11 years wind series recorded at Bujaraloz station to see the sensitivity to the length of the measuring period and also the dependence on geographical location.

Meteorological measurements

To avoid data lacking during the measurements period one cups anemometer (model A100R - Vector Instruments) and a weathervane (model W200P - Vector Instruments) were located, by means of a PVC tripod, at 2 m a.g.l. at the same 25 m^2 fenced precinct where the SIAR station is sited. It was assumed that the records supplied by this equipment represent those supplied by SIAR station. The measurements were collected during the whole experiment period by a data logger (CR10X Campbell) connected to the anemometer and the weathervane. 1 minute means, from 6 values corresponding to ten seconds, were stored for wind velocity and direction.

Similar equipments than that one described above, except for the weathervane (Figure 1), were used to collect wind data for these thirteen sites during three different measuring periods (Table 1). With these measurements, subsequently, the WAsP predictions would be checked.

Table 1. UTM coordinates and wind data serial for the reference site Valfarta SIAR station, the Bujaraloz INM station and the thirteen predicted sites.

Site	X	Y	Z	Serial data
SIAR	738048	4601902	354	August 13th 2003 to August 13th 2005
INM	735850	4600809	357	July 6th, 1992 to July 5th, 2003
7	736056	4599995	360	12:35 Febr. 17th, 2005 to 7:05 Febr. 18th, 2005
9	736056	4601995	360	12:35 Febr. 17th, 2005 to 7:05 Febr. 18th, 2005
25	739056	4600995	361	12:35 Febr. 17th, 2005 to 7:05 Febr. 18th, 2005
36	741056	4598995	316	12:35 Febr. 17th, 2005 to 7:05 Febr. 18th, 2005
6	736056	4598995	340	14:39 Febr. 28th, 2005 to 9:38 March 1st, 2005
23	739056	4598995	320	14:39 Febr. 28th, 2005 to 9:38 March 1st, 2005
33	740056	4596995	320	14:39 Febr. 28th, 2005 to 9:38 March 1st, 2005
45	743056	4597995	300	14:39 Febr. 28th, 2005 to 9:38 March 1st, 2005
49	744056	4596995	320	14:39 Febr. 28th, 2005 to 9:38 March 1st, 2005
13	737056	4599995	339	19:16 March 1st, 2005 to 10:08 March 4th, 2005
21	738056	4601995	355	19:16 March 1st, 2005 to 10:08 March 4th, 2005
30	740056	4599995	320	19:16 March 1st, 2005 to 10:08 March 4th, 2005
52	745056	4595995	320	19:16 March 1st, 2005 to 10:08 March 4th, 2005

Figure 1: Measurement equipment: Cup anemometer on a tripod connected to a data logger fed by a solar panel.

Data pre-processing

The wind data from the Valfarta SIAR station (2 years, 30 min interval) and the wind data collected with the anemometers during three different periods (1 to 4 days, 1 min interval) differ in terms of sampling interval and period covered. To make the data sources comparable for the WAsP validation it was necessary to adjust the data sets to a common period and time resolution. The first problem was solved, as it has been just described above, calculating one different wind atlas for any of the three measuring periods. The second problem was solved averaging the 1 min data along the 30 min period. For this, the wind velocity was treated as a vector. First, each 1 min value was projected into its vertical and horizontal components. The average value for the horizontal component and the average value for the vertical component along the 30 min period were calculated and then, the wind velocity magnitude and direction was calculated again.

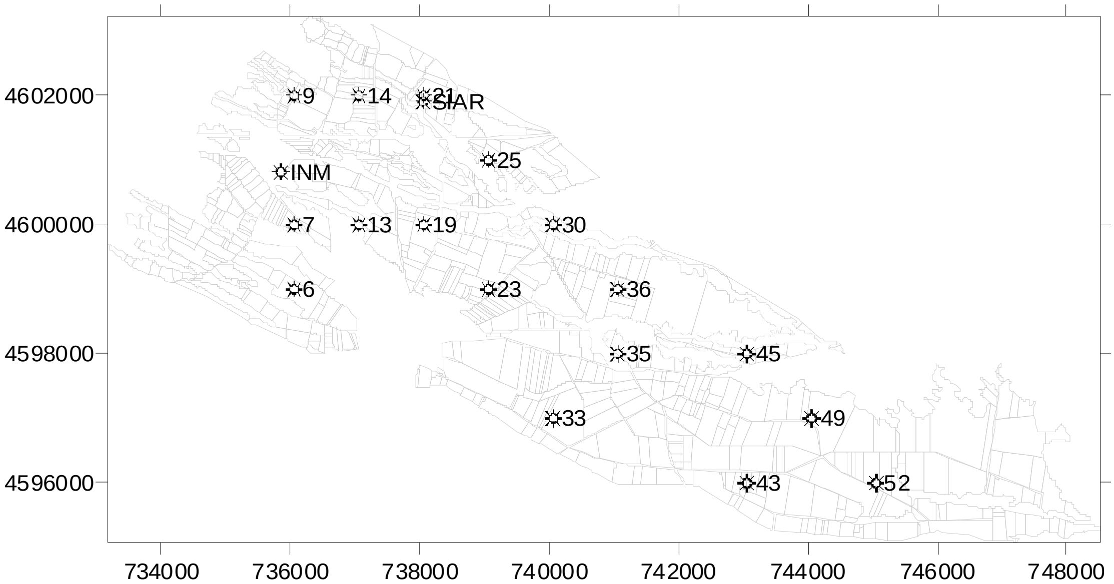


Figure 2. Spatial distribution within the irrigation distribution for the reference site Valfarta SIAR station, the Bujaraloz INM station and the thirteen predictive sites.

ADOR-Sprinkler irrigation model description

A sprinkler irrigation simulation model based on ballistic theory was used to simulate irrigation events in the Montesnegros Irrigation District. It was presented by Playán et al. (200X).

The model requires a combination of meteorological and operational conditions in order to simulate an irrigation event. Wind conditions were derived from the values modelled by WAsP. Two sprinkler spacings were simulated: a triangular spacing with a distance of 18 meters among irrigation lines and 18 meters between sprinklers within the same irrigation line (T18x18), and a triangular spacing with a distance of 15 meters among irrigation lines and 18 meters between sprinklers within the same irrigation line (T18x15). The selected spacings are the two common choices for new solid-sets in the area. 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. The Christiansen Uniformity Coefficient (CUC) (Christiansen, 1942) and the Wind Drift and Evaporation Losses (WDEL), expressed as a percentage of the emitted discharge, were obtained as results. The WDEL are calculated according to this expression:

$$WDEL = 24.1 + 1.41U - 0.216RH \qquad (2)$$

where U is the wind velocity (m/s) and RH the relative humidity (%). Equation (1) was developed for day and night operation conditions (Playán et al. 2005).

Suitable time for irrigation (STI)

For this work it has been used the methodology described by Zapata et al. (2006).

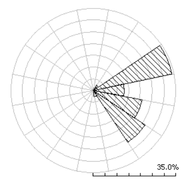
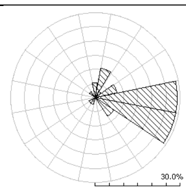
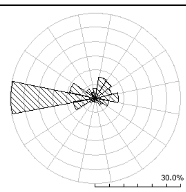
STI is determined according to different irrigation management strategies, four for this work. Three of them are based on the irrigation performance parameters: a standard strategy when CUC³84% and WDEL≤20%, restrictive when CUC³90% and WDEL≤15% and relaxed when CUC³80% and WDEL≤25% and, also, a fourth one, based on a wind threshold: U<3 m/s. For any design, STI was calculated according to these strategies. For the time series studied, STI is the available time when the thresholds fixed to these parameters are exceeded, in the case of the CUC, and not exceeded for the WDEL.

3 RESULTS AND DISCUSSION

Validation of the WAsP model

Table 2 displays the observed and modelled wind for all the 13 sites and for the reference station at Valfarta.

Table2. Observed and modelled wind for all the 13 sites and for the reference station at Valfarta Included are wind direction conditions at the reference Valfarta SIAR site during the recording periods at those sites.

Site	Period	N[1]	Obs. (m/s)	WAsP (m/s)	Valfarta SIAR Wind Rose
Valfarta SIAR station			4.76	4.69	
7	17/02 to 18/02	1136	4.89	4.74	
9	17/02 to 18/02	1136	4.63	4.23	
25	17/02 to 18/02	1136	4.71	5.17	
36	17/02 to 18/02	1136	4.74	4.62	
Valfarta SIAR station			3.12	3.12	
6	28/02 to 1/03	1140	3.49	3.18	
23	28/02 to 1/03	1140	3.07	3.06	
33	28/02 to 1/03	1140	3.00	3.06	
45	28/02 to 1/03	1140	2.74	3.16	
49	28/02 to 1/03	1140	2.71	2.91	
Valfarta SIAR station			2.66	2.64	
13	1/03 to 4/03	3773	3.01	2.63	
21	1/03 to 4/03	3773	2.80	2.60	
30	1/03 to 4/03	3773	2.30	2.64	
52	1/03 to 4/03	3773	3.14	2.53	

[2] Number of raw wind data.

Agreement was good for all the predicted points. The greatest difference between observed and modelled values was 0.61m/s at the site 52 (23% of the mean velocity at the reference site during the same period). For this site, the difference between the observed velocities at the site and at the reference station was 0.48 m/s (18% in regard to observed wind velocity at the reference site). The average of the absolute values of the differences was 0.23 m/s. The wind conditions recorded at the Valfarta SIAR station site during the three measurement periods were roughly different regarding to direction (Table 2). Only during the recording period of 1 to 3 March, the predominant wind direction was that most frequent in the area, the so-called Cierzo, a WNW-NW strong wind.

Due to this agreement, wind speed at the 13 sites was predicted. It was input a wind atlas calculated at the reference site processing a two years wind series collected at the Valfarta station.

WAsP data prediction

Table 3 lists the wind velocity mean values and the Weibull distribution parameters predicted for the period August 2003-August 2005. The Weibull distribution parameters match the mean speed with the weighted sum of the sector-wise mean speeds modelled by WAsP.

Table 3. Wind velocity mean values (U) and Weibull distribution parameters predicted for the period August 2003-August 2005.

Site	Weibull-A (m/s)	Weibull-k	U (m/s)
SIAR	2.9	1.17	2.72
6	2.7	1.07	2.63
7	2.7	1.2	2.52
9	2.5	1.11	2.45
13	2.6	1.15	2.44
21	2.6	1.19	2.47
23	2.6	1.18	2.42
25	3.6	1.2	3.36
30	2.8	1.18	2.6
33	2.6	1.21	2.48
36	2.6	1.16	2.46
45	2.7	1.17	2.59
49	2.6	1.18	2.49
52	2.6	1.17	2.46

Table 3 indicates that differences in wind velocity among stations were quite small but the site 25. Mean wind velocity at the Valfarta SIAR station was slightly greater than that modelled at the predicted sites but site 25. However, these differences are not much higher, 0.38 m/s the greater, 0.22 m/s the mean of the differences (site 25 excluded). Nevertheless, the interest of this study is focussed on the sprinkler irrigation and whether the differences are noticeable would be declare according to irrigation parameters.

Suitable time for irrigation (STI)

The ADOR-Sprinkler solid-set simulation model was used to calculate the STI for the analysed designs. For any combination of wind velocity (0 to 8 each 0.5 m/s) and direction (from 0 to 360, each 5 º), the values of CUC and WDEL wer e simulated for the four design choices (two sprinkler models by two sprinkler spacings). Then, the quality irrigation parameter thresholds describing each management strategy provided the wind limits adequate for sprinkler irrigation for each on-farm design and wind direction range (Table 4).

Table 4. Wind thresholds for adequate irrigation performance indices for each management strategy, on-farm design characteristics, and wind direction range.

Sector	Standard CUC≥84 and WDEL≤20				Restrictive CUC≥90 and WDEL≤15				Relaxed CUC≥80 and WDEL≤25			
	18X18		18X15		18X18		18X15		18X18		18X15	
	RC	VYR	RC	VYR	RC	VYR	RC	VYR	RC	VYR	RC	VYR
N	3	3	4	4.5	2.5	2	3	2	3	3.5	5	5
NNE	3	3	4.5	4.5	2.5	2	3	2	3.5	4.5	5.5	6.5
NE	3	3.5	4	4	2.5	1.5	3	2	3.5	5	4.5	5
ENE	3.5	3.5	4	4	2.5	1.5	3	2	4	5	5	5
E	3.5	3.5	4.5	4.5	2.5	1.5	3	2	4	5	5.5	5.5
ESE	3	3.5	4	4	2.5	1.5	3	2	3.5	4.5	4.5	5
SE	3	3.5	4.5	4.5	2.5	2	3	2	3.5	4.5	5.5	5.5
SSE	3	3	4.5	4	2.5	1.5	3	2	3	4.5	5	5.5
S	3	3	4	4.5	2.5	2	3	2	3	3.5	5	5
SSW	3	3.5	4.5	4.5	2.5	2	3	2	3.5	4.5	5	5.5
SW	3	3.5	4	4	2.5	1.5	3	2	4	4.5	4	5
OSW	3.5	3.5	4	4.5	2.5	1.5	3	1.5	3.5	4.5	4	5.5
W	3.5	3.5	4	4	2.5	1.5	3	2	3.5	5	5	5
WNW	3	3.5	4.5	4.5	2.5	1.5	3	2	3.5	5	4.5	5
NW	3.5	3.5	4.5	4.5	2.5	2	3	2	3.5	4.5	5	5.5
NNW	3.5	3.5	4.5	4.5	2.5	2	3	2	3.5	4.5	5	5

Table 4 figures out that the wind velocity thresholds among sectors are quite small for the Standard and Restrictive strategies (≤0,5 m/s) but greater for the Relaxed strategy (≤1,5 m/s). These results confirm that a good irrigation net design must consider the sprinklers bearing lines orientation in regard to the most frequent wind direction. Tarjuelo et al. (1992) proposed a threshold of 3 m s-1 for irrigation operation in a triangular 18 m x 18 m sprinkler spacing. The results point out that this threshold could be too high for a restrictive strategy according to the designs tested in this study.

The WAsP program may output the wind climatology expressed as a set of sector-wise Weibull parameters describing the wind speed distribution in sectors. Therefore, the relative and/or accumulative frequency of occurrence of any wind speed threshold could be calculated for any sector. The WAsP program also output the wind frequency distribution by sectors.

The combination of Table 4 and WAsP outputs provided the percentage number of hours adequate for sprinkler irrigation (STI) for each management strategy and each on-farm design at the 13 prediction sites and the reference Valfarta site (Table 5).

Table 5. Suitable time for irrigation (%) calculated for any site and for the reference station.

Site	Standard CUC≥84 & WDEL≤20				Restrictive CUC≥90 & WDEL≤15				Relaxed CUC≥80 & WDEL≤25				<3
	18X18		18X15		18X18		18X15		18X18		18X15		
	RC	VYR	RC	VYR	RC	VYR	RC	VYR	RC	VYR	RC	VYR	
6	72.8	74.1	79.2	80.6	61.0	42.8	68.3	50.6	74.9	85.9	85.5	86.8	68.33
7	73.8	75.1	80.6	82.1	61.1	42.2	69.0	50.1	76.0	87.5	87.2	88.6	69.03
9	74.8	76.4	81.4	83.1	63.6	45.7	70.9	53.3	77.0	87.6	87.1	88.6	70.86
13	74.9	76.5	81.6	83.1	63.2	44.8	70.7	52.8	77.2	88.1	87.7	89.0	70.71
14	70.4	71.9	77.5	79.3	58.1	40.3	65.8	47.5	72.9	84.8	84.5	86.3	65.82
19	74.1	76.1	81.1	83.0	62.8	44.7	70.3	52.5	76.7	87.6	87.0	88.6	70.27
21	74.4	75.7	81.0	82.5	61.9	43.0	69.7	51.0	76.5	87.8	87.4	88.8	69.70
23	75.6	76.8	81.9	83.2	63.3	44.4	70.9	52.5	77.5	88.5	88.2	89.4	70.92
25	61.0	62.8	68.8	71.2	49.1	32.1	56.8	38.6	64.4	75.4	73.4	79.2	56.76
30	72.4	73.7	79.1	80.6	59.8	41.2	67.5	49.1	74.6	86.3	85.9	87.4	67.53
33	74.2	75.5	80.9	82.4	61.7	42.7	69.5	50.7	76.3	87.6	87.1	88.9	69.45
35	76.3	77.8	83.4	85.4	63.1	43.0	71.5	50.7	78.8	89.4	88.1	91.5	71.51
36	74.6	76.3	81.5	83.2	62.9	44.4	70.5	52.2	77.0	88.0	87.7	89.1	70.46
43	74.3	75.6	80.6	82.0	62.3	43.7	69.8	51.6	76.2	87.2	86.8	88.1	69.83
45	72.8	74.1	79.4	80.8	60.5	42.0	68.2	49.8	74.9	86.4	86.1	87.4	68.15
49	74.7	76.0	81.3	82.8	62.4	43.3	70.2	51.3	76.7	87.8	87.4	88.9	70.21
52	74.4	75.6	80.7	82.2	62.4	44.3	69.8	52.0	76.3	87.5	87.1	88.5	69.77
SIAR	**70.3**	**71.8**	**77.0**	**78.6**	**58.9**	**41.6**	**66.2**	**48.8**	**72.5**	**83.8**	**83.3**	**85.0**	**66.19**

Averaging the values at the SIAR site for every design and strategy, the STI was 78.1% for the standard strategy, 46.4% for the restrictive and 84.7% for the relaxed; 66.5% for the 18x18 spacing and 73.2% for the 18x15; 71.4 for the RC 130H sprinkler and 68.3% for the VYR 70.

The suitable time for irrigation is directly related to the capacity of the irrigation network. Irrigation Districts affected by strong winds, and Montesnegros and many other located in the central Ebro Valley do, need to select the best on-farm irrigation hardware combination as possible to improve the irrigation performance. Within the different strategies, STI depends on this choice. The Montesnegros Irrigation District presents a 2.66 m/s mean wind velocity, a probability of 52.3% of winds exceeding a 2 m/s wind velocity or a probability of 28.8% of winds exceeding 3.5 m/s (data calculated from the Valfarta series at the SIAR site). Actually, this District, even doing its best, could hardly develop a restrictive management strategy.

Table 6 summarizes the differences on STI between each prediction site and the reference Valfarta site.

Table 6. Differences in STI (%) between that calculated for each site and that calculated for the Valfarta SIAR reference station.

Site	Standard CUC≥84 & WDEL≤20				Restrictive CUC≥90 & WDEL≤15				Relaxed CUC≥80 & WDEL≤25				<3
	18X18		18X15		18X18		18X15		18X18		18X15		
	RC	VYR	RC	VYR	RC	VYR	RC	VYR	RC	VYR	RC	VYR	
6	2.5	2.3	2.2	2.0	2.1	1.3	2.1	1.9	2.3	2.1	2.2	1.8	2.1
7	3.5	3.3	3.6	3.5	2.2	0.6	2.8	1.3	3.5	3.7	3.8	3.6	2.8
9	4.5	4.6	4.4	4.4	4.7	4.1	4.7	4.5	4.4	3.9	3.8	3.6	4.7
13	4.6	4.7	4.6	4.5	4.3	3.2	4.5	4.0	4.6	4.4	4.3	4.0	4.5
14	0.1	0.1	0.6	0.7	-0.9	-1.3	-0.4	-1.3	0.3	1.0	1.2	1.2	-0.4
19	3.7	4.3	4.1	4.4	3.9	3.1	4.1	3.8	4.1	3.9	3.7	3.6	4.1
21	4.0	3.9	4.0	3.9	3.0	1.5	3.5	2.3	3.9	4.0	4.1	3.8	3.5
23	5.3	5.0	4.9	4.6	4.4	2.9	4.7	3.7	4.9	4.7	4.9	4.3	4.7
25	-9.3	-9.0	-8.2	-7.4	-9.8	-9.5	-9.4	-10.1	-8.2	-8.4	-10.0	-5.8	-9.4
30	2.1	1.9	2.1	2.0	0.9	-0.4	1.3	0.4	2.1	2.6	2.6	2.4	1.3
33	3.9	3.7	3.9	3.8	2.7	1.1	3.3	2.0	3.7	3.9	3.8	3.8	3.3
35	6.0	5.9	6.4	6.7	4.2	1.4	5.3	2.0	6.3	5.6	4.8	6.5	5.3
36	4.3	4.5	4.5	4.6	3.9	2.8	4.3	3.5	4.4	4.3	4.3	4.0	4.3
43	3.9	3.7	3.6	3.3	3.4	2.1	3.6	2.8	3.6	3.4	3.4	3.1	3.6
45	2.5	2.3	2.4	2.2	1.6	0.4	2.0	1.1	2.4	2.6	2.8	2.3	2.0
49	4.4	4.2	4.3	4.1	3.5	1.8	4.0	2.5	4.2	4.0	4.0	3.9	4.0
52	4.0	3.8	3.7	3.6	3.4	2.8	3.6	3.2	3.7	3.7	3.7	3.5	3.6

The values listed at Table 6 point out that the differences among the predicted sites, and between each predicted site and the SIAR site, were small but the site 25 (ranging the absolute value of the differences for this site close to 10% on STI for every design or strategy). Site 25 excluded, the greatest difference was 6.7% and the smallest 0.1. The average value of the differences on STI between each site and SIAR was 3.3%.

Sensitivity to the length of the measuring period and geographical location.

The wind data series recorded at the Bujaraloz (July 6th, 1992 to July 5th, 2003) and the Valfarta (August 13th 2003 to August 13th 2005) stations were not overlapped. However, both wind predictions for the Valfarta SIAR station site were calculated by WAsP, one self prediction with the 2 years series and the other with wind data input from the Bujaraloz INM station for a 11 years period. Figure 3 shows the differences between these predictions.

It must be said that, even when these two stations are very close (2455 m), the zone could be defined like non-complex terrain and the land uses are quite similar, the data series are not overlapped, therefore, any conclusion about this section should be carefully made.

According to the experience and previous works (Puicercús et al., 1994; Hernández Navarro, 2002; Martínez-Cob y Tejero-Juste, 2004), the predominant wind direction for the area is not that described at the Figure 3.a. that corresponds to the wind series used for the 13 sites prediction but the described at the Figure 3.b. Nevertheless, since the series are not overlapped, it is not possible any feasible analyses.

The differences on the mean wind velocity and the Weibull parameters are very small.

Despite the results of this comparison it is recommended to observe the wind spatial variability during longer series.

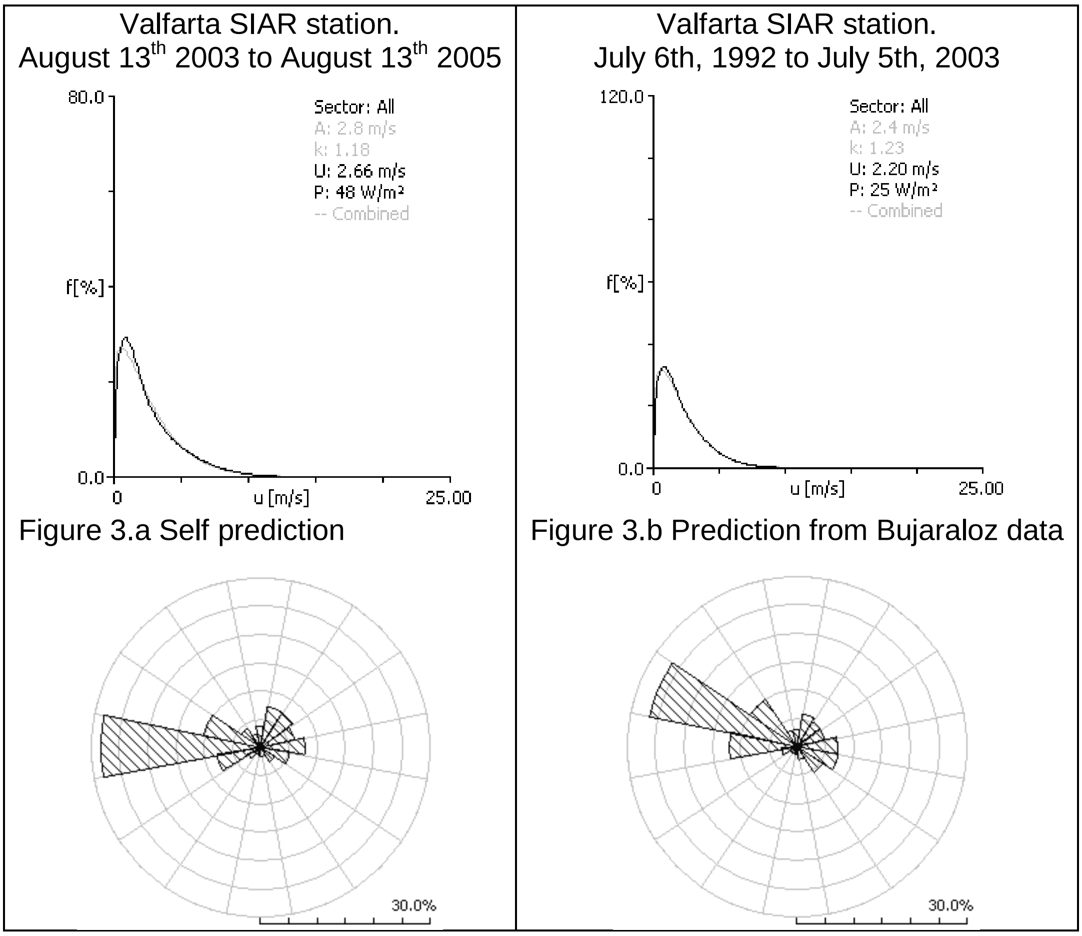


Figure 3. Comparison of the predicted wind climate at the Valfarta site using: A) the 2-year data available at this site; and B) the 11-year data available at the Bujaraloz site.

4. CONCLUSIONS

A methodology has been proposed to study the spatial wind variability over an irrigation district and to evaluate its consequences on irrigating performance. This methodology would be especially useful in zones with no -or few- wind measurements but with wind measurements from a nearby meteorological station.

The methodology involves the use of the WAsP program for the estimation of the local near-surface wind conditions and the use of the ADOR-Sprinkler program to calculate the irrigation performance parameters once the wind conditions are estimated.

The WAsP program has been tested and validated within this studied area. It is a very powerful and robust analysis tool. A comparison was carried out between observed and predicted mean wind velocities at 13 sites at the district. Agreement was very good for all the predicted points. The average of the absolute values of the differences was 0.23 m/s. WAsP allows fast analyses of the wind climate like the frequency of the wind distribution for different directions, probability of winds exceeding a threshold velocity, changes on the wind conditions according to site conditions (different roughness, sheltering effects, topography…)

However, WAsP, intrinsically, is a physical model extremely sensitive to the surface conditions. Therefore, the inputs requirements are many and these require a high quality that may be unavailable in some zones or applications. Moreover, predictions for shorter periods to that initially input could not be done but wind mean values for the whole period. This is a handicap for irrigation applications in which may be very interesting to discriminate between one period or other attempting to criteria like irrigating or not irrigating season, wind conditions when the most evaporative demand occur, etc.

On the other hand, to use ADOR-Sprinkler to model the irrigation within a range of met conditions, a set of technical parameters (nozzles size, sprinkler type, pressure at nozzle, sprinkler height) should be first calibrated for an ample range of met conditions.

There were not found differences between the wind mean values predicted at 12 of the 13 sites and the SIAR station. Therefore, very small differences were found for the STI among sites. The Valfarta SIAR station has been considered suitable to supply the weather reports for the whole district. Differences are supposed to be found within districts whether complex terrain, heterogeneous land uses distribution or many shelters occurs.

An important topic to consider in further research is the spatial variability of the irrigation performance quality. Great differences could be found for the same wind distribution because of variations on the on-farm irrigation hardware combination (sprinkler type and spacing in this study). Up to 24.6% differences of the suitable time for irrigation were found within the restrictive management strategy between the greatest and the smallest values of STI.

This study is part of an integral model to improve the sprinkler irrigation management in districts affected by frequent and hard wind episodes. The global model will include a ballistic simulation model for sprinkler irrigation already calibrated and validated, real time information about the pressure variability along the irrigation net and about the wind velocity all over the district territory and an advanced programming model which will include uniformity and efficiency criteria when determining the optimum time to irrigate.

The water distribution by sprinkler systems under windy conditions means a low efficient water use. According to the water scarcity and competition for its use, an irrigation district could use this tool here presented to optimise water resources rebating proper scheduling or penalizing in case of inappropriate management. This tool allows predicting the wind conditions on every plot within zone where the model would be representative. This way, once input the on-farm irrigation hardware design for each plot, an irrigation performance quality, based on CUC and WDEL, could be calculated for the wind series of interest.

Although the wind direction within the Montesnegros Irrigation District is clearly NW dominant (*Cierzo*), it should be stressed that wind directions less frequent could be a constraint to develop a quality irrigation performance because of the interaction between the azimut of the sprinklers bearing-line and wind direction.

The duration of the periods with strong wind conditions is a very important parameter for the sprinkler irrigation management too. This would be studied in further works.

REFERENCES

Achberger C., Ekström M. and Bärring L. 2002. Estimation of local near-surface wind conditions– a comparison of WASP and regression based techniques. Meteorol. Appl. 9, 211–221.

Ayotte K. W., Davy R. J., Coppin P. A. 2001. A Simple Temporal and Spatial Analysis of Flow in Complex Terrain in the Context of Wind Energy Modelling, Boundary-Layer Meteorology, 98 (2): 275 – 295.

Bowley S.R. 1999. A Hitchhiker´s Guide to Statistics in Plant Biology. Any Old Subject Books Inc. Guelph, Ontario, Canadá.

Christiansen JE (1942) Irrigation by sprinkling. Univ Calif Berkeley. Agric Exp Sta Bull 670

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.

Devore J., Peck R. 1986. Statistics, the exploration and analysis of data. West Publishing Company. Saint Paul, EE.UU. 699 pp.

Hernández Navarro M.L. 2002. Frecuencia e intensidad del viento en Zaragoza. Geographicalia (2ª época). 27: 63-75.
http://dataservice.eea.eu.int/dataservice/available2.asp?type=findkeyword&theme=clc2000
http://sigpac.mapa.es/fega/visor/
http://www.wasp.dk/
Kaimal J.C., Finnigan J.J. 1994. Atmospheric Boundary Layer Flows. Their Structure and Measurement. Oxford University Press. New York. Oxford.
Keller, J. and Bliesner, R. D., 1990. Sprinkle and trickle irrigation. Van Nostrand Reinhold, New York, NY, USA. 652 pp.
Landberg L, Mortensen NG. A Comparison of physical and statistical methods for estimating the wind resource at a site. In Proceedings of the Fifteenth BWEA Wind Energy Conference, Pitcher KF (ed.). BWEA London, 1994; 119–125.
Landberg L., Myllerup L., Rathmann O., Petersen E.L., Jørgensen B.H., Badger J., Mortensen N.G. Wind Resource Estimation - An Overview. 2003. Wind Energy 6 (3). 261-271.
Manwell J.F., Rogers A.L., McGowan, Bailey B.H. 2002. An offshore wind resource assessment study for New England. Renewable Energy 27: 175–187.
New England
M.A.P.A. 2001. Plan Nacional de Regadíos: Horizonte 2008. Ministerio de Agricultura Pesca y Alimentación. Dirección General de Desarrollo Rural. Madrid. (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.
Mortensen, N.G.; Heathfield, D.N.; Myllerup, L.; Landberg, L.; Rathmann, O., Wind atlas analysis and application program: WAsP 8 help facility (online). (2005)
Mortensen N.G., Petersen E. L. and Landberg L. 1993. Wind Resources, Part II: Calculational methods. European Community Wind Energy Conference 611-614
Nielsen M., Landberg L., Mmortensen N. G., Barthelmie, R. J., Joensen A. 2001. Application of Measure-Correlate-Predict Approach for Wind Resource Assessment, Proc. EWEA. 773-776.
Oke T.R. 1984. Boundary Layer Climates. 2nd edn. Methuen, London and New York.
Petersen E.L., Mortensen N.G., Landberg L., Højstrup J., Frank H.P. (1998). Wind power meteorology. Part II: Siting and models. Wind Energy. 1 (2). 55-72.
Playán E., Salvador R., Faci J.M., Zapata N., Martínez-Cob A., Sánchez I. 2005. Day and night wind drift and evaporation losses in sprinkler solid-sets and moving laterals. Agricultural Water Management (in press).
Playán, E., Zapata, N., Faci, J. M., Tolosa, D., Lacueva, J. L., Pelegrín, J., Salvador, R., Sánchez, I. and Lafita, A., 200X. Assessing sprinkler irrigation uniformity using a ballistic simulation model. Agric. Wat. Manage., Submitted.
Puicercús J.A., Valero A., Navarro J., Terrén R., Zubiaur R., Martín F., Iniesta G. (1994), Atlas Eólico de Aragón. Diputación General de Aragón, Departamento de Industria, Comercio y Turismo, 127 pp.
Rogers A. L., Rogers J. W., Manwell J. F. 1994 Comparison of the perfomance of four measure-correlate-predict algorithms. Journal of Wind Eng. And Ind. Aerodyn. 93, 243-264.
Tarjuelo, J. M., Valiente M. and J. Lozoya. 1992. Working conditions of sprinkler to optimize application of water. J. Irrig. Drain. Engrg., ASCE 118(6): 895-913.
Troen I, Petersen E.L. 1989. European Wind Atlas. Risø National Laboratory, Roskilde, Denmark. 46-47 pp.

Zapata, N., Playán, E., Martínez-Cob, A., Sánchez, I., Faci, J. M., Lecina, S. 2006. From on-farm solid-set sprinkler irrigation design to collective irrigation network design in windy areas. Agric. Wat. Manage., Submitted.

ACKNOWLEDGEMENTS

This research was financially supported by the projects AGL2004-06675-CO3 (Plan Nacional de I+D+I) and PIP090/2005 (Diputación General de Aragón). The authors are specially grateful to Daniel, Pilar, Raúl, Raquel, Piluca and Florian for helping us with the hard field work; to Morten Nielsen, Charlotte Hassager, Niels G. Mortensen, Olle Rathman and Lysbeth Myllerup, form the Risoe National Laboratory, (Denmark), for their help with the WAsP model and the wind physics; to Raúl López and Rosa Gómez for their help supporting and managing images and DEM, to Jesús Gaudó and Miguel Izquierdo for the manufacturing of the tripods, to Carmelo Lorente, manager of the Montesnegros Irrigation District and to Miguel Pérez Alloza from the INM office in Zaragoza. The authors also would like to thank to the CAI-Programa Europa the economical supporting for the stay at Denmark.