Day and Night Wind Drift and Evaporation Losses in Sprinkler Solid-Sets and Moving Laterals

by

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Abstract

Wind drift and evaporation losses (*WDEL*) represent a relevant water sink in sprinkler irrigation, particularly in areas with strong winds and high evaporative demand. The objectives of this paper include: 1) Characterize *WDEL* under day and night operation conditions for solid-set and moving lateral configurations; 2) Propose adequate predictive equations; and 3) Prospect the effect of sprinkler irrigation on the meteorological variables and on the estimates of reference evapotranspiration. A total of 89 catch can irrigation evaluations were performed in both irrigation systems and

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under day and night conditions. Different predictive equations of *WDEL* were proposed for combinations of the two irrigation systems and the two operation times. The equations were selected based on their capability to explain and predict *WDEL*. Most equations use wind speed alone as an independent variable, although some use relative humidity or combinations of both variables plus air temperature. In the semi-arid meteorological conditions of Zaragoza (Spain), the average *WDEL* for the solid-set were 15.4 % and 8.5 % during day and night irrigations, respectively. For the experimental moving lateral, losses amounted to 9.8 % during the day and 5.0 % during the night. The effect of sprinkler irrigation on the meteorological variables was moderate, with small increases in relative humidity (3.9 %) and decreases in air temperature (0.5 °C) during the irrigation event and a few minutes afterwards. Consequently, reference evapotranspiration, estimated by the Penman-Monteith method, decreased during the irrigation event by 0.023 mm h⁻¹ on the average. This decrease represents 2.1 % of *WDEL*, suggesting that the *WDEL* do not significantly contribute to satisfy crop water requirements, and therefore constitute a consumptive water loss.

Key Words: Sprinkler irrigation wind drift evaporation losses

1 **Introduction**

2 During a sprinkler irrigation, a relevant part of the water discharged by the irrigation
 3 system does not reach the crop canopy. This unaccounted water is referred to as “Wind
 4 Drift and Evaporation Losses” (*WDEL*), and is expressed as a percentage of the gross
 5 volume of irrigation water. Several authors have identified irrigation system and
 6 meteorological variables influencing *WDEL* (Table 1).

7 Among the system variables, the nozzle and drop diameter have a significant effect on
 8 *WDEL*. A large nozzle diameter results in large drop diameters (Keller and Bliesner,
 9 1990). Large drops are more resistant to drift and present less area per unit of mass. As
 10 a consequence, they are less affected by *WDEL*. An increase in operating pressure
 11 results in a decrease in the resulting drop diameters (Montero et al., 2003), with an
 12 increase in *WDEL*. Increasing nozzle elevation over the soil surface has been reported
 13 to increase *WDEL*, due to a longer drop trajectory and increased wind exposure (since
 14 the wind profile over a crop canopy is logarithmic). As a consequence, many new
 15 center pivot designs set the nozzles about 2 m lower than they used to be, and many
 16 existing center pivots have been modified to lower the nozzles (Dechmi et al., 2003b).
 17 Despite all these practical developments, a decrease in *WDEL* with nozzle elevation has
 18 not yet been confirmed in experimental conditions, neither for solid-sets (Tarjuelo et
 19 al., 2000), nor for moving laterals (Faci et al., 2001; Playán et al., 2004). An additional
 20 system variable is the difference between solid-sets and moving laterals (center pivots
 21 and rangers). The differences between these systems in terms of field coverage, drop
 22 diameter and trajectory will surely result in differences in *WDEL*, but these differences
 23 have not been explicitly documented to date.

The most cited meteorological variables affecting *WDEL* are wind speed (U , m s^{-1}), air temperature ($^{\circ}\text{C}$), relative humidity (RH , %) and vapour pressure deficit ($e_s - e_0$, kPa) (Tarjuelo et al., 2000). Wind speed has often been recognized as the most relevant meteorological variable affecting *WDEL*. Solar radiation was introduced by Seginer (1971). Keller and Bliesner (1990) introduced reference evapotranspiration (ET_0), a variable which integrates all the previously discussed meteorological variables into an estimate of the atmospheric evaporative demand.

The magnitude of *WDEL* can be very relevant under certain conditions. While some authors reported losses of 5-10 % under moderate evaporative demand (Keller and Bliesner, 1990), other authors signalled maximum losses of 30 % (Yazar, 1984; Montero, 1999) or up to 50 % (Frost and Schwalen, 1955; Faci and Bercero, 1991). It is a general belief that *WDEL* are not fully consumptive, since they partly contribute to decrease crop water requirements (Tarjuelo et al., 2000). The common *WDEL* measurement techniques, based on catch cans, may be subjected to relevant measurement errors and even evaporation from the catch cans themselves during the experiments (Seginer et al., 1991). The diameter of the catch can used in experiments to evaluate *WDEL* can have an effect in the results. In fact, the International Standards for Sprinkler Evaluation recommend catch can diameters higher than 85 mm (Anonymous, 1995).

Night sprinkler irrigation has long been practised by farmers in many areas of the world, since the environmental factors inducing *WDEL* are milder during the night time. The decrease in wind speed additionally results in increased irrigation uniformity during the night time (Dechmi et al., 2004b). In order to illustrate this issue, Table 2 presents day and night monthly data for three key meteorological variables in Zaragoza (Ebro Valley, Spain). The distinction between night and day was daily

established on the basis of solar radiation. The data represent averages of hourly records over the period 1994-2003, covering the irrigation season (March-October). Air temperature and wind speed are reduced by 32 and 37 % during the night (respectively), while relative humidity increases by 39 %.

Proper management of sprinkler irrigation systems will result in a minimization of *WDEL*, thus promoting water conservation. The optimum selection of the irrigation timing requires an adequate design of the water delivery network, which must be able to convey irrigation water in a reduced operation time, focusing on night and low-wind periods.

The objectives of this work are to: 1) Characterize *WDEL* under day and night operation conditions for solid-set and moving lateral configurations typical of the Ebro Valley of Spain; 2) Evaluate the adequacy of some *WDEL* predictive equations found in the literature, and propose equations for day and night irrigation in solid-sets and moving laterals; and 3) Prospect the effect of sprinkler irrigation on the field meteorological conditions and on the estimates of reference evapotranspiration.

Materials and Methods

Meteorological stations

Two agrometeorological stations were located at a distance of 20 m from the solid-set and the moving lateral experiments, respectively. Both experiments were performed at the experimental farm of the CITA, and were separated by a distance of 3 km. In the solid-set experiment, the meteorological station was located within the area wetted by the sprinklers. In the moving lateral experiments, the meteorological station was located in an adjacent surface-irrigated grass plot out of the reach of the sprinklers of the moving lateral.

Both stations recorded the following meteorological variables: a) air temperature and relative humidity at 1.5 m height above soil level using a Vaisala probe (model HMP45AC); b) wind speed and wind direction at 2.0 m height above soil level; these two variables were measured using a cup anemometer (Vector Instruments, model A100R) and a potentiometer vane (Vector Instruments, model W200P) at the moving lateral experiment weather station; a wind monitor (Young, model O1503) was used instead at the solid-set experiment. 5-min averages of the above mentioned meteorological variables were recorded using a Campbell Scientific datalogger (CR10 at the solid-set experiment; CR10X at the moving lateral experiment).

Likewise, several other meteorological variables were recorded every 30 minutes at the solid-set experiment meteorological station: a) solar radiation at 2.0 m height, using a CM3 (Kipp & Zonen) pyranometer; b) net radiation using a Q-7 sensor from Radiation and Energy Balance Systems (REBS); c) soil heat flux using two Hukseflux (model

HFP01) plates buried at 0.1 m depth. Soil heat flux readings were corrected according to Allen et al. (1996) as follows:

$$G = \frac{F1+F2}{2} \frac{\Delta T_s}{\Delta t} d_z \rho_b (840 + 4190 \theta) \quad [1]$$

where; G , soil heat flux at the soil surface (W m^{-2}); $F1, F2$, readings of both soil heat flux plates (W m^{-2}); ΔT_s , soil temperature change between two consecutive half hour periods ($^{\circ}\text{C}$); Δt , 1800 s (in this case); d_z , reading depth for soil heat flux plates; ρ_b , bulk density, 1.4 Mg m^{-3} (figure obtained from undisturbed soil samples taken at the beginning of the campaign); and θ , volumetric soil water content. No soil water content measurements were available for the campaign. Analysis of the abovementioned soil samples lead to use a value of $\theta = 0.19$ for the whole campaign; this value is relatively close to field capacity and was assumed because the plot was frequently irrigated during the campaign.

Catch can size experiments

Field experiments devoted to the assessment of sprinkler irrigation performance are regulated by a number of international standards (Anonymous, 1987; Anonymous, 1990; Anonymous, 1995). One aspect regulated in these norms is the catch can diameter, which should exceed 85 mm. When prospecting materials for the realization of these studies, a plastic commercial catch can (a rain gauge) with a diameter of 79 mm was found to be well suited for the experiments, since it was marked in mm for direct readout (up to 40 mm), and it was mounted on a plastic stick for quick installation at 0.5 m over the soil surface. The catch can was conical in its lower part (145 mm), and cylindrical in its upper part (30 mm). An experiment was performed to

compare this small catch can (S) with two larger, cylindrical catch cans with diameters of 130 and 210 mm (medium and large, M and L, respectively).

The experiment was performed on a solid-set field (1.2 ha, grass crop), with a 15 x 15 m square sprinkler spacing (Fig. 1 a). The whole field was irrigated simultaneously during each catch can size experiment. The sprinklers were of the model VYR70 (manufactured by VYRSA™, Briviesca, Brugos, Spain), and mounted two nozzles with diameters of 4.4 and 2.4 mm. The nozzle height was 2 m, and the average operating pressure was 380 kPa. The discharged precipitation amounted to 8.3 mm h⁻¹. The catch cans were located in the central sprinkler spacing of 15 x 15 m. At each of the 25 catch can locations three catch cans were located (S, M and L), separated 0.3 m in a triangular arrangement. The location of each catch can in the vertices of this triangle was randomised.

Three preliminary experiments were performed to measure sprinkler discharge. The pressure at the nozzle, the irrigation time and the sprinkler discharged volume were measured, and the nozzle coefficient was determined. A total of thirteen 3-hour irrigation experiments were then performed, four during the night time and 9 during the day time. In each experiment the operating pressure, the meteorological conditions and the catch can readings (3 x 25) were recorded. The irrigation discharge was determined from the operating pressure, the nozzle diameter and the nozzle coefficient. *WDEL* was computed as:

$$WDEL = \frac{q_{ss} t - 9 \sum_{i=1}^{25} z_i}{q_{ss} t} 100 \quad [2]$$

where q_{ss} is the sprinkler discharge in the solid-set ($\text{m}^3 \text{s}^{-1}$), t is the irrigation time (s), 9 m^2 is the area represented by each catch can, and z_i is the catch can irrigation depth (m).

The statistical analysis focused on the differences in catch can reading at each location. Differences were computed for S-M, S-L and M-L. The meaningfully paired observation test (Steel and Torrie, 1980) was based on the hypothesis that the population of differences did not differ from 0 (probability ≤ 0.05).

Catch can evaporation experiment

Following the concerns expressed by Tarjuelo et al. (2000) an experiment was devised to quantify the effect of catch can water evaporation during the irrigation event on the estimation of *WDEL*. For this purpose, 20 small catch cans were filled with irrigation water at levels ranging from 2 to 40 mm, weighed and covered to prevent evaporation. The solid-set field was irrigated for 3 hours. Immediately after irrigation shut off, the catch cans were installed in the middle of the field and uncovered. The experiment lasted for one hour. During this time, the catch cans were frequently hand sprayed on their outside to reproduce irrigation conditions. After the experiment, the catch cans were dried on the outside and weighed. The difference in weigh was due to catch can evaporation under conditions similar to an irrigation event. The experimental conditions were in fact more extreme than if the sprinkler system had been on. Therefore the results should be regarded as an upper bound to catch can evaporation during irrigation.

WDEL measurement experiments

Experiments were performed on a solid-set and a moving lateral from July 10 to September 18, 2001. One of the objectives of the experiment was to adequately characterize day and night irrigations. The use of irrigation programmers was very important to attain this goal. The catch cans (of type S) were read shortly after the end of the irrigation, to avoid additional evaporation losses. The process could be completed in 20 min, since catch cans were graded for direct readout. Additional details on the experimental procedure can be found in Salvador (2003).

The solid-set experimental set up has been previously described. The experiments were generally performed at 2 and 10 h GMT, and lasted for one hour. A total of 37 experiments were performed in solid-sets, with 19 night experiments and 18 day experiments.

An experimental irrigation machine (Playán et al., 2004) was used to perform the moving lateral experiments (Fig. 1 b). The lateral has a span of 26 m, and is suspended in its centre from a tower which can travel along a railway. A total of 9 Rotating Plate Spray Sprinklers were installed in the moving lateral at a spacing of 3 m and an elevation of 2.05 m. The sprinklers were six-groove Nelson R3000 Rotator™, with 6.7 mm diameter nozzle. A pressure regulator (140 kPa) was installed just upstream of each sprinkler. The sprinkler discharge was determined in preliminary experiments from discharged volume and irrigation time. In all experiments performed in this research the machine remained static and irrigated a bare soil in which a matrix of catch cans (type S) had been installed. The matrix consisted of three rows of 24 catch cans. The catch can spacing was 1 x 1 m. Due to the prevalence of the *Cierzo* wind (with

a NNO direction), the matrix was shifted towards the right side of Fig. 1 b. A total of 52 experiments were performed in the moving lateral, with 31 day time experiments and 21 night time experiments. *WDEL* in the moving lateral was computed as follows:

$$WDEL = \frac{q_{il} t - I \sum_{i=1}^{72} z_i}{q_{il} t} 100 \quad [3]$$

where q_{il} is the sprinkler discharge in the moving lateral ($\text{m}^3 \text{s}^{-1}$), t is the irrigation time (s), 1 m^2 is the area represented by each catch can, and z_i is the catch can irrigation depth (m).

***WDEL* predictive equations**

The experimental values of *WDEL* were related to the meteorological variables recorded during the experiments, and correlations were performed. Eight predictive equations for *WDEL* were tested, and results were presented for both irrigation systems and day/night conditions. The predictive equations are presented in Table 3. These equations were derived using different sprinkler irrigation systems and parameters.

The next step was to derive predictive equations from the experimental data set. Equations were developed using four meteorological variables as independent variables: wind speed, air temperature, relative humidity, and solar radiation. These variables were chosen due to their widespread availability. In each case, the independent variables (X) were considered in the following mathematical forms: X , $\log(X)$, $1/X$, e^X and X^Y , where Y is an empirical coefficient. A variety of regression models were used in conjunction with different numbers of independent variables and

their mathematical forms in order to create a population of predictive equations. A procedure was established to select the best suited, most simple predictive equations:

1. The equations were screened so that the equations themselves, the independent variables and the constant were statistically significant (probability ≤ 0.05).
2. The equations were classified in groups according to the required meteorological variables, in an effort to provide equations based on a variety of meteorological data.
3. In a given group, equations were discarded if presenting low values of the determination coefficient (R^2).
4. A sensitivity analysis was performed to ensure that in the common ranges of each independent variable, the trends identified in Table 1 were respected by the equation. Plots were prepared presenting *WDEL* as a function of a given variable, maintaining the rest constant.
5. Simplicity criterion: equations involving a number of independent variables were only accepted if their R^2 was better than that of simpler equations.
6. A Student t test for coupled samples was applied to pairs of measured and estimated values of *WDEL*. The retained equations surpassed the 95 % probability threshold.
7. Predictive capability: two additional statistics were introduced at this point: the Average Magnitude of the Relative Error (*AMRE*, %) and the Prediction level 25 (*Pred*[0.25]) (Dolado, 1999). *AMRE* can be computed as:

$$AMRE = \frac{1}{n} \sum_{i=1}^n \left| \frac{e_i - \bar{e}_i}{e_i} \right| \quad [4]$$

where e and $\bar{e}$ are the measured and estimated values of $WDEL$, and n is the number of samples. The Prediction level 25 is the percentage of the estimated $WDEL$ values differing from the measured value by less than 25 %.

Influence of irrigation and $WDEL$ on selected meteorological variables

As previously discussed, the meteorological station in the solid-set plot was located within the sprinklers. It therefore recorded the evolution of the meteorological variables during and after the irrigation event. Among the recorded variables, the relative humidity and the air temperature were affected by the irrigation. In order to quantify this effect, regression lines were established between all the 5 min values of the variable 1 hour before and 1 hour after the irrigation event (the 10 min following the irrigation were excluded, since the meteorological variables were often influenced by the irrigation). This permitted to compare the average value of the variable and the average estimated value during the irrigation event. As a result, the effect of the irrigation event on relative humidity and air temperature could be established under day and night conditions.

A similar procedure was followed with reference evapotranspiration, which was estimated at 5 min intervals from the recorded meteorological variables using the FAO 56 Penman-Monteith method (Allen et al., 1998). Since the solid-set plot had a short grass crop, the ET_0 is a direct estimator of crop evapotranspiration. The next step was to estimate the ET_0 which would have occurred if the irrigation had not been performed. The method used for the other meteorological variables did not prove adequate neither for day nor for night irrigations. The day time irrigations were performed at a time very close to the peak of the day, with its corresponding inflection point. During the night time irrigations, the ET_0 values were very low and did show

1 clear trends. An estimation of non-irrigation ET_0 was performed in 16 of the 18 day
2 time irrigation events. The process was based on drawing a line from the last ET_0 value
3 before the irrigation event to the first point after the irrigation event in which ET_0
4 recovered from the effect of the irrigation event. This line permitted to estimate the
5 decrease in ET (mm) due to the irrigation. This amount was compared to the total ET
6 during the irrigation and to the $WDEL$.

1 **Results and Discussion**

2 **Catch can size experiments**

3 During the 13 catch can size experiments the wind speed ranged from 0.6 to 6.7 m s⁻¹
 4 (with an average of 3.0 m s⁻¹), the air temperature ranged from 14.5 to 33.0 °C and the
 5 relative humidity ranged from 32.4 to 82.8 %. The average *WDEL* were 19.2, 18.4 and
 6 17.9 % for the S, M and L catch cans, respectively.

7 Significant differences were found between the irrigation depth in the S and M catch
 8 cans in four experiments. The average wind speed of these four experiments was 3.7
 9 m s⁻¹, and the differences in *WDEL* (S-M) were 2.1, -2.0, 3.8 and 5.5 %. When the
 10 comparison was established between the S and L catch cans, significant differences
 11 were found in four experiments (three of them were the same as for S-M). The average
 12 wind speed for these four experiments was 3.6 m s⁻¹, and the differences in *WDEL* (S-L)
 13 were -2.2, 6.8, 2.7 and 4.3 %. The differences between the M and L catch cans were non
 14 significant in all 13 experiments.

15 Figure 2 plots the differences in *WDEL* as a function of wind. In two cases (S-M and
 16 S-L) regression lines could be established with $P \leq 0.05$. The differences concerning the
 17 S catch can remain moderate up to wind speeds of 4.0 - 4.5 m s⁻¹. When the wind speed
 18 is beyond this threshold, the small catch can overestimates *WDEL* by 3 - 6 %. The
 19 differences between the M and L catch cans are not statistically related to the wind. All
 20 three series of data show relevant scattering, indicating that the determination of
 21 *WDEL* is subjected to important experimental errors. The air temperature and the

relative humidity could not be statistically related to the differences in *WDEL* among catch cans.

When the wind speed exceeds the abovementioned threshold, the M or L catch cans will be better suited than the S catch can. Such strong winds were observed in three of the thirteen experiments. The S catch can has however a number of practical advantages, like direct reading and ease of installation. These circumstances are very important for this study, in which catch cans were read more than 5,000 times. This is why this catch can was finally adopted, taking into consideration that overestimation of *WDEL* may occur at high wind speeds.

Catch can evaporation experiment

Figure 3 presents the evaporation losses from the S catch can during a period of one hour when subjected to a wind speed of 2.1 m s^{-1} , an air temperature of $32.9 \text{ }^{\circ}\text{C}$, a relative humidity of 27.8 %, and an ET_0 of 0.62 mm h^{-1} . The evaporation losses grow with the catch can reading, due to its conical shape. Under the experimental solid-set, the catch can will receive 7.3 mm in one hour (Table 4), with an average reading of 3.7 mm (during the irrigation event: from 0 to 7.3 mm). The corresponding estimated evaporation losses will be 0.039 mm h^{-1} . This amount represents a *WDEL* of 0.5 % (considering that the solid-set discharge is 8.3 mm h^{-1}). These evaporation losses are affected by the atmospheric evaporative demand. Since the ET_0 during the experiment was close to the local maximum, 0.5 points of *WDEL* could be considered as an estimation of the upper bound of catch can evaporation under the local conditions.

The results of this experiment suggest that the difference between the sprinkler discharged and the catch can collected irrigation water is primarily due to *WDEL*.

Considering the results of the previous experiment, out of the 19.2 % lost water, less than 0.5 % were due to catch can evaporation, while the rest constituted “real” *WDEL*.

***WDEL* measurement experiments**

A summary of the experimental results is presented in Table 4. In each irrigation system the day/night fluctuations in catch can irrigation depth resulted in relevant differences in *WDEL*. Switching from day to night irrigation reduced *WDEL* by 55 and 62 % for the solid-set and the moving lateral, respectively. On the average, moving lateral losses amounted to 55 % of the losses measured in the solid-set. These figures should be interpreted with caution, since the experiments of the two irrigation systems were not performed under similar meteorological conditions (Table 4). The largest differences were found in the wind speed, which reached an average value of 2.38 m s^{-1} in the solid-set, while in the moving lateral the average wind was 1.87 m s^{-1} . It seems clear that the solid-set was more exposed to wind than the moving lateral. Within a given irrigation system, the day and night *WDEL* differences can be more readily compared. However, the night/day wind speed ratio in the experiments (48 % for the solid-set and 33 % for the moving lateral) is much lower than in the long-term meteorological record for the same location (63 % from Table 2).

***WDEL* predictive equations**

In order to characterize the statistical relationships between *WDEL* and the four recorded meteorological variables, Fig. 4 was prepared. The figure shows scatter plots with symbols differentiating the two irrigation systems and the day/night conditions. Simple regressions were performed to evaluate how the meteorological variables could explain *WDEL*. These regressions were performed with all the available records, and

with the four combinations of irrigation system x time of the day. Wind speed was the most explicative variable: statistical significance ($P \leq 0.05$) was found in all cases, with the exception of night experiments in laterals. Relative humidity followed, and could explain *WDEL* globally and in day and night irrigations in solid-sets. Solar radiation and air temperature performed poorly. Temperature could explain *WDEL* in day experiments in solid-sets, but the slope of the regression line was negative, in contradiction with the findings reported in Table 1. Solar radiation could explain *WDEL* with all available records, but only due to the effect of the zero-radiation night values.

The next step was to evaluate the predictive capability of some previously proposed equations. Figure 5 presents scatter plots of the observed *WDEL* values and their predictions using eight equations. Two scatter plots are presented for each equation, separating solid-sets and moving laterals. Day and night values use different symbols. The figure indicates the irrigation system(s) for which the equation was originally derived. Even within a given irrigation system, differences in *WDEL* may be due to a number of system and operational variables. Among the three equations presented by Tarjuelo et al. (2000), the one obtained in on-farm tests was used in this analysis, since the only difference with our experiments was the sprinkler manufacturer. The work by Faci et al. (2001) was performed on isolated spray sprinklers of the same type and diameter used in this work. The experiments by Dechmi et al (2003) were conducted using a very similar irrigation hardware and at virtually the same experimental site. Finally, the experiments by Playán et al (2004), were performed in the same experimental moving lateral using a variety of spray sprinklers and a different methodology for the determination of the gross irrigation volume.

The results presented in Fig. 5 are discouraging, since most of the equations perform poorly. In general, the equations tend to yield better results when reproducing *WDEL* in the irrigation system for which they were designed. The equations by Montero (1999), Faci et al. (2001), and Dechmi et al. (2003a) show some adequacy for at least one irrigation system. The reasons for this poor performance seem to be in measurement errors and in the effect of the irrigation system variables, which should receive further attention in order to produce more general predictive equations.

Since none of the analysed equations could perform an adequate *WDEL* prediction on the experimental data set, statistical procedures were used to develop a group of new equations. The goal was to produce equations adapted to different irrigation systems and day/night operation, using independent meteorological variables which are easy to obtain. The resulting 29 equations involved one or two independent variables, and were tested for their explicative and predictive capabilities, as well as for their statistical significance. Table 5 presents the selected equations, together with their main statistics. In general *WDEL* prediction benefits from considering both irrigation systems separately, and from referring to day time periods. Equations based on wind speed alone were proposed for all nine considered cases, while relative humidity was found alone in four cases. In some cases the inclusion on an additional meteorological variable resulted in a relevant increase in the predictive capability of the equation. Seven equations included the wind speed and an additional independent variable. In six cases it was the relative humidity, while in just one case air temperature was introduced.

The predictive equations can be used for the estimation of *WDEL* under irrigation system conditions similar to the experimental ones, and within the experimental range

of the independent variables (Table 4). The user should also bear in mind that the small catch can could result in overestimation of *WDEL* for wind speeds beyond 4.0 – 4.5 m s⁻¹. Catch can evaporation could be a small, additional overestimation factor at all wind levels.

The equations presented in Table 5 permit to generalise on the *WDEL* of these two irrigation systems and day/night operation. For this purpose, predictive equations based on wind speed alone (Eqs. 21, 22, 25 and 26 in Table 5) were used together with the average day and night wind speed of the irrigation season in Zaragoza (Table 2). The average day time *WDEL* would be 15.4 % for the solid-set and 9.8 % for the moving lateral. During the night time, losses would be restricted to 8.5 % for the solid-set and 5.0 % for the moving lateral. *WDEL* are cut by 36 and 41 % when switching from the solid-set to the moving lateral during the day and night, respectively. When switching from day to night operation, the *WDEL* are cut by 45 and 49 % in solid-sets and moving laterals, respectively.

These figures justify the selection of the adequate irrigation system and operation time (day or night). Additionally, the wind speed must always be considered when scheduling sprinkler irrigation. The effect of wind speed on irrigation performance is not limited to *WDEL*. Keller and Bliesner (1990) discussed its effect on irrigation uniformity. In the last decades, models have been developed to estimate the effect of wind speed on irrigation uniformity (Fukui et al., 1980; Carrión et al., 2001; Montero et al., 2001). Recently, Dechmi et al. (2004a; 2004b) used such models to analyse wind effects on crop yield, through its effect on uniformity and *WDEL*.

Influence of irrigation and WDEL on selected meteorological variables

It has long been accepted that meteorology can affect sprinkler irrigation performance, but it is not so clear today how irrigation affects the meteorological variables within the irrigated plot. Installing an automatic meteorological station within the solid-set field created an opportunity for documenting such effect.

Figure 6 presents two plots representing the time evolution of relative humidity, absolute humidity (g of water per kg of air), air temperature and wind speed. The time span partially covers four experimental days. Four solid-set irrigation events were performed during this time, and are signalled in the figure with grey bars. The effect on the meteorological variables varies among irrigations and with the selected variable. The most affected variable is relative humidity, which often increases during the irrigation. However, in particular cases it decreased during the irrigation. The absolute humidity tends to increase, and the air temperature slightly decreases. The magnitude of all these effects is smaller than that of other short-term changes which can be appreciated in the graphs and which are not irrigation related. These irrigation events lasted for just one hour, but longer irrigations did not result in a clearer effect on the meteorological variables (data not shown).

The use of statistical regression permitted to estimate the increase in relative humidity due to the irrigation. On the average, an increase of 3.9 % could be observed, with corresponding figures of 5.3 % and 2.6 % for day and night time irrigations, respectively. Regarding air temperature, the results are even milder. On the average, temperature dropped 0.5 °C during the irrigation events. During the day time, the decrease was 0.8 °C, and during the night time the decrease was 0.3 °C. It could be

argued that the magnitude of these effects would be related to the wind speed, which would renew the air, thus decreasing the irrigation effect. An additional statistical analysis revealed that this was not the case.

If sprinkler irrigation does not modify solar radiation or wind speed, and has mild effects on relative humidity and air temperature, the effect on Penman-Monteith ET_0 (Allen et al., 1998) can not be large. Figure 7 presents two plots of ET_0 vs. time, partially covering four experimental days. During the night irrigations the effect on ET_0 could not be quantified, since ET_0 was low and often subjected to short-term variations. The effect on the day time irrigations is small. The use of trend lines on 16 daily irrigation events showed that the average decrease in ET_0 was 0.023 mm/h. When compared to the amount of water lost to $WDEL$ in each of these irrigations, the decrease in ET_0 represented an average 2.1 % of $WDEL$ (between 0.08 % and 8.85%). This ratio could be statistically related to the wind speed. For winds under 2 m s⁻¹ the average ratio is 2.7 %, while for winds beyond 4 m s⁻¹ the ratio is 0.8 %.

These results suggest that the contribution of $WDEL$ to crop ET is very small, and non relevant in hydrological terms. As a consequence, $WDEL$ are essentially consumptive and do not replace crop ET . These results should be regarded with due precaution, since a number of weaknesses could be identified in the methodology. The most important is probably the estimation of ET_0 during the irrigation event using the automated station. Further research on this topic should involve weighing lysimeters located inside the irrigated plot.

1 Conclusions

2 The catch can diameter is related to the capability of adequately collecting irrigation
 3 water under wind conditions. Our experiments permitted to conclude that using a rain
 4 gauge with a diameter of 79 mm can lead to adequate *WDEL* measurements if the wind
 5 speed is lower than 4.0 - 4.5 m s⁻¹. Catch can evaporation can be an additional source of
 6 error. An experiment permitted to characterize an upper bound of catch can
 7 evaporation in the experimental conditions of this research: 0.5 points of *WDEL*.

8 Eight *WDEL* predictive equations drawn from the literature were used to predict the
 9 experimental values of *WDEL*, with little success. A group of 29 new predictive
 10 equations was proposed for combinations of the two irrigation systems and the two
 11 operation times. The purpose of these new equations is to permit comparisons between
 12 two types of irrigation systems and day/night operation. Most of the proposed
 13 equations use wind speed alone as an independent variable, although some use
 14 relative humidity or combinations of both variables plus air temperature.
 15 Unfortunately, many system design and management variables have a relevant effect
 16 on *WDEL*. As a consequence, our equations can not be considered representative of all
 17 solid-sets or moving laterals. Additionally, they should not be used out of the
 18 evaluated range of the independent variables.

19 In the average meteorological conditions of Zaragoza (Spain), the seasonal average
 20 *WDEL* for the solid-set would be 15.4 % and 8.5 % during day and night irrigations,
 21 respectively. For the experimental moving lateral, losses would amount to 9.8 % during
 22 the day and 5.0 % during the night. These data highlight the relevance of choosing the
 23 adequate irrigation system and timing in order to promote water conservation.

1 The effect of sprinkler irrigation on the meteorological variables was moderate, with
2 small increases in relative humidity (3.9 %) and decreases in air temperature (0.5 °C)
3 during the irrigation event and a few minutes afterwards. Consequently, reference
4 evapotranspiration decreased during the irrigation event by 0.023 mm h⁻¹ on the
5 average. This decrease represents 2.1 % of the observed *WDEL*, suggesting that *WDEL*
6 do not significantly contribute to satisfy crop water requirements, and therefore
7 constitute a consumptive water loss. These results should only be considered as
8 preliminary, since a number of factors could affect their validity. The estimation of
9 crop *ET* during an irrigation event using a standard agrometeorological station could
10 require lysimeter validation.

11 The characterization of *WDEL* under different irrigation systems and day/night
12 operation should lead to a discussion on the benefits of moving laterals over solid-sets
13 and night time irrigation over day time irrigation. Making the most of night time
14 irrigation and avoiding episodes of high wind will require additional capacity and
15 flexibility in the conveyance systems, which will lead to increased structural costs. The
16 prospects for water conservation in a context of water scarcity can make these
17 investments necessary and attractive.

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Table 1. Bibliographical reports on the influence of irrigation system and meteorological variables on WDEL. The considered variables are: D_{nozzle} (nozzle diameter), D_{drop} (drop diameter), h (nozzle elevation), P (operating pressure), U (wind speed), T (air temperature), RH (relative humidity), $e_s - e_0$ (vapour pressure deficit), R (solar radiation), and ET_0 (evapotranspiration).

Table 2. Monthly day and night average values of air temperature ($^{\circ}\text{C}$), relative humidity (%) and wind speed (m s^{-1}) for the irrigation period (March-October) in Zaragoza (Spain). The original data set covers the period 1994-2003.

Table 3. Empirical equations used for WDEL estimation. The independent variables are: nozzle diameter (D_{nozzle} , mm), vapour pressure deficit ($e_s - e_a$, kPa), operating pressure (P , kPa), wind speed (U , m s^{-1}), evapotranspiration (ET_0 , mm day^{-1}) and air temperature (T , $^{\circ}\text{C}$).

Table 4. Average values and ranges (in parenthesis) of catch can irrigation depth (mm), WDEL (%), wind speed (U , m s^{-1}), Relative Humidity (RH , %) and air temperature (T , $^{\circ}\text{C}$) in the solid-set and moving lateral experiments. Results are presented separating day and night irrigations.

Table 5. Selected predictive equations for WDEL. Equations are presented for solid-sets, moving laterals and both irrigation systems; and for day, night and both conditions. Quality indicators are supplied for each equation: R^2 (Determination Coefficient), AMRE (Average Magnitude of the Relative Error) and $\text{Pred}[0.25]$ (Prediction level 25 %). Three dependent variables are used in the equations: Wind

- 1 *Speed at an elevation of 2 m (U , $m\ s^{-1}$), Relative Humidity (RH, %), and Air*
- 2 *Temperature (T , $^{\circ}C$).*
- 3

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Authors	System Variables				Meteorological Variables					
	D_{nozzle}	D_{drop}	h	P	U	T	RH	$e_s - e_0$	R	ET_0
Frost and Schwalen (1955)	-			+	+	+	-	+		
Seginer (1971)					+	+	-		+	
Hermesmeier (1973)			+		+	+	-			
Yazar (1984)				+	+	+		+		
Edling (1985)		-	+		+					
Trimmer (1987)	-			+	+			+		
Keller and Bliesner (1990)	-			+	+					+
Faci and Bercero (1991)					+					
Tarjuelo (1995)		-			+	+	-			
Silva and James (1988)		-			+	+	-			
Montero (1999)				+	+			+		
Tarjuelo et al. (2000)	-	-	+	+	+			+		
Faci et al. (2001)	-				+	+				
Playán et al. (2004)					+					

Table 2. Monthly day and night average values of air temperature ($^{\circ}\text{C}$), relative humidity (%) and wind speed (m s^{-1}) for the irrigation period (March-October) in Zaragoza (Spain). The original data set covers the period 1994-2003.

Month	Air Temperature ($^{\circ}\text{C}$)			Relative Humidity (%)			Wind Speed (m s^{-1})		
	Night ($^{\circ}\text{C}$)	Day ($^{\circ}\text{C}$)	Night/Day (%)	Night (%)	Day (%)	Night/Day (%)	Night (m s^{-1})	Day (m s^{-1})	Night/Day (%)
March	7.7	14.3	54	83	61	136	1.98	3.16	63
April	9.9	16.4	60	79	57	140	2.15	3.60	60
May	14.1	20.6	69	80	57	140	1.94	3.08	63
June	18.0	25.1	72	74	51	145	2.05	3.10	66
July	20.1	27.1	74	74	51	145	2.03	2.99	68
August	20.1	27.0	74	78	55	142	1.69	2.60	65
September	15.8	22.2	71	82	60	137	1.63	2.71	60
October	12.1	17.8	68	89	71	126	1.46	2.38	61
Seasonal	14.7	21.3	68	80	58	139	1.87	2.95	63

Table 3. Empirical equations used for WDEL estimation. The independent variables are: nozzle diameter (D_{nozzle} , mm), vapour pressure deficit ($e_s - e_a$, kPa), operating pressure (P , kPa), wind speed (U , m s⁻¹), evapotranspiration (ET_0 , mm day⁻¹) and air temperature (T , °C).

Reference	Empirical Equation
Trimer (1987)	$WDEL = \left[1.98 D_{nozzle}^{-0.72} + 0.22 (e_s - e_a)^{0.63} + 3.6 \cdot 10^{-4} P^{1.16} + 0.4 U^{0.7} \right]^{4.2}$
Keller and Bliesner (1990)	$WDEL = \left[1 - \left(0.976 + 0.005 ET_0 - 0.00017 ET_0^2 + 0.0012 U - \right. \right. \\ \left. \left. IG (0.00043 ET_0 + 0.00018 U + 0.000016 ET_0 U) \right) \right] 100$ <p>where $IG = \frac{0.032 P^{1.3}}{D_{nozzle}}$. If $IG < 7$, then $IG = 7$; If $IG > 17$ then $IG = 17$.</p>
Faci and Bercero (1991)	$WDEL = 20.44 + 0.75 U$
Montero (1999)	$WDEL = 7.63 (e_s - e_a)^{0.5} + 1.62 U$
Tarjuelo et al. (2000)	$WDEL = 0.007 P + 7.38 (e_s - e_a)^{0.5} + 0.844 U$
Faci et al. (2001)	$WDEL = -0.74 D_{nozzle} + 2.58 U + 0.47 T$
Dechmi et al (2003)	$WDEL = 7.479 + 5.287 U$
Playán et al (2004)	$WDEL = 1.55 + 1.13 U$

Table 4. Average values and ranges (in parenthesis) of catch can irrigation depth (mm), WDEL (%), wind speed (U , $m\ s^{-1}$), Relative Humidity (RH, %) and air temperature (T , $^{\circ}C$) in the solid-set and moving lateral experiments. Results are presented separating day and night irrigations.

Irrigation system	Day/night conditions	Irrigation depth (mm)	WDEL (%)	Wind Speed ($m\ s^{-1}$)	Relative Humidity (%)	Air Temperature ($^{\circ}C$)
Solid-Set	All	7.3	12.1 (1.6-27.6)	2.38 (0.23-7.94)	65.1 (39.1-88.8)	20.0 (9.7-28.1)
	Day	7.0	16.5 (7.6-27.6)	3.20 (0.63-7.94)	55.8 (39.1-74.2)	23.3 (18.3-28.1)
	Night	7.7	7.4 (1.6-17.5)	1.52 (0.23-2.74)	74.9 (55.4-88.2)	16.5 (9.7-21.5)
Moving lateral	All	37.3	6.6 (1.2-14.7)	1.87 (0.06-4.51)	53.6 (23.8-88.7)	23.9 (9.9-34.3)
	Day	36.4	8.8 (4.3-14.7)	2.28 (0.62-4.51)	39.7 (23.8-61.2)	27.7 (17.5-34.1)
	Night	38.9	3.3 (1.2-6.6)	0.75 (0.06-1.98)	74.3 (49.7-88.7)	18.3 (9.9-23.2)

Table 5. Selected predictive equations for WDEL. Equations are presented for solid-sets, moving laterals and both irrigation systems; and for day, night and both conditions. Quality indicators are supplied for each equation: R^2 (Determination Coefficient), AMRE (Average Magnitude of the Relative Error) and Pred[0.25] (Prediction level 25 %). Three dependent variables are used in the equations: Wind Speed at an elevation of 2 m (U , $m\ s^{-1}$), Relative Humidity (RH, %), and Air Temperature (T , $^{\circ}C$).

Irrigation System	Day or Night	Eq. #	WDEL =	R^2 (%)	SE (%)	AMRE (%)	Pred[0.25] (-)
Solid-Set	All	E15	$20.3 + 0.214 U^2 - 2.29 \cdot 10^{-3} RH^2$	0.80	3.1	0.31	62
		E14	$26.1 + 1.64 U - 0.274 RH$	0.79	3.2	0.31	59
		E5	$38.6 - 0.407 RH$	0.67	3.9	0.37	49
		E23	$4.4 + 3.60 U^{0.9}$	0.60	4.3	0.51	43
		E4	$5.2 + 2.90 U$	0.60	4.3	0.51	43
	Day	E13	$20.7 + 0.185 U^2 - 2.14 \cdot 10^{-3} RH^2$	0.75	2.8	0.11	89
		E12	$24.1 + 1.41 U - 0.216 RH$	0.69	3.1	0.13	79
		E21	$12.3 + 0.552 U^{1.6}$	0.59	3.5	0.17	79
		E1	$13.0 + 0.246 U^2$	0.58	3.5	0.18	79
		E20	$10.5 + 1.89 U$	0.57	3.5	0.17	74
	Night	E22	$3.2 + 1.84 U^{1.7}$	0.55	3.2	0.43	56
		E2	$3.7 + 1.31 U^2$	0.55	3.2	0.42	61
		E3	$29.9 - 0.300 RH$	0.39	3.7	0.53	28
Moving Lateral	All	E18	$-2.1 + 1.91 U + 0.231 T$	0.74	1.8	0.33	58
		E7	$2.7 + 2.31 U$	0.60	2.2	0.42	54
		E27	$2.4 + 2.70 U^{0.9}$	0.60	2.2	0.42	56
	Day	E17	$7.0 + 1.65 U - 1.16 \cdot 10^{-3} RH^2$	0.51	1.8	0.17	81
		E16	$8.9 + 1.67 U - 0.097 RH$	0.50	1.8	0.17	81
		E25	$5.1 + 1.78 U^{0.9}$	0.38	2.0	0.20	77
		E24	$5.4 + 1.48 U$	0.38	2.0	0.20	77
	Night	E26	$3.1 + 0.00600 U^{9.2}$	0.28	1.2	0.40	43
		E6	$239 / RH$	0.11	1.3	0.45	38
Both Irrigation Systems	All	E11	$3.1 + 2.95 U$	0.58	3.7	0.49	51
		E8	$8.6 + 0.337 U^2$	0.51	3.8	0.28	62
		E28	$8.4 + 0.409 U^{1.9}$	0.51	3.8	0.28	64
	Day	E19	$5.7 + 2.29 U$	0.51	3.8	0.29	56
		E29	$3.2 + 0.761 U^{2.6}$	0.59	2.5	0.48	46
	Night	E9	$3.4 + 0.512 U^3$	0.59	2.5	0.47	46
		E10	$10.3 - 8.97 \cdot 10^{-4} RH^2$	0.12	3.7	0.70	36

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