Discharge Efficiency in Sprinkling Irrigation: Analysis of the Evaporation and Drift Losses in Semi-arid Areas

J.F. Ortega, J.M. Tarjuelo, J. Montero, J.A. de Juan

Centro Regional de Estudios del Agua. Instituto de Desarrollo Regional. Universidad de Castilla-La Mancha.
Campus Universitario s/n, E02071 Albacete, SPAIN.
Phone: (+34) 967599200 ext. 2835
Telefax: (+34) 967599233
e-mail: tarjuelo@prov-ab.uclm.es

ABSTRACT

A proper understanding of factors affecting evaporation and drift losses in sprinkle irrigation is important for developing water conservation strategies. It is important to highlight that this study has been centred on soil set irrigation systems. So, for estimating drift and evaporation losses during the set sprinkler irrigation event, several outdoor single-sprinkler and block irrigation tests have been conducted. Various sprinkler-nozzle-riser height combinations were used and the variation of evaporation and weather conditions (i.e. air temperature, relative humidity, vapour pressure deficit and wind speed) was measured during the test. In addition, several on-farm solid set evaluations have been performed to evaluate evaporation and drift losses. Mathematical modelling is complex, and several simplifications should be assumed. A statistical approach has been used with these data to estimate losses using a linear model. The losses were estimated as a function of the sprinkler type, nozzle combination, vapour pressure deficit to the power of 0.5 and wind speed. Other climatic and operating factors did not have significant effect on the losses developed in this study. The model can be a useful tool to determine the irrigation timing as a function of environmental and operational conditions (e.g. working pressure, air temperature, relative humidity, etc.) in order to minimise evaporation and drift losses.

Key words: sprinkler irrigation, efficiency, spray evaporation, wind drift, losses, modelling.

INTRODUCTION

The study of evaporation and drift losses during the water application by means of sprinkle irrigation has been reported in many studies (e.g. laboratory, field tests and analytic studies). Since these studies are not defined under the same terms and have different accuracy levels, attained results vary a great deal. So, for tests performed with catch cans, losses ranged from 2% to 40% (mainly 10% to 20%) (Yazar, 1984; Kolh *et al.*, 1987; Kincaid, 1996; Kincaid *et al*., 1996). Evaporation and drift losses are estimated as the difference between the amount of water discharged by sprinklers and the amount of water collected by catch cans. In the case of analytic, laboratory tests, losses ranged from 0.5 to 2% (Kohl *et al*., 1987). Kincaid and Longley (1989) showed that spray evaporation losses are usually smaller than 2-3%, even under high air temperature and low air relative humidity.

Edling (1985) showed a rapid depletion of evaporation and drift losses when the drop diameter increases from 0.3 to 1 mm, as well as a high dependency of losses on wind speed and riser height in the case of 0.3-mm drop diameter. This dependency is much less important for drop diameters over 0.6 mm. Edling (1985), Kohl *et al*. (1987), and Kincaid and Longley

(1989) inferred from their experiences that drop evaporation in sprinkle irrigation is almost negligible from a drop diameter of 1.5-2 mm on.

Kohl *et al.* (1987) showed that the problems associated with water-collecting devices (catch cans) and common experimental errors in the measurement process have promoted the idea that losses are very important from a quantitative point of view. However, in theory, the transfer of energy to drops during flight is not sufficient for evaporating over 1-2 % of water discharged. Note that they used large nozzles (6.4 mm) working at low pressure (100 kPa), where there are low proportions of small drops.

Spray evaporation losses within the air mainly depend on air relative humidity, air and water temperature, drop size and wind speed (Yazar, 1984). Wind drift losses depend on wind speed, drop size and the distance to be covered before landing. An accurate knowledge of drop size distributions in the sprinkling irrigation equipment is important because evaporation and drift losses are controlled by the extreme small size ranges, and drop impact energy on the soil is determined primarily by the largest size ranges (Kincaid *et al*., 1996).

Kincaid (1996) showed the distribution of drop size for a large number and variety of sprinklers, including impact sprinklers fitted with nozzles both square and circular in shape and sprayers with several types of deflector plates (flat, grooved, etc.). The drop size was measured by using the laser-optic method. From the results we can highlight:

- In sprinklers: working pressure has more importance in the size of the drop than the size of the nozzle, agreeing with that obtained by Kohl (1974). In sprayers: nozzle size is more important than pressure.
- The ratio (R_t = Dq/H) of nozzle diameter (D_q in m) to pressure (H in m), is a useful parameter to characterise the drop size distribution of impact sprinklers.
- The impact energy increased significantly as the simulated wind speed increased ($E_w=E_k+W^{1.5}$, being E_w the energy with wind; E_k is the energy with no wind and W is wind speed in m/s). Nozzle elevation had little effect on drop energy.

When using the concept of spray evaporation losses it must be assumed that the entire difference between the discharged volume and the collected one should not be considered as losses. The reason is that the microclimate generated above the crop during irrigation and the water retention by crop itself implies, among other effects, substantial crop transpiration depletion.

Seginer *et al.* (1991) showed that there are two approaches (both physical and statistical) for estimating spray evaporation, that essentially lead to the same formulation. The physical approach of spray evaporation is based on a transfer equation, relating the evaporation rate to the specific humidity (or vapour pressure) difference between water drops and the surrounding air.

In a statistical approach, measured bulk evaporation losses are related to environmental and operational parameters. Yazar (1984), testing with a lateral of sprinklers, obtained:

$$E = 0.389\, e^{(0.18W)}\, (e_s - e_a)^{0.7} \qquad (1)$$

where: E is the percentage of discharged flow lost due to evaporation (%); W is wind speed (m/s); e the neperian logarithm base; and (e_s–e_a) is vapour pressure deficit (kPa). The former can be calculated by means of the following expression (Murray, 1967):

$$(e_s - e_a) = e_s\left(1 - \frac{H}{100}\right) = 0.611\ e^{\left(\frac{17.27\,T_a}{237.3 + T_a}\right)}\left(1 - \frac{H}{100}\right) \qquad (2)$$

where: e_s and e_a are the saturation vapour pressure and the actual vapour pressure of the air (kPa); T_a is air temperature (ºC); H is relative humidity (%). The saturation vapour pressure may be also obtained as follows (Wright, 1982):

$$e_s = 6.15 + 4.44\ 10^{-1}\ T_a + 1.43\ 10^{-2}\ T_a^2 + 2.62\ 10^{-4}\ T_a^3 + 2.95\ 10^{-6}\ T_a^4 + 2.56\ 10^{-8}\ T_a^5 \quad (3)$$

Yazar's regression was recalculated by Seginer *et al.* (1991) with wet-bulb depression as an independent variable. The resulting prediction equation is:

$$L = Q_e / Q_S = 0.0087\ e^{\,0.213\ W}\ (T_a - T_w)^{0.58} \quad (4)$$

where: L means losses defined as the ratio of Q_e to Q_S; Q_e is evaporation water discharge (m^3/s); Q_S is sprinkler water discharge (m^3/s); W is wind speed (m/s); T_a is dry bulb temperature (ºC); and T_w is wet bulb temperature (ºC).

The vapour pressure deficit (e_s–e_a) may be expressed as a function of the wet bulb depression (T_a -T_w) by means of the expression (Campbell, 1995):

$$(e_s - e_a) = 0.00066\ (1 + 0.00115\ T_w)\ (T_a - T_w)\ P \quad (5)$$

where: P is the air pressure (kPa).

Moreover Seginer *et al.* (1991) obtained under semiarid conditions, in tests with a single sprinkler under field conditions, the following relationship:

$$M = (Q_e + Q_d)/Q_S = 0.0322\ e^{\,0.075W}\ (T_a - T_w)^{0.69} \quad (6)$$

where: M is losses defined as the ratio of Q_e+Q_d to Q_S; and Q_d is drift water discharge (m^3/s).

When comparing the results of models presented in equation 4 and 6, it is shown that values of L are almost 50% the values of M. Kohl *et al*. (1987) obtained a 60 % of losses due to spray evaporation and a 40 % of losses due to wind drift.

Considering the wind as the only factor to estimate evaporation losses, Yazar (1984) obtained, by testing with a lateral of sprinklers, the following regression equation:

$$E = 1.68\ e^{0.29w} \quad (7)$$

In the same way, Yazar (1984) estimated drift losses (D_r) by means of regression of experimental data depending on wind speed:

$$D_r = 0.25 W^{2.15} \quad (8)$$

where: D_r is discharged-flow percentage due to drift losses (%) at 21 m from the sprinkler lateral.

The number of operating sprinklers and their combination influence the rate of spray evaporation. This is due to a negative feed back, because spray evaporation reduces the air evaporative demand (Seginer *et al.*, 1991).

The suppression of the evaporation from the catch cans on field distribution tests is difficult to achieve (Marek *et al.*, 1985). To overcome this, peripheral collectors surrounding the pattern can be used to estimate collector evaporation during the test.

OBJECTIVES

The objective of this study is to estimate evaporation and drift losses in set sprinkler irrigation under semiarid conditions. A mathematical model will be obtained.

With the aim of both measuring and modelling evaporation and drift losses three different trials were carried out in the open field:

1. Outdoor single-sprinkler tests were performed according to the existing literature.
2. Tests on an experimental irrigation plant where operating conditions were under control.
3. Tests on an actual irrigation plant under normal operating conditions. The final goal of this study is to determine evaporation and drift losses under these conditions.

MATERIALS AND METHODS

We consider *losses* as the difference between the volume discharged by sprinklers and the measured in catch cans after irrigation.

Losses include: (1) evaporation and drift losses; (2) evaporation in catch cans, either during the irrigation event or during the reading process; and (3) measurement errors. Losses may differ among catch cans according to the location and volume of water collected. The larger the difference between the area of the catch can opening and the ground surface that they represent, the lower the sampling accuracy. In our case, white catch cans were used whose opening diameter was 16 cm arranged in a square two-meter grid. A possible error of 5 % is admissible due to these conditions (Keller and Bliesner, 1990).

For the analysis of evaporation and drift losses in set sprinkler irrigation systems, various outdoor single sprinkler tests have been conducted with several sprinkler-nozzle combinations and two riser heights. In addition block irrigation tests both in an experimental solid set system and on-farm plant have been performed. Among the factors, which affect the irrigation process (e.g. working pressure, sprinkler type, size and number of nozzles, use of jet-straightening vane, riser height, etc.), the ones affecting the drop size are essential for the evaporation and drift losses. Thus, it is possible to find out different relationships between losses and climatic conditions for different working conditions.

The standards ISO 7749/1 (1986), ISO 7749/2 (1990), ASAE S330.1 (1993) and UNE 68-072 (1986) have been taken into account to determine the spatial water distribution pattern in both single sprinkler and irrigation block tests. Plastic, white catch cans were used in tests with 0.16 m opening diameter and 0.15 m height.

Single-sprinkler tests

The sprinkler was arranged in the centre of a square two-meter grid of catch cans, at an equal distance from the four catch cans that surround it. A grid of 22 by 22 rows of collectors was used (Fig. 1). The sprinkler was supplied with water through a flexible hose. The riser allows the sprinkler nozzle to be placed 0.6 m or two meters above the catch can openings.

To conduct tests, a pumping set supplied from a tank that maintains a constant level of water, with an adjustment valve at the outlet and a by-pass device to regulate a wide range of pressures and flows was used. Moreover, the equipment has a valve to regulate pressure; an electromagnetic flow meter with an error range below 2%, which records mean flow into a data logger (CR10, Campbell Scientific) every minute and an Annubar® probe with an accuracy of 0.25%; a pressure transducer that collects the working pressure every minute (with an accuracy of 0.2% range from 0 to 700 kPa).

Weather conditions (e.g. temperature, air humidity, and speed and direction of the wind at three heights (one, two and four meters)) are registered with an automatic weather station, located 40 m away from the test site. All this information is registered with one-minute frequency. The parameters and instruments to control environmental conditions that we used in the experiment were: wind speed measured with an anemometer with an accuracy of 0.1 m/s and a measurement range from 0.25 to 75 m/s; air temperature, with a temperature probe with an accuracy of 0.2 ºC and a measurement range from –22 to +55 ºC; and air relative humidity, with an accuracy of 2% and measurement range from 0 to 100%.

Tests had a one-hour duration. Once testing is over, the water collected in each catch can is measured volumetrically with a calibrated test tube, making sure that the same reading order is always followed. These readings are done on two rows at a time, starting with the outermost part of the wetted pattern and ending with the central part. The catch cans arranged on the edges are read first since they contain less water, in order to reduce evaporation losses. These measurements took approximately between 30 and 40 minutes. Three different types of sprinklers were used in single-sprinkler tests: Agros-35 ®; Agros-46®; Rain Bird-46®. Sprinkler-nozzle-riser height combinations are shown in Table 1. These tests have been carried out with 350 kPa working pressure.

Table 1. Summary of sprinkler-nozzle combinations. Number of outdoor-single sprinkler tests. Where: A is 4.4 + 2.4 mm; B is 4.8 mm; V is jet-straightening vane (VP); VI is built-in jet-straightening vane; N3 is III-type secondary nozzle; NN is Naan-type secondary nozzle.

	Number of tests and nozzle identification																	
	A		AV		AVI		AVN3		AVNN		B		BV		BVI		Total	
Riser height (m)	0.6	2	0.6	2	0.6	2	0.6	2	0.6	2	0.6	2	0.6	2	0.6	2	0.6	2
Agros-35	9		13	9			7		7		8		9	4			53	13
Agros-46	5										5						10	
Rain Bird-46	7		10	3		4					5		5			4	27	11
															Total		114	

Block irrigation tests

Block irrigation tests were conducted in an installation composed by four laterals of aluminium pipeline (76 mm in diameter), with four sprinklers per lateral (Fig. 2). The irrigation spacing was 18 m x 18 m. A square two-meter grid is arranged among the four central sprinklers. Operating and weather data were gathered with same devices used in single-sprinkler tests.

Two different types of sprinklers were used in block irrigation tests: Agros-35 and Rain Bird-46. The different sprinkler-nozzle-riser height combinations are shown in Table 2. These tests have been carried out with 350 kPa working pressure.

Table 2. Sprinkler-nozzle combinations tested in block irrigation

	Number of tests and nozzle identification				
	AV	BV	AVI	BVI	TOTAL
Agros-35	18	21	-	-	39
Rain Bird-46	17	-	14	11	42

Weather conditions (e.g. temperature, air humidity, and speed and direction of the wind at three heights (one, two and four meters)) are registered with an automatic weather station, located 40 m away from the test site. All this information is registered with one-minute frequency. The parameters and instruments to control environmental conditions that we used in the experiment were: wind speed measured with an anemometer with an accuracy of 0.1 m/s and a measurement range from 0.25 to 75 m/s; air temperature, with a temperature probe with an accuracy of 0.2 ºC and a measurement range from –22 to +55 ºC; and air relative humidity, with an accuracy of 2% and measurement range from 0 to 100%.

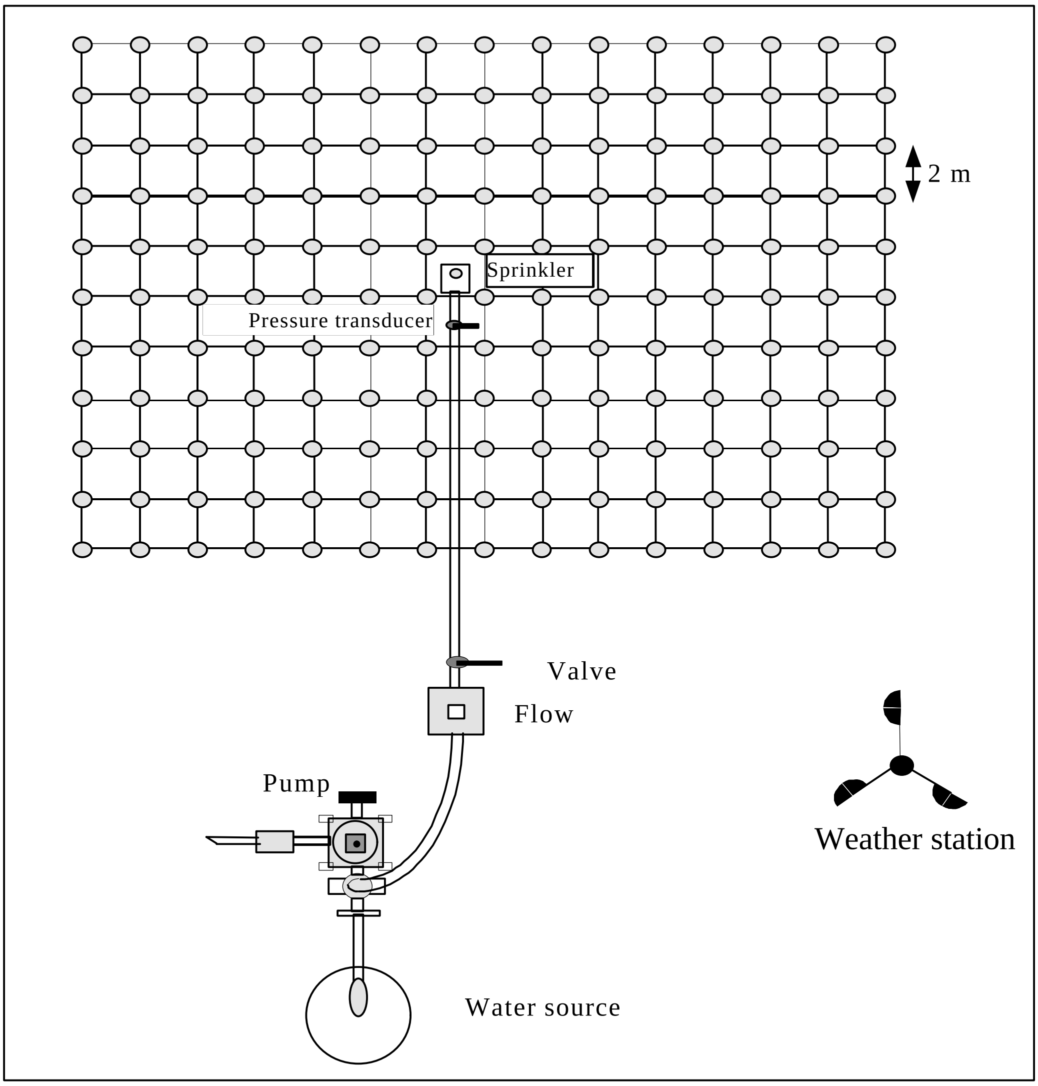

Figure 1. Schematic of the outdoor single sprinkler test installation (it represents a 22 × 22-catch can grid).

Tests had a one-hour duration. Once testing is over, the water collected in each catch can is measured volumetrically with a calibrated test tube, making sure that the same reading order is always followed. These readings are done on two rows at a time, starting with the outermost part of the wetted pattern and ending with the central part. The catch cans arranged on the edges are read first since they contain less water, in order to reduce evaporation losses. These measurements took approximately between 30 and 40 minutes. Three different types of sprinklers were used in single-sprinkler tests: Agros-35 ®; Agros-46®; Rain Bird-46®. Sprinkler-nozzle-riser height combinations are shown in Table 1. These tests have been carried out with 350 kPa working pressure.

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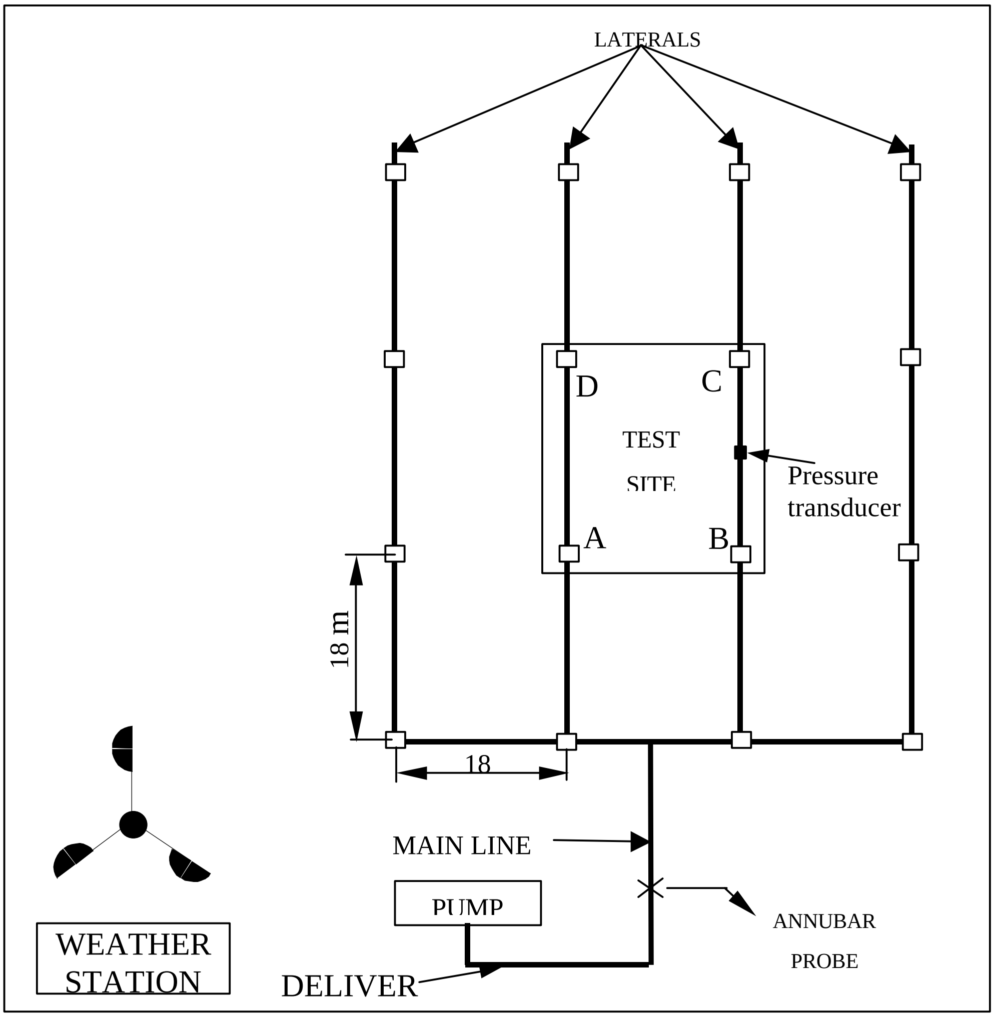

Figure 2. Schematic of the block irrigation test installation.

Agros-35 and Agros-46 are trademarks registered by COMETAL, S.L. (Albacete, Spain). Rain Bird 46 is a trademark registered by RAINBIRD Corp. (Glendon, CA, USA). Makes are given only for informative purposes.

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On-farm tests

Merrian and Keller's methodology (1978) was followed for the evaluation of an actual irrigation plant. In the case of on-farm tests actual irrigation plants in an irrigated land were used. Evaluations were conducted in actual working conditions. Only one sprinkler-nozzle combination was available (Rain Bird-46 fitted with 4.4- + 2.4-mm VP nozzles). The sprinklers were located about two meters above the ground. The irrigation spacing in the different fields ranged from 15.35 m to 17.50 m, with a close square layout. Irrigation plants were tested under actual working conditions. Fields with different operating pressure were evaluated. Both portable anemometers and thermohygrometers have been used in the case of in-farm evaluations. Data were measured every 15 minutes.

Evaporation in catch cans

The avoidance of evaporation in catch cans during field tests is quite difficult to achieve (fig. 1 and 2). To attain an estimate of them, a set of six catch cans was located close to the test as a reference. The catch cans contained an approximate value of water expected for the catch cans to collect. Evaporation was measured in these control catch cans every 15 minutes during the test.

In every catch can, the volume of water collected can be corrected to quantify losses during the irrigation event (one hour in our case). The reading of catch cans has been increased in an amount equal to the half of evaporation losses estimated by means of control catch cans during the reading process (roughly 35 minutes for single-sprinkler tests and 10 minutes for block irrigation). We followed such proceeding assuming that the major evaporation losses in catch cans take place since the microclimate generated by the spray disappears. In addition, we noticed that losses are proportionally greater when decreasing the collected volume in agreement with Doorenbos and Pruitt (1984). Regarding these issues, the reading process has been performed describing circles, starting from the catch cans located at the outermost end (which collects less water) and finishing with the catch can located at the centre of the wetted area.

As a first approximation, we used the model proposed by Seginer *et al*. (1991), correcting the collector evaporation on the basis of evaporation measured in peripheral collectors. The bulk spray evaporation and drift losses are related empirically to wind speed and wet-bulb depression and the lost water amounts can be added to the volumes of water, registered in collectors. We suppose that spray evaporation is proportional to local water application.

Statistical analysis

For the modelling process a statistical analysis has been conducted starting with the relationship existing between the different explanatory variables and the dependent variable, which is determined by means of a first graphical analysis of the parameters assumed in tests. If necessary, variables will be properly converted in order to fit the model. The statistical analysis of evaporation and drift losses was carried out with the software packages SPSS rel. 7.5 (SPSS Inc., 1997) and S-PLUS rel. 4 (MathSoft Inc., 1997). The goal is to achieve a model that estimates evaporation and drift losses by assuming the influence of the sprinkler, riser height and nozzle's "nested" effect within every sprinkler. The former is justified by the experimental design from the relationships found in the graphical analysis. The model uses a linear relation between evaporation and drift losses whether to the rest of variables (e.g. (e_s-e_a), W, T_a and H) or the mathematical conversion of them (e.g. to the power of 0.5). The conversion is recommended due to the graphical analysis of relationships between variables and evaporation and drift losses.

In consequence, we can conclude that our model assumes both quantitative variables (covariables) and qualitative variables (factors). In the case of in-farm evaluations, only weather conditions were used in the model, since only one sprinkler-nozzle combination was available.

The Pearson's Chi-square version of the AIC criterion was used as selection criteria (Akaike's criterion) that is based upon the C_p statistical for the local quadratic model. If the overall model is introduced (i.e. with the whole factors and variables), those terms with lower values for the C_p statistical are successively excluded. Whenever a term is included, the value of the AIC statistical is calculated for the fitted model and is compared with the value obtained from the previous model. If this value lowers, the process continues with the exclusion of one or more terms; otherwise the process halts (Canavos, 1989).

Regardless of the linearity hypothesis that the model implies, the experimental error should verify, for every group defined by the major sort factor, the following characteristics (Norles, 1987): normality (is verified by means of the Kolmogorov-Smirnov, Shapiro-Wilks tests); variance homogeneity (is contrasted with the Levene's statistical); and observation independence (is checked due to the absence of tendency in residues). The fact of demanding these hypothesis to the error is equivalent to demand it in the observations of the variable to be explained (e.g. evaporation and drift losses), since the explanatory variables are determinist.

Once the model is justified and the possible terms that will take part are determined, the significance of factors and covariables considered should be dealt with. The analysis of covariance (specific to fit models wherein there are factors and covariances) provides the significance of the terms used. The hierarchic method is used as a tool for factorising the sum of squares.

After checking the significance of the terms included in modelling, the model parameters with its major statistical significance are estimated. In this way, as shown in results, a mathematical expression that allows simulating evaporation and drift losses under several scenarios will be inferred. To complete the process, a detailed analysis of residues is performed, with the aim of guaranteeing the absence of any type of trend that suggests that any of the hypothesis managed around the methodology of the modelling has defaulted. A special attention will be paid to the linearity condition (prior assumed) of several terms of evaporation and drift losses, as well as to the fit profitability and to the non-correlation of residues.

Whenever it is possible, it is interesting to compare the differences on evaporation and drift losses, which are due to the different combinations (sprinkler-nozzle). The significance of the average differences between factors will be obtained by means of an analysis of multiple comparisons. Homogeneous-behaviour clusters will be attained for the factor checked (in this case nozzle for every sprinkler). Hence as a function of the classification obtained, it will be possible to advice, regarding a certain sprinkler type, the combination of nozzles (single nozzle or double nozzle) that minimises evaporation and drift losses. To analyse this topic, a new variable, obtained from the relationships established in the model itself, will be generated. This variable will provide the information on the effect to be checked. Among all multiple-comparison tests the following proceedings are used: Scheffé, Duncan, B of Tukey, as a way of comparing the various methods and having different criteria when deifying the different groups. Their levels of demand are compared to each other for detecting the significant differences among clusters to be established.

RESULTS AND DISCUSSION

A summary of the sprinkler-nozzle-riser height combinations and number of tests single sprinkler tests and block irrigation tests is presented in Tables 1 and 2, respectively.

Single sprinkler tests

Table 3 shows the values of the quantitative variables considered in the process and registered during testing for the case of single sprinkler tests. Figure 3 summarises the relationships of the explanatory variables to evaporation and drift losses that justify the linearity associated to the model, as well as the need of making a conversion of the vapour pressure deficit for achieving that linear relationship. The conversion involves the calculation of (e_s-e_a) to the power of 0.5 ($(e_s-e_a)^{0.5}$).

Table 3. Descriptive analysis of variables. Outdoor single sprinkler tests.

	Losses (%)	T_a (ºC)	H (%)	(e_s-e_a) (kPa)	W (m/s)
Number of observations	114	114	114	114	114
Arithmetic mean	20.70	20.35	54.97	1.29	3.29
Variance	90.12	37.10	429.38	0.95	3.31
SD	9.49	6.09	20.72	0.97	1.82
Minimum	0.55	7.18	13.33	0.01	0.54
Maximum	42.25	34.14	99.30	4.31	8.07
Range	41.69	26.96	85.97	4.30	7.53
Kurtosis	-0.83	-0.75	-1.04	0.39	-0.56
CV(%)	45.86	29.93	37.70	75.28	55.25

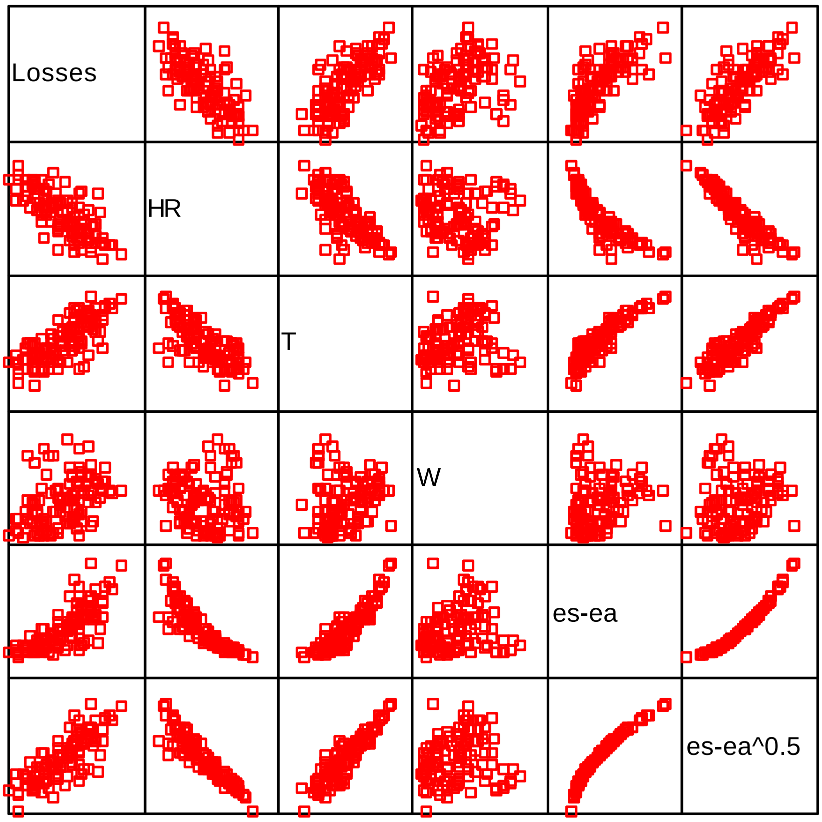

Figure 3. Relationship among Losses, T_a, H, W, e_s-e_a and $(e_s\text{-}e_a)^{0.5}$.

A model that quantifies the influence of the effects "sprinkler" and "the nozzle's "nested" within every sprinkler" (nozzle within sprinkler) will be fitted. In addition the model should linearly relate evaporation and drift losses to the rest of variables selected by the criterion shown. The following factors and variables non-redundant into the model are obtained: sprinkler (SPR), nozzles within sprinkler (NOZ(SPR)), $(e_s\text{-}e_a)^{0.5}$ and wind speed (W).

The model proposed is:

$$LOSSES_{ijk}=a + SPR_i + NOZ(SPR)_{j(i)} + b\,(e_s\text{-}e_a)^{0.5}{}_{k(ij)}+c\,W_{k(ij)} + e_{k(ij)} \qquad (9)$$

where: $LOSSES_{ijk}$ are evaporation and drift losses for each sprinkler-nozzle configuration; *a*, *b* and *c* are fit coefficients; subscript *i* notes the sprinkler type (i=1, 2, 3); *j*(*i*) is the index that denotes the nozzle *j* within the sprinkler *i* (note that not every SPR-NOZ combinations were tested); subscript *k* denotes the replications from the same sprinkler-nozzle combination (*ij*); and $e_{k(ij)}$ is the experimental error.

The model involves the prior-checked hypothesis of linearity that is later validated by means of the analysis of residues. Thus, after checking the hypothesis of the model, the model is fitted. Prior to this, the Analysis of Covariance (ANCOVA) provides the significance of factors and covariables (they were selected as non-redundant, also resulting significant).

The whole terms of the model resulted highly significant. The linear fit of the model, quantified by means of the coefficient of determination (R^2), was considerably acceptable (0.832). Note that the model is complex when factors and covariables take part. In addition, there are no observations for every possible combination of analysed factors.

Table 4 shows the estimates of the model parameters, the standard errors of estimates and significance for every factor and covariable. The variable selection criteria did not introduce the riser height into the model. It did not result as significant although the model was forced to assume this variable. However data behaviour itself suggests its possible participation in the simulation model (but slightly modifying some either environmental or working conditions in the experimental process), at least for certain combinations. In consequence, the future extension of studies about this subject will be a very important issue.

Table 4. Estimates of effects and parameters. Single sprinkler tests.

Variable	Fit value	Standard error
Interception	8.63	2.32
Agros-35 sprinkler (1)	-8.67	2.43
Agros-46 sprinkler (2)	-11.17	2.85
Rain Bird-46 sprinkler (3)	0	-
Nozzle A within sprinkler 1	-4.98	1.83
Nozzle AV within sprinkler 1	-3.39	1.48
Nozzle AVN3 within sprinkler 1	-0.83	2.04
Nozzle AVNN within sprinkler 1	-7.60	2.07
Nozzle B within sprinkler 1	-5.32	1.88
Nozzle BV within sprinkler 1	0	-
Nozzle A within sprinkler 2	-2.22	2.67
Nozzle B within sprinkler 2	0	-
Nozzle A within sprinkler 3	-12.86	2.71
Nozzle AV within sprinkler 3	-12.10	2.45
Nozzle AVI within sprinkler 3	-7.21	3.04
Nozzle B within sprinkler 3	-12.01	2.90
Nozzle BV within sprinkler 3	-15.31	2.88
Nozzle BVI within sprinkler 3	0	-
$(e_s-e_a)^{0.5}$	18.10	1.12
W	1.41	0.23

The estimates of effects and parameters are shown in the column known as *fit value*. Fit values are determined with the hierarchic method. These estimates are shown together with standard errors. For instance, when the Agros-35 sprinkler is fitted with the nozzle AV, and the climatic conditions registered are $(e_s-e_a)^{0.5}$ and w, the prediction of losses is calculated by successively summing the effects that affect it:

$$\text{LOSSES} = 8.63 - 8.67 - 3.39 + 18.10*(e_s-e_a)^{0.5} + 1.41*w \tag{10}$$

If the Agros-46 sprinkler is fitted with the nozzle B under the same climatic conditions, the estimate will be:

$$\text{LOSSES} = 8.63 - 11.17 + 0 + 18.10*(e_s-e_a)^{0.5} + 1.41*w \tag{11}$$

The estimates of mean losses in the clusters defined by the factor “sprinkler” are shown in Table 5. The two-sample comparison tests show as significant the difference between the Agros-35 and Rain Bird-46 sprinklers. No significant differences are found concerning to the Agros-46 sprinkler, but note that experimentation on this sprinkler is very reduced, what may condition results. However its incorporation into the prediction model did not report problems since its effect resulted as significant.

Table 5. Two-sample comparisons among the three types of sprinklers (mean estimates are compared at their levels). Asterisks show significant differences at 0.05 level.

Sprinkler (i)	Sprinkler (j)	Difference of means (i-j)	Standard error	Significance
Agros-35	Agros-46	-0.075	1.463	0.959
	Rain Bird-46	-2.446*	0.927	0.010
Agros-46	Rain Bird-46	-2.370	1.529	0.124
	Agros-35	0.075	1.463	0.959
Rain Bird-46	Agros-46	2.370	1.529	0.124
	Agros-35	2.446*	0.927	0.010

The dispersion graphic of losses against predicted values (PRED-LOSSES) for the model is required for checking the hypothesis of linearity prior assumed within the explanation of losses by the rest of variables and effects, as well as the accuracy of the fit.

The graphic of residues against predicted values of losses is used for checking the hypothesis of non-correlation among errors. There is no trend that suggests the failure to comply with this hypothesis.

Residues obtained with the model fit have an average around zero (average: $4.61\ 10^{-16}$) a typical deviation of 3.891, a coefficient of asymmetry of 0.080 (standard error: 0.226) and a coefficient of kurtosis of 0.263 (standard error 0.449). These figures are a clear indicator of the profitability of the fit achieved with the model.

Once the prediction model is fitted, differences due to the type of nozzle for every sprinkler are identified, and “homogeneous” clusters of nozzles are obtained regarding to the prediction of losses. In the fitted model of losses by equation 9, the prediction of losses within sprinkler *i* and the nozzle *j* is as follows:

$$\text{PRED-LOSSES}_{ij}=a + SPR_i + NOZ(ASP)_{j(i)} + b\,(e_s\text{-}e_a)^{0.5} + cw + e_{k(ij)} \qquad (12)$$

To analyse the effect of each nozzle fitted with the different sprinklers a new variable (EFT-NOZ) is generated from the own model (equation 13). This new variable involves the effect aimed along with the experimental error corresponding the process. The experimental error is randomly distributed –which is corroborated by means of an analysis of residues- and does not influence the new variable to quantify the effects of nozzles within the sprinkler on evaporation and drift losses.

$$\text{EFT-NOZ}_{ijk} =\text{LOSSES}_{ijk} – (a + SPR_i + b\,(e_s\text{-}e_a)^{0.5}{}_{ijk} +c\,W_{ijk}) \qquad (13)$$

Thus, it is logical to isolate this variable for each sprinkler and ask for multiple comparisons incorporated by the factor nozzles. The ANOVA in clusters defined by the Agros-35 and Rain Bird-46 sprinklers resulted as significant. For the Agros-46 sprinkler, the comparison between the only two types of nozzles tested (A and B) did not result significant, assigning the same statistical behaviour to the two types of nozzles.

Table 6 shows the difference of mean LOSSES in clusters defined by nozzles in Agros-35 and Rain Bird-46 sprinklers. In the case of the Agros-35 sprinkler, only the Scheffé test showed differences between AVNN and BV-type nozzles. The homogeneous sub clusters built by means of Tukey, Duncan and Scheffé tests are shown in Table 7 ($P<0.05$).

Table 6. Test, mean values of EFT-NOZ variable and standard deviation (SD).

Sprinkler		A	AV	AVI	AVN3	AVNN	B	BV	BVI
Agros-35	Test	9	22		7	7	8	13	
	Mean	-4.95	-3.36		-0.79	-7.55	-5.29	0.02	
	S D	5.131	4.087		3.112	4.825	3.686	5.685	
Rain Bird-46	Test	7	13	4			5	5	4
	Mean	-12.84	-12.09	-7.20			-11.99	-15.29	-0.01
	SD	2.015	4.861	2.809			2.759	2.876	2.524

Table 7. Homogeneous sub clusters of nozzles within sprinkler Agros-35.

Test	Nozzles	Trials	Block 1	Block 2	Block 3
Tukey's B	AVNN	7	-7.555		
	B	8	-5.294	-5.294	
	A	9	-4.955	-4.955	
	AV	22	-3.364	-3.364	
	AVN3	7		-0.791	
	BV	13		0.025	
Duncan	AVNN	7	-7.555		
	B	8	-5.294	-5.294	
	A	9	-4.955	-4.955	
	AV	22	-3.364	-3.364	-3.364
	AVN3	7		-0.791	-0.791
	BV	13			0.025
Scheffé	AVNN	7	-7.555		
	B	8	-5.294	-5.294	
	A	9	-4.955	-4.955	
	AV	22	-3.364	-3.364	
	AVN3	7	-0.791	-0.791	
	BV	13		0.025	

In the case of the Rain Bird-46 sprinkler both Scheffé and Duncan tests showed significant differences between nozzle BVI and the rest of nozzles. The Duncan test also showed significant the differences between nozzles AVI and BV. The homogeneous sub clusters of nozzles that appear in sprinkler the Rain Bird-46 sprinkler are shown in Table 8 ($P<0.05$).

Table 8. Homogeneous clusters of nozzles for sprinkler Rain Bird-46.

Test	Nozzles	Trials	Block 1	Block 2	Block 3
Tukey's B	BV	5	-15.296		
	A	7	-12.843	-12.843	
	AV	13	-12.091	-12.091	
	B	5	-11.994	-11.994	
	AVI	4		-7.200	
	BVI	4			-0.005
Duncan	BV	5	-15.296		
	A	7	-12.843		
	AV	13	-12.091		
	B	5	-11.994		
	AVI	4		-7.200	
	BVI	4			-0.005
Scheffé	BV	5	-15.296		
	A	7	-12.843	-12.843	
	AV	13	-12.091	-12.091	
	B	5	-11.994	-11.994	
	AVI	4		-7.200	-7.200
	BVI	4			-0.005

Block irrigation

Results from the analysis of evaporation and drift losses in block irrigation are shown in Table 9, which reports a descriptive summary of variables measured or calculated for the set time in testing. A number of 81 tests were performed. Climatic variables, together with the effects incorporated by the factors assumed (sprinkler, nozzle and riser height), is the base for modelling evaporation and drift losses in block irrigation.

Table 9. Descriptive analysis of variables. Block irrigation tests.

	Losses (%)	T_a(ºC)	H (%)	es-ea (kPa)	W (m/s)
Number of observations	81	81	81	81	81
Arithmetic mean	13.36	19.70	51.62	1.26	3.31
Variance	40.62	29.62	297.61	0.54	4.09
SD	6.37	5.44	7.25	0.74	2.02
Minimum	0.95	7.84	22.30	0.00	0.63
Maximum	29.41	32.53	99.90	3.81	9.87
Range	28.46	24.69	77.60	3.81	9.24
Kurtosis	-0.65	-0.41	0.27	1.59	1.22
CV (%)	47.71	27.63	33.81	58.68	60.98

The variables below have been selected for the prediction model in block irrigation, according to the AIC criterion. Remaining variables were not selected or did not result significant in the model. The following model is proposed:

$$LOSSES_{ijk}=a + SPR_i + NOZ(SPR)_{j(i)} + b\,(e_s-e_a)^{0.5}{}_{k(ij)} + cW_{k(ij)} + e_{k(ij)} \qquad (14)$$

where: subscript *i* notes the kind of sprinkler (i=Agros-35 (1), Rain Bird-46 (3)); j(i) is the index that denotes the nozzle *j* within the sprinkler *i* (note that not every SPR-NOZ combinations were tested); *j*(*i*) varies around the set of nozzles tested for the sprinkler *i*; subscript *k* denotes the test from the same sprinkler-nozzle combination (*ij*); and $e_{k(ij)}$ is experimental error.

Table 10 shows the results of parameters estimated during the fit process along with the standard errors obtained for every estimate as shown in Table 4. The coefficient of determination (R^2) is 0.940. In this process of modelling the term of interception did not result as significant.

Table 10. Fit parameters for the terms of the model. Block irrigation tests.

Variable	Fit value	Standard error
Agros-35 sprinkler	-2.02	1.73
Rain Bird-46 sprinkler	-5.29	1.94
Nozzle A within sprinkler 1	-0.58	1.23
Nozzle AV within sprinkler 1	0	-
Nozzle A within sprinkler 3	1.65	1.47
Nozzle AVI within sprinkler 3	3.10	1.52
Nozzle AVN3 within sprinkler 3	0	-
$(e_s-e_a)^{0.5}$	9.56	1.28
W	1.85	0.22

The dispersion graphic of evaporation and drift losses as a function of predicted values is used for checking that the linearity hypothesis prior assumed in the analysis is valid. The graphic of residues against predicted values shows the non-correlation among errors and no tendency is shown that could condition the profitability of results. On the other hand, residues got into groups around zero (average: $1.92\ 10^{-15}$); the standard deviation was 3.636; the coefficient of asymmetry was –0.041 (standard error: 0.267) and the coefficient of kurtosis was –0.286 (standard error 0.529).

There are no significant differences between evaporation and drift losses estimated for the two types of sprinklers (Agros-35 and Rain Bird-46) considered in the study. The analysis of variance is not significant and, logically, two-sample-comparison tests (Table 11) did not result significant in any case. Hence, from a statistical viewpoint, differences of means were not important enough. In consequence, differences were due to random, but not to the factor.

Table 11. Two-sample-comparison tests. Effect introduced by the factor "sprinkler".

Sprinkler (i)	Sprinkler (j)	Differences of means (i-j)	Standard error	Significance
Agros-35	Rain Bird-46	1.401	0.908	0.127
Rain Bird-46	Agros-35	-1.401	0.908	0.127

To check out possible differences introduced by the factor "nozzle" into every block defined by the sprinkler (e.g. nested-effect model), the variable EFT-NOZ was generated from the fitted model. This variable assumes the effects introduced by nozzles (what was justified in methodology). Then, an analysis of variance was then performed for this variable as well as multiple comparison tests.

Table 12 shows the means for the new variable (considering the effect of nozzle within sprinkler), along with the number of tests in every case and the standard deviation associated to the mean. There were no significant differences between nozzles tested in both types of sprinklers (Agros-35, two nozzles were tested with this sprinkler, and Rain Bird-46, that was tested with three nozzles). In this way, by means of an analysis of variance, there were no differences from a statistical viewpoint between means checked out in every block. In consequence the effects introduced by the factor nozzle within sprinkler were sorted in an isolated homogeneous group.

Table 12. Comparison of means for the variable "effect of nozzle within each sprinkler".

Sprinkler	Statistical	AV	BV	AVI	BVI
Agros-35	Tests	18	21	-	-
	Mean	-0.578	-0.0004	-	-
	SD	4.02	2.805	-	-
Rain Bird-46	Tests	17	-	14	11
	Mean	1.647	-	3.104	0.0002
	SD	4.437	-	3.154	4.256

However, factors checked out (e.g. sprinkler and nozzle within sprinkler) are necessary in the modelling process, since they behaved as non-redundant, significant variables, but whose differences of means are not large enough to conclude that they belong to statistically-different clusters.

Comparing with modelling in single sprinkler, this results are a consequence of: (1) the performance of block irrigation itself, which is probably influenced by the generation of a very different microclimatic environment around the control area with respect to single sprinkler irrigation; (2) the partitioning of evaporation and drift losses within the field (at least partially); and (3) other possible effects introduced by the behaviour of rainfall within block irrigation.

To determine the evaporation and drift losses during the irrigation process in a block, taking into account the climatic conditions, the following general model has been deduced:

$$LOSSES = 7.63\ (e_s - e_a)^{0.5} + 1.62W \quad (R^2=0.96) \qquad (15)$$

Figure 4 shows the values of simulated LOSSES against measured LOSSES, where it can be proved that the resulting points are situated around the line 1:1. Figure 5 shows the LOSSES values measured (sequenced in a increasing way) and the values of simulated LOSSES, which range around the first ones.

The mean absolute error resulting when applying the proposed model is of 2.4%, with maximum deviations of ±6%. So, it can be said that the general proposed model is acceptable.

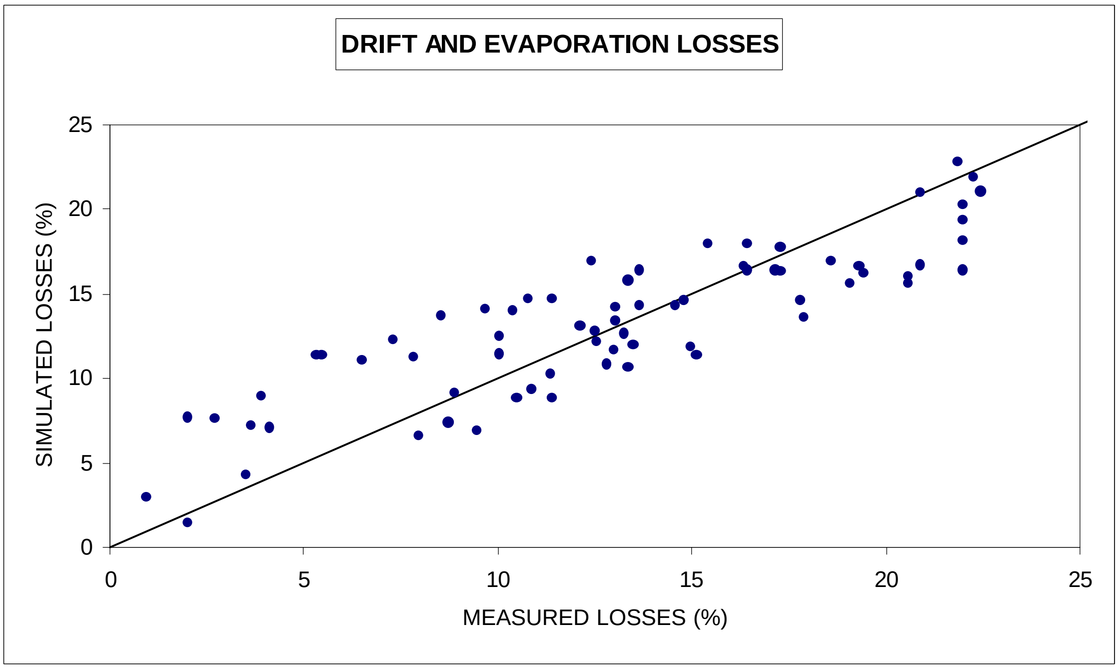

Figure 4. Representation of the measured Losses against the simulated losses with the general proposed model for block irrigation tests.

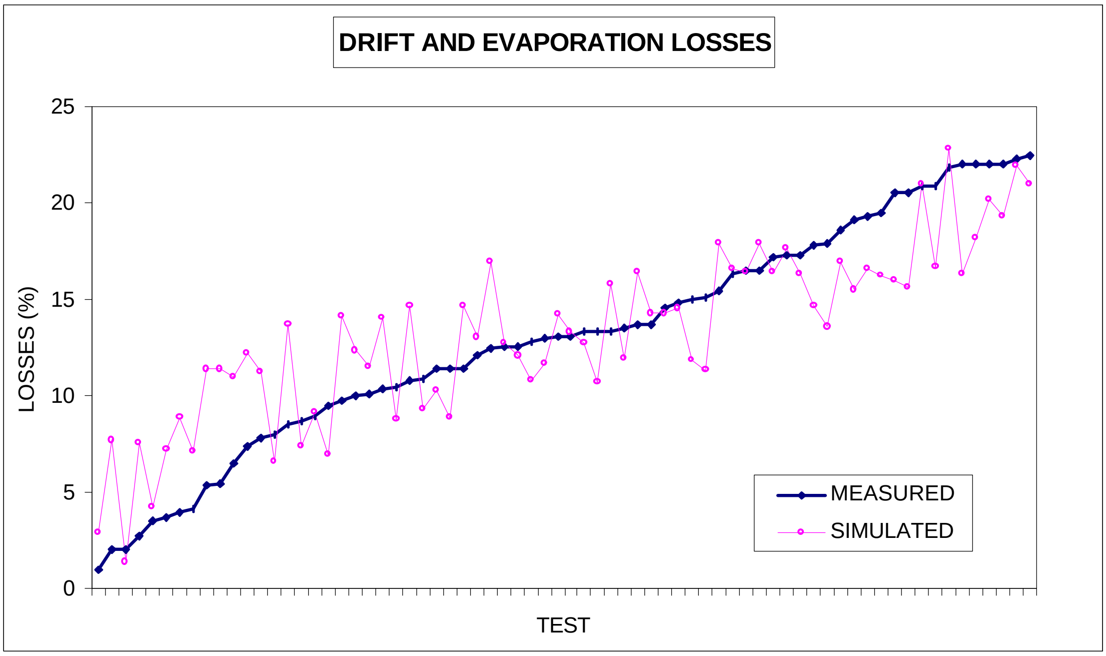

Figure 5. Representation of the measured Losses against the simulated losses with the general proposed model for block irrigation tests.

On-farm tests

Table 13 shows the values of the quantitative variables considered in the process and registered during testing. In this case the same sprinkler (Rain Bird-46), the riser height (h = 2 m), and nozzle configuration (4.4. + 2.4 mm VP) was used.

Table 13. Descriptive analysis of variables of on-farm tests (P = working pressure).

	Losses (%)	P (kPa)	T_a (ºC)	H (%)	$(e_s\text{-}e_a)$ (kPa)	W (m/s)
Number of observations	20	20	20	20	20	20
Arithmetic mean	14.64	362	26.54	46.46	1.93	2.27
Variance	12.64	6075.47	17.78	27.03	0.34	1.85
SD	3.55	77.74	4.22	5.20	0.59	1.36
Minimum	7.90	250	18.40	37.60	1.02	0.22
Maximum	20.60	476	32.30	56.90	2.77	4.61
Range	12.70	226	13.90	19.30	1.75	4.39
Kurtosis	-0.39	-1.37	-1.15	-0.58	-1.47	-1.12
CV (%)	24.29	21.53	15.88	11.19	30.34	59.96

Working pressure -that ranged between 250 and 476 kPa- conditioned differences concerning to the proportion of the different drop sizes generated from the jet-break-up process. The analysis, where there were no factors since there was the same sprinkler-nozzle combination in the whole installations, was performed by means of a linear model computed with multivariable regression.

In order to deal with the model fit, the variable vapour pressure deficit was converted once again into the power of 0.5. Then a clear linear relationship between losses and the different explanatory variables is achieved, improving the value attained by the coefficient of determination as well. Data follows a normal distribution.

The model has the following structure:

$$\text{LOSSES} = a\ P + b\ (e_s\text{-}e_a)^{0.5} + c\ W + e \qquad (15)$$

where: LOSSES are evaporation and drift losses (%); *a*, *b*, and *c* are fit coefficients; P is working pressure (kPa); $(e_s\text{-}e_a)$ is vapour pressure deficit (kPa); W is wind speed (m/s); and *e* is the experimental error.

As a consequence of experimental data (e.g. relative uniformity in climatic parameters against certain pressure heterogeneity), we should also assume that methodology followed for the measurement of climatic conditions (e.g. isolated sampling every 15 minutes) may, in some cases, condition both results and behaviour of losses (the need of converting vapour pressure deficit to the root square to achieve a linear relationship is not so clear now). Pressure is the variable that explains at a highest level the variance of evaporation and drift losses. The two other variables considered were also selected as non-redundant by means of the criterion shown in methodology resulting high significant in the analysis, too.

The fit parameters as well as the expression of the model are:

$$\text{LOSSES} = 0.007\ P + 7.380\ (e_s\text{-}e_a)^{0.5} + 0.844\ W \qquad R^2 = 0.972 \qquad (16)$$

With the aim of checking out the model it is desirable to analyse the behaviour of residues, which follow normal distributions. They did not show tendencies against the dependent variable and got into groups around zero. Their average value is –0.05 with low

SD. Hence it is concluded that a linear model (where pressure, vapour pressure deficit, converted to the power of 0.5, and wind speed take part) offers a proper estimate and simulation of evaporation and drift losses during the irrigation event for our conditions and the sprinkler-nozzle combination tested. The profitability parameters of the model were adequate and the analysis of residues resulted satisfactory (getting into groups around zero and non-correlated). Results are encouraged to be checked with trials in experimental installations, where pressure is assured to be constant along the test. A continuous and accurate record of weather conditions will be also required. Anyway, results imply a first approach to the influence of pressure, through its effect on the drop size, on evaporation and drift losses.

CONCLUSIONS

- A linear model has been fitted using factors and co variables, by analysing the effect of sprinkler, nozzle and riser height on the evaporation and drift losses. Both the effect of the sprinkler and the nested effect of the nozzle within the sprinkler are required by the model. Parameters checking the profitability of the fit show the model suitability.
- From available data, riser height (2.0 and 0.6 meters were tested) did not influence evaporation and drift losses, either in single sprinkler or block irrigation.
- It is desirable to consider both air temperature and air relative humidity through the vapour pressure deficit within the modelling process. In addition this new variable must be converted into the power of 0.5 in order to be included in the linear model.
- Evaporation and drift losses are higher in single sprinkler irrigation than in block irrigation. The reason can be found in the different microclimate that exists in both situations for the different number of sprinklers working simultaneously. These differences are not only referred to the amount of their average values for similar climatic conditions, but they also have a great effect on different explicative patterns.
- In the case of single sprinkler tests there are significant differences which affect the sprinkler type and nozzles. However differences are not significant in the case of block irrigation.
- In case of in-farm solid set irrigation, working pressure is important in order to explain the variability of losses. In addition, less quadratic tendency of losses with respect to vapour pressure deficit is shown. This could probably be attributed to the effect of block irrigation itself combined with the lower accuracy when measuring climatic parameters. In future works two priority issues should be assumed: on one hand the effect of the riser height on certain combinations. On the other hand, to deal -taking as basis the recorded experiences- the analysis of variable-pressure block irrigation along the lines of in-farm tests. To achieve that goal a proper experimental design will be conducted.

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REFERENCES

- ASAE S330.1. 1993. Procedure for sprinkler distribution testing for research purposes. Campbell Scientific, 1995. CR10X Measurement and Control Module. Instruction manual. Campbell Scientific, Inc., Leicester, UK.
- Canavos G.C. 1989. Probabilidad y estadística. Aplicaciones y Métodos. McGraw-Hill. México.
- Doorenbos J. and Pruitt W.O. 1984. Crop Water Requirements. Irrig. and Drain. Paper 24, FAO. Rome. Italy.
- Edling R. 1985. Kinetic energy, evaporation and wind drift of droplets from low pressure irrigation nozzles. Trans. ASAE 28, 1543-1550.
- ISO 7749/1. 1986. Norme internationale. Matériel d'irrigation. Asperseurs rotatifs. Partie 1: Exigences de conception et de fonctionnement.
- ISO 7749/2. 1990. Norme internationale. Matériel d'irrigation. Asperseurs rotatifs. Partie 2: Uniformité de la distribution et méthodes d'essai.
- Keller J. and Bliesner R.D. 1990. Sprinkle and Trickle Irrigation. AVI Book. Van Nostrand Reinhold. New York. USA.
- Kincaid D.C. and Longley C. 1989. A water droplet evaporation and temperature model. Trans. ASAE 32, 457-463.
- Kincaid, D.C., Solomon K.H., and Oliphant J.C. 1996. Drop size distributions for irrigation sprinklers. Trans. ASAE 39, 839-845
- Kincaid, D.C. 1996. Spraydrop kinetic energy from irrigation sprinklers. Trans. ASAE 39, 847-853.
- Kolh, R.A. 1974. Drop size distribution from medium-sized agricultural sprinkler. Trans. ASAE 17, 690-693.
- Kohl K.D., Kohl R.A., and de Boer D.W. 1987. Measurement of low pressure sprinkler evaporation loss. Trans. ASAE 30, 1071-1074.
- Marek, T.H., Schneider, A.D., Baker, S.M., and Popham, T.W. 1985. Accuracy of three sprinkler collectors. Trans. ASAE 28, 1191-1195.
- MathSoft. 1997. S-PLUS 4. MathSoft Inc. Seattle. Washington. USA.
- Merrian, J.L. and Keller J. 1978. Farm irrigation system evaluation: a guide for management. UTAH State University. Logan. Utah. USA.
- Murray, J. 1967. On the computation of saturated vapour pressure. J. Appl. Meteo., 6, 203-204.
- Norles, A. 1987. Estadística Teórica y Aplicada. Santiago Rodrigues, S.A. y Ediciones Sol, S.A. Madrid. Spain.
- Seginer, I., Kantz, D., and Nir, D. 1991. The distortion by wind of the distribution patterns single sprinklers. Agr. Water Mngt., 19, 341-359.
- SPSS Inc. 1997. SPSS para Windows versión 7.5. SPSS Inc., Chicago. USA.
- UNE. 68-072. 1986. Aspersores rotativos. Requisitos generales y métodos de ensayo.
- Wright, C. 1982. New evaporation crop coefficients. J. Irrig. Drain. Div. ASCE, 108, 57-74.
- Yazar, A. 1984. Evaporation and drift losses from sprinkler irrigation systems under various operating conditions. Agr. Water Mngt. 8, 439-449.