Development of an automatic test bench to assess sprinkler irrigation uniformity in different wind conditions

B. Salvatierra-Bellido [a], J. Montero-Martínez [b], L. Pérez-Urrestarazu [c, *]

[a] *Sistema de Asistencia al Regante, Instituto de Investigación y Formación Agraria y Pesquera de Andalucía, Camino de Esparragosa s/n, 11550 Chipiona (Cadiz), Spain. E-mail address: benito.salvatierra@juntadeandalucia.es*

[b] *Departamento de Producción Vegetal y Tecnología Agraria. Universidad de Castilla La Mancha. Campus Universitario, s/n.02071 Albacete. Spain. E-mail address: jesus.montero@uclm.es*

[c] *Urban Greening & Biosystems Engineering Research Group. Area of Agro-Forestry Engineering. Universidad de Sevilla. ETSIA Ctra. Utrera km.1, 41013. Seville. Spain. E-mail address: lperez@us.es*

*Corresponding author

Abstract

In sprinkler irrigation the water distribution uniformity in field conditions is not always a known factor, mainly due to the many variables involved, especially the wind. The main objective of this study was to design, install and test an automatic sprinkler bench to measure the irrigation uniformity of solid set systems for multiple wind conditions in real time. The system developed measures the different wind speeds and directions while simultaneously recording the rainfall distribution automatically. Consequently, the system requires little manual intervention, thus reducing the operating costs. All the information generated is stored in a database, obtaining multiple results of irrigation uniformity for each stable wind regime. As a second step, uniformities in different situations (layouts and wind directions) were studied. In addition, this study shows the potential for assessing the influence of different variables on irrigation uniformity for several sets of sprinklers. As an example of possible applications, 12150 results of uniformity coefficients for conventional impact rotary head sprinklers with hexagonal nozzles in windy conditions were generated. These data were used to establish comparisons between different sprinklers. To do this, a multiple linear regression methodology was applied in order to analyse the influence of the different contour variables on the irrigation uniformity. The test bench presented along with the methodology to simulate and generate multiple scenarios constitutes a powerful tool for designers, farmers and technicians both for the improvement of existing installations and for future designs. The generation of a large amount of irrigation uniformity results for sprinkler irrigation in different wind conditions will lead to a large database with the potential to be able to determine the irrigation uniformity in all common scenarios.

Keywords: Solid set sprinkler systems; irrigation evaluation; automation

1. Introduction

The modernization processes carried out in the irrigated areas have led to the installation of pressurized networks. This fact has induced a change from surface irrigation to sprinkler or trickle irrigation, which are purported to have higher water application efficiencies, better control of the water depth applied and enable automation. However, sprinkler systems have certain disadvantages with respect to trickle irrigation. The most important is the poor uniformity of irrigation in wind conditions and the means to determine it. Water application uniformity is the main indicator of irrigation quality. It can be expressed through different parameters or coefficients, such as the Distribution Uniformity (DU) (Merriam and Keller, 1978) or the Christiansen's

Uniformity coefficient (CU) (Christiansen, 1942). Irrigation management with sprinkler irrigation systems would benefit from site-specific, comprehensive and accurate information about irrigation uniformity, especially in windy conditions. With one study using a well-executed irrigation schedule based on crop requirements, yield increased with a higher irrigation uniformity (Li., 1998). According to Keller and Bliesner (1990), most irrigation sprinkler systems require a minimum CU value greater than 80%. Bralts et al. (1994) indicated that a 5-12% increase in CU could lead to 3-17% more yield in wheat grain. Moreover, according to Tarjuelo et al. (1999b), low CU values generally indicate a faulty combination of the number and size of nozzles, pressure and spacing of sprinklers.

Many factors affect the performance of sprinkler irrigation. However, the wind is an uncontrollable variable and has a decisive influence on sprinkler irrigation efficiency and uniformity (Tarjuelo et al., 1999b). Therefore, knowing the DU for each irrigation scenario and possible wind regime is desirable. This allows for determining the optimal timing for irrigation in order to minimize the effects due to wind (Sánchez et al., 2011). .

Wind speed and direction are the main parameters that have a greater impact on the water distribution model (Tarjuelo et al., 1999b) and play an important role in drift and evaporation losses (Tarjuelo et al., 2000; Keller and Bliesner, 1990). Many authors indicate that the influence of the wind depends greatly on system design parameters, such as working pressure, spacing, nozzle size or type of sprinkler (Keller and Bliesner, 1990).

Different methods can be used to determine sprinkler irrigation uniformity. Each procedure is adapted to information requirements, with a more or less limited scope of results. In a Radial model (Vories and Von Bernuth, 1986), an isolated and windless evaluation of the sprinkler is performed, using a certain nozzle and a specific operating pressure. It is basically an evaluation with a row of rain gauges along the radius of the wet area of the sprinkler. The results obtained are used to measure the irrigation uniformity that the entire wet area in the field would have. It is mainly used to characterize the sprinklers and nozzles in ideal conditions without wind (Tarjuelo et al., 1999a). It is required information for sprinkler manufacturers which offer basic data for the irrigation design.

The Matrix model (ISO 15886-3:2012, 2012) is also an evaluation of an isolated sprinkler, but having the advantage of knowing the complete water distribution pattern of the sprinkler in the whole wet area. It is mainly used to characterize the sprinkler and the nozzles in windy conditions. It consists in setting a network of rain gauges covering the wetted surface of an isolated sprinkler. This will allow for overlapping data according to the operation layout. This procedure has three disadvantages: (1) the variability of the climatic conditions during the test, (2) the different evaporation rate in the peripheral collectors with respect to the central ones and (3) the high manpower requirements for each test. It is mainly used in research centres dedicated to the study of sprinkle irrigation.

Lastly, the evaluation of the system (Merriam and Keller, 1978; Merriam et al., 1980) consists of the actual field evaluation of an existing irrigation facility. It is performed in a sample area of the installation and by the provision of a network of collectors. It is ideal to determine the quality of irrigation in specific conditions (wind, pressure, etc.) in which the evaluation is done.

However, in recent decades, many simulation models for irrigation have been developed with different theories, in order to avoid the problems of experimental field tests. Ballistic models are based on simulating the trajectory of drops of water in the air when they come out of the sprinkler and are distorted by the action of wind (Seginer et al., 1991; Carrion et al., 2001; Montero et al., 2001; Playan et al., 2006; Li et al, 2015 and Yongchong et al., 2015). Semi-empirical models simulate the shape of water distribution distorted by the wind, starting from results in windless conditions (Richards and Weatherhead, 1993; Han et al., 1994; Molle and Le Gat, 2000; Granier et al., 2003 and Oliveira et al., 2013). Other models use mathematical techniques of artificial neural networks, simulating the effect of the wind on the sprinkler water distribution pattern (Lazarovitch et al., 2009; Hinnell et al., 2010; Sayyadi et al., 2012). In each case, the simulation models should be calibrated and validated through experimental tests.

Depending on the chosen method, the quantity and quality of information will vary. In ballistic models, a large database that characterizes all the sprinklers can be obtained but only for the conditions of operation without wind. Semi-empirical models can be considered the most accurate and their results can be easily extrapolated. However, this evaluation is costly both in time and resources, and requires a specific infrastructure. In the third case, many field evaluations can be performed but in such specific conditions that they will not readily adapt to other circumstances.

For obtaining water distribution data from isolated sprinklers, radial or matrix models can be used. Both can be automated to avoid labour costs, while they have the advantage of reducing the error due to evaporation from the collectors during the test. Hodges et al. (1990) used the matrix system in an automated test facility programmed to operate unattended when wind speed exceeded 2.2 $m \cdot s^{-1}$. Although, as has been stated, previous attempts have been made, it is necessary to consolidate a system in order to have an operational tool that addresses the lack of knowledge about irrigation uniformity under multiple real operating conditions.

The main objective of this work is the design of an automatic test bench for the study of uniformity in solid set sprinklers systems in different wind conditions. The main differences with respect to the bench developed by Hodges et al. (1990) are:

- Increasing the surface area of the bench so as to permit rain collection with winds greater than 2.2 $m \cdot s^{-1}$.
- Improving measurement precision by increasing collector size.
- Having a more accurate and efficient data acquisition system which permits real-time data analysis. This allows for instantaneous extraction of data concerning water distribution and wind speed and direction, therefore permitting the execution of more trials per working day thus increasing bench performance.

The development of this equipment involves a complex data acquisition and processing system which allows further analysis. This tool will not only generate a large amount of experimental data, but coupled with the simulation method proposed by Han et al. (1994) will be able to recreate solutions for any real situation that may occur in the field.

2. Materials and methods

2.1. Design requirements

The test bench was located at the Agrarian Research and Training Centre of Chipiona in Cadiz, Spain (Geographical coordinates: 36.751351,-6.4003860). The following requirements were contemplated:

1. Isolated sprinkler test following the method proposed in ISO 15886-3:2012 (2012).

2. Instant and continuous measurement of the temporal and spatial water distribution, using automatic rain gauges with a tipping bucket, that register the amount and the time in which water is collected at each sampling point. The sprinkler is located in the centre of the grid of rain gauges, which are electronically interconnected, with a spacing of 2 by 2 meters.

3. Instantaneous measurement of the wind speed and direction at all times with an automatic wind sensor. The relative wind directions are standardized in a later simulation, with respect to the irrigation lateral (Norenberg et al., 2017), in three directions: parallel, oblique and perpendicular, independent of the wind direction (Figure 1). This allows for the organization and simplification of the substantial amount of results obtained.

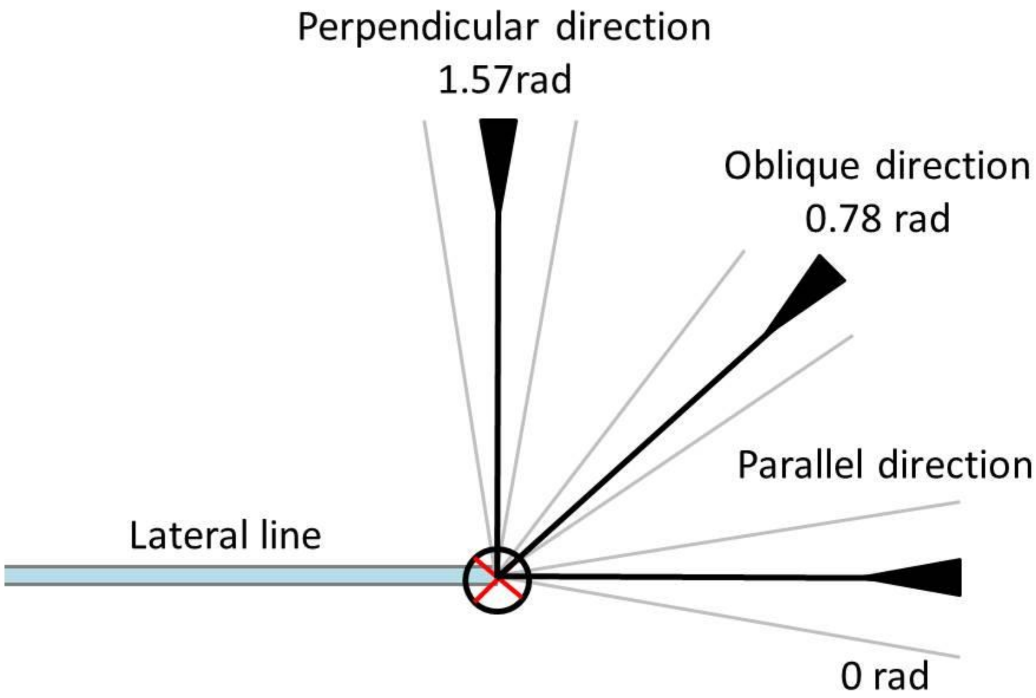

Figure 1. Standardization of relative wind directions with respect to the lateral line.

4. Obtaining and processing of data: All values of instant rainfall at each sampling point and wind speed and direction were stored in a data acquisition and storage system. They were processed for all results of irrigation uniformity with respect to the recorded wind in the different situations.

The equipment was prepared to keep working non-stop, in order to acquire data from different wind regimes throughout the trial period.

2.2. System Architecture

The bench consists of six functional units (Figure 2) each of which is described below.

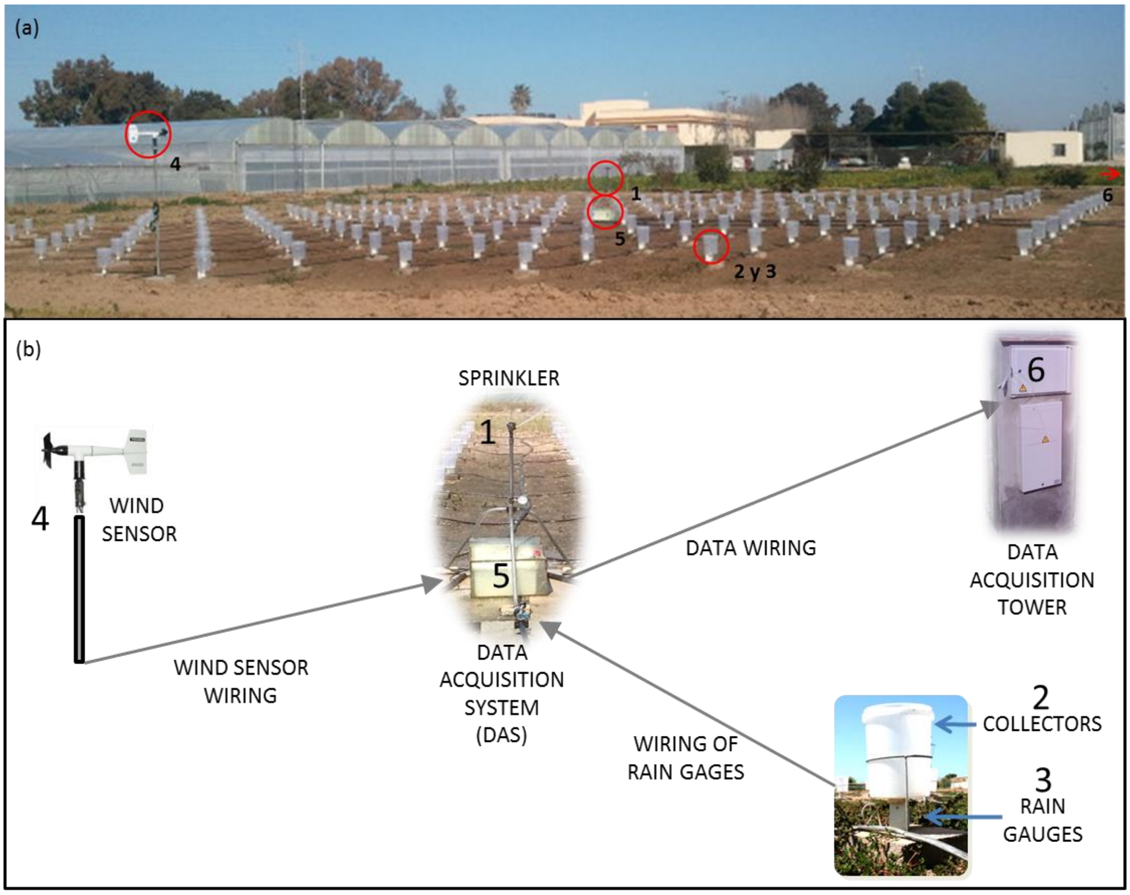

Figure 2. (a) In-field test and (b) components of test bench. (1) sprinkler, (2) catch can, (3) automated rain gauges, (4) wind sensor, (5) Data Acquisition System (DAS), and (6) data acquisition tower.

2.2.1. Hydraulic system

Water was supplied from a well by means of a 2.2 kW pump Prisma 35 N (ESPA 2025 S.L., Banyoles, Spain). A polyethylene 90 mm pipe carries water from the pump to the sprinkler (Figure 3).

According to the standard ISO 15886-3:2012 (2012), changes of pressure must not be over 2% throughout the trial. Therefore, a pressure regulator is placed downstream of the pump in order to ensure the exact required pressure at all times. Two flowmeters (ARAD, model M25, one inch in diameter) were installed to register the flow (with an accuracy of $5 \cdot 10^{-5}$ m^3). Both were located before the pressure regulator with a series arrangement for detecting measurement errors. A tripod supported the trial sprinkler, where the pressure data was collected with a glycerine manometer with a range of up to 600 kPa.

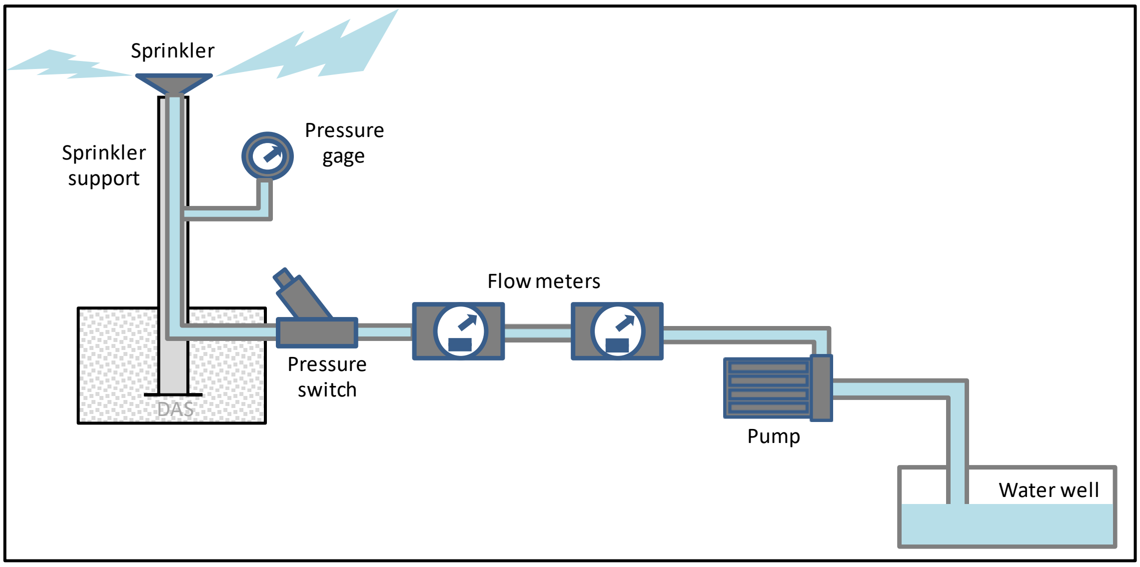

Figure 3. Hydraulic design of test bench.

2.2.2. Catch cans and rain gauges

The catch cans (also called collectors) were cylindrical plastic containers (Figure 4) with 7.5 L of capacity, with an inner diameter of 0.21 m and a height of 0.265 m. Their dimensions are compatible with the requirements of the standard ISO 15886-3:2012 (2012).

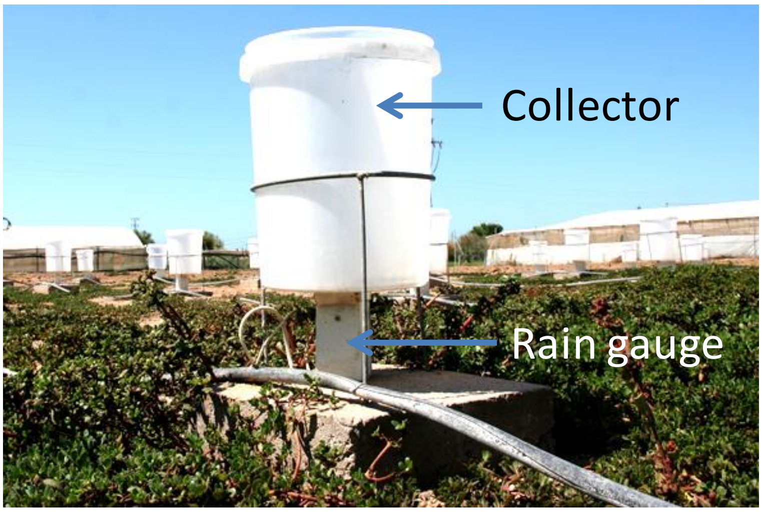

Figure 4. Collector attached to each automatic rain gauge

They were placed on the top of the rain gauges (Figure 4) and their main function is to increase the surface of water collection to improve accuracy. In order to measure the water received at each point of the evaluation zone, automatic cup rain gauges Rain-O-Matic® Small (Pronamic, Ringkøbing, Denmark) were used. They are individual prismatic collectors (0.1 x 0.1 x 0.05 m) with a pyramidal trunk water inlet where the collected water empties into small holes that allow their passage to a calibrated tilting bucket that emits an electric pulse each 5 mL of water. The time in which the pulse is generated and the identification number of the corresponding rain gauge are recorded by the Data Adquisition System.

2.2.3. Wind sensor

A wind sensor model 05106 (Campbell Scientific Spain, S.L.) with a range of 0 to 100 $m \cdot s^{-1}$ of wind speed (accuracy of 0.3 $m \cdot s^{-1}$) is employed. It measures wind direction from 0 to 6.28319 rad with a margin of error of 0.0523599 rad.

2.2.4. Data Acquisition System (DAS)

The Data Acquisition System (DAS) is designed to obtain data from 178 sensors, two of which correspond to wind speed and direction and the rest to 176 rain gauges. The DAS is mounted inside a weatherproof box located under the sprinkler (Figure 2).

2.2.5. Data acquisition tower

Outside the trial area a tower has been placed with a double function: (1) regulation and power supply, and (2) laptop connection point to access the DAS. The tower was connected to the DAS by means of two wires, one for power and one for communication (RS232). It enables both online data connecting for maintenance and checking the system operation.

2.3 Electronic control subsystem

This is the most complex subsystem of the bench and is closely associated with the DAS. Its components are:

- Data Logger (DL) model CR1000 (Campbell Scientific), with 8 inputs for sensor data. They are connected to the wind sensor and the expansion modules collecting data from each of the 176 rain gauges. It includes a microcontroller, an internal clock, a data storage unit, an interface for communication with the laptop that will collect the data and a console to connect the sensors.
- 13 data Expansion Modules (EM) SDM-IO16 16 Channel Input/Output (Campbell Scientific), with 16 inputs each, allowing data acquisition of 176 entries of automatic rain gauges. The expansion modules will be connected in parallel via 3 inputs to the DL.
- Weather protection box LE129GX (Campbell Scientific), which isolates the entire DAS from outdoor humidity conditions. In order to avoid the direct action

of the water, this outdoor enclosure is covered by a custom-built rigid outer casing.

The EM collects the pulses of each rain gauge, which are identified, registered and ordered in time in the DL (Figure5). Each EM previously references the signal coming from each rain gauge. Each measurement is recorded in the DL and organized by date and time thanks to the internal clock. The connection to a laptop allows for the transfer of data in addition to a control in real time of the system when required. The connection between the EM and the rain gauges is performed by pairs of rain gauges (a primary rain gauge and a satellite) to optimize the cost of wiring between the DAS and the rain gauges. Subsequently, the first EM will be directly connected to the DL and the remaining will be connected among them in cascade and in parallel (Figure 6).

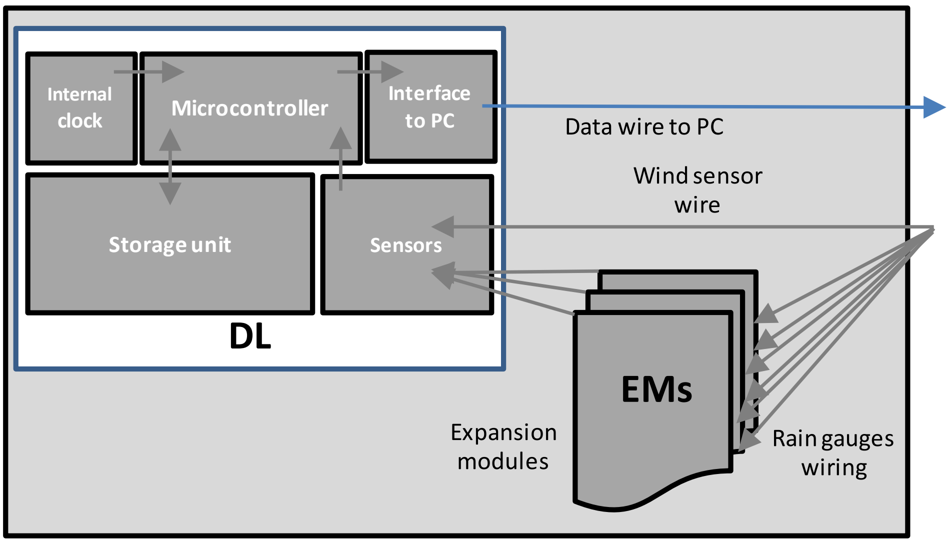

Figure 5. Scheme of the Data Acquisition System (DAS).

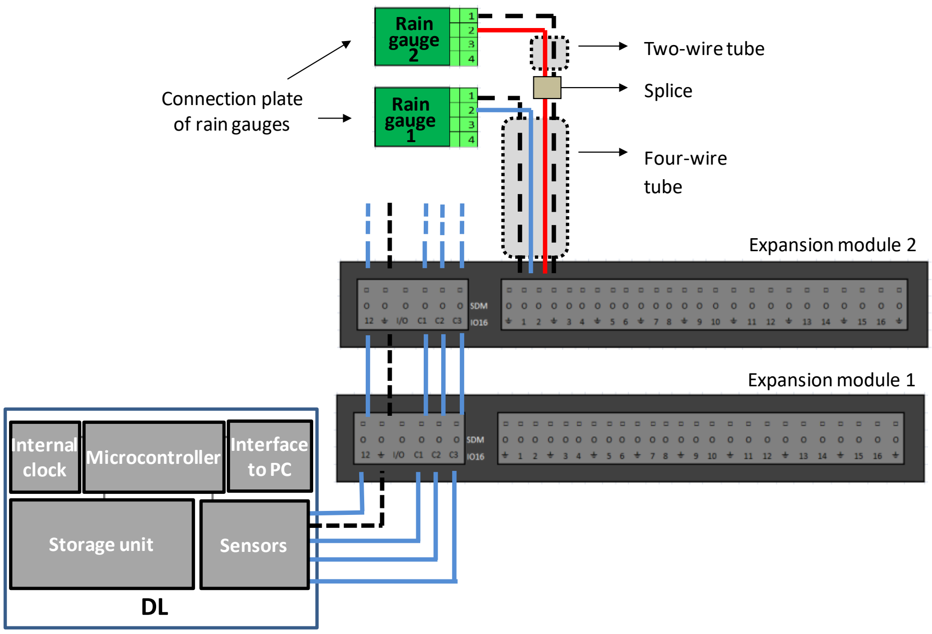

Figure 6. Scheme of connection among the expansion modules and one pair of rain gauges.

2.4 Software and data processing

Treatment and analysis of the data is completely computerised. Several concatenated software programs have been used in the development of the methodology for the collection and processing of data, from the programming of the DL internal software, to the results of DU for the different configurations of sprinklers.

2.4.1 DL data management

Two software programs from Campbell Scientific have been used for the programming of the DL and downloading data. *LoggerNet 4.4* allows the data to be communicated and downloaded from the DL to the laptop. *Short Cut 3.2.2* is the program editor for the DL.

2.4.2 Data processing

A worksheet (Microsoft Excel 2010) was used for the data selection, the generation of tables and graphics of the results as well as the processing of data to adapt them to the requirements of the sprinkler irrigation simulation program. This worksheet's main function is to extract multiple groups of data with the same conditions from the main dataset. Due to the fact that in each trial day the conditions are variable over time, intervals with small variations in wind direction and speed values are chosen according to a criterion of restricted variability.

2.4.3. Overlapping of the results to different layouts

SpacePro 3.0 (Center for Irrigation Technology, 2010) was used to overlap the isolated sprinkler test results obtained by the test bench to simulate different layouts of multiple sprinklers. It allows a wide range of configurations and combinations of distances between sprinklers and different wind directions. This software is used to calculate uniformity of distribution, DU (Merriam and Keller, 1978); the Christiansen uniformity coefficient, CU (Christiansen, 1942); rainfall ($mm \cdot h^{-1}$); and the Scheduling Coefficient (SC) over 5% of the surface (Butter, 1990) from a given pluviometer distribution in the form of a data matrix.

2.5. Maintenance and calibration.

Although each rain gauge was factory calibrated and certified, they all have to be periodically recalibrated. Routine maintenance and calibration tasks are necessary especially when the information from a certain rain gauge is not being received in the DAS. This usually means that there is some problem such as deposition and formation of mud in the bowl of the automatic rain gauge, obstruction of the rain gauges produced by spontaneous fauna like snails, poor electrical contacts, etc. Therefore, the maintenance plan included two fundamental tasks: cleaning the rain gauges and its subsequent calibration.

The cleaning operations consisted of removing the collector and the rain gauge cover and washing with a pressure hose. When the presence of weeds or snails was detected, herbicides and helicides were applied to keep the mechanism of the rain gauge free of obstacles.

A recalibration of the rain gauges was carried out in each maintenance task. In it, the value measured by each rain gauge is corrected with respect to a known rainfall value. This generated a correction coefficient for each rain gauge.

The calibration consisted of the following steps: activation of the bench without sprinkler, pouring 0.25 L of water into each rain gauge during 2.5 minutes (3 s per pulse), simulating the maximum flow rate that a sprinkler can give and not exceeding the range of measuring capability provided by the manufacturer of the rain gauge. Once provided the correct amount of water in all gauges, data from the DAS is downloaded and the correction coefficient is calculated for each rain gauge to be subsequently applied to all measurements.

2.6. Example of use.

As an example of how the test bench can be used, multiple tests were performed with different sprinklers in diverse conditions taking into account eight variables (Table 1).

Table 1. Summary of the number of values defined for each test variable.

Variable	**Number of values**

Manufacturer	5
Sprinkler models per manufacturer	2
Number of nozzle combinations per model	1-4
Working pressures per combination	3
Wind speeds per combination	2
Wind directions per wind speed	3
Layouts per combination	81
Layout shapes per combination	2

The first three variables (manufacturer, sprinkler model and nozzle combination) refer to the most common sprinklers used in Spain (Table 2). The following (pressure, wind speed and direction of the wind and layout) correspond to the following values:

- Tested pressures: 200, 250, and 350 kPa.
- Wind speeds: 2 values preferably were processed only for each sprinkler model, one with slight wind (less than 2 $m \cdot s^{-1}$) and the other with moderate wind (between 2 and 4 $m \cdot s^{-1}$).
- Wind directions: parallel, oblique and perpendicular with respect to the lateral, categorising the multiple results that could be obtained in those three.
- The layouts studied correspond to all the combinations ranging from 10 x 10 m to 18 x 18 m in all possible configurations with an interval of 1 m between each layout variation.
- The two shapes studied are rectangular and triangular.

Table 2. Manufacturer, sprinkler models and nozzle combinations considered.

Manufacturer	Sprinkler model	Nozzle combination		
		Main nozzle (diameter in mm)	Jet-straightening vane (Yes or No)	Secondary nozzle (diameter in mm)
Unirain	F46	2.6	Y	
		3.6	Y	
		3.2	Y	
		4.0	Y	
			Y	2.4
	F46-PRO	4.4	Y	2.4
		4.8	Y	2.4
		3.6	Y	
Naandanjain	6025 SD	3.5	Y	
	5035 SD	3.5	Y	2.5
		4.0	Y	2.5
Senninger	3023-2	3.2	Y	2.4
		4.0	Y	2.4
Vyrsa	Vyr 36	4.0	Y	2.4
		3.6	Y	2.4
	Vyr 37	4.0	Y	2.4
		3.6	Y	2.4
Nelson	R33-LP	4.0	N	
		4.8	N	
		4.4	N	
	R2000-WF	3.6	N	
		3.2	N	

Afterwards, the data obtained for an isolated sprinkler was used to simulate multiple scenarios, calculating irrigation uniformity for different layouts. For the analysis, three sets of sprinklers have been considered:

- Set 1: Conventional impact sprinklers with hexagonal nozzles.
- Set 2: Non-conventional impact rotary head sprinklers with bayonet nozzles
- Set 3: Rotary sprinklers.

3. Results and discussion

The test bench developed enables the performance analysis of sprinklers with different operating characteristics and wind conditions. In order to show the potential of the information generated, an example of application of the equipment was described. Furthermore, analysis of the results and the potential to determine the influence of different variables on the water uniformity distribution were presented.

3.1. Example of data extracted in a field test.

The results presented correspond to one in-field irrigation test extracted from the total dataset, and are always characterized by a constant wind speed and direction (wind speed standard deviation not exceeding 1 m·s^{-1} and 20º in direction). Figure 7 represents an example of the data obtained from the DAS with the boundary conditions displayed in Table 4.

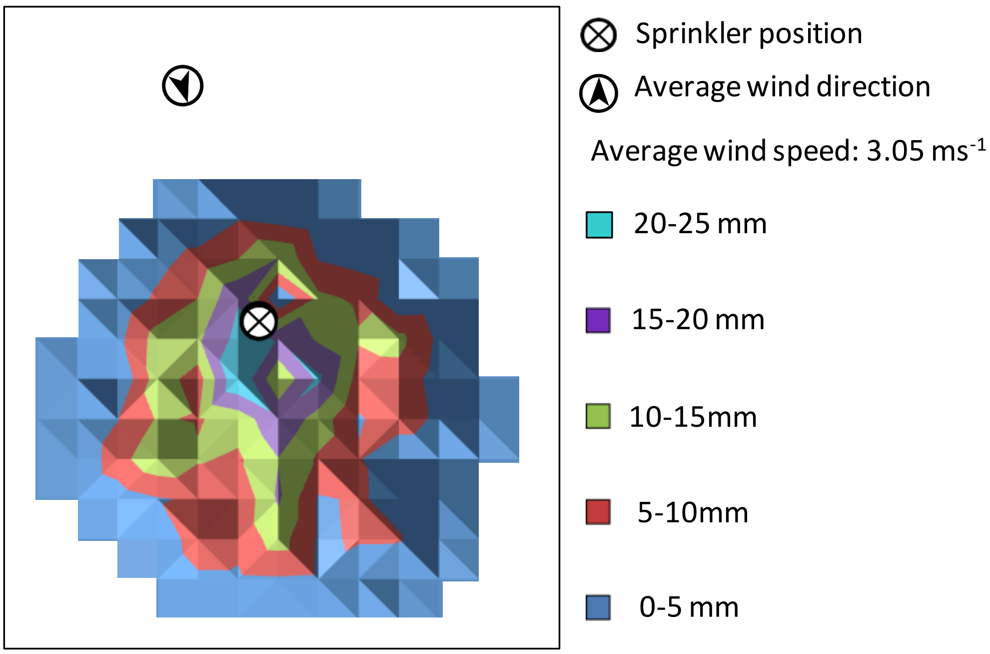

Figure 7. Unirain F46 sprinkler water distribution pattern during one in-field test

Table 4. Variables involved in the test

Variable	Description
Tested sprinkler	Unirain F46 sprinkler (Unirain S.A., Spain)
Nozzles diameter	3.17 mm (primary) and 2.38 mm with vane (secondary)
Working pressure	300 kPa
Test duration	60 min
Sprinkler height	1.30 m
Average wind speed	3.05 $m \cdot s^{-1}$
Average wind direction	5.99 rad with respect to geographic North
Sprinkler flow rate	954 $L \cdot h^{-1}$

Afterwards, the numerical data of these results was introduced in the Space Pro program to calculate CU and DU with different irrigation layouts and wind directions. In this way, the water distribution for different irrigation layout configurations is calculated for the three already defined wind directions. Figures 8 and 9 show the results for the most common irrigation layouts in Spain. These results are only a sample of the capacity for analysis of sprinkler irrigation uniformity. In addition, any other layouts and wind direction can also be simulated.

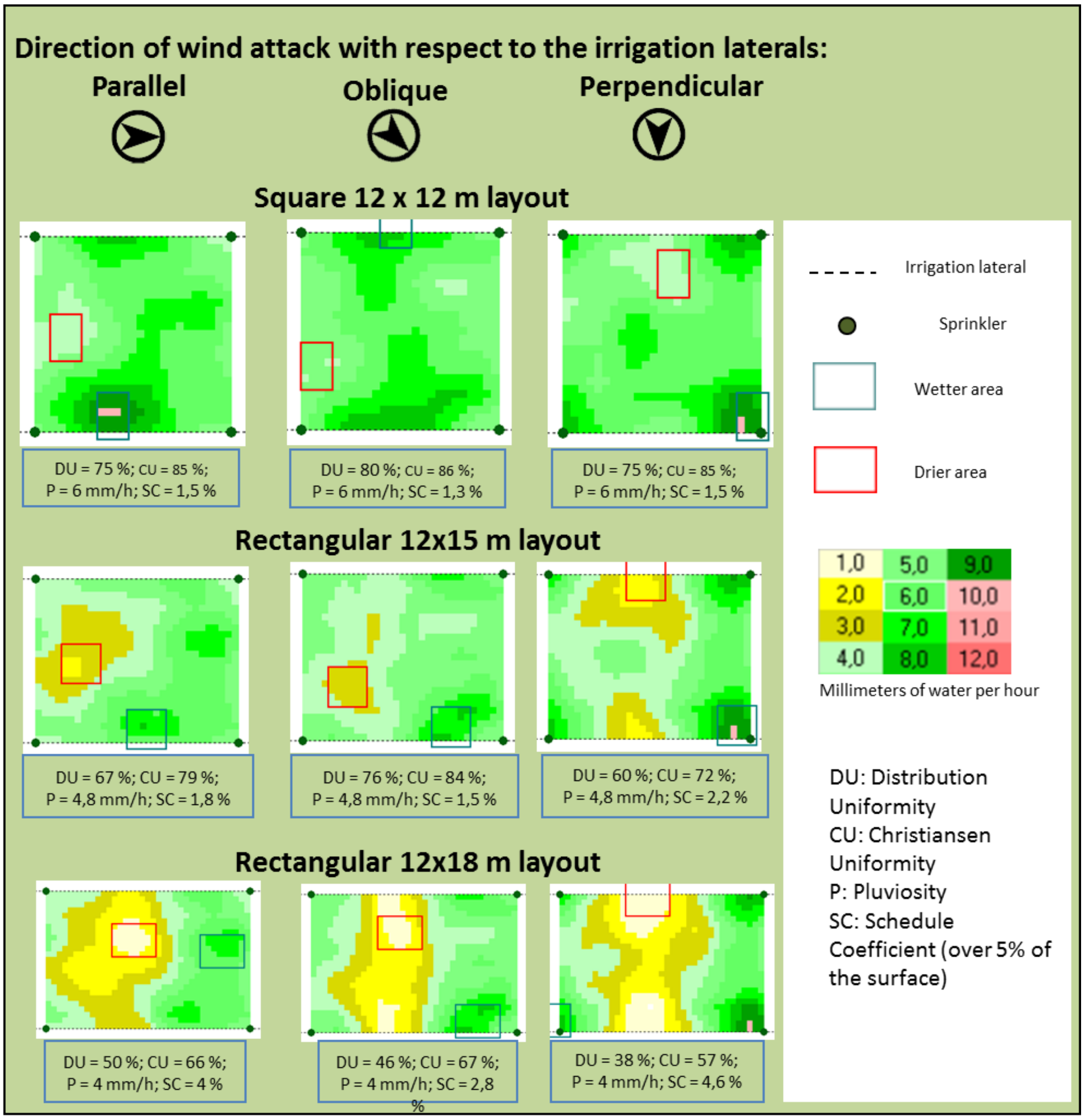

Figure 8. Results of the trial for an example with three irrigation layouts and three wind directions.

Figure 8 shows the results for 12 x 12, 12 x 15 and 12 x 18 m layouts in three wind directions (parallel, oblique and perpendicular to the irrigation lateral). The best values of uniformity indicators are obtained for the 12 x 12 m layout, which differ depending on the wind direction. For all the layouts, a small improvement in DU is observed with an oblique wind, compared to other conditions, while the perpendicular wind direction offers the worst results. For the 12 x 15 m and 12 x 18 m layouts, the coefficients obtained present lower values (the worst being the latter) and the differences between the three types of wind direction are more pronounced. In the third case, the differences between parallel and oblique types are attenuated, being the perpendicular wind which leads to the worst coefficients.

On the other hand, the option of using similar layouts with different shapes has been studied. Figure 9 shows a comparison between the 12 x 15 m rectangular configuration analysed in the previous case with a triangular staggered 15 x 12 m sprinkler layout. Similar values of the coefficients are observed with an oblique wind. However, if the wind is parallel or perpendicular to the laterals, a considerable improvement using a triangular layout is obtained. Therefore, in a situation where the wind direction is not oblique or often changes, a triangular configuration would be recommended for this layout. Thus, thanks to this type of analysis, an improvement in uniformity can be achieved by simply changing the configuration without any additional investment cost.

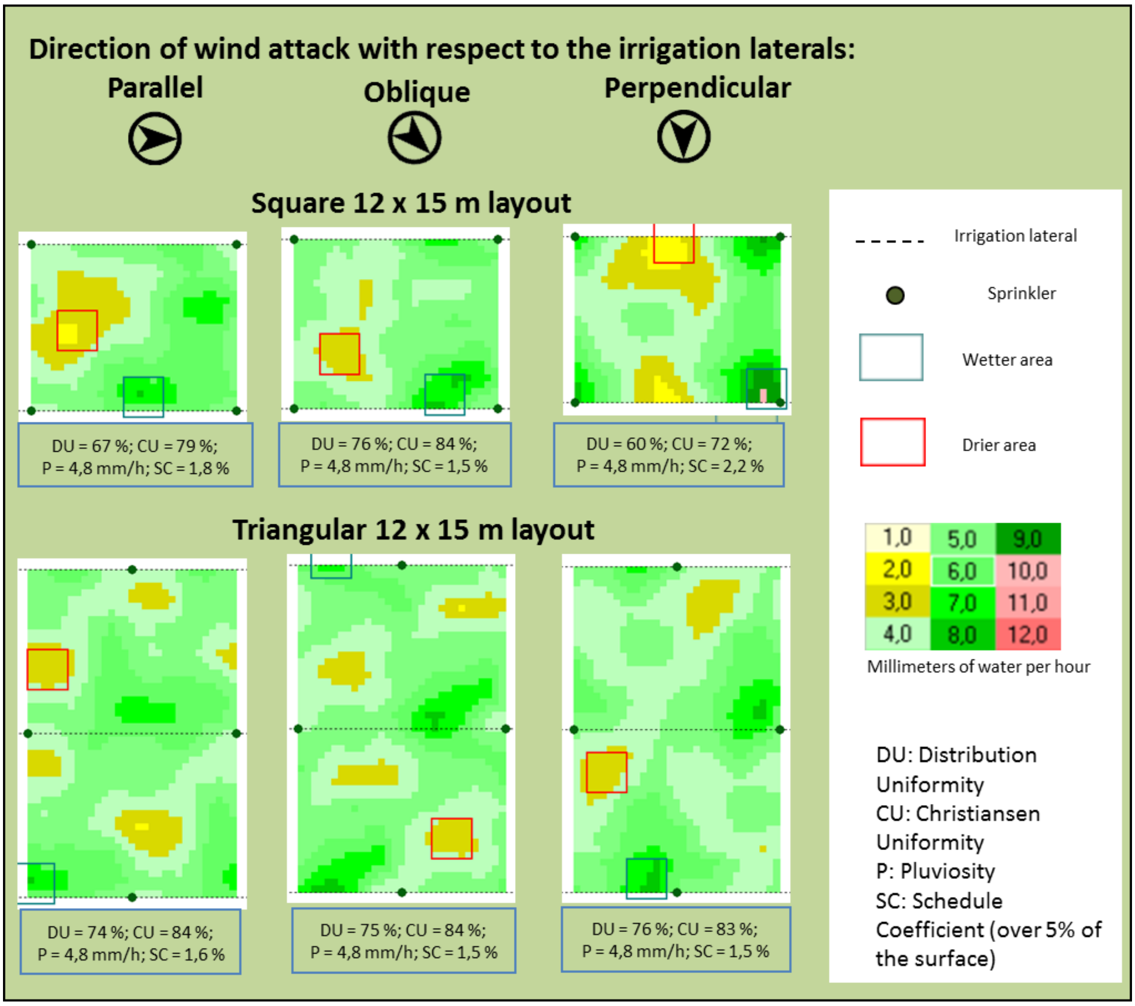

Figure 9. Results of the trial comparing the rectangular layout with the triangular 12 x 15 m layout.

Taking into account all the combinations, there were 29160 results generated with the automatic bench. Therefore, the irrigation uniformity in most common situations occurring in the field was analysed. In addition to this number of results, any wind scenario could be extrapolated from existing experimental data using the methodology proposed by Han et al. (1994).

With the design of this prototype of automatic test bench, and thanks to the combination of methodologies for data treatment, overlapping layouts and simulation of multiple wind directions, a vast amount of information is available for each one of the tested sprinklers. Therefore, by means of a query tool in the results database, any scenario can be assessed as desired.

3.2. Example study of the influence of several variables on the irrigation uniformity for different types of sprinklers.

The set of results obtained with the test bench can be used for multiple objectives with a strategic purpose. This section presents an example of use for the generated results. In this case, a mathematical model for a global data analysis with both dependent and independent variables is used. This technique allows researchers to establish relationships among dataset variables. The results have been classified according to the sprinkler type as determined in the Materials and methods section:

- Set 1: 12150 results of uniformity coefficients for conventional impact rotary head sprinklers with hexagonal nozzles.
- Set 2:10206 results of uniformity coefficients for non-conventional impact rotary head sprinklers with bayonet nozzles.
- Set 3: 6804 results of uniformity coefficients for rotary sprinklers.

Figure 10 shows the result of applying a multiple linear regression to the three sets of sprinklers. The R^2 values are: 0.5801 for all analysed sprinklers, 0.7392 for the conventional impact sprinklers, 0.6017 for not conventional impact sprinklers, and 0.581 for rotary sprinklers. All are acceptable values for a multiple linear regression. The influence of each variable on the irrigation uniformity for the different groups of sprinklers considered is estimated in the graphic.

This analysis produces ample information for irrigation management and system design decisions. For example, when using conventional impact sprinklers, the layout or wind conditions had less influence. However, the working pressure and the existence of a secondary nozzle were key factors. On the other hand, for non-conventional impact or rotary sprinklers, the layout and the wind were the most important variables, based on a large dataset.

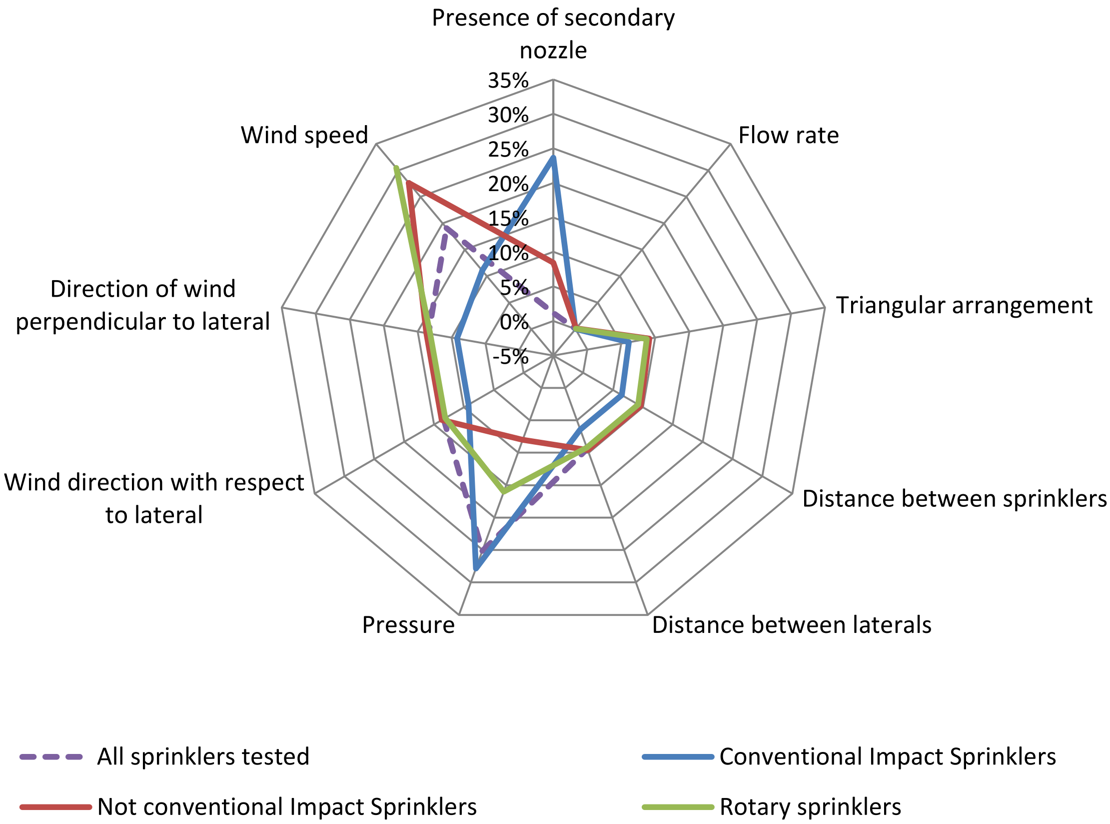

Figure 10. Influence of each variable on the irrigation uniformity of in each set of sprinklers tested with wind.

The scale of analysis can be reduced as shown in Figure 11, which compares the set of conventional impact sprinklers with and without wind (7128 results obtained from a conventional radial bench). The R^2 values are: 0.6345 with no wind and 0.7392 in windy conditions. In this case the number of results is lower and the objective of the analysis is different. In this example, pressure and layout of the sprinklers are less important in wind conditions than with no wind, but the presence of a secondary nozzle has a greater effect when there is wind.

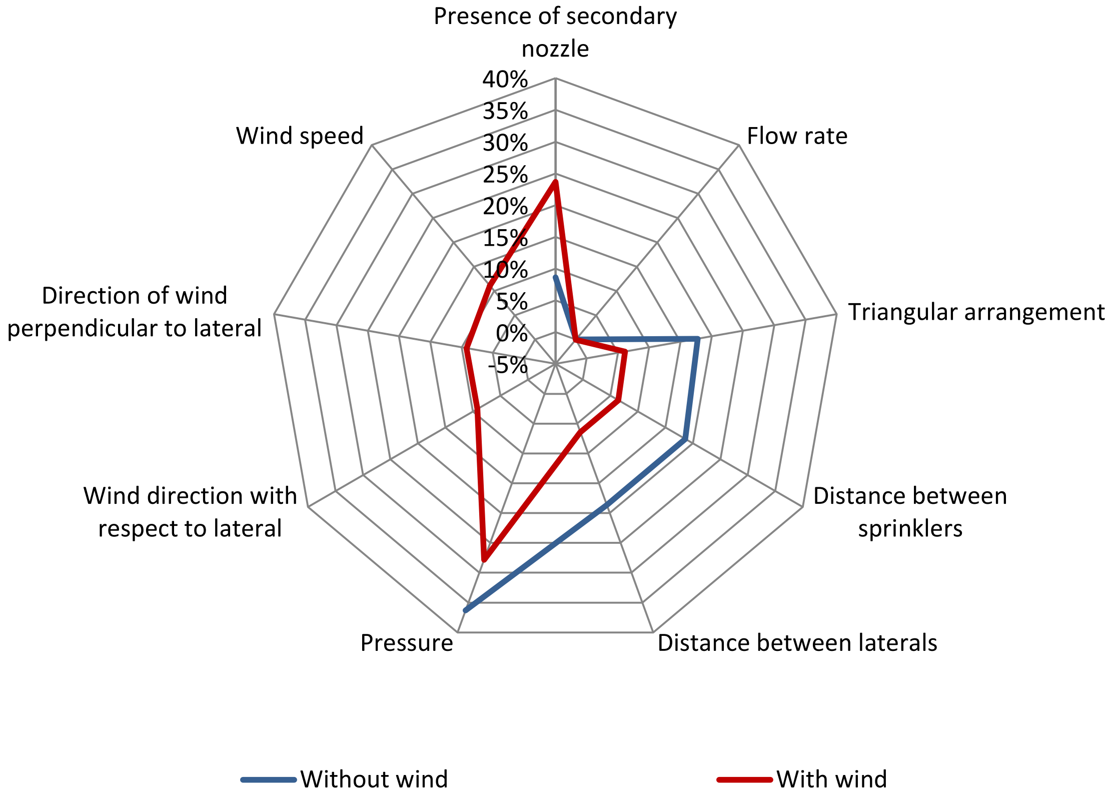

Figure 11. Influence of each variable on the irrigation uniformity of conventional impact sprinklers with and without wind.

Other authors like Faria et al. (2013) have also pointed out the potential of using computational simulation as an aid to determine the water distribution uniformity of sprinklers working under different conditions. Thanks to the large amount of data generated, the most impactful variables in play for each situation can be determined.

4. Conclusions

The automatic sprinkler test bench developed is a useful tool that allows generating a vast amount of experimental data regarding irrigation uniformity for sprinklers. With the application of semiempirical models of wind simulation, it will be possible to predict any irrigation situation that might occur in reality. It can be used for in-field tests of different models of sprinklers and wind conditions, speeding up the information gathering time required to simulate the uniformity of sprinkler irrigation systems.

By performing multiple tests for different sprinklers, a database will be obtained, serving as support for an expert system for characterizing any scenario that can occur in the field. This constitutes an unprecedented tool for advising both on the design of the sprinkler irrigation systems and on optimal operation. It will also serve to optimize existing facilities by introducing small changes in their management, not involving large investments.

Acknowledgements

We would like to thank the 'Instituto de Investigación y Formación Agraria y Pesquera de Andalucía' for the financing of the project through the 'Sistema de Asesoramiento al Regante' program.

References

Bralts, V.F., Pandey, S.R., Miller, A. 1994. Energy saving and irrigation performance of a modified center pivot irrigation systems. App Eng Agric 10(1): 27–36.

Butter, A. 1990. Scheduling coefficient as a function of sprinkler spacing. American Society of Agricultural Engineers 90-2613 6 pp.

Carrion P., Tarjuelo J.M., Montero J. 2001. SIRIAS: a simulation model for sprinkler irrigation: I. Description of model. Irrig Sci 20: 73-84.

Center for Irrigation Technology.California. 2010.Software SPACE Pro. https://www.fresnostate.edu/jcast/cit/software/. Jordan College Of Agricultural Sciences & Technology. California State University, Fresno, EEUU.

Christiansen, J. E. 1942. Irrigation by sprinkling. Univ. Calif. Agr. Exp. Sta. Bull. 670.

Faria, L. C., Prado, G., Colombo, A., Oliveira, H. F., & Beskow, S. 2013. Simulação da distribuição de água em diferentes condições de vento e espaçamentos entre aspersores. Revista Brasileira de Engenharia Agrícola e Ambiental, 17(9), 918-925. https://dx.doi.org/10.1590/S1415-43662013000900002

ISO Standard 15886-3, 2012. Agricultural Irrigation Equipment. Sprinklers. Part 3. Characterization of distribution and test methods. Geneva, Switzerland.

Granier, J.; Molle, B.; Deumier, J. M. 2003.IRRIPARC-Part 1: Modeling spatial water distribution under a sprinkler in windy conditions. International workshop, Montpellier, p. 14-19, Sep.

Han, S., Evans, R. G., Kroeger, M. W. 1994. Sprinkler Distribution Patterns in Windy Conditions. Transactions of the ASAE 37(5): 1481-1489. (doi: 10.13031/2013.28231)

Hinnell A.C, Lazarovitch N, Furman A, Poulton M, Warrick AW. 2010. Neuro-Drip: estimation of subsurface wetting patterns for drip irrigation using neural networks. Irrig Sci 28 (6): 535-544.

Hodges, K.J. Evans, R.G. James, L G. Kroeger, M.W., Ley, T.W. 1990: Automated facility for sprinkler performance testing. Applied Engineering in Agriculture 6(4): 437-440.

Keller, J., Bliesner, RD. 1990. Sprinkle and Trickle Irrigation. AVI Book. Van Nostrand Reinhold. New York. USA.

Lazarovitch N, Poulton M, Furman A, Warrick AW. 2009. Water distribution under trickle irrigation predicted using artificial neural networks. J Eng Math 64: 207-218.

Li, J. 1998. Modeling crop yield as affected by uniformity of sprinkler irrigation. Agricultural Water Management. Volume 38, Issue 2, 1 December 1998, Pages 135-146

Li, Y., Bai, G., Yan, H. 2015. Development and validation of a modified model to simulate the sprinkler water distribution. Computers and Electronics in Agriculture 111: 38–47.

Merriam, J.L., Keller, J. 1978. Farm irrigation system evaluation: a guide for management. UTAH State University. Logan. Utah. USA

Merriam, J.L., Shearer M.N., Burt C.M. 1980. Evaluating irrigation systems and practices. In: Design and Operation of Farm Irrigation Systems (ed. M.E. Jensen) ASAE monograph no. 721-760.

Molle B, Le Gat Y. 2000. Model of water application under pivot sprinkler: II. Calibration and results. J Irrig Drain Eng 126(6): 348-354.

Montero J, Tarjuelo JM, Carrion P. 2001. SIRIAS: a simulation model for sprinkler irrigation: II. Calibration and validation of the model. Irrig Sci 20: 85-98.

Norenberg, B.G., Faria, L.C., Rettore Neto, O., Beskow, S., Colombo, A., Timm, L.C., Manke, E.B. 2017. Wind speed and direction on water application uniformity of a mechanical lateral-move irrigation system. Applied. Engineering in Agriculture, v. 33, p. 543-549, 2017.

Oliveira, H.F. E., Colombo, A., Faria, L C., Beskow, S., Prado, G. 2013. SIA: Modelo para simulação da irrigação por aspersão - Calibração e validação. Revista Brasileira de Engenharia Agrícola e Ambiental (Online), v. 17, p. 253-260,

Playan E, Zapata N, Faci JM, Tolosa D, Lacueva JL, Pelegrin J, Salvador R, Sanchez I, Lafita A. 2006. Assessing sprinkler irrigation uniformity using a ballistic simulation model. Agricultural Water Management 8(4): 89-100.

Richards PJ, Weatherhead EK. 1993. Prediction of raingun application patterns in windy conditions. J Agric Eng Res 54(4): 281-291.

Sánchez, I., Zapata, N. Faci, J.M., Martínez-Cob, A. 2011. The spatial variability of the wind in a sprinkler irrigated district: Implications for irrigation management. Biosystems engineering 109: 65 -76.

Sayyadi, H., Sadraddini, A.A., Farsadi Zadeh D., Montero, J. 2012. Artificial neural networks for simulating wind effects on sprinkler distribution patterns. Span J Agric Res 10(4), 1143-1154

Tarjuelo, JM, Montero, J, Carrión, PA, Honrubia, FT, Calvo, MA. 1999b. Irrigation uniformity with medium size sprinklers Part II: influence of wind and other factors on water distribution. Transaction of the ASAE 42(3): 677–689.

Tarjuelo, JM, Montero, J, Valiente, M, Honrubia, FT, Ortiz, J. 1999a. Irrigation uniformity with medium size sprinklers Part I: characterisation of water distribution in no-wind conditions. Transaction of the ASAE 42(3): 665–675.

Tarjuelo, JM, Ortega, JF, Montero, J, de Juan, JA. 2000. Modelling evaporation and drift losses in irrigation with medium size impact sprinklers under semi-arid conditions. Agricultural Water Management 43: 263–284.

Vories, E., Von Bernuth, R. 1986. Single nozzle sprinkler performance in wind. Transaction of the ASAE 29(5): 1325-1330.

Yongchong, L., Geng, B., Haijun, Y. 2015. Development and validation of a modified model to simulate the sprinkler water distribution. Computers and Electronics in Agriculture 111: 38–47