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Assessing sprinkler irrigation uniformity using a ballistic simulation model

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ABSTRACT

Experiments were performed in the Ebro Valley of Spain to provide the basis for the calibration and validation of a ballistic simulation model of sprinkler irrigation. The experiments included evaluations of isolated sprinklers and solid-sets. Two different sprinklers, two principal nozzle diameters and three operating pressures were considered in the experiments, which also covered the usual range of wind speeds in the study area. Model calibration served the objectives of predicting the Christiansen Coefficient of Uniformity (CU) and the water application pattern. The resulting standard error of CU estimation was 3.09%. Tables of simulated uniformity were produced for the two sprinklers using different nozzle diameters, sprinkler spacings, operating pressures and wind speeds. These tables can be used for design and management purposes, identifying options leading to adequate irrigation uniformity. A simple simulation software has been produced and disseminated to assist irrigation professionals and farmers in decision making.

1. Introduction

The uniformity of sprinkler irrigation depends on a number of factors, including the sprinkler and nozzle type, the irrigation layout and the environment (Keller and Bliesner, 1990). The combination of these factors greatly complicates the assessment of irrigation uniformity for a given on-farm irrigation system and a set of environmental conditions. As a consequence, sprinkler irrigation design and management rules are very site specific, change with the irrigation materials, and often rely on unstructured experiments and life-long professional experience.

Sprinkler irrigation has only limitedly benefited from modelling approaches. Ballistics constitute the most common modelling approach to sprinkler irrigation. While the theory behind this approach has been available for decades (Fukui et al., 1980), its application is progressing quite slowly. The main problem for the generalization of ballistic models is that model calibration is currently required for every combination of sprinkler type, nozzle type and diameter, operating pressure, nozzle elevation and wind speed (Montero et al., 2001). As a consequence, an intense experimental work is required for the applicability of ballistic models for a particular situation. Once the model is calibrated and validated, it can yield information leading to improved irrigation design and management. Dechmi et al. (2004b) calibrated a ballistic model for a particular irrigation layout under variable wind conditions. These authors reported on a number of model

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applications for successful sprinkler irrigation in the central Ebro Valley of Spain, a region where the yearly average of wind speed can exceed 2.4 m s^{-1}.

In this paper we present the experimental and computational process required to calibrate and validate a ballistic simulation model for two sprinklers, each with two nozzle diameters, operating under a wide range of pressures and wind speeds, and covering a large set of sprinkler spacings. The results permit to establish a comparison between the two sprinklers, and to highlight their respective strengths and weaknesses. Beyond the regional relevance of this comparison, the presented methodology represents a contribution to the applicability of ballistic models to sprinkler irrigation practice.

2. Materials and methods

2.1. Model description

Fukui et al. (1980) presented the basic equations and procedures for ballistic simulation of sprinkler irrigation. Their work was followed by a number of contributions which improved the original approach in different aspects (Vories et al., 1987; Seginer et al., 1991). Recently, Carrión et al. (2001) and Montero et al. (2001) presented the SIRIAS software, which further developed ballistic theory and presented it in a user-friendly environment. The SIRIAS model was calibrated and validated for a number of cases involving different sprinklers and nozzle configurations, layouts and operating conditions. The mean absolute error in the estimation of the Christiansen Coefficient of Uniformity (CU) (Burt et al., 1997) was 2.7%. Dechmi et al. (2004a,b) presented a ballistic sprinkler irrigation model which was used in combination with a crop model. They showed that the sprinkler irrigation model could successfully reproduce the water distribution pattern observed in the field ($R^2 = 0.871^{***}$). Moreover, a crop simulation model using the simulated water distribution pattern as input resulted in simulated values of yield reduction which could explain the field observed values ($R^2 = 0.378^{***}$).

The main characteristics of the ballistic model used in this work are presented in the following paragraphs. Additional specifications can be found in Dechmi et al. (2004a), who presented an early version of this model. General details on the construction and testing of ballistic models can be found in Carrión et al. (2001) and Fukui et al. (1980).

A sprinkler is simulated as a device emitting drops of different diameters. It is assumed that drops are formed at the sprinkler nozzle, and travel independently until reaching the soil surface (or the crop canopy, or the experimental catch-can). In the absence of wind, and for a given sprinkler configuration, the horizontal distance between the drop landing point and the sprinkler nozzle is a function of the drop diameter. Ballistic theory is used to determine the trajectory of each drop diameter subjected to an initial velocity vector and a wind vector (**U**, parallel to the ground surface). The action of gravity (acting in the vertical direction) and the resistance force (opposite to the drop trajectory) complete the analysis of forces acting on the water drop. The drop velocity with respect to the ground (**W**) is equal to the velocity of the drop in the air (**V**) plus the wind vector (**U**).

According to Fukui et al. (1980) the three directional components of the movement of each drop can be expressed as:

$$A_x = \frac{d^2x}{dt^2} = -\frac{3}{4}\frac{\rho_a}{\rho_x}\frac{C}{D}\mathbf{V}(\mathbf{W}_x - \mathbf{U}_x) \quad (1)$$

$$A_y = \frac{d^2y}{dt^2} = -\frac{3}{4}\frac{\rho_a}{\rho_W}\frac{C}{D}\mathbf{V}(\mathbf{W}_y - \mathbf{U}_y) \quad (2)$$

$$A_z = \frac{d^2z}{dt^2} = -\frac{3}{4}\frac{\rho_a}{\rho_W}\frac{C}{D}\mathbf{V}\mathbf{W}_z - g \quad (3)$$

where x, y, z are the coordinates referring to the ground (with origin at the sprinkler nozzle), t the time, ρ_a the air density, ρ_W the water density, A the acceleration of the drop in the air, D the drop diameter, and C is a drag coefficient, which can be expressed as a function of the Reynolds number of a spherical drop and the kinematic viscosity of the air (Fukui et al., 1980; Seginer et al., 1991).

Eqs. (1)–(3) are solved in the model using a fourth order Runge-Kutta numerical integration technique (Press et al., 1988). The main result of each drop trajectory solution is constituted by the x and y coordinates of the drop when the z coordinate equals 0 (the soil surface), or the crop canopy elevation, or the catch-can elevation. In order to reproduce the water application pattern resulting from an isolated sprinkler, these equations must be solved for a number of horizontal sprinkler angles (due to the sprinkler rotation) and for a number of drop diameters. The model typically uses 180 horizontal sprinkler angles and 180 drop diameters, evenly distributed between 0.0002 and 0.007 m. When the landing coordinates of each drop diameter are combined with the fraction of the sprinkler discharge which is emitted in this drop diameter, the water application pattern can be simulated.

The measurement of sprinkler drop size has been performed using a variety of indirect methods. It is only recently that optical spectropluviometers have been used for sprinkler drop size characterization (Montero et al., 2003). These devices result in accurate and automated measurements. An alternative procedure consists on using the ballistic model to simulate the landing distance of different drop diameters resulting from a given sprinkler model, nozzle elevation and operating pressure in the absence of wind. The percentage of the irrigation water collected at each landing distance can be used to estimate the percentage of the irrigation water emitted in drops of a given diameter.

Li et al. (1994) proposed the following empirical model to fit the drop diameter distribution curve:

$$P_V = (1 - e^{-0.693(D/D_{50})^n})100 \quad (4)$$

where P_V is the percent of total sprinkler discharge in drops smaller than D, D_{50} the mean drop diameter, and n is a dimensionless exponent. Eq. (4) permits to establish a functional relationship between the drop diameter and the sprinkler discharge. The estimation of the parameters of this equation permits to characterize the drop diameter distribution resulting from a given sprinkler, nozzle diameter and operating pressure.