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SPRINKLER APPLICATION EFFICIENCY AND STEMFLOW EFFECTS ESTIMATION BY SOIL WATER CONTENT MONITORING AND AN INFILTRATION MODEL

I. Bevilacqua, D. Canone, M. Previati, S. Ferrari, D. Pognant, S. Ferraris

Dipartimento di Economia e Ingegneria Agraria, Forestale e Ambientale, Università degli Studi di Torino

ABSTRACT

Sprinkler irrigation application efficiency in corn crops is influenced by soil water distribution through crop canopy water partitioning.
The aim of this work was to develop a methodology to evaluate sprinkler irrigation application efficiency considering stemflow effects on soil water distribution profiles.
Soil moisture monitoring was carried out on eight points for a center pivot irrigation.
Three water distribution estimation methods were employed: the raw measured soil moisture values, the spline interpolation of measured data and the simulation of the infiltration processes. The infiltration process was modeled by means of the two dimensional (2D) Richards equation. The simulations were calibrated on the eight measured data points. The stemflow was obtained as additional model fitting parameter.
During center pivot irrigation, 34% of the water delivered in the interrow was conveyed in the row. Soil water distributions calculated from measured and interpolated data overestimated and underestimated the irrigation application efficiency by approximately 15% and 30%, respectively. The water application efficiency obtained from simulation of water infiltration processes was 99.6%.
The proposed simulation method evaluates stemflow effects on the water distribution profile, leading to accurate application efficiency calculations.

Keywords: Application efficiency, Time Domain Reflectometry, Stemflow.

1 INTRODUCTION

In most Mediterranean countries, the agricultural sector is the major user of water resources (OECD, 2006). To comply with diversion restrictions, an optimal management of water resources at the farm level is needed, especially in view of increasing water demands and limited resources (Kumar and Singh, 2003). In the scenario described above, the most efficient and affordable irrigation technique must be chosen so that water consumption is optimized. To obtain the required water savings, it is also important to perform the irrigations properly and to choose the right irrigation scheduling so that the optimal water distribution in soil is achieved. The way that water redistribution occurs in the soil after irrigation must be analyzed in order to improve application efficiency. In sprinkler irrigation, the water is partitioned by the crop canopy into stemflow, throughfall, and interception storage.

Several studies have examined such processes under either natural rainfall or sprinkler systems. van Wesenbeeck and Kachanoski (1988) reported evidence of the importance of water partitioning by the crop canopy to determine spatial patterns of soil water content. Their results showed that the preferential recharge and drying at row position cause higher temporal variance of the row positions compared to the interrow positions. Lamm and Manges (2000) focused their study on water partitioning by the corn canopy under sprinkler irrigation performed with one high-pressure impact sprinkler system and two low-pressure spray systems. They also considered water partitioning by the crop canopy during rain events. They reported a correlation between the partitioning of sprinkler irrigation and rain when water was delivered above the canopies.

Different techniques for the description of soil water distribution profiles were proposed and tested by several authors (Bruckler et al., 2004; Fernández-Gálvez et al., 2006). Soil water distribution patterns can be determined by interpolation techniques as reported by Fernández-Gálvez et al. (2006). They observed that large errors can affect the estimation of the water content profile when it is based on soil water content measurements at few depths. Bruckler et al. (2004) modeled the root uptake and infiltration processes under the corn canopy taking into account stemflow effects on water supply homogeneity. The results of their work provided a description of the water distribution in the root soil layer.

The first aim of this work was to develop and experimentally test a methodology for the evaluation of sprinkler irrigation application efficiency that considers stemflow influences on soil water distribution patterns. In order to investigate such influences, soil water content measurements were performed and water distribution patterns were estimated. However, a sufficiently detailed TDR (Time Domain Reflectometry) water content spatial distribution measurement is not suitable for routine efficiency estimation. Therefore, the second objective is to develop a new technique for the estimation of water distribution profiles.

2 MATERIAL AND METHODS

2.1 Irrigation monitoring, data interpolation and simulation of the water infiltration process

During the growing season of the year 2008, a corn (*Zea mais* L.) center pivot irrigation event was monitored. The soils of the farm belong to the *loamy-sand* textural class. Measurements were carried out to define the following parameters: i) the total field irrigation water depth; ii) the time duration of the irrigation event; and iii) the water depth stored in the soil root layer. To evaluate the irrigation water depth delivered during the irrigation event, four rain gages were installed in the field above the corn canopy. Soil water content measurements were carried out using a device composed of one TDR che sigla è??cable tester (Tektronix Metallic Cable Tester 1502C) connected to a notebook, a multiplexer and eight 150 mm long TDR probes, which allowed automatic measurements of soil moisture at eight points along the soil profile at 5 minutes intervals. The probes were horizontally inserted into the soil at four depths below the row and the interrow, to monitor the entire root zone depth, which was limited by a layer of stones located at 0.5 m depth. The employment of a greater number of probes is not advisable, because the system would become both too expensive for routine measurements and too slow for simultaneous measurements across the profile. In order to obtain a detailed description of the water content distribution, both a spline interpolation method and a simulation method were tested.

In the first step, the soil water content distribution along the row - interrow vertical profile was estimated on a square grid with cells of 1 by 1 cm, by using the thin plate spline as described by Wahba (1990). It does not require any assumption on the spatial covariance of the data, which are necessary in kriging-based interpolation methods (Cressie 1991). In the second step, the finite volume ADHYDRA code (Manzini and Ferraris, 2004) was employed to simulate the infiltration process. This code simulates the two-dimensional infiltration process by solving the Richards equation (1931) on an arbitrarily chosen grid, which in our work was set up as a square grid with cells of 1 by 1 cm.

The initial conditions were given by the water content measured at the beginning of the irrigation, whereas the boundary conditions were as follows: on the surface boundary the stemflow flux was imposed on the first ten centimeters horizontally taken from the center of the row, the residual rainfall flux was imposed on the remaining surface; a no flux condition was imposed on the vertical boundaries because of the symmetry; unit gradient condition was imposed on the bottom boundary. The simulations were calibrated on data measured at eight control points.

In this study, the van Genuchten equation (1980) and the Brooks and Corey relation (1964) were chosen as water retention and hydraulic conductivity models, respectively.

Scale parameters (saturated hydraulic conductivity K_S and the matric potential scale parameter h_g) were obtained by fitting on the observed water content data. Two K_S values were obtained separately for the row and the interrow soil profiles to account for the varying degree of soil compaction. The scale parameter θ_S was estimated by TDR measurement after the irrigation event. The shape parameters m, n and η were obtained following the method proposed by Lassabatère et al. (2006).

2.2 Application efficiency estimation

In this work, three techniques for the description of the water distribution patterns were employed.

Water distribution in the root layer profile was described by means of:

- the measured data related to a grid of eight cells;
- the interpolated related to a grid of 5 by 5 cm square cells;
- the simulated data related to a grid of 5 by 5 cm square cells.

The water distribution in the soil profile was calculated at two times: the beginning of the irrigation event (t_0); the time at which the redistribution became negligible if compared to evapotranspiration effects (t_1).

According to this procedure, the depth of water stored within a cell at time t_i (St_{ijk}) is given by:

$$St_{ijk} = \theta_{ijk} \cdot l_k \qquad (1)$$

where θ_{ijk} [L^3L^{-3}] is the soil water content assigned to the considered cell at time t_i, with i equal to 0 or 1 and l_k [L] is the thickness of the cells. The subscript j ($1 \leq j \leq p$) indicates the assumed cell along the horizontal axis perpendicular to the corn row, and q[-] is the number of cells along the horizontal axis. The subscript k ($1 \leq k \leq q$) indicates the considered cell along the vertical axis, r [-] is the number of cells along the vertical axis,. The field water application efficiency, defined by Kruse et al. (1990) as the average depth of water stored in the root zone divided by the average depth of water applied to a field, is given by:

$$E_a = \frac{\dfrac{\sum_{j=1}^{q}\sum_{k=1}^{r} St_{1jk} - \sum_{j=1}^{q}\sum_{k=1}^{r} St_{0jk}}{q \cdot w}}{P} \qquad (2)$$

where w [L] is the width of the cells and P [L] is the precipitation depth during the irrigation event corresponding to the average of water depth applied to the field.

3 RESULTS AND DISCUSSION

The efficiency term in the presentation and the discussion of results and conclusions will be followed by the subscript "*m*" to indicate an estimation based only on measured data, by the subscript "*i*" to indicate an estimation based spline interpolation results and by the subscript "*s*" to indicate an estimation based on simulation results.

3.1 Experimental monitoring of stemflow effects on water infiltration and redistribution

The analysis of soil water content data recorded after the irrigation system was stopped showed a water stock reduction below the corn row with a negligible soil water content increase at the bottom of the profile, which implies a horizontal distribution of water in direction of the interrow. It also showed that the water dropped in the center of the interrow was maintained in the first two layers of the soil without any flow toward the deeper layers. The above considerations imply that half an hour after the irrigation system was stopped, the soil water content could not be considered constant on the horizontal axis perpendicular to the corn lines and deep percolation losses were negligible.

To evaluate the error to which a wrong estimate of water distribution can lead, the application efficiency was computed on the data measured during an irrigation (E_{am}). The E_{am} achieved the unrealistic value of 112.3 %. To evaluate the effect of the heterogeneity of water content distribution and the inadequacy of the E_{am}, the measured soil water contents were interpolated using the thin plate spline, and the infiltration process was simulated using the ADHYDRA code.

3.2 Estimation of water distribution patterns by using the thin plate spline

The thin plate spline interpolation was performed in order to estimate the water distribution pattern in the row-interrow profile. Figure 1 shows the results of soil water content interpolation at time t_0 and t_1. The water distribution patterns are generally acceptable, but a detailed analysis reveals some unlikely results. The interpolation generates water content values lower than the minimum measured water content. The water distribution patterns generated by thin spline generally underestimate the soil water content below a depth of 0.4 m, where the bottom of the soil profile at t_1 looks drier than it was at t_0. Such errors in water content estimation cannot be controlled by the interpolation procedure. The E_{ai} value (101.3 %) shows that the water estimation of the distribution patterns obtained by interpolation is still unacceptable.

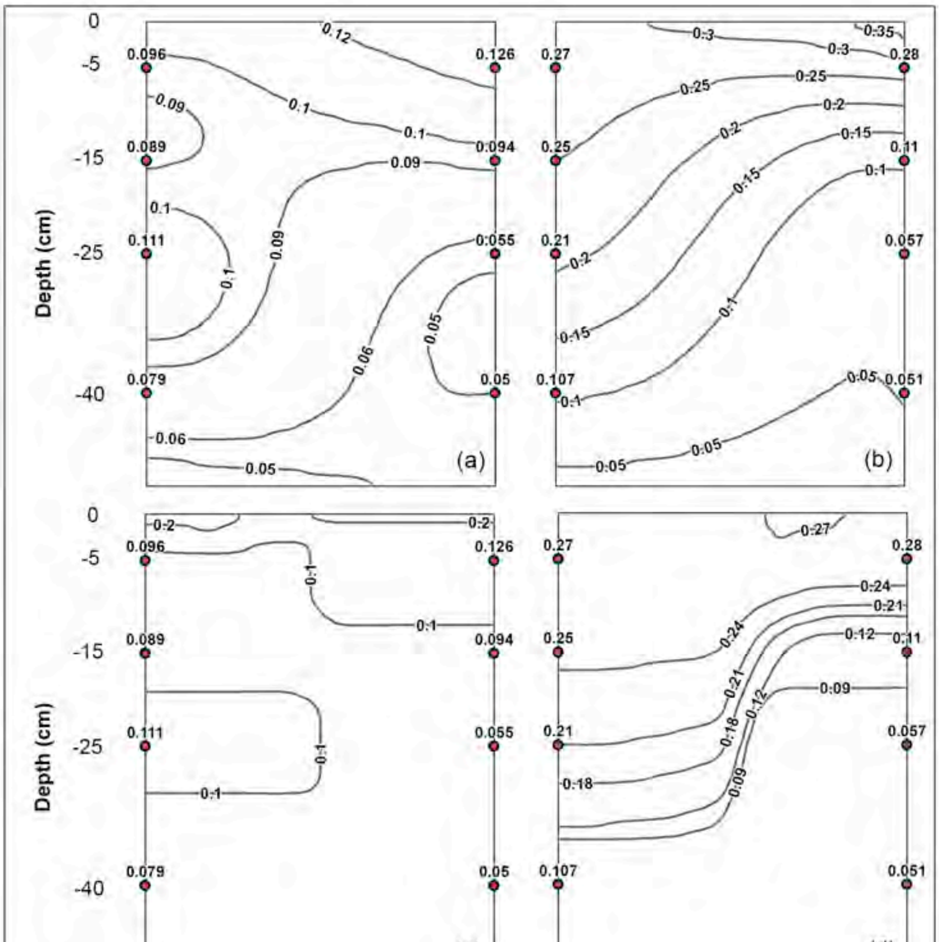

Figure 1. Vertical 2D distribution of soil water content during the center pivot irrigation event before the irrigation (t_0) and at the end of the simulation (t_1). Figures 8a and represent the soil water content interpolated by using thin spline method. Figures (8c and 8d) represent the soil water content distribution simulated by using the ADHYDRA code.

3.3 Estimation of stemflow, water distribution patterns and application efficiency by simulation of the infiltration process

The estimation of water partitioning by the corn canopy was obtained as a parameter for the fitting of the results of the simulation of the infiltration process onto water content measured data. The value of the parameter was estimated while minimizing the RMSE between simulated and measured data. The minimum RMSE was found when one third of the inflow water depth was infiltrated in the interrow and two thirds were infiltrated in the row. The stemflow value obtained from the simulation of the infiltration process (34 %) is similar to those reported by Parkin and Codling (1990), which ranged between 27 and 50%.

The differences between the simulated and the measured data were calculated at t_1. The differences show a good agreement between the model results and the measured data. The greatest difference was observed at a depth of 0.4 m below the row, where the result of the simulation showed a water content value 0.027 m^3m^{-3} lower than the measured data. No difference was found at the same depth below the interrow, where neither monitoring nor simulation registered any change in water content. The differences at the control nodes located at 0.05 m below the row and at 0.05 and 0.15 m were -0.015 m^3/m^3. In the other locations, the differences were lower than the instrumental resolution of the Tektronix 1502C, which is 0.004 m^3m^{-3} (Hook and Livingston, 1996).

The water distribution patterns obtained by the simulation were always consistent with the infiltration process, and local estimation errors determined by the interpolation process are avoided. Moreover, the simulation method allows for the estimation of the stemflow.

The application efficiency calculated for the center pivot irrigation (E_{as}) was 99.6 %. The E_{as} value is physically acceptable and consistent with the negligible deep percolation water loss measured at the bottom of the profile. The E_{as} value show the importance of an infiltration model for the estimation of the water distribution patterns to calculating the water application efficiency.

4 CONCLUSION

In this study, monitoring of soil water content profiles was carried out during an irrigation event to evaluate the sprinkler irrigation application efficiency considering the stemflow influence on water distribution profiles. A thin spline interpolation method and a 2D simulation of the infiltration processes performed by means of the ADHYDRA code (Manzini and Ferraris, 2004) were tested, to develop a new technique for the estimation of water distribution profiles. Field-scale soil hydraulic parameters were derived from TDR water content measurements and soil particle size analysis.

The results of TDR monitoring of the irrigation event highlighted the need for a higher resolution in water content data obtainable either by an interpolation method or by the simulation of the infiltration process. The thin spline interpolation results were not always consistent with the infiltration processes. The comparison among observed water content, interpolated water content data and the calibrated ADHYDRA simulations showed that this model is able to correctly reproduce the water spatial distribution in the row – interrow soil profile. Such detailed infiltration simulations allowed us to calculate the water application efficiencies accounting for the effects of stemflow caused by the corn canopy.

The water application efficiency was calculated from the water content values estimated over the soil profile by the simulation of the infiltration process between the row and in the interrow. The efficiency calculated was approximately 99 %.

Our work showed that it is not advisable to calculate water application efficiency based only on soil water measurements if the infiltration rate is highly variable over the field surface. In such cases, we recommend the determination of soil hydraulic parameters to perform detailed water infiltration simulations and to refine the estimation of the actual water distribution patterns.

5 References

Brooks RH, Corey AT (1964) Hydraulic properties of porous media. Hydrology Paper 3. Colorado State University, Fort Collins

Bruckler L, Lafolie F, Doussan C, Bussières F (2004) Modeling soil-root water transport with non-uniform water supply and heterogeneous root distribution. Plant Soil 260(1): 205-224. doi:10.1023/B:PLSO.0000030187.33135.b8

Cressie NAC (1991) Statistics for Spatial Data. John Wiley & Sons, New York

Fernández-Gálvez J, Simmonds LP, Barahona E (2006) Estimating detailed soil water profile records from point measurements. Eur J Soil Sci 57(5): 708-718. doi:10.1111/j.1365-2389.2005.00761.x

Hook WR, Livingston NJ (1996) Errors in converting time domain reflectometry measurements of propagation velocity to estimates of soil water content. Soil Sci Soc Am J 60: 35-41

Kruse EG, Bucks DA, von Bemuth RD (1990) Comparison of irrigation systems. In: Stewart BA, Nielsen DR (eds) Irrigation of Agricultural Crops Agron Monogr No 30. Am Soc Agron, Madison, pp 475-508

Kumar R, Singh J (2003) Regional water management modelling for decision support in irrigated agriculture. J Irrig Drain Eng ASCE 129: 432-439.

Lamm FR, Manges HL (2000) Partitioning of Sprinkler Irrigation Water by a Corn Canopy. Trans ASAE 43(4): 909-918

Lassabatère L, Angulo Jaramillo R, Soria Ugalde JM, Cuenca R, Braud I, Haverkamp R (2006) Beerkan estimation of Soil Transfer Parameters trough Infiltration Experiments-BEST. Soil Sci Soc Am J 70: 521-532. doi:10.2136/sssaj2005.0026

Manzini G, Ferraris S (2004) Mass-conservative finite volume methods on 2-D unstructured grids for the Richards' equation. Adv Water Resour 27(12): 1199-1215

OECD (2006) Report on the OECD workshop on agriculture and water: sustainability, markets and policies. OECD, Adelaide

Parkin TB, Codling EE (1990) Rainfall distribution under a corn canopy: implication for managing agrochemicals. Agron J 82: 1166-1169

Richards LA (1931) Capillary conduction of liquids through porous medium. Physics 1: 318-333

Roth K, Schulin R, Fluehler H, Attinger W (1990) Calibration of TDR for water content measurement using a composite dielectric approach. Water Resour Res 26(10): 2267-2273. doi: 10.1029/WR026i010p02267

van Genuchten MTh (1980) A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44: 892-898

van Wesenbeeck IJ, Kachanoski RJ, (1988) Spatial and temporal distribution of soil water in the tilled layer under a corn crop. Soil Sci Soc Am J 52: 363-368