A SIMULATION MODEL FOR LEVEL FURROWS:

I. ANALYSIS OF FIELD EXPERIMENTS

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ABSTRACT

The level-furrow irrigation system consists of furrowing a level-basin. In level-furrows, irrigation proceeds just like in level-basins: the field is flooded from one point and water spreads to irrigate each furrow. Several authors have reported that this irrigation system has a potential to conserve water as compared to level-basin irrigation. However, no comparative studies on the performance of both irrigation systems are available, and the simulation of level-furrows has not been attempted. In this work, two field experiments are reported. Both of them were performed in the same soil and in the same conditions. In the first experiment, infiltration was estimated for a series of furrow irrigation discharges and for a level basin. In the second experiment, a level furrow

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irrigation event was evaluated. A simulated level basin irrigation event in the level furrow experimental field required six times more time and water to complete advance. Infiltration equations including the irrigation discharge or the wetted perimeter as independent variables were proposed for the experimental furrow conditions. Application of a furrow simulation model to the level furrow experiment resulted in an underestimation of the time of advance. To overcome this problem, a simulation model for level furrows was developed and is presented in a companion paper. The reported field experiments were used to validate the model, which was applied (in a companion paper) to explore adequate conditions for level furrow irrigation performance.

INTRODUCTION

Surface irrigation is widely practiced throughout the world. In industrialized countries, the area devoted to surface irrigation is steadily decreasing due to the development of pressurized systems. In the United States, the yearly irrigation survey of the Irrigation Journal revealed that in 1985 the surface irrigated area was 15.3 million ha, whilst the area irrigated with pressurized systems was 9.0 million ha. In 2000 the situation had changed significantly: pressurized irrigation systems, with 12.8 million ha, dominated over the surface irrigated area, which had diminished to 11.5 million ha. In the same period of time, the irrigated acreage in the United States increased from 24.5 to 25.6 million ha. It is interesting to note that in States such as California, Nevada, Colorado and Utah surface irrigation still occupies well over 50 % of the irrigated acreage. Snyder et al. (1996) performed a survey on the statistics of the irrigation systems in California. The authors found that surface irrigation was used in two-thirds of Californian

agriculture, and that this irrigation system was associated to field crops (90 % of the area) and vegetable crops (70 % of the area).

Considering the current social and water context, irrigation systems that will prevail in the future are those that attain high efficiency, have low construction and maintenance costs and require little labor. Among them, two are discussed in this work: level furrow and level basin. Level basin irrigation has become very popular in recent decades. In this irrigation system, large plots (up to five hectares) leveled to zero slope and surrounded by a continuous dike are irrigated from one or several point sources (Dedrick et al., 1978). The level furrow irrigation system emerged as a modification of the level-basin irrigation system (Erie and Dedrick, 1979), in which the level basin area is furrowed and crops are established on top of the inter furrow strips. Since runoff is not allowed and the field is leveled to zero slope, water finds its way to irrigate each furrow.

Although level basin irrigation often attains high irrigation efficiencies, in particular cases problems can arise. On one hand, in level basins the infiltrated depth may be too high for the soil water holding capability. In fact, level basins tend to apply large irrigation depths, which can result in relevant deep percolation losses in shallow and/or coarse soils; on the contrary, furrow irrigation is characterized by having the potential to apply light irrigation depths. Following this reasoning, Walker and Skogerboe (1987) stated that level furrows can be more efficient than level basins. On the other hand, level basins may not be adapted to all crops, since some crops greatly benefit from growing on top of a furrow. This applies to most vegetables and to a number of field crops, such as corn or cotton. In such cases, level furrows can be recommended or at least constitute

a feasible alternative. Since switching from level basins to level furrows is as easy as performing an additional tillage operation, predictive tools are required to assist in decision-making based on irrigation performance in each irrigation system. The key to the sustainability of level furrow and level basin systems is the quality of land leveling. The generalization of laser leveling techniques in the last decades has greatly contributed to the success of these irrigation systems (Dedrick et al., 1978; Erie and Dedrick 1979).

Numerical models have been developed for the simulation of surface irrigation in general (Clemmens and Strelkoff, 1999; Walker, 2001) and level-basins in particular (Playán et al., 1994a; Playán et al., 1994b). General surface irrigation models can be used in level furrows assuming that the irrigation event is identical in all furrows. However, specific simulation models are not available for the interconnected flow typical of level furrows. This circumstance has limited the quantification of its alleged advantages over level basins.

In this work, two field experiments are presented and analyzed. Infiltration equations are derived from the first experiment to estimate infiltration for level basin and level furrow conditions. An effort was made to characterize infiltration in furrows as a function of discharge or wetted perimeter. The second experiment consisted of an evaluation of a level furrow irrigation event, in which advance times and flow depths in a furrow section near the inlet were measured. Field evaluation results were compared with the simulation of level basin irrigation in the same experimental conditions.

DESCRIPTION OF THE FIELD EXPERIMENTS

An experimental field was set up at the research farm of the Agricultural Research Service (SIA) of the Government of Aragón in Zaragoza, Spain, during the summer of 2000. The soil, developed from alluvial deposits, was classified as a Typic Xerofluvent, coarse loam, mixed (calcareous), mesic (Soil Survey Staff, 1992). The experimental field was tilled in preparation for the experiments, which represented the first irrigation of the season.

Two separate experiments were performed in consecutive days (Figure 1). The first experiment was conducted to determine furrow infiltration. Four irrigation evaluations were performed in four identical and isolated level furrows using different inflow discharges, and one irrigation evaluation was performed in a level basin. The second experiment consisted of an evaluation of level furrow irrigation performance, involving a 40-furrow setup. Since both experiments were conducted on the same field, contiguously arranged, and performed under similar initial soil water conditions, the infiltration curves developed in the first experiment are considered representative of the second experiment.

All furrows were built using the same field machinery. Average furrow dimensions (and their coefficients of variation, CV) were determined from nine cross-sectional measurements taken on three different furrows before the experiments. The resulting average base width was 0.14 m ($CV = 0.015\%$); the top width was 0.80 m ($CV = 6\%$); depth was 0.24 m ($CV = 11\%$); and width at half of the furrow depth was 0.44 m ($CV =$

5 %). These dimensions resulted in the following geometrical relations (Walker and Skogerboe, 1987):

$$A_0 = a1 h^{a2} \quad ; \quad A_0 = 1.15 h^{1.65} \quad [1]$$

$$WP = b1 h^{b2} \quad ; \quad WP = 3.30 h^{0.87} \quad [2]$$

$$A_0 R^{2/3} = p1 A_0^{p2} \quad ; \quad A_0 R^{2/3} = 0.474 A_0^{1.32}, \quad [3]$$

where A_0 is the cross sectional flow area at the upstream flow depth (m^2); h is the flow depth (m); WP is the wetted perimeter (m); R is the hydraulic radius (m); and $a1$, $a2$, $b1$, $b2$, $p1$ and $p2$ are empirical coefficients.

The experimental field was laser leveled to zero slope just before the preparation of the experimental setup. The standard deviation of soil surface elevation, determined from 36 survey points at the bottom of the furrows, was 14 mm, a figure that is close to the technical limit of the laser technology (Playán et. al, 1996). The following paragraphs detail the procedures followed in both experiments.

First experiment:

Evaluation of four individual level furrows and a level basin

A total of five irrigation events were evaluated to estimate infiltration (four furrows and one level basin). The furrow length was 48 m, the furrow spacing was 1.3 m and the basin width was 2.04 m. Stations were marked along each furrow or basin every 5 m.

The irrigation evaluation involved monitoring of the advance phase exclusively.

Irrigation was cut off in each evaluation after completion of advance. The advance times to each station, and the evolution of the upstream flow depth hydrograph were measured. Water was diverted to the furrows and the basin using the supply channel as

a reservoir. For this matter, the gate separating the infiltration experiment from the level furrow experiment was kept closed during the first experiment. A pump was used to extract water from the supply channel and to divert a constant discharge into each furrow and basin. Discharge was measured using a volumetric water meter installed in the water supply pipeline, downstream from the pump. The flow rates used for each irrigation evaluation are detailed in Table 1.

Parameters of the empirical Kostiakov infiltration equation were estimated from the advance data, using a volume balance method similar to the one proposed by Walker (1989). However, instead of using two points, all the measured advance points were used to determine the empirical power advance function needed by the volume balance calculations. The Kostiakov equation is:

$$Z = k\tau^a, \quad [4]$$

where Z is the infiltrated depth ($\text{m}^3 \text{m}^{-1}$), τ is the opportunity time (min) and k and a are empirical coefficients. The volume balance equation (Walker and Skogerboe, 1987) expresses that at any time during the irrigation event the inflow irrigation volume (V_i) is equal to the overland volume (V_h) plus the infiltrated volume (V_z). Therefore, the infiltrated volume can be determined as:

$$V_z = V_i - V_h \quad [5]$$

A potential regression of advance distance (x) vs. time (t) permits to estimate for each irrigation event the advance parameters p and r :

$$x = pt^r \quad [6]$$

Introducing the surface storage shape factor (σ_y , assumed equal to 0.77) and the subsurface shape factor (σ_z), Eq. [5] can be expressed as:

$$V_z = \sigma_z k t^a x = \frac{a + r(1-a) + 1}{(1+a)(1+r)} k t^a x = Q t - \sigma_y A_0 x \quad [7]$$

The right-hand side of Eq. [7] (V_z) can be computed for each advance time using [1] for A_0 and the upstream flow depth. The potential regression of V_z on time permits to estimate a and k . The coefficient of determination (R^2) exceeded 90 % in all cases.

The resulting infiltration parameters are presented in columns (3) and (4) of Table 1, while the corresponding infiltration curves are presented in Figure 2. In the figure the dimensions of furrow infiltration are volume per unit infiltrating area, which come from dividing infiltration by the furrow spacing (1.3 m). As expected, infiltration in furrows grows with the inflow discharge, due to the corresponding increase in the wetted perimeter. In this experiment the spatial variability of soil physical properties did not create relevant problems in the measurement of infiltration. Although only one furrow was used for each discharge, the soil area involved seemed to be sufficient to obtain a reasonable spatially averaged infiltration estimate.

By expressing furrow infiltration in units of length, one can compare the magnitude of furrow and basin infiltration. The curves show that under the experimental conditions, infiltration from the level basin is much larger than infiltration from furrows. For the same discharge, and an opportunity time of 50 min, basin infiltration is 70 % larger than furrow infiltration. This is the first basis for the potential water saving in the experimental level furrow system. Of course the comparison between these two irrigation systems heavily depends on the furrow spacing. The dependence is not expected to be linear, since at narrower furrow spacings the magnitude of the furrow infiltration equation in $\text{m}^3 \text{m}^{-1}$ would decrease due to the interference in the cross sectional patterns of the wetted soil. At the experimental furrow spacing, discharge and

advance times this interference could not be appreciated, since the inter furrow strip remained dry throughout the experiment.

The Manning n coefficient was calibrated by matching the measured and simulated values of the final upstream depth. The SIRMOD simulation software (Walker, 2001) was used for this purpose. Table 1 presents both flow depths and the best estimates of Manning n . The four furrow evaluations resulted in very similar values of Manning n , around 0.05, while the estimated value for the basin was 0.11. The differences between furrow and level-basin Manning n may be partly due to inaccuracies of the infiltration estimation procedure. However, the dependence of Manning n on flow depth, discharge and geometry was already discussed in the classic work by Chow (1959). Similar findings were recently reported by García-Navarro et al. (2000).

This difference in roughness following similar tillage operations constitutes a second basis for the potential water saving in the experimental level furrows. The larger value of Manning n will slow down advance and induce a large flow depth in level basin irrigation. Both factors will lead to an increase in the volume of infiltrated water. If the target irrigation depth is small (as in shallow, coarse soils), the application efficiency will be reduced. Figure 3 presents the observed and simulated advance curves corresponding to the four furrow evaluations plus the level basin evaluation.

The estimation of infiltration and roughness parameters in the experimental field has identified two potential disadvantages of level-basin irrigation as compared to level furrow irrigation: increased infiltration and increased roughness. Further field

experimentation will be required to assess if these findings can be generalized for other soils or soil conditions.

Second experiment:

Evaluation of level furrow irrigation

The second experiment consisted of 40 irrigation furrows 50 m long and spaced 1.3 m (Figure 1). The experimental field size (0.25 ha) was very small in comparison with most level furrow applications, but was very adequate to optimize field measurements. References were marked on the field every 5 m in one every five furrows to measure advance. The furrows were connected to each other by upstream and downstream distribution channels. The purpose of these channels was to allow water redistribution among the irrigation furrows. Their geometry was characterized at eight locations. The channel base averaged 0.32 m; the top width was 0.88 m; the channel depth was 0.22 m; and the width at half of the channel depth was 0.60 m. Since the infiltration characteristics of the distribution channels had not been evaluated, they were covered with a plastic film to prevent infiltration. In this way, the efforts of characterizing infiltration were concentrated on the infiltration furrows.

The field was irrigated from the supply channel, and the irrigation discharge was measured using a Cipoletti weir (Fig. 1). The average discharge was 52.6 L s^{-1} , and lasted for 31 minutes. The time of cut off was coincident with the time of advance. Advance was monitored by a group of observers who identified the location of the advancing front in each of the furrows at 1, 6, 14, 19, 23 and 30 minutes. Figure 4 presents the location of the advancing front along the furrows for each of the six

observation times. Water fully covered furrow #1 before the 6 min measurement. The outflow from furrow #1 to the downstream distribution channel irrigated neighboring furrows from their downstream extreme. Thus, for some furrows water advanced from both ends. Towards the end of the irrigation event, the flow of both distribution channels seemed to equilibrate and the meeting point of the two advancing fronts shifted towards the middle of the field. Since at this time the flow was severely reduced by infiltration, the flow depth decreased and advance tended to be dictated by minor differences in furrow elevation, or by the particular conditions at the junction nodes. As a consequence, the last furrow to complete advance was not the last one (# 40), but furrow # 35 (its reach spanning from 14 m to 21 m was uncovered at time 30 min). The resulting experimental advance diagram is presented in Figure 5.

The flow in furrow # 1 was analyzed in more detail. Flow depth and discharge were measured at the upstream end of this furrow every minute from the start of the irrigation to a time of 13 min. A propeller meter was used to measure flow velocity. Flow depth and discharge stabilized after 7 min at 0.140 m and 5.13 L s^{-1} , respectively.

The total field area can be computed as $2,600 \text{ m}^2$ (50 m by 52 m). Considering the total irrigation volume (97.8 m^3), the resulting average irrigation depth was 37.6 mm. This relatively light irrigation depth is common in furrow irrigation systems.

LEVEL FURROWS vs. LEVEL BASIN

The experimental program did not include the irrigation of a level basin similar to the level furrow field. Therefore, in order to compare both irrigation systems under the experimental conditions we simulated a level-basin irrigation event in the level furrow

experimental field. For this purpose, the two-dimensional hydrodynamic level basin model B2D (Playán et al., 1994a; Playán et al., 1994b) was used. The field geometry reproduced the second field experiment: 2,600 m² discretized using 21 rows of nodes spaced 2.6 m, and 21 columns spaced 2.5 m (a total of 441 nodes). The hypothetical level basin was irrigated from the same corner as in the experiment. The infiltration and roughness parameters were as determined during the evaluation process for the level basin, and presented in Table 1. The irrigation discharge was the same used in the level furrow experiment, and the time of cutoff was set at the time of advance.

Simulation results were very different from the level furrow field experiment. The advance time was 185 min, almost six times more than for level furrows (Figure 5). The average infiltrated depth increased from a moderate 37.6 mm in level furrows to an undesirable 223 mm in the level basin. In this case, the differences in irrigation performance seem to be due primarily to the high infiltration in level basin irrigation, and particularly to the high value of the a exponent, resulting in a large infiltration rate even at large opportunity times. Figure 6 depicts a map of the location of the advancing front at different times in the level basin irrigation simulation. The graph reproduces the radial advance pattern described by Playán et al. (1994b) for this type of irrigation configurations.

INFILTRATION AND DISCHARGE IN LEVEL FURROWS

Several authors have explored the relationship between flow depth (or discharge) and furrow infiltration (Fangmeier and Ramsey, 1978; Izadi and Wallender, 1985; Samani et al., 1985; Trout, 1992; Schmitz, 1993). Recently, Rodríguez (2002) proposed a

procedure for the estimation of sloping furrow Kostiakov infiltration at untested discharges. The procedure uses the volume balance approach, and is based on the hypothesis that when a furrow is irrigated using different discharges, the Kostiakov exponent remains constant. Therefore, the effect of the variations in discharge is reflected only on the value of the k parameter. This hypothesis is confirmed by the relative stability of the a estimates in Table 1 when compared to the k estimates.

The proposed expression to consider the effect of the wetted perimeter on furrow infiltration (Walker and Skogerboe, 1987) is:

$$Z_{ne} = Z_e \left(\frac{WP_{ne}}{WP_e} \right)^\varphi, \quad [8]$$

where Z_{ne} and Z_e represent the volume of infiltrated water per unit of furrow length corresponding to the non-evaluated and evaluated wetted perimeters (WP_{ne} and WP_e , respectively); while φ represents an empirical exponent. A linear regression analysis showed that 99 % of the variability in k can be explained by the variability in the wetter perimeter alone. Thus, in the present data set, $\varphi=1$ is an adequate choice. This implies that the k coefficient varies linearly with the wetted perimeter. The following paragraphs will be devoted to the derivation of an equation to estimate furrow infiltration at untested discharges under the condition of $\varphi=1$, adapting the previous work of Rodriguez (2002).

The Manning equation can be written as:

$$Q = \frac{60}{n} \cdot p1 \cdot A_0^{p2} \sqrt{S_0}, \quad [9]$$

where Q is the irrigation discharge ($\text{m}^3 \text{min}^{-1}$), and S_0 is the longitudinal furrow slope.

From equation [3]:

$$p1 \cdot A_0^{p2} = A_0 \cdot R^{2/3} = A_0 \cdot \left(\frac{A_0}{WP} \right)^{2/3} \quad [10]$$

Substituting [10] in [9] and rearranging:

$$WP = \left(\frac{60}{n} \right)^{3/2} \frac{A_0^{5/2}}{Q^{3/2}} S_0^{3/4} \quad [11]$$

According to this equation, the ratio between the wetted perimeters corresponding to non evaluated and evaluated conditions can be expressed as:

$$\frac{WP_{ne}}{WP_e} = \left(\frac{A_{0ne}}{A_{0e}} \right)^{5/2} \left(\frac{Q_e}{Q_{ne}} \right)^{3/2} \quad [12]$$

While from Manning equation the following relation can be derived among the cross sectional flow areas at the upstream end:

$$\frac{A_{0ne}}{A_{0e}} = \left(\frac{Q_{ne}}{Q_e} \right)^{1/p2} \quad [13]$$

Substituting [13] in [12]:

$$\frac{WP_{ne}}{WP_e} = \left(\frac{Q_{ne}}{Q_e} \right)^{\frac{2.5}{p2}-1.5} \quad [14]$$

According to [8] and the Kostiakov equation [4]:

$$Z_{ne} = k_e \cdot \tau^a \left(\frac{WP_{ne}}{WP_e} \right) \quad , \quad [15]$$

or:

$$Z_{ne} = k_e \cdot \tau^a \left(\frac{Q_{ne}}{Q_e} \right)^{\frac{2.5}{p2}-1.5} \quad , \quad [16]$$

where k_e is the Kostiakov coefficient corresponding to the evaluated discharge.

Eqs. 15 and 16 are mathematically equivalent. However, they use two additional independent variables; discharge and wetted perimeter. Both variables have been used

in the literature to express the variability in the infiltration rate resulting from variations in flow depth. Use of Eq. 15 may seem like an adequate choice, since in the experimental conditions infiltration grows linearly with wetted perimeter. However, in experiment 1 the upstream wetted perimeter increased in time up to the end of the irrigation evaluations (because the field was leveled to zero slope). Therefore, there is not an easy choice for the reference wetted perimeter. The option remains to associate each furrow in experiment 1 to the inlet discharge, and use Eq. 16 as a general infiltration equation for the experimental conditions.

In order to derive numerical parameters for Eqs. 15 and 16, any of the field evaluated discharges can be used as Q_e . However, since the inflow discharge of 52.6 L s^{-1} largely exceeds the furrow discharges used for infiltration estimation, it seems adequate to use the largest evaluated discharge, in the hope to minimize extrapolation errors. Therefore, using $Q_e = 4.53 \text{ L s}^{-1}$, $k_e = 0.0111$, $a = 0.515$, $WP_e = 0.515 \text{ m}$ (from the final flow depth and Eq. 2), and $p2 = 1.32$ in Eqs. 15 and 16, the following infiltration equation can be deduced:

$$Z = 0.0213 WP \tau^{0.515} \quad [17]$$

$$Z = 0.00607 Q_{ne}^{0.4} \tau^{0.515} \quad [18]$$

These infiltration equations were validated by comparing measured and estimated infiltration depth using the remaining three values of irrigation discharge (1.03 , 2.12 and 3.01 L s^{-1}) and for opportunity times up to 30 min . Measurements were obtained from the irrigation evaluation for each advance observation (Equation 7). Estimations were determined using Eq. [18]. Figure 7 presents the resulting scatter plot, in which the points are satisfactorily distributed along the diagonal line. The fact that this infiltration

equation incorporates the value of the furrow inflow discharge makes it adequate to be introduced in a simulation model, in which the time and space variability in discharge are part of the solution to the problem. However, a global, constant discharge or a local, variable discharge can be used for this purpose. The application of the proposed infiltration equation is reported in the companion paper.

SIMULATING LEVEL FURROW IRRIGATION

WITH A FURROW IRRIGATION SIMULATION MODEL

The flow rate dependent infiltration function [18] was used to simulate an irrigation in the level furrow field. The SIRMOD model was used for this purpose, under the crude hypothesis that the level furrow setup irrigated with 52.6 L s^{-1} can be represented by a set of 40 furrows irrigated in parallel with $52.6/40 = 1.32 \text{ L s}^{-1}$ each. This is equivalent to a situation in which a gated pipe conveying 52.6 L s^{-1} , and running parallel to the 52 m field side, delivered water simultaneously to the 40 isolated 50 m long furrows.

For this discharge, [18] results in:

$$Z = 0.00678 \tau^{0.515} \quad [19]$$

The simulated advance time to the end of the furrow was 23.6 min. This is 24 % lower than the experimental value of 31 min. This result is subjected to a number of sources of experimental and computational error. However, we believe that it illustrates the potential problems of using a furrow irrigation model to simulate level furrow irrigated fields. A specific model is therefore required to simulate the level furrow irrigation system and to explore the conditions in which this irrigation method can be an interesting alternative to other irrigation systems. The companion paper reports the development, validation and application of such a model.

SUMMARY AND CONCLUSIONS

In this paper, experimental results have been presented supporting the common perception that level furrow irrigation performance can exceed that of level basin systems. While the reported experimental results cannot be generalized, they illustrate the need for further research in this area. The advantage of level furrow irrigation could be partly due to the differences in infiltration and roughness detected in the first experiment. For a similar discharge, level basin irrigation infiltration exceeded that of furrow irrigation by 70 %. The differences in roughness (the value of Manning n for the level basin more than doubled the corresponding value for furrow irrigation) seem to be due to the differences in flow bed geometry. In a comparison of experimental and simulated data, the differences between level basin and level furrow irrigation in terms of irrigation time and average infiltrated depth were very relevant, in a proportion of about one (level furrow) to six (level basin).

A number of additional experiments are required to determine conditions under which level furrows show a clear advantage over level basins. The variables to be explored include field dimensions, furrow spacing, conveyance capacity of the distribution channels, soil roughness and soil infiltration characteristics. All this experimentation would be very costly in terms of time and research resources. This is the reason why part of this research was oriented towards the development of a simulation model that can answer these questions while minimizing the required field experimental work. Experiments will however be required to characterize furrow infiltration as a function of inflow discharge in each particular soil type and furrow geometry.

The simulation of the level furrow experiment with a furrow irrigation simulation model resulted in a 24 % underestimation of the time of advance. Moreover, such a model can not reproduce with any accuracy the advance features presented in Fig. 4. To overcome this problem, in a companion paper, a simulation model for level furrows is presented and validated using the reported field experiments. The proposed model is further used to explore adequate conditions for level furrow irrigation performance. The insight derived from this series of two papers is limited by the use of the field derived infiltration equations, which are representative of one particular soil at a point in time.

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APPENDIX: REFERENCES

- Clemmens, A. J., and Strelkoff, T. (1999). "SRFR, Version 4.06." U. S. Water Conservation Laboratory. Agricultural Research Service, Department of Agriculture, Phoenix. Arizona.
- Chow, V. T. (1959). Open-channel hydraulics, McGraw-Hill, Tokio.
- Dedrick, A. R., Replogle, J. A., and Erie, L. J. (1978). "On-farm level-basin irrigation - save water and energy." *Civil Engineering*, 48(1), 60-65.
- Erie, L. J., and Dedrick, A. R. (1979). "Level basin irrigation: A method for conserving water and labour." *USDA Farmers' Bulletin*, 2261, 23.
- Fangmeier, D., and Ramsey, M. K. (1978). "Intake characteristics of irrigation furrows." *Transactions of the ASAE*, 21(4), 696-705.
- García-Navarro, P., Playán, E., and Zapata, N. (2000). "Solute transport simulation in overland flow: application to fertigation." *ASCE J. Irrig. Drain. Div.*, ASCE, 126(1), 33-40.
- Izadi, B., and Wallender, W. W. (1985). "Furrow hydraulic characteristics and infiltration." *Transactions of the ASAE*, 28(6), 1901-1908.
- Playán, E., Walker, W. R., and Merkley, G. P. (1994). "Two-dimensional simulation of basin irrigation. I: Theory." *ASCE J. Irrig. Drain. Div.*, 120(5), 837-856.
- Playán, E., Walker, W. R., and Merkley, G. P. (1994). "Two-dimensional simulation of basin irrigation. II: Applications." *ASCE J. Irrig. Drain. Div.*, 120(5), 857-870.
- Playán, E., Faci, J. M., and Serreta, A. (1996). "Modelling microtopography in basin irrigation." *ASCE J. Irrig. Drain. Div.*, 122(6), 339-347.
- Rodríguez, J. A. (2003). "Estimation of advance and infiltration equations in furrow irrigation for untested discharges." *Agricultural water management*, 60(3), 227-239.

- Samani Z.A., Walker W.R., Jeppson R.W. and Willardson L.S., 1985. Numerical solution for unsteady two-dimensional infiltration in irrigation furrows. *Transactions of ASAE*. 28(4), 1186-1190.
- Schmitz G.H., 1993. Transient infiltration from cavities I: Theory. *ASCE J. Irrig. Drain. Div.*, 119(3), 443-457.
- Snyder, R. L., Plas, M. A., and Grieshop, J. L. (1996). "Irrigation methods used in California: grower survey." *ASCE J. Irrig. Drain. Div.*, 122(4), 259-262.
- Soil Survey Staff. (1992). *Keys to soil taxonomy*, Pocahontas Press, Inc., Balcksbourg, VA, USA.
- Trout, T. J., 1992. Flow velocity and wetted perimeter effects on furrow infiltration. *Transactions of ASAE*. 35(3), 855-863.
- Walker, W. R., and Skogerboe, G. V. (1987). *Surface irrigation. Theory and practice*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.
- Walker, W. R. (1989). *Guidelines for designing and evaluation surface irrigation systems*, FAO Irrigation and Drainage Paper 45, Rome, Italy.
- Walker, W. R. (2001). "SIRMOD III." Utah State University, Logan, Utah.

APPENDIX: NOTATION

φ	Empirical exponent for the relationship between the increase in wetted perimeter and the increase in infiltration;
σ_y	Surface storage shape factor
σ_z	Subsurface shape factor
τ	Opportunity time, independent variable of the Kostiakov infiltration equation;
a	Empirical exponent of the Kostiakov infiltration equation;
$a1$	Empirical coefficient of the relationship between flow depth and cross-sectional area;
$a2$	Empirical exponent of the relationship between flow depth and cross-sectional flow area;
Ao	Cross-sectional flow area;
$b1$	Empirical coefficient of the relationship between flow depth and wetted perimeter;
$b2$	Empirical exponent of the relationship between flow depth and wetted perimeter;
CV	Coefficient of variation;
e	Subindex denoting evaluated conditions;
h	Flow depth; and
n	Manning roughness coefficient;
ne	Subindex denoting non-evaluated conditions;
p	Parameter for the advance function;
$p1$	Empirical coefficient of the relationship between cross sectional area and hydraulic radius;

p^2	Empirical exponent of the relationship between cross sectional area and hydraulic radius;
Q	Discharge;
r	Exponent for the advance function;
R	Hydraulic radius;
S_0	Field longitudinal slope;
t	Irrigation time;
V_h	Overland volume;
V_i	Irrigation volume;
V_z	Infiltrated volume;
WP	Wetted perimeter
x	Advance distance; and
Z	Infiltration.

APPENDIX: TABLES

Table 1. *Characteristics of the infiltration experiments: type of irrigation unit, discharge, Kostiakov k and a , final flow depth, as measured and simulated, and estimated Manning n .*

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Type (1)	Discharge (L s ⁻¹) (2)	k (*) (3)	a (4)	Final flow depth (m)		Manning n (7)
				Measured (5)	Simulated (6)	
Furrow	1.03	0.00489	0.616	0.065	0.068	0.05
	2.12	0.00845	0.500	0.099	0.098	0.05
	3.01	0.0104	0.497	0.110	0.112	0.05
	4.53	0.0111	0.515	0.120	0.119	0.04
Basin	4.52	0.00970	0.617	0.064	0.062	0.11

*) The units of k are m³m⁻¹min^{-a} for the furrows and m min^{-a} for the basin

APPENDIX: FIGURES

Figure 1. *Experimental setup used for infiltration estimation and for the evaluation of level furrow irrigation.*

Figure 2. *Infiltration equations estimated for the four furrows and the basin of the infiltration experiment. Furrow infiltration equations have been converted to units of m, dividing by the furrow spacing (1.3 m).*

Figure 3. *Advance curves corresponding to the five evaluations of the infiltration experiment as observed (symbols) and simulated with SIRMOD.*

Figure 4. *Schematic representation of the observed location of the advancing front at different times in the level furrow evaluation.*

Figure 5. *Advance diagram for the level furrow experiment (dots) and for the simulated level basin irrigation event (line).*

Figure 6. *Location of the advancing front at different times (min) in the level furrow evaluation simulation.*

Figure 7. *Comparison of the volumes of infiltration estimated with equation [18] and those obtained through the evaluation procedure.*

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