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# OPTIMIZATION OF FIELD TOPOGRAPHY IN SURFACE IRRIGATION

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## ABSTRACT

This work presents and applies a new methodology to find the optimal topography of a surface irrigation field, achieving a theoretically uniform surface irrigation.

For any variant on surface irrigation (basin, border or furrow, with open or blocked end), the method's result is a particular curved topographical shape of a field. This shape distributes water evenly over the field, so that distribution uniformity is theoretically 100% and deep percolation disappears.

The methodology is applied to two theoretical cases: a 1-D blocked-end field and a 2-D square field with corner inflow. For each case, the methodology reaches a particular topography where distribution uniformity is near 100%.

To put into practice this methodology, the optimized topography (which has a curved shape) must be approached to a set of slopes. A real example is shown where a real field was laser-levelled with two consecutive slopes to fit the optimized topography, previously calculated with the methodology here presented. The irrigation was evaluated before and after the optimization. The results indicate an increase of distribution uniformity from 82% to 96%.

The topographic optimization methodology offers new information about topography influence on irrigation performance indicators, and main practical conclusion is that this method can be useful to determine the best slope, set of slopes or curved shape when levelling any field for surface irrigation, in order to get a uniform surface irrigation.

## INTRODUCTION AND OBJECTIVES

In surface irrigation, most water loss at the plot level is from deep percolation (and surface runoff when end field is open). In general, surface irrigation is not uniform because the areas nearest the water entry point receive more water. In any variant of surface irrigation (basin, border or furrow, with open or blocked end), the distribution is less uniform than with pressurised irrigation systems (FAO 2002; Walker and Skogerboe 1987). At present, to improve surface irrigation uniformity there are several techniques: drainback, adjusting cutoff time or inflow rate, surge flow, cablegation, inflow cutback, runoff reuse, adjusting design (length, width), zero-leveling and, finally, leveling with slope (Walker and Skogerboe 1987, Hoffman *et al.* 2007).

Due to the increasing water scarcity due to climate change or population growth, the modern levelling techniques available for irrigated plots (laser, Global Positioning System GPS) justify studying the influence of the field surface topography on irrigation uniformity (Playán *et al.* 1996).

A small slope in the advance direction can improve performance (Khanna and Malano, 2006), and the selection of best slope requires careful analysis for every case (Khanna *et al.*, 2003). In one-dimensional approach, this best slope can be obtained with a simulation tool, as SIRMOD (Walker, 1998) or WinSRFR (Bautista *et al.*, 2015). or with non-dimensional graphs (González-Cebollada *et al.*, 2011). In the other hand, the system becomes increasingly sensitive to inputs when slope increases, and management problems are often proportional to the longitudinal slope (Playán, 2006).

The best slope is very useful in practice because it maximizes the distribution uniformity under 1-D approach. To improve the uniformity even more, it is necessary to use more than one slope, or to leave the 1-D approach with a 2-D conception. In these cases, there are not practical tools to find out easily the best topographical configurations. In the limit, the existence of a particular curved topography with theoretical 100% uniformity can be conjectured for each particular case, but there is no way to calculate it until now.

The objective of this work is to present and apply a method which lets us find the best curved topography of a field to help distribute the water uniformly over the field, getting a theoretical distribution uniformity of 100%. It can be applied to any surface irrigation system (basin, border or furrow; open or closed contours; 1-D or 2-D) under realistic conditions.

For each particular case, optimal topography will depend on the infiltration parameters, the Manning's roughness coefficient, the flow rate, the geometry of the field and the water required depth.

The results obtained with this method can be adjusted in practice with one or more slopes or planes, leading to more precise configurations than the configurations obtained with a 1-D single slope approach, to avoid water loss through deep percolation as much as possible.

## METHODOLOGY

To reach the proposed objective, a new methodology was developed to find a theoretically perfect topography for each particular case. This methodology, through an iterative process, leads to a curved ground surface which in theory obtains 100% distribution uniformity (*DU*) without deep percolation (*DP*) in any variant of surface irrigation (basin, border or furrow, with open or blocked end). Distribution uniformity is defined here as the quotient between minimum infiltration and average infiltration.

The method is computational and iterative. It needs hydraulic simulation software. The infiltration parameters, the Manning's roughness coefficient, the flow rate, the geometry of the field and the water required depth must be known, and wave model (complete, diffusive, kinematic), time step and space step must be properly selected. Some of these parameters can vary throughout time, so average values must be used. Spatial variations of infiltration parameters or Manning coefficient can be considered in the simulation software or can be averaged. The method starts simulating a horizontal topography (zero levelled) of the field which is going to be optimized. Each simulation let us to know where there is more infiltration and where there is less infiltration.

In each iteration of the method, the more infiltration point is raised (to decrease its infiltration), and the less infiltration point is lowered (to increase its infiltration). These elevation changes are made in the computational model. Then, a new hydraulic simulation is run, adjusting the irrigation time so that minimum infiltration ($z_{min}$) coincides with the required depth ($z_{req}$). In this new situation, the new more infiltration point is detected to be raised in the next iteration, and the new less infiltration point is detected to be lowered in the next iteration.

The iterative repetition of these operations leads to an evolution of the ground topography until a particular curved shape where theoretically perfect water distribution uniformity is reached. Each step of this computational methodology is given below.

**Step 1: Read data.** Data are: infiltration parameters, Manning's coefficient, water flow rate, field geometry and required depth. In the case of furrow irrigation, the corresponding geometric parameters must also be known. The initial topography of the field is considered to be horizontal.

**Step 2: Adjust irrigation time and calculate.** Using a hydraulic simulation tool, adjust the irrigation time by trial and error until minimum depth matches required depth. Then, detect the point in the field with more infiltration and the point with less infiltration. Evaluate distribution uniformity.

**Step 3: If the irrigation is uniform, stop.** When distribution uniformity reaches a desired value (99% for example), the process ends, and the optimal topography has been reached.

**Step 4: Raise the point of greatest infiltration.** The level of the point with more infiltration is raised to reduce its infiltration.

**Step 5: Lower the point of least infiltration.** The level of the point with less infiltration is lowered to increase its infiltration.

**Step 6: Go to step 2.** Going to the step 2, the loop of the iterative process is closed, adjusting again the irrigation time with the new topography derived from steps 4 and 5.

Figure 1 shows this procedure in a flow chart. Note that each loop requires several simulations, because irrigation time must be adjusted by trial and error.

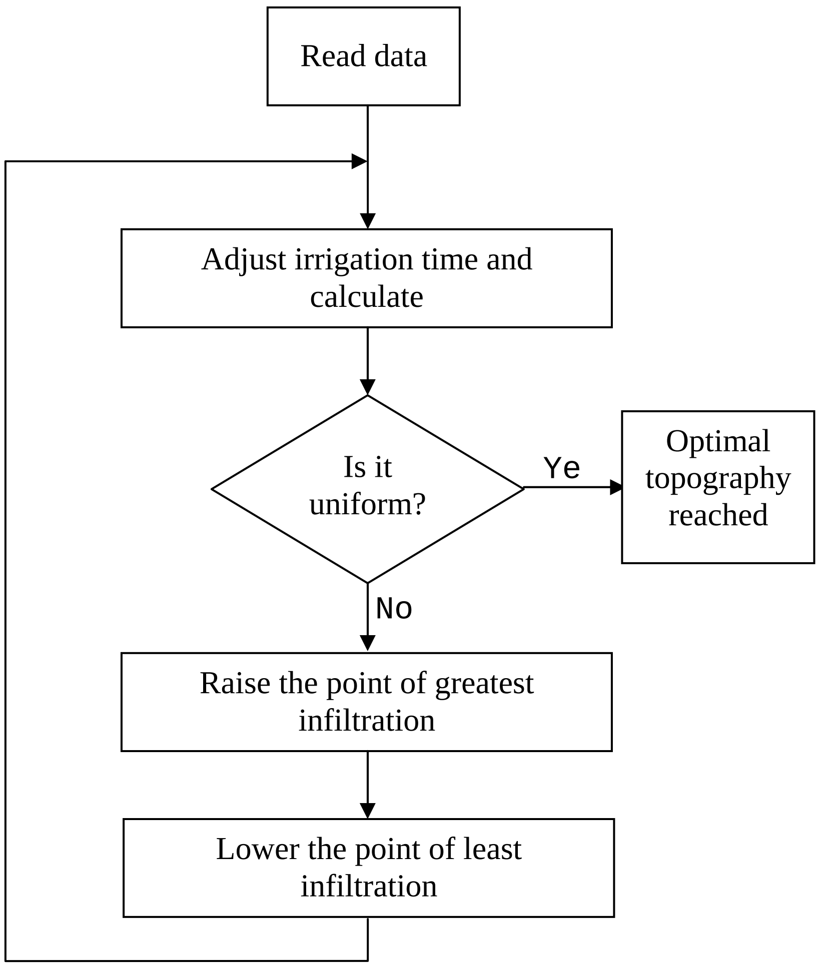

**Figure 1. Flow chart to reach the optimal topography in surface irrigation.**

This computational and iterative process tends to improve distribution uniformity by topographical modifications, assuming that the flow rate is higher than a minimum value that can be calculated. Theoretically, the final curved shape of the field is 100% uniform, including open-end surface irrigation fields. In practice, the optimized topography could be adjusted to a set of planes by means of laser levelling or other levelling techniques.

## RESULTS.

The methodology has been applied to two surface irrigation cases: a 1-D blocked-end field and a 2-D square field with corner inflow.

**Case 1: One-dimensional blocked-end field.**

This first test case has been extracted from Dholakia et al. (1998). The field is 185.9 m length, with 10.93 l/s/m inflow rate. Required depth is 100 millimeters (mm), Manning coefficient is 0.1 $s/m^{1/3}$ and Kostiakov infiltration function is $z=73.72 \cdot t^{0.6}$, where z is the infiltration depth in mm and t is time in hours (Kostiakov, 1932).
We used POZAL software for this first case, which automatically concludes the iterative process in about 14 minutes with a standard computer, with about 200 iterations. POZAL software was specifically developed for this work and applies the complete hydraulic model of the one-dimensional equations of free surface flow (Saint-Venant equations), using the finite differences method according to the MacCormack scheme (Dholakia *et al.* 1998; García-Navarro *et al.* 1992), by dividing the field into 100 equal parts. More popular programs, like WinSRFR (Bautista *et al.* 2015) or SIRMOD (Walker, 1998) could be used here instead of POZAL. In that case, the iterative process must be applied manually, taking a few hours of work.

Figure 2 shows the results of this case in three different graphs: the first shows the evolution of distribution uniformity, cut-off time and deep percolation throughout the iterative process of the methodology; the second graph shows the advance-recession diagram for the initial (zero slope) and final (optimized topography) situations of the process; the third graph shows the final topography of the optimized field, and the infiltration process with the optimized topography, together with the final infiltration topography when there is no slope.

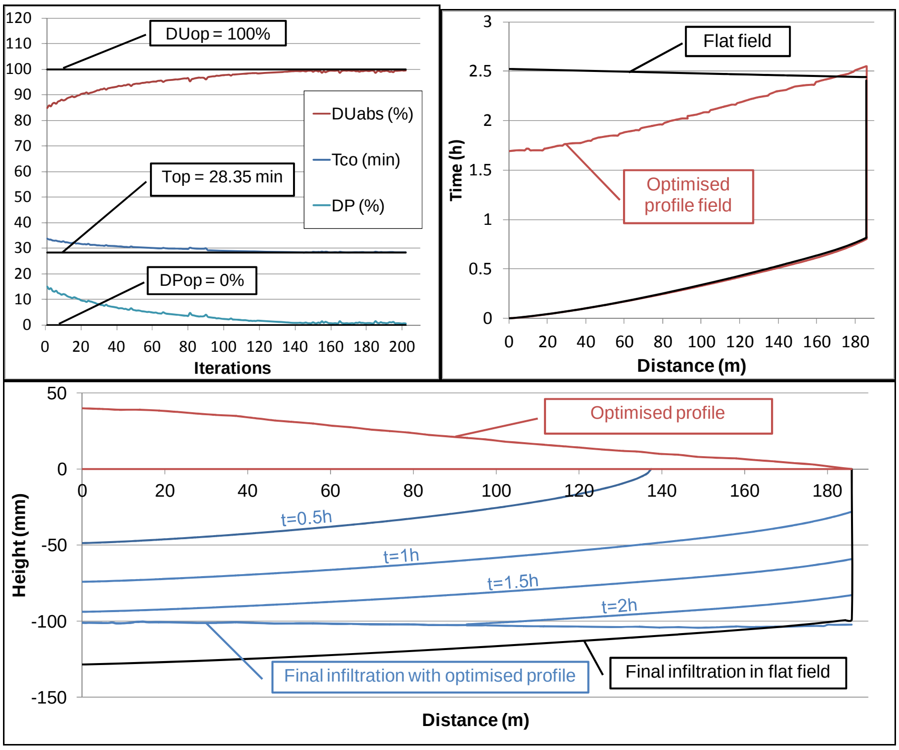

**Figure 2. Case 1: evolution of indicators, advance-recession diagram and final profiles.**

Note the parallelism between the advance curve and the recession curve of the optimized topography. This indicates that the opportunity times of all the points are similar, so infiltrations are similar. This leads to the practically horizontal final infiltration profile, coinciding with the required depth, as observed in the third graph of Figure 2.

Before, distribution uniformity was 85.3%, with the best slope is 95.0% and after the optimization it increases to 99.4%. Deep percolation disappears in practice (from 14.7% to 0.6%) and time and water saving are 13.1% after the optimization.

**Case 2: Square field with a corner inflow.**

Second example deals with a corner inflow in a square field. It’s a two-dimensional case, solved with the help of the B2D programme, published by Utah State University, USA (Playán *et al.* 1994a, 1994b).

The field is a 90x90m square, with 200 l/s inflow rate and 60mm required depth. Manning coefficient is 0.04 s/m$^{1/3}$ and the infiltration is adjusted by $z=251.96t^{0.504}+7.02e\text{-}4t$.

Again, the methodology eliminates practically all deep percolation and raises DU to 100% (first graph of Figure 3). The ground topography evolves until a final topography shown in the second graph of Figure 3, with an average slope of 0.027%.

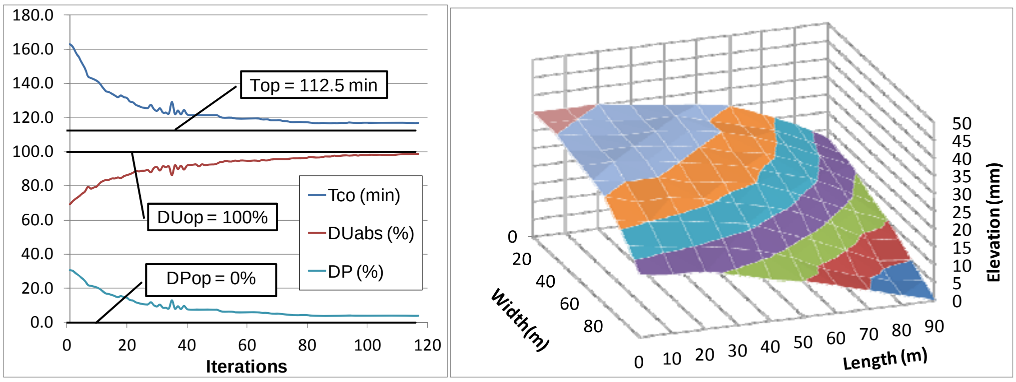

**Figure 3. Case 2: evolution of indicators and optimized field topography.**

Figure 4 shows the three-dimensional representation of the evolution of water depth (first column) and infiltration depth (second column) over the length and width of the field in five different, evenly spaced instants: at the start, a quarter of the total time, half the total time, three quarters of the total time, and end. Again, we observe homogeneous infiltration thanks to the new field topography. Water level (water depth, first column) shows the water storage in the lower points that increases the distribution uniformity.

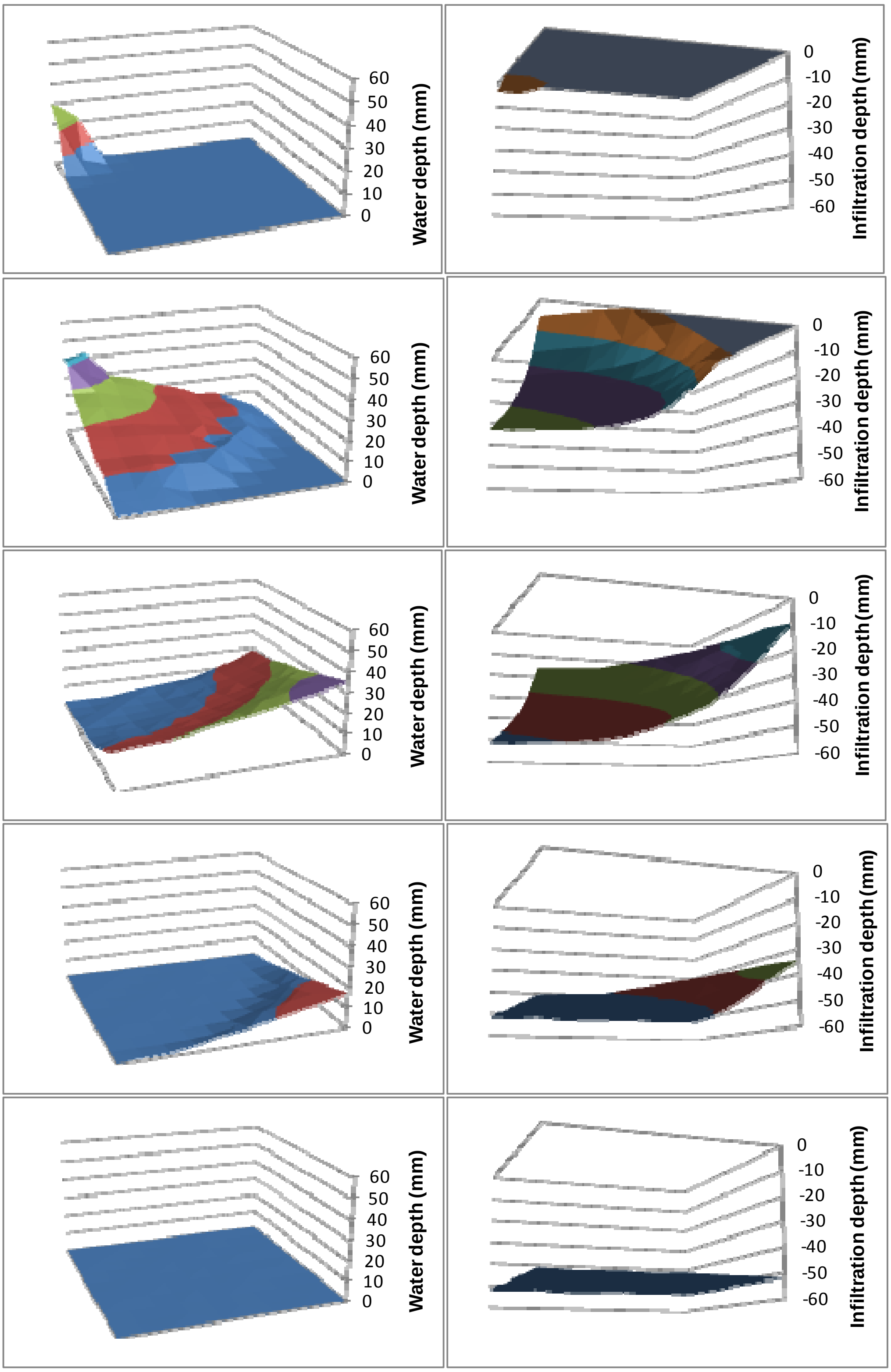

**Figure 4. Case 2: evolution of depth and infiltration for t=1min, t=63.2min, t=126.1min, t=189.0min and t=252.5min.**

Before, distribution uniformity was 70.9%, and after the optimization it increases to 98.5%. Deep percolation decreases from 29.0% to 1.2% and time and water saving are 11.2% after the optimization.

## FIELD VALIDATION.

To validate the method of topographic optimization, a field test was conducted in a plot located in Almudévar (Huesca, Spain). The plot is 100 meters long by 26 meters wide, and it is irrigated with a constant flow rate of 47 l/s from one end of the plot, which is considered a one-dimensional irrigation, with blocked end. The infiltration function was experimentally determined by cylinder infiltrometers, with measurements in the center of each half of the field that were averaged, yielding $z = 79.95 \cdot t^{0.5837}$, where z is infiltration depth in mm and t is time in hours. Soil moisture was low enough and the soil was bare (Manning coefficient 0.04 $s/m^{1/3}$). The micro-topography was not measured.

Two irrigation trials were conducted:

1. Before: Plot leveled without slope.
2. After: Plot leveled with two consecutive slopes. The first half of the plot leveled with 0.12% slope and the second half with 0.07% slope. These two slope values were obtained by a least squares fit of the results obtained with topographical optimization method described in this article. Figure 5 shows the optimal topography obtained with the computer applying the methodology here presented and the two- slopes approach. The position of the slope change point could be optimized with the adjust, which could be object of further research.

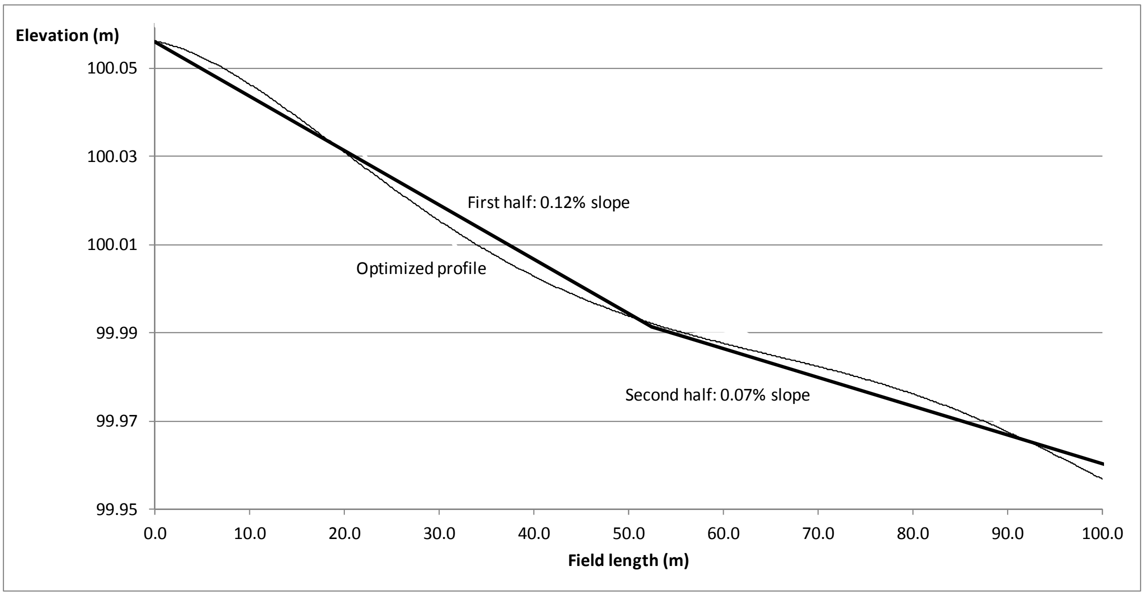

**Figure 5. Field validation: optimized topography and two-slopes fit.**

In each trial, 344 $m^3$ of water were applied to the field, which means an average infiltration of 132 mm of water. Throughout the plot, 11 measuring stations were located (every ten meters), and the advance and recession times were recorded in each of them. Then, opportunity time and infiltration depth was calculated at each station.

In the results, we observe that the topographic optimization improved irrigation uniformity. Figure 6 indicates a more uniform infiltration, despite the existence of a slight flooding at the end of the first half of field, which could be due to a slight inaccuracy in connecting the two slopes.

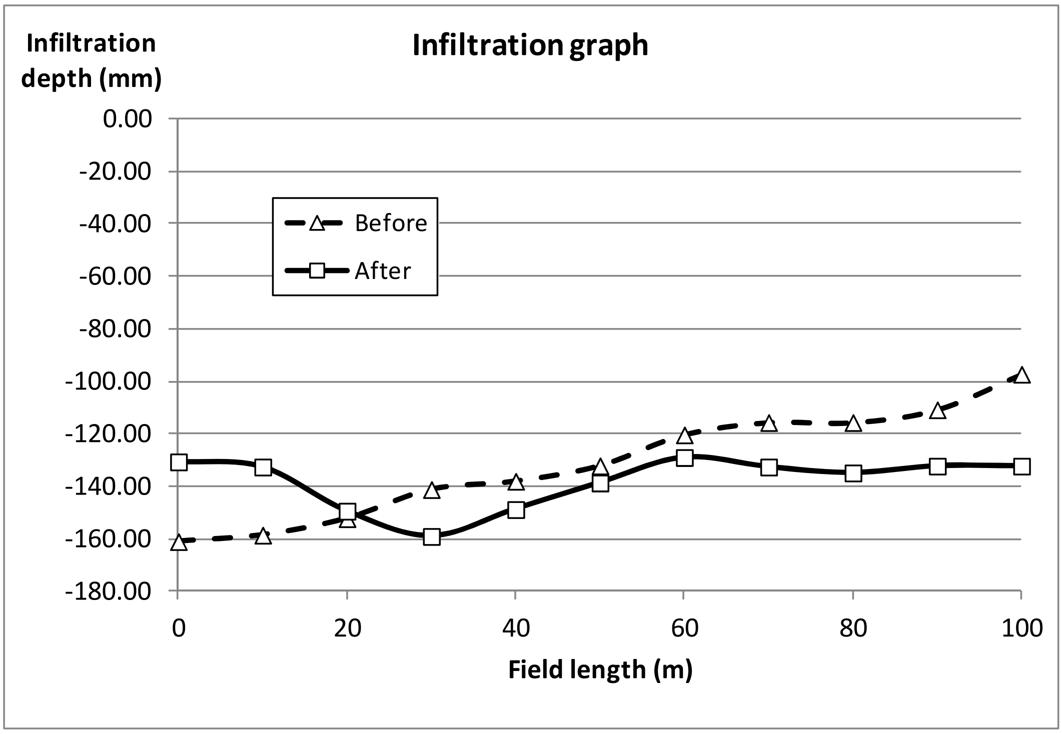

**Figure 6. Field validation: infiltration before and after the topographic optimization.**

Figure 7 is the advance-recession graph, and shows a faster advance of the water thanks to the topographic optimization, and a greater parallelism between advance and recession curves, indicating opportunity times more homogeneous.

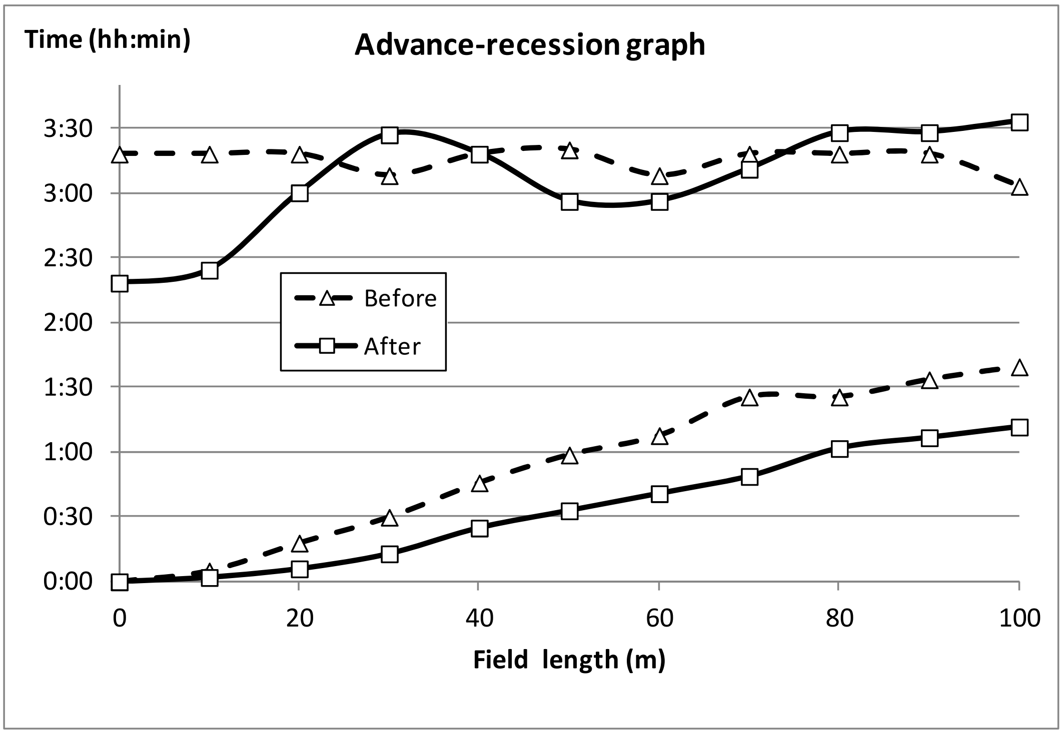

**Figure 7. Field validation: advance and recession before and after the topographic optimization.**

Table 1 provides the main indicators of distribution uniformity, calculated before and after the topographic optimization.

| Uniformity Distribution | Definition | Before | After |
|---|---|---|---|
| $UD_{abs}$ | mínimum infitration / average infiltration | 74.1% | 93.3% |
| $UD_{lq}$ | low quarter minimum infiltration / average infiltration | 82.3% | 96.3% |

**Table 1. Experimental validation: uniformity indicators before and after the topographic optimization.**

In general, an important improvement in distribution uniformity is observed, which would likely have been even higher without the slight inaccuracy in connecting the two slopes.

Figure 8 compares the data collected and the results of WinSRFR model. Some differences can be observed, associated to the variability of the parameters (Manning, infiltration coefficients, flow rate…) and to the practical difficulties to connect properly the two slopes or to determine the moment of the end of the infiltration in each station.

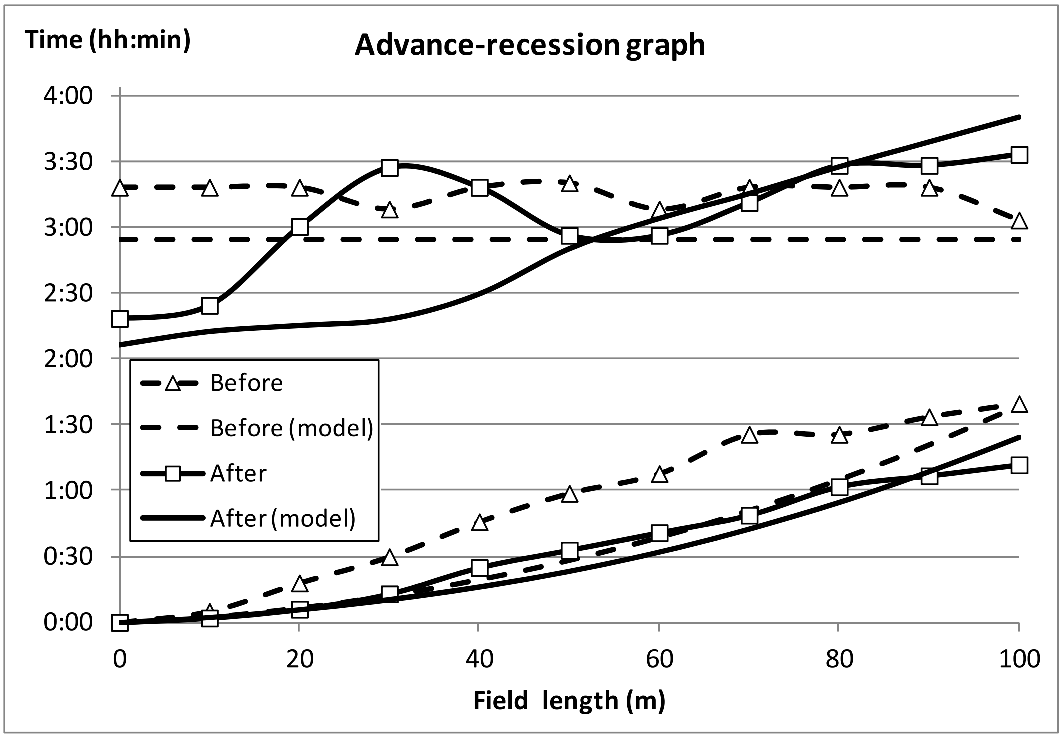

**Figure 8. Advance and recession: experimental results and model results.**

Finally, Table 2 shows the differences in low quarter distribution uniformity between theory and practice in this study case. As in Figure 8, theoretical results have been obtained with WinSRFR software.

| **Topography** | **Practice** | **Theory** |
|---|---|---|
| Zero slope | 82.3% | 86.0% |
| One slope | - | 97.6% |
| Two slopes | 96.3% | 98.0% |
| Optimized | - | 100% |

**Table 2. Experimental validation: Low quarter DU values in practice and in theory under different topographical configurations.**

Obviously, the experimental results are worse than the theoretical results, but both show significant improvements introduced by the topography optimization. In this case, one single slope gets 97.6% in theory and double slope gets 98%. As the experimental field used in this validation is small, there are no significant differences between one or two slopes in this case. But in a long field, or a wider field, or a non-rectangular field, these differences could be appreciable and the topographical optimization could open new levelling possibilities (not only with two longitudinal slopes) with better uniformity and with no additional cost in comparison to one single slope leveling.

## SENSITIVITY ANALYSIS.

Throughout an irrigation season, the main parameters can vary notably, which harms the robustness of the optimized topography (of the sloping irrigation in general). The sensitivity of the optimized topography to parameters variation has been evaluated theoretically in the previous field validation case. Starting from an ideal situation (optimized topography with 100% uniformity), when flow rate decreases 10%, low quarter distribution uniformity decreases to 95%, and when flow rate increases 10%, uniformity decreases to 92%. When infiltration decreases 10%, uniformity is 86%, and when infiltration increases 10%, uniformity is 93%. When Manning coefficient doubles, uniformity is 97%. Finally, when required depth decreases 10%, uniformity is 96% and when required depth increases 10%, uniformity is 94%.

## CONCLUSIONS.

From a strictly theoretical point of view, the main conclusion is that the presented method achieves uniform surface irrigation, optimizing the topography of the field. In the cases analyzed, computational and real, the method achieves the main objective of getting distribution uniformity near 100%. As minimum infiltration depth matches required depth, deep percolation disappears.

In many cases, particularly when the 1D approach can be applied and the fields are not too long, a single slope calculated by trial and error with conventional software can be enough to reach a high uniformity. In the Case 1, uniformity with one slope was 95.0% and in the field validation was 97.6%. These values are close to 100% of topographical optimization. In these cases, a two-slope configuration doesn’t provide a significant improvement and probably it isn’t worth to optimize the topography. Besides, it is important to remark that important parameters are considered constant in theory, but, in real irrigation, infiltration parameters, Manning coefficient and flow rate can vary throughout space and/or time in an irrigation season. The variation of uniformity due to this variability can be greater than the improvement on uniformity due to two-slopes configuration instead of one slope configuration. The optimal topography is calculated for a fixed required depth, but it can vary too, depending on the needs of the crop and the soil. For this reason, the optimal topography should be calculated for the most frequent required depth, and other parameters should be properly averaged.

The sensitivity analysis confirms these considerations, showing an important influence of flow rate and infiltration function in the real uniformity, and a minor influence of Manning coefficient. The analyzed case suggests that low infiltration values, high flow and high required depth rate values should be considered in the topography optimization.

In any case, the optimized topography offers new information about topography influence on irrigation performance indicators, which can be useful when levelling a field with no-zero slope. The number of slopes and the position of the slope changes are parameters that can be analyzed in depth after topographic optimization. The knowledge of the shape of the topographic optimization can help us to make decisions about it. So, optimized topography can be useful:

- **To give an optimal slope to a field.** When levelling a field, it is interesting to know the theoretical optimal slope. It could be known with simulation models or with graphs, but only with one-dimensional approximation. With this method, any case can be solved.

- **To give two or more slopes to a field.** Knowing the optimal topography, it is easy to adjust a set of slopes, bringing the field near to its optimal form, including 2D cases.

- **To give a curved topography to a field.** It is technically more difficult, but it is the more efficient option and theoretically makes deep percolation disappear, getting theoretical uniform surface irrigation.

Finally, optimized topography can be useful to better understand the relationship between topography and efficiency indicators in surface irrigation, and their sensitivity to parameters variation.

## AKNOWLEDGES

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