OPTIMIZATION OF SOIL SURFACE TO SAVE WATER IN SURFACE IRRIGATION

OPTIMISATION DE LA SURFACE DU SOL POUR SAUVER D'EAU DANS L'IRRIGATION DE SURFACE

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ABSTRACT

In a surface irrigation field, most water loss is deep percolation (and surface runoff if field end is open). In general, surface irrigation is not uniform because there is more irrigation time near the water supply points. To avoid deep percolation, this paper analyzes the influence of soil surface shape on water distribution uniformity. One and two-dimensional hydrodynamic simulation models were applied to develop three different strategies to optimize soil surface profiles.

Firstly, the optimal field slope was studied, getting a set of twenty dimensionless graphs that offer optimal field slope in any real case. Secondly, a curved soil surface profile was studied. A new methodology called chinachana was developed to find a theoretically perfect soil surface profile in each particular case. This methodology reaches a curved soil surface profile that gets a theoretical distribution uniformity of 100%. Finally, the two-dimensional case is tackled. Chinachana methodology is also applied to a two-dimensional case to simulate a real distribution of water in the field. Once again, the method gets an optimal curved field surface shape, with a theoretically perfect water distribution.

So, to level a real surface irrigation field, the results offer three theoretical possibilities: an optimal constant slope, a 1-D curved soil surface profile or a 2-D curved soil surface shape. They could be taken into account to decide how to level a field to save as much water as possible in surface irrigation.

The disadvantages of practical application of the obtained results are discussed and reflected in conclusions. The main conclusion of this work is that the results can be useful when the availability of water is a limiting factor, because it can lead to substantial water savings

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through the careful shaping of the topography of irrigated fields. In other cases, the results can serve as a guideline for deciding on the appropriate slope for the field, or a set of two or three slopes, bringing the field near to its optimal form.

Key words: *Surface irrigation, water saving, Saint-Venant equations, optimal slope, land leveling, irrigation uniformity.*

RESUME ET CONCLUSIONS

Dans un champ d'irrigation de surface, la plupart de perte d'eau est par percolation profonde (et par le ruissellement de surface, si la fin du champ est ouvert). En général, l'irrigation de surface n'est pas uniforme car le temps d'irrigation est plus près des points d'approvisionnement en eau. L'uniformité d'irrigation est inférieure dans l'irrigation de surface (bassin, planches, sillon etc.) par rapport à l'irrigation par pression (aspersion, goutte à goutte etc.).

Le besoin d'économiser l'eau (changement climatique, surpopulation) et les techniques disponibles de nivellement de terrain (topographiques, laser ou GPS) justifient l'étude de l'impact du profil de terrain sur l'uniformité d'irrigation. Pour éviter la percolation profonde, cet article analyse l'influence du profil de la surface du sol sur l'uniformité de distribution d'eau (DU). L'objectif principal de cette étude est d'obtenir les formes de surface du sol pour répartir de manière correcte l'eau sur le terrain. Les modèles de simulation hydrodynamique 1D et 2D ont été utilisés pour mettre au point trois stratégies différentes pour optimiser les profils de surface du sol.

Tout d'abord, la pente optimale du champ a été étudiée. Sur la base des travaux de Clemmens et Dedrick (1982), une analyse sans dimension a été utilisée pour trouver la relation entre la pente du champ et les autres variables impliquées (dimensions du terrain, uniformité de distribution, paramètres d'infiltration et coefficient de Manning etc.).

Ensuite, un profil de la courbe de surface du sol a été étudié. Une nouvelle méthodologie appelée chinachana a été développée pour trouver un profil de surface de sol parfait dans chaque cas particulier.

Enfin, un cas à deux dimensions a été abordé. La méthodologie chinachana est utilisée dans le cas de deux dimensions pour simuler une distribution réelle de l'eau dans le champ. La méthode retient un profil optimum de la courbe de surface du sol avec une distribution parfaite de l'eau.

Donc, au niveau d'un champ d'irrigation réel, les résultats offrent trois possibilités théoriques : une pente optimale constante, un 1-D profil de la courbe de surface du sol ou un 2-D profil de la courbe de surface du sol. Ils pourraient être prises en compte pour conserver sur le champ autant d'eau que possible dans l'irrigation de surface.

En conclusion, les inconvénients de l'application pratique des résultats obtenus ont été discutés.

Selon la pricipale conclusion, les résultats de cette étude pourraient être utiles où la disponibilité *de l'eau est limitée. Cette étude peut permettre à l'économie majeure de l'eau en optimisant le profil de la topographie des champs irrigués.*

Mots clés : *Irrigation de surface, économie d'eau, équations Saint-Venant, pente optimale, au niveau du champ, uniformité d'irrigation.*

1. INTRODUCTION

In a surface irrigation, most water loss occurs due to deep percolation (and surface runoff if field end is open). In general, surface irrigation is not uniform because there is more irrigation time near the water supply points. In any variant of surface irrigation (basin, border, furrow, with open or blocked end), irrigation uniformity is lower than in pressurized irrigation (sprinkle, drip) (Walker and Skogerboe, 1987; FAO, 2002).

The growing need for saving water (climate change, overpopulation) and the available techniques of land leveling (topographical, laser or GPS) justify the study of the impact of field profile on irrigation uniformity. To avoid deep percolation, this paper analyzes the influence of soil surface profile on water distribution uniformity (DU). The main objective is to get *soil surface shapes that help water be properly distributed on the field*. One and two-dimensional hydrodynamic simulation models were applied to develop three different strategies to optimize soil surface profiles.

Firstly, the optimal field slope was studied. Based on Clemmens and Dedrick's (1982) works, dimensionless analysis was applied to find the relationship between field slope and the other variables involved (field dimensions, distribution uniformity, infiltration parameters, Manning coefficient, inflow rate and cutoff time). One-dimensional free surface Saint-Venant equations, including infiltration terms, were solved by finite differences method in about 50,000 different cases. The result was a set of twenty dimensionless graphs that show optimal field slope in any real case.

Secondly, a curved soil surface profile was studied. A new methodology called *chinachana* was developed to find a theoretically perfect soil surface profile in each particular case. This methodology solves one-dimensional Saint-Venant equations too, in an iterative process, and reaches a curved soil surface profile that gets a theoretical *DU* of 100%.

Finally, the two-dimensional case was tackled. Chinachana methodology was applied to two-dimensional case to simulate a real distribution of water in the field. Once again, the method gets an optimal curved field surface shape, with a theoretically perfect water distribution.

2. OPTIMISING SOIL SURFACE SHAPE

2.1 Optimal slope: dimensionless analysis

Clemmens et al. (1981) applied the technique of dimensional analysis to the hydrodynamic problem of irrigation of a level basin with blocked end, for analyzing the dependency of the distribution uniformity with other relevant parameters.

$$DU = \Psi(k, a, n, t_{co}, q_{in}, L) \qquad (1)$$

In expression (1), *DU* is the distribution uniformity (defined as the minimum infiltration depth z_n divided by the average infiltration z_g); k and a are the Kostiakov's infiltration parameters; *n* is Manning coefficient; t_{co} is the cutoff time; q_{in} is the inflow rate per unit of width, defined as inflow rate *q* divided by field width *b*; and *L* is the field length. Kostiakov function (Kostiakov, 1932) relates the infiltration depth *z* with the opportunity time τ according to the expression (2).

$$z(\tau) = k \cdot \tau^a \qquad (2)$$

Cutoff time t_{co} is supposed to be the strictly necessary time to ensure that the entire field receives the required depth z_d, so that $z_n = z_d$.

With the Saint-Venant governing equations and the appropriate reference variables and approximations, Clemmens et al. (1981), the expression (1) leads to:

$$DU = f(a, q_{in}^*, L^*) \qquad (3)$$

Where,

$$q_{in}^* = \frac{q_{in}}{Q} \qquad (4)$$

$$L^* = \frac{L}{X} \qquad (5)$$

$$Q = X \cdot z_n \cdot \tau_n^{-1} \qquad (6)$$

$$X = \tau_n^{2/3} \cdot z_n^{7/9} \cdot \left(\frac{n}{C_u}\right)^{-2/3} \qquad (7)$$

In (6) and (7), τ_n is the time needed to infiltrate a depth $z_n = z_d$, and C_u is a units coefficient that in the international system is 1.0 $m^{1/2}/s$. In expression (3), variables *DU* and a are dimensionless.

Clemmens and Dedrick (1982) took eight different values for a (0.1, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 1.0) and for each of them drew a chart representing the functional relationship

$$DU = f(q_{in}^*, L^*) \qquad (8)$$

They used a hydrodynamic one-dimensional computer model of surface irrigation and executed a sufficient number of different scenarios, solving for Saint-Venant equations (mass and momemtum conservation) with the finite difference method on the model of zero inertia.

The Clemmens and Dedrick graphs serve as a basic reference used in the design of level basins with borders. With them one can determine the distribution uniformity as functions of q_{in}*, L*.

Previous development starts from the premise that the field has no longitudinal slope. As seen above, to give the field a certain slope to improve the distribution uniformity may occasionally be useful. To study this case from the perspective of dimensional analysis, S slope would be a new independent variable.

$$DU = \Psi(k,a,n,t_{co},q_{in},L,S) \tag{9}$$

Application of the dimensional analysis leads now to:

$$DU = f(a,q^*_{in},L^*,S^*) \tag{10}$$

The derived dimensionless slope S* is proportional to real slope S. For convenience, we´ll use real slope. Expression (10) can be seen as a generalization of the analysis of Clemmens and Dedrick (1982) which considers any longitudinal field slope. In this new approach, the particular case S=0 is equivalent to the development of Clemens and Dedrick (1982), and then expression (10) is equal to expression (3).

For the graphical representation of expression (3), Clemmens and Dedrick (1982) gave different values to the parameter a, on the basis that it is only possible to represent graphically functions that depend on two variables, either through isolines (as Clemmens and Dedrick did) or through three-dimensional graphics.

The graphical representation of (10) is somewhat more complicated because an additional variable intervenes. This leads us to fix a set of specific values for two dimensionless numbers, not only for one as in the previous case. So, the total number of graphics would be increased by an order of magnitude.

For example, in expression (10) we might fix a specific set of values for a and L*. Thus, we achieve graphics representing the functional relationship between the distribution uniformity, the field slope and dimensionless unit flow rate.

$$DU = f(S,q^*_{in}) \tag{11}$$

These charts let us, for example, find the best slope of the field for given flow conditions or find a better flow rate for a given slope.

2.2 Optimal soil free shape: the chinachana method

In order to find a theoretically perfect ground surface profile for each particular case, a new methodology called chinachana was developed. 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, as long as the flow rate is above a certain threshold.

In each iteration of the *chinachana* method, the part of the field which receives the most water in the previous simulation is raised, and the part which receives the least water is lowered. After the ground profile modifications have been carried out, a new hydraulic simulation is run, adjusting the irrigation time so that minimum infiltration (z_{min}) coincides with the required depth (z_{req}). The iterative repetition of these operations leads to an evolution of the ground profile until a theoretically perfect water distribution uniformity is reached. Each step of the chinachana methodology is given below.

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

Step 2: Adjust irrigation time. Using a hydraulic simulation tool, adjust the irrigation time by trial and error, so that there is neither too little or too much water, i.e., zmin=zreq is fulfilled. In this case, detect the point in the field with the greatest infiltration, the point with least infiltration and calculate the distribution uniformity and other irrigation indicators.

Step 3: If the irrigation is uniform, stop. At the moment when distribution uniformity reaches the desired value, the process ends and the results are saved.

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

Step 5: Lower the point of least infiltration. The level of the point with the least infiltration is raised to increase it. This step is omitted when the field end is open, as it can mean permanently raising the level of the last point in the field, producing excessive surface runoff.

Step 6: Go to step 2. The loop of the iterative process is closed.

This iterative process tends to improve distribution uniformity depending on how much the field topography varies. In steps 4 and 5, the amount the ground level should be raised or lowered must be suited for the degree of refinement sought for the solution. The iterative process is faster if larger changes are made to levels in the first steps, later establishing smaller changes in order to profile better and smooth out the final shape of the optimized field.

3. RESULTS

3.1 Optimal slope: dimensionless graphs

For the parameter a, values similar to those of Clemmens and Dedrick (1982) are taken, and for *L**, we can take a set of five values that cover a wide range of practical possibilities.

$$a \in \{0.4, 0.5, 0.6, 0.7\} \quad (12)$$

$$L^* \in \{0.3, 0.4, 0.6, 0.8, 1.0\} \quad (13)$$

Thus, we must configure *4x5=20* different graphs. Each graph must contain a sufficiently large number of simulations covering the entire plane formed by *S* and q_{in}* dimensionless numbers. For dimensionless unit inflow rate, thirteen values are taken and fifteen values for slope.

$$q_{in}^{*} \in \{0.1, 0.2, 0.3, 0.4, 0.6, 0.8, 1.0, 2.0, 3.0, 4.0, 5.0, 8.0, 10.0\} \quad (14)$$

$$S \in \left\{ \begin{matrix} 0,\ 0.0001,\ 0.0002,\ 0.0003,\ 0.0004,\ 0.0005,\ 0.0006,\ 0.0007, \\ 0.0008,\ 0.0009,\ 0.001,\ 0.002,\ 0.003,\ 0.005,\ 0.01 \end{matrix} \right\} \quad (15)$$

Then, twenty graphs are represented, with *13x15=195* simulation points in each of them. A simulation point implies a set of about eight irrigation simulations to find optimal cutoff time (when minimal infiltration z_n is equal to required infiltration z_d). In brief, the total number of simulations is *20* graphs x *195* simulation points x *8* irrigation simulations = *31,200* simulations.

Figures 1 and 2 show the final graphs. Figure 1 represents graphs for *a=0.4* and *a=0.5*, and Figure 2 shows the cases where *a=0.6* and *a=0.7*. Vertically, dimensionless length *L** increases from *0.3* to *1.0*, making the peak lower and displacing it from down to up. A black line in Figs. 1 and 2 shows the moment when cutoff ratio is 85%. This indicator is the ratio of advance at cutoff to field length, and when it is lower than 85%, there is an increasing risk that water will not reach the end of the field if actual conditions depart from the input data. Clemmens and Dedrick (1982) used this line as a design criteria too, a *limit for practical level-basin design*, as they titled their work.

Example: determination of the best field slope

If we know the parameters k and a of the Kostiakov infiltration function (through field experiments or using tables), the Manning n coefficient (using tables based on soil and crop), the opportunity time τ_n (from the required infiltration z_d and the infiltration function), unit inflow rate qin (dividing irrigation flow by the field width) and the field length *L*, we can calculate q_{in}* and *L** from (4) and (5). Then, we choose the graph that best matches *L** and a. As we know q_{in}*, we can observe what slope offers a better distribution uniformity.

An example. A *200x50m* surface irrigation field is irrigated with an inflow rate of *100 l/s*, the Manning *n* is $0.20\ s/m^{1/3}$, the required depth is *100 mm* and the infiltration function is $z(mm)=46.84 \cdot t(h)^{0.5}$. What's the best slope? With these data, qin is 0.002 m^2/s; from Eq. (2) we have τ_n=16408 s; from (6) Q is $1.92 \cdot 10\text{-}3\ m^2/s$; from Eq. (7), *X = 314.96 m*. Then, from Eq. (5), *L** ≅ 0.6. We will take the graph corresponding to *a=0.5* and *L*=0.6* (see Fig. 3).

As equation (4) gives $q_{in}^*=1.04$, the graph indicates that maximal distribution uniformity will occur when field slope is about *0.0004*. This is the best slope for this field in these conditions, and theoretical distribution uniformity will be near *95*% and $z_n=z_d$, application efficiency will be *95*% too. In practice, these almost perfect values will not occur, but they will be the highest possible with the slope calculated in Fig. 3.The resulting design point matches the black line in 3D graph in Fig. 3, so cutoff time is about *85*%; the designed slope can be considered valid.

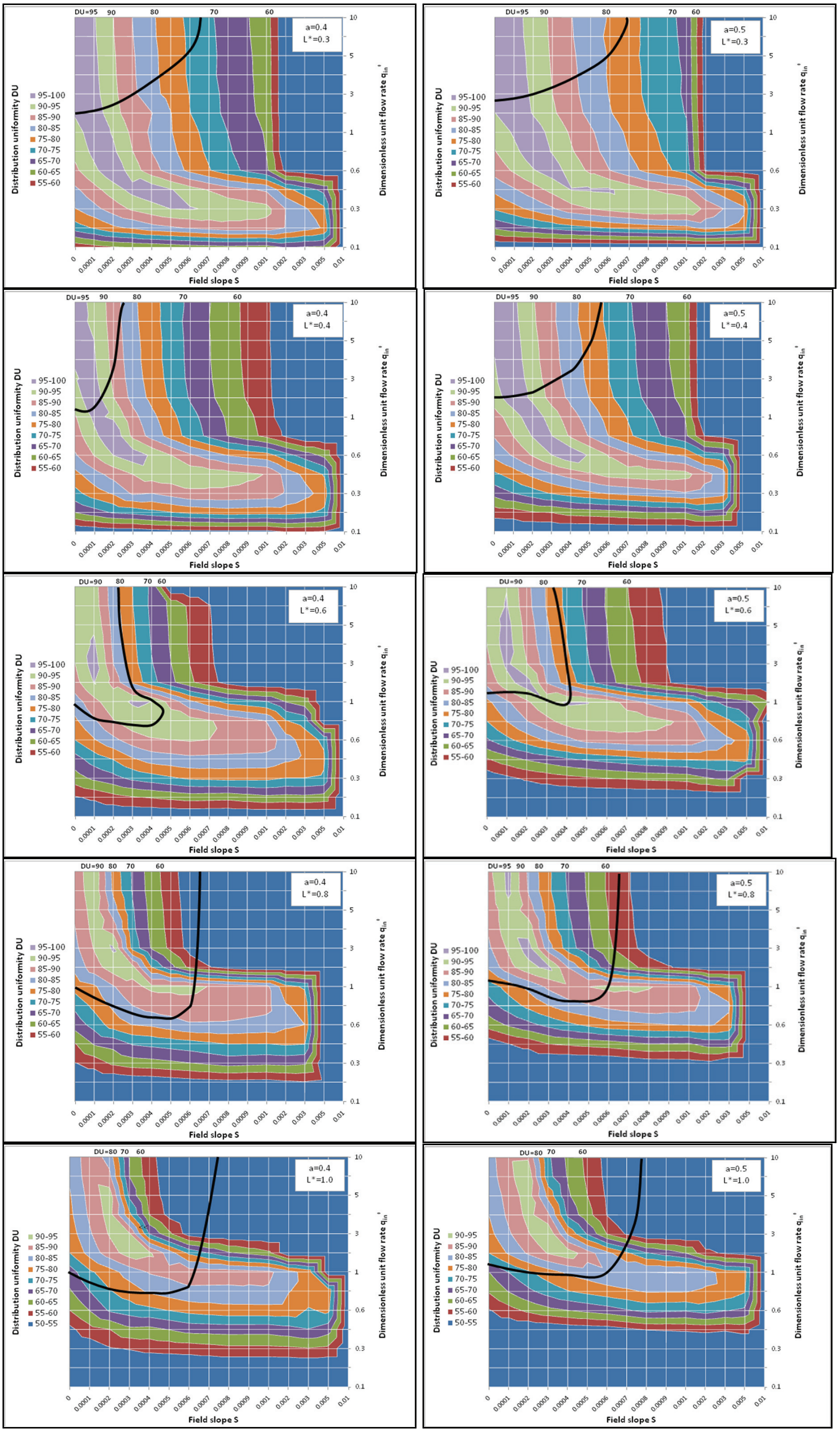

Fig. 1. Distribution uniformity for a=0.4 and a=0.5 (Uniformité de la distribution pour a=0.4 et a=0.5)

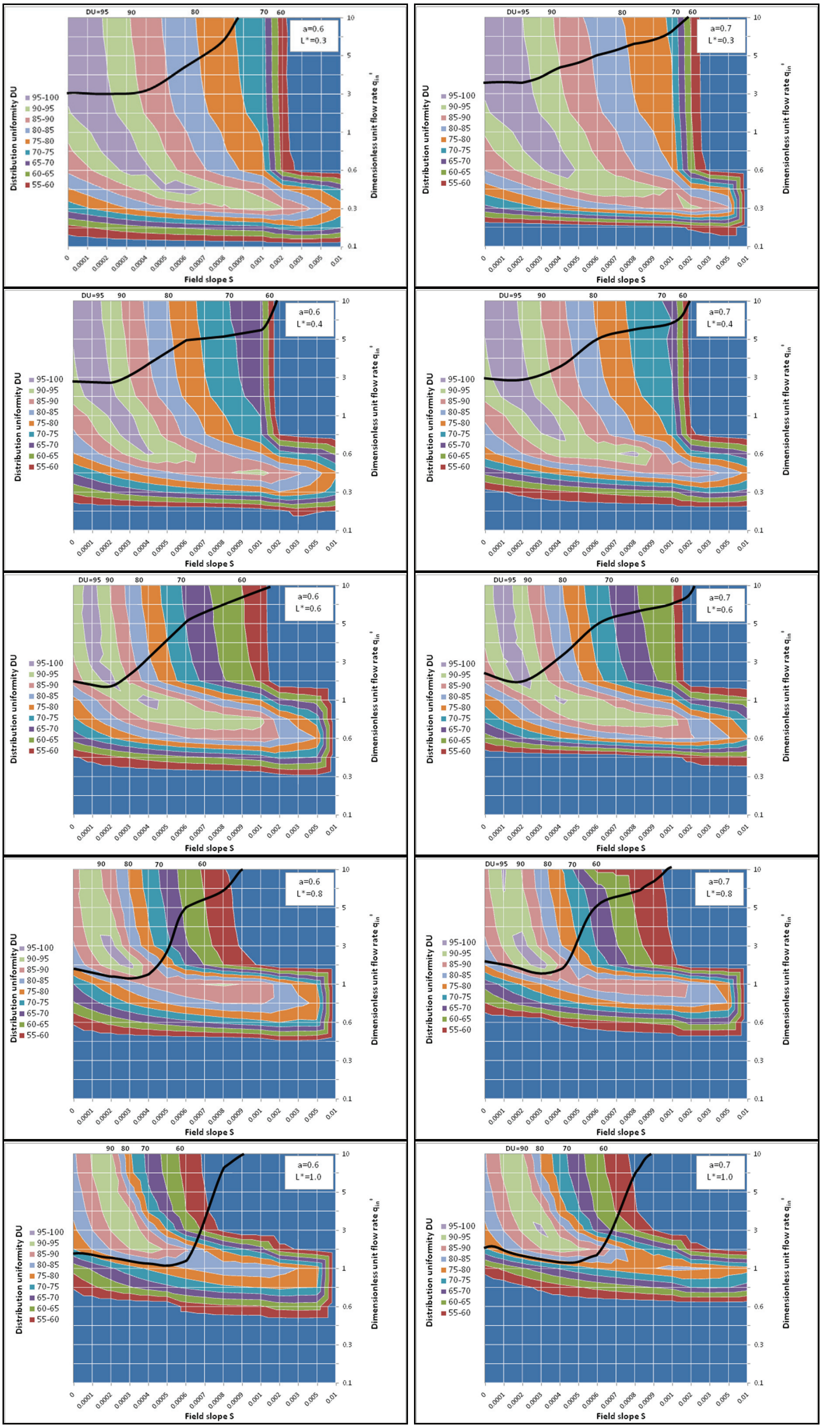

Fig. 2. Distribution uniformity for a=0.6 and a=0.7 (Uniformité de la distribution pour a=0.6 et a=0.7)

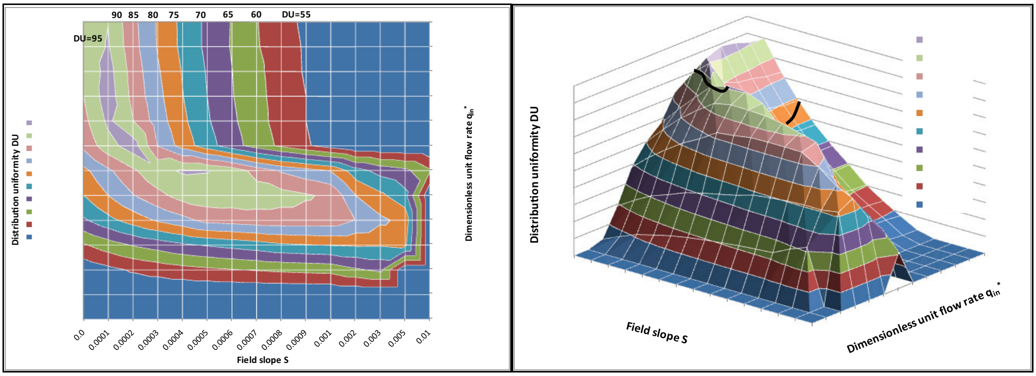

Fig. 3. Example of determination of the best field slope (Exemple de détermination de la pente meilleur du champ)

3.2 Optimal shapes: the chinachana methodology

Below, three practical cases of soil shape optimization are shown: case 1 is a one-dimensional level basin with blocked end, case 2 is another basin with open end and case 3 is a two-dimensional with blocked end. In the three cases, the chinachana methodology was applied.

Case 1. One-dimensional level basin, blocked end

Case 1 represents a *185.9 m* long basin, irrigated with a 10.93 l/s/m inflow rate. The Manning coefficient is $0.10\ s/m^{1/3}$, the infiltration function is $z(mm)=73.72 \cdot t(h)^{0.6}$ and the required depth is *100 mm*. These data were extracted from (Clemmens, 1979).

This case was solved with *POZAL*, software developed specifically for this work, which implements the *chinachana* methodology. *POZAL* uses 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). POZAL software automatically concludes the iterative process in about 14 minutes to solve the case 1. For the remaining cases the *chinachana* methodology was applied manually.

Figure 4 shows the results of case 1 in three different graphs: the first shows the evolution of the distribution uniformity, the cut-off time and deep percolation throughout the iterative process of the *chinachana* methodology; the second graph shows the advance-recession diagram for the initial and final situations of the process; the third graph shows the final shape of the topographically optimised field, and the infiltration process with the optimised profile, together with the final infiltration of the field without a slope.

For this case we made a video of the evolution of the ground profile throughout the iterative process, starting with the horizontal ground and ending with the optimised profile. URL of the video is: http://www.youtube.com/watch?v=mNozM1rTDMk

Note the parallelism between the advance curve and the recession curve of the optimised profile. This indicates that the opportunity times (when there is infiltration) of all the points are similar. This leads to the practically horizontal final infiltration profile, coinciding with the required depth, observed in the third graph of Fig. 4.

Case 2. One-dimensional border, open end

This second case is an open-end field. Its length is *182.88 m*, the inflow rate is *2.323 l/s/m* and the Manning *n* is 0.15 $s/m^{1/3}$. The infiltration function is $z(mm)=25.23 \cdot t(h)^{0.748}+7$ and the required depth is *50.8 mm*.

To solve this case, WinSRFR program was used. WinSRFR program was developed by the Arid Land Agricultural Research Center of the US Department of Agriculture. It uses the zero-inertia model for solving the Saint-Venant equations via the finite differences model, although for steeper slopes it applies a kinematic wave model (Bautista et al., 2009a, 2009b). Case 2 data are extracted from example files of WinSRFR 3.1.

When the end of the level basin is open, there is no ideal field shape which enables all the irrigation water to be used, as there will be unavoidable surface runoff during all the time that water is infiltrating the final point in the field, which must be at least τ_n. The amount of water running off the field during this time will depend on the way the runoff happens, which can be modelled, for example, as a uniform flow or as a discharge.

The *chinachana* methodology applied to a case of these characteristics can still be useful in some cases, however, as it lets us obtain a final solution in which deep percolation is not produced, as can be seen in Fig. 5. The evolution of the topographical ground profile leads, as can be seen in the first graph, to reduced deep percolation and increase runoff (RO). Distribution uniformity tends to increase towards its maximum value of *100%*.

Thus, in cases where runoff does not really mean water loss (because of reuse downstream, return to the source, or pumping back to the start of the field), the chinachana methodology can be useful, offering in theory irrigation without deep percolation, at the cost of increased runoff.

As in the other cases, the first graph shows the asymptotes of the evolutions of the parameters: *DU* tends to *100%*, *DP* tends to *0%* and t_{co} tends to the optimal irrigation time (time needed to supply the required water volume).

Case 3: Two-dimensional level basin, blocked end

Finally, a two-dimensional case is presented, resolved with the help of the B2D program. This software is a two-dimensional surface irrigation hydraulic simulator which also applies the finite differences method to solve the two-dimensional free surface flow equations through the explicit leapfrog scheme. The B2D software was published by Utah State University, USA (Playán et al., 1994a, 1994b).

The case 3 deals with a *60 l/s* corner inflow in a square field (*90x90m*). The Manning coefficient is *0.04* $s/m^{1/3}$ and the required depth is *50 mm*. The infiltration function is

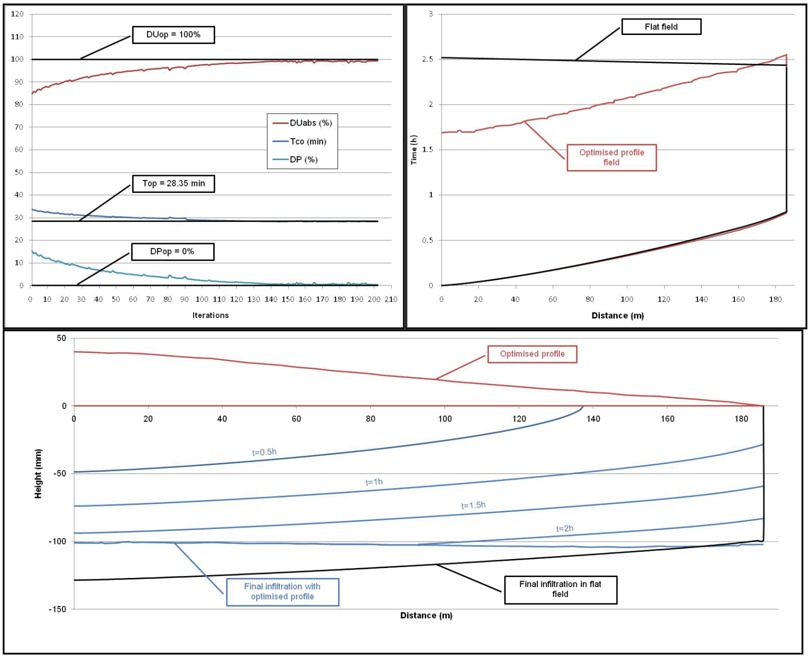

Fig. 4. Case 1: evolution of indicators, advance-recession diagram and profiles (Cas 1: évolution des indicateurs, diagramme d'avance-récession et les profils)

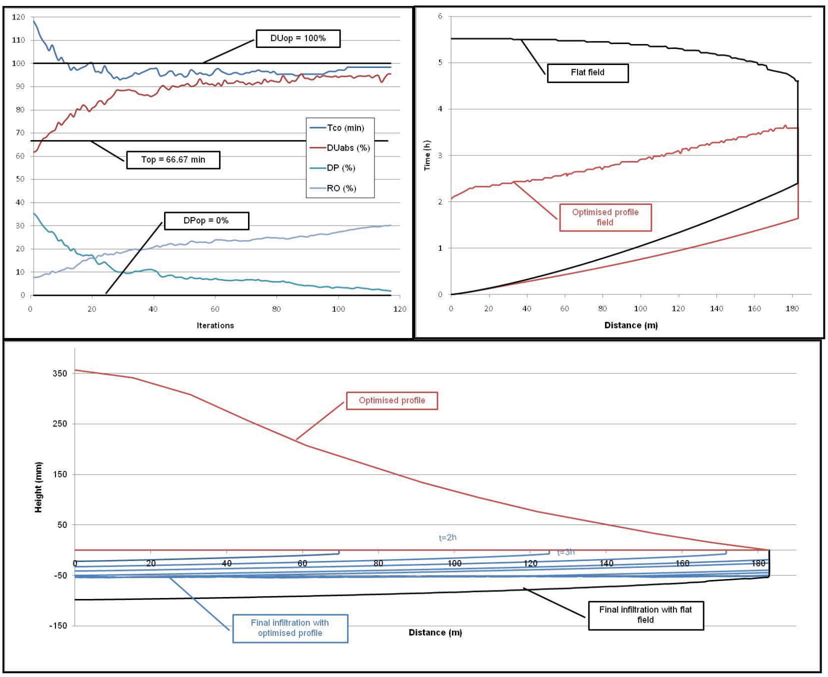

Fig. 5. Case 2: evolution of indicators, advance-recession diagram and profiles (Cas 2: évolution des indicateurs, diagramme d'avance-récession et les profils)

$z(m)=0.032 \cdot t(min)^{0.504}+1.17e\text{-}4 \cdot t(min)$. This case is based on Demo2.b2d example file of B2D software.

Again, the *chinachana* methodology eliminates practically all deep percolation and raises DU to 100% (figure 6). The ground shape evolves until it is as shown in Fig. 7.

Figure 8 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 due to the specific field shape.

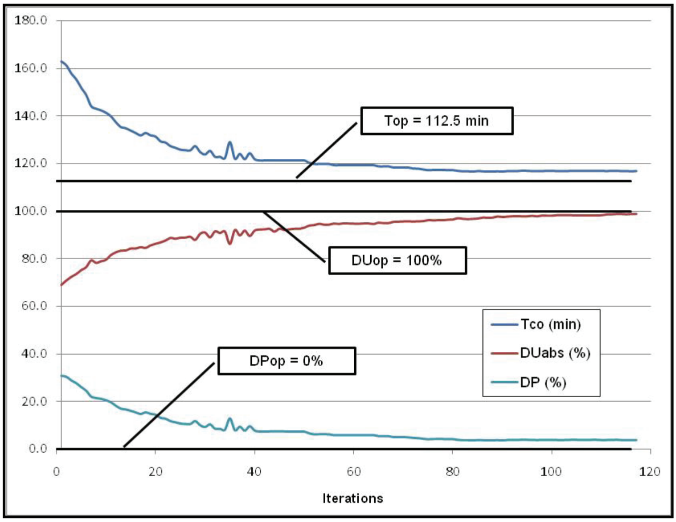

Fig. 6. Case 3: evolution of indicators (Cas 3: évolution des indicateurs)

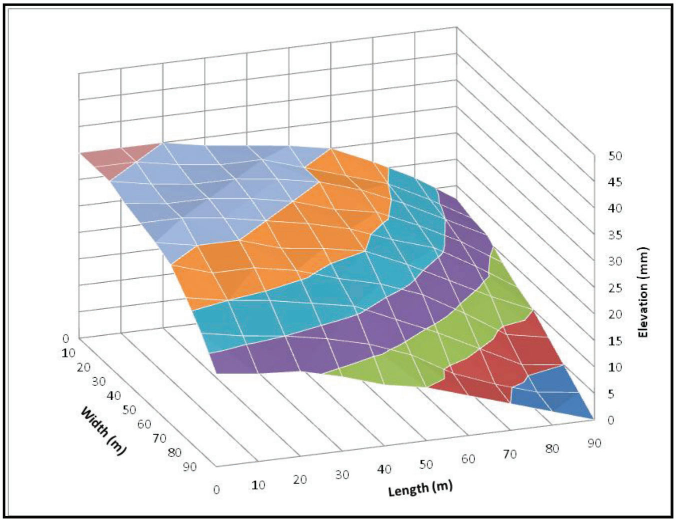

Fig. 7. Case 3: optimised field shape (Cas 3: forme du champ optimize)

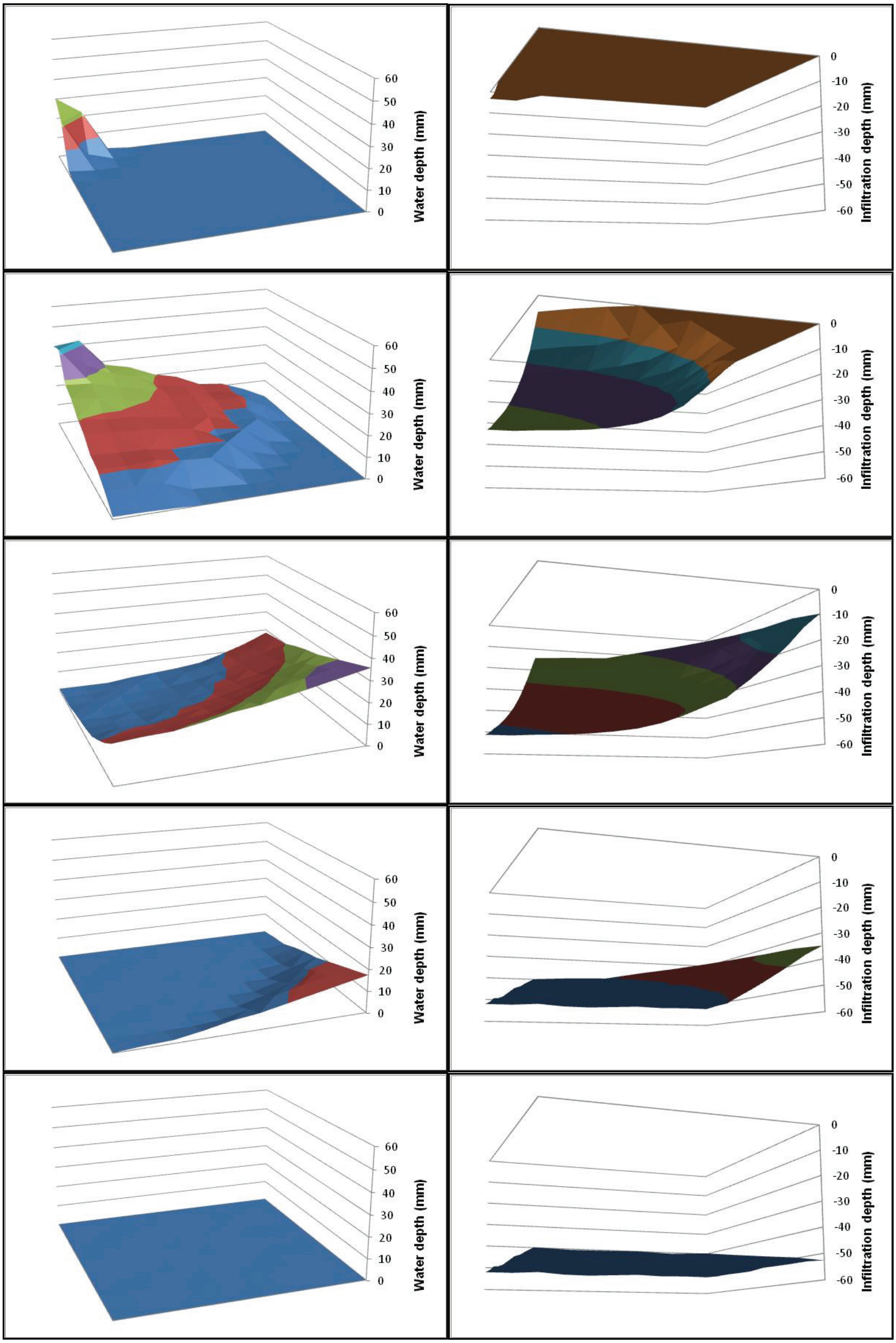

Fig. 8. Case 3: evolution of water depth and infiltration depth for t=1min, t=63.2min, t=126.1min, t=189.0min and t=252.5min (Cas 3: évolution de la profondeur de l'eau et la profondeur d'infiltration pour t=1min, t=63.2min, t= 126.1min, t=189.0min et t=252.5min)

Results summary

Table 1 shows how *DU*, *DP*, irrigation time and irrigation water volume are modified between the initial situation (flat field) and the final situation (field with optimised shape) when *chinachana* method was applied.

Table 1. Cases 1, 2 and 3: results (Cas 1, 2 et 3: résultats)

Case	Distribution uniform. (%)		Deep percolat. (%)		Cut-off time (min)		Water volume (m^3)		Water and time saving
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	
1	85.3	99.4	14.7	0.6	33.50	29.10	1138	989	13.1%
2	61.9	94.9	35.3	2.1	118.2	98.4	2008	1672	16.7%
3	69.2	98.9	30.7	3.8	163.0	117.0	586	421	28.2%

The last column of the table shows the saving, always theoretical, in water and irrigation time reached for each of the cases, due basically to the elimination of deep percolation.

4. CONCLUSIONS AND DISCUSSION

Firstly, it is important to note that surface irrigation on fields with a gradient fields requires a precise handling of irrigation water, either in furrows or basin/border systems. If more water than expected is applied, it will go to the end of the field, and some crops cannot tolerate excessive ponding. Moreover, in long fields, the end dikes must be high to avoid overflow risk. However, results could be useful in real design and management of surface irrigation fields. In the example of Fig. 3, theoretical distribution uniformity and application efficiency were 95% with a slope of 0.0004. Putting this case into practice, real values will be lower (perhaps 85%?). But in any case, calculated slope will get maximal values for both indicators. Graphs also offer information about sensitivity of the design point. Nevertheless, this work is purely theoretical. For its possible application, there must be a series of practical considerations:

- Absolute homogeneity of infiltration has been assumed for the whole field, and the importance of microtopography in irrigation behaviour has been disregarded (Playán et al., 1996; Zapata and Playán, 2000). There can be no doubt that infiltration is more heterogeneous in practice.
- In many cases, the irrigation flow rate can be variable during a surface irrigation event.
- Manning's coefficient is difficult to estimate, and can vary from one part of the field to another. It can also vary during an irrigation season due to variations in the surface structure of the ground or the resistance by the crop to the advance of the water.
- The optimal profile or slope is calculated for a given required depth, but this can vary throughout an irrigation season, depending on the needs of the crop and the soil. For this reason, the profile should be calculated for the most frequent depths, and when different depths must be applied, irrigation will be less efficient.

- It is technically more difficult to give a field a curved from rather than a straight one (with or without slope). For this reason, the optimal shape obtained could be used simply to decide the single slope or set of slopes of the field.
- The associated levelling and earth moving have an economic cost that has not been considered. This cost could exceed the saved cost in time and water, making the presented optimisation economically unviable.
- Excessive earth moving may eliminate the fertile topsoil layer, so it is important to evaluate the impact of earth moving on this layer.

From a strictly theoretical point of view, the *chinachana* method achieves uniform surface irrigation, optimising the shape of the field, as long as the irrigation flow rate is above a limit rate. In the case of an open ended field, the method can eliminate deep percolation, but at the cost of increased runoff, which can be useful in some cases, as remarked above.

In the view of the considerations set out in this section, we can conclude that the results can be useful when the availability of water is a limiting factor, because it can lead to water savings, which may be substantial, through the careful shaping of the topography of irrigated fields.

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