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DESIGN OF PAIRED LATERALS ON UNIFORMLY SLOPING FIELDS

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Abstract

Knowledge of the maximum length for paired drip laterals facilitates the economic optimization of micro-irrigation systems. The methodologies proposed to date have been based on complicated mathematical procedures that make certain restrictive assumptions, such as fixed pressure head variation, and disregard emitter flow variation; this has limited their application. The methodology presented in this study, which assumes the basic equations for the analysis of a drip lateral based on the energy gradient line, allows evaluating the maximum length of paired drip laterals with non-pressure compensating emitters, when diameter and slope are known and pipe is laid on a uniformly sloping field. The results show that the maximum length of a paired drip lateral with given diameter is almost constant for any slope, although there is a maximum slope above which the lateral pipe diameter needs to be reduced. The maximum slope can be obtained when the ratio between the difference in elevation and the head loss due to friction of the downhill lateral exceeds one. A method is also proposed to determine the lateral pipe diameter for a fixed length.

Introduction

The basic unit of a micro-irrigation system is the irrigation subunit. An irrigation subunit contains a set of pipes with emitters, known as laterals, which receive water from another pipe, known as manifold. As the flow rates in both of these pipes (laterals and manifold) diminish from the beginning to the end, the hydraulic analysis is similar and therefore, the proposed methodology can be applied to both laterals and manifolds with laterals with the same length of drip with non-compensating emitters.

In the design process, either diameter or length can be taken as the design variable. The advantage of using length as the design variable is that length is a continuous variable and so will facilitate the adaptation of the design to such determining factors as allowable pressure variation. In contrast, the diameter is a discrete variable as only a limited number of commercial diameters are available on the market.

When designing large-scale irrigation systems with no restrictions on the length of the laterals, it is very useful to know the maximum lateral or manifold length for a given pipe diameter.

An irrigation system design in which the manifolds feed laterals on both sides - known as paired laterals - allows us to minimize total manifold length and thereby minimizes cost. In figure 1 two alternative designs are shown to irrigate the same area. As can be seen in figure 1a the length of the manifold is twice that shown in figure 1b. Though the diameter of the manifold should be larger in case b than in case a, the cost increase due to the diameter is less than the increase in cost associated with doubling the length.

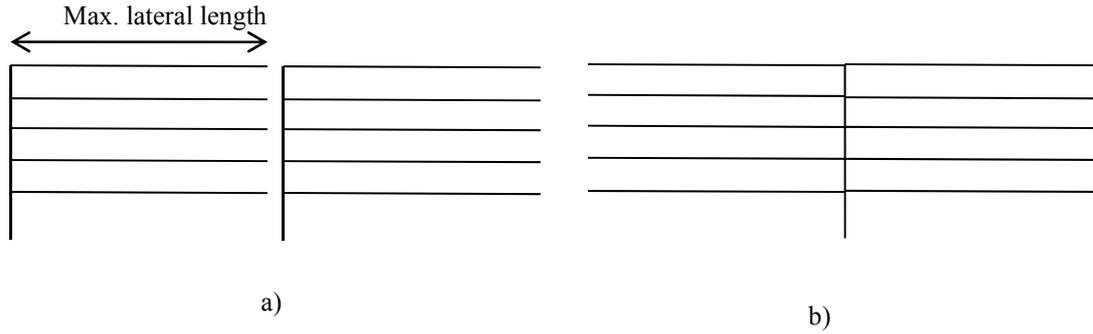


Figure 1. Design alternatives: a) Single laterals, b) Paired laterals

When the ground is level, the length of the laterals on either side is the same because the hydraulic conditions are the same. However, when there is a slope, the length of the uphill lateral has to be lower than that of the downhill lateral, since the pressure head variation in the uphill lateral is greater than in the downhill lateral. When designing laterals under this condition it is important to define the optimum feed point, otherwise called the best manifold position (BMP), which is defined as the ratio between the length of the uphill lateral (L_u) and the total length of the lateral L_T .

Keller and Bliesner (1990) proposed finding the BMP based on the condition of the minimum pressure head of the uphill lateral being the same as that of the downhill lateral. The expression they obtained is:

$$\frac{\Delta z_T}{\Delta H_T} - 0.36 \left(\frac{\Delta z_T}{\Delta H_T} \right)^{1.57} = (1 - BMP)^{2.75} - BMP^{2.75} \quad (1)$$

where:

Δz_T , absolute difference in elevation between the distal ends of the pair of laterals (m)

ΔH_T , head loss due to friction for a single lateral with a total length and flow equal to that of the pair of laterals (m)

BMP , best manifold position = L_u/L_T

Kang and Nishiyama (1996) applied the finite-element method to analyse the hydraulics of single and paired laterals. The method is accurate but requires specific software to solve the problem. One of the most significant results of their study is that with sloping laterals there is a minimum length below which it is pointless to divide the lateral into two parts and for which the optimum result is to use a single downhill lateral. They also observed that, for the BMP that they obtained, the ratio of the minimum pressure heads in uphill and downhill laterals was not equal to one, which means that the condition set out by Keller and Bliesner (1990) was not met.

Jiang and Kang (2009) developed a simpler method to determine the BMP based on the Energy Gradient Line approach (Wu, 1975). Nonetheless, they used the condition that the ratio of the minimum pressure heads in uphill and downhill laterals was equal to one, despite the observation of Kang and Nishiyama (1996) that this was not met.

Baiamonte, Provenzano, and Rallo (2015) presented a new analytical method for calculating friction head losses along a lateral, based on a rather complex mathematical concept, called the generalized harmonic number. However, this procedure, does not take into account local losses due to the emitters' insertions. Based on this methodology, they obtained an analytical solution for the maximum length of paired drip laterals. Another of the drawbacks to this methodology is

that it assumes that the minimum pressure head of the lateral is 90% of the emitter design pressure head, regardless of the characteristics of the emitter (Monserrat and Barragan, 2016). However an important result can be extracted from the study by Baiamonte, Provenzano, and Rallo (2015), namely that the maximum lateral length for an allowed pressure variation is almost constant for different slopes.

Ju et al. (2015) proposed a new condition to find the BMP, namely the average pressure head of the uphill lateral being the same as that of the downhill lateral (in accordance with Juana et al. (2004)) and, at the same time, equal to the design pressure head. In this way, the average flow rate of the emitters will be similar to the design flow rate. Meeting the proposed condition, for the case of smooth turbulent flow and considering local head losses they obtained equation (2):

$$(1 - BMP)^{2.75} - BMP^{2.75} = \frac{\Delta z_T}{2 \cdot 0.733 \cdot \Delta H_T} \quad (2)$$

If $BMP = 0$ is substituted in equation (2), then $\frac{\Delta z_T}{\Delta H_T} = 1.466$, which is the maximum value of the ratio between the difference in elevation and the friction head loss (which can also be called $J = \frac{\Delta z_T}{\Delta H_T}$), represents the value beyond which paired laterals cease to be viable according to the arguments put forward by Kang and Nishiyama (1996).

For a lateral of given diameter and slope, both equation (1) and (2) can be iteratively solved. Ju et al. (2015) compared the results of equations (1) and (2), noting discrepancies for values of $J > 1$ with a maximum BMP error of 0.07.

Ju et al. (2015) derived a simple expression to obtain the maximum length of a paired lateral.

$$\frac{(1 - EU_{lh}) h_d}{\beta_{min} x \Delta H_T} = 1 \quad (3)$$

where: EU_{lh} , lateral emission uniformity due to hydraulic causes; h_d , emitter design pressure head; x , emitter discharge exponent and β_{min} , a dimensionless parameter.

The values of β_{min} can be obtained from one of the following regression equations:

$$\begin{aligned} 0 \leq J \leq 0.818; \quad \beta_{min} &= -0.1316 J^2 + 0.1547 J + 0.0399 \\ 0.818 < J \leq 1.467; \quad \beta_{min} &= 0.0544 J^2 + 0.0395 J + 0.0101 \end{aligned} \quad (4)$$

Using an iterative procedure and testing different L_T values, ΔH_T and Δz_T can be calculated until equation (3) is satisfied.

One limitation of this methodology is that it does not account for emitter flow variations due to emitter manufacturing (Karmeli and Keller, 1975; Bralts, Wu and Gitlin, 1981). Another drawback is that it uses the EU of the lateral, contrary to the normal use of EU that is related to the irrigation subunit.

When designing micro-irrigation systems, it is important to have simple and reliable methods that ensure an economic installation with the desired uniformity. This paper presents a simple method for non-pressure compensating emitters which, using the basic equations for the design of laterals based on the energy gradient line, allows determination of the maximum length of a paired lateral for a given diameter and slope or also the pipe diameter for a fixed lateral length.

Methods

The first step in the design of irrigation subunits is to determine the emitter minimum flow rate based on requested subunit emission uniformity (EU) and on the emitter hydraulic characteristics. Keller and Karmeli (1974) suggested correlating EU to the flow rate variations due to hydraulic variability and emitter manufacturing coefficient,

$$EU = \left(1 - 1.27 \frac{CV_m}{\sqrt{e}}\right) \frac{q_{min}}{q_d} \quad (5)$$

where: CV_m , coefficient of variation of emitter flow due to emitter manufacturing; e , number of emitters per plant; q_{min} , minimum emitter discharge in the subunit; q_d , design emitter discharge.

Alternatively, the equation proposed in Barragan, Bralts and Wu (2006) can also be used.

Using q_{min} and the emitter discharge equation, the minimum subunit pressure head (h_{min}) can be calculated, and the allowable subunit head variation (Δh_s) can be obtained with the following rule of thumb, (Keller and Bliesner, 1990).

$$\Delta h_s = 2.5 (h_d - h_{min}) \quad (6)$$

where: h_d is the emitter design pressure, and h_{min} the minimum subunit pressure head

The maximum allowable lateral pressure head variation (Δh_{lm}) is usually calculated as half of the subunit head variation (Δh_s). However, bearing in mind that in an irrigation subunit the total length of the laterals is much longer than that of the manifold, a reduction in the size of the lateral diameter could be obtained if the fraction of head variation in the lateral is greater than $\frac{1}{2}$, for example $\frac{2}{3}$. It would therefore be possible to achieve a reduction in the total subunit cost.

Once Δh_{lm} has been determined, the aim is to calculate the maximum length of the uphill and downhill lateral and the inlet pressure head for a given slope and pipe diameter.

The methodology used for the hydraulic analysis of a lateral is based on the energy gradient line (Wu, 1975), in other words on the continuous decrease of the flow rate in the lateral and, therefore, the pressure head distribution can also be approximated as a continuous function.

The lateral friction head loss (ΔH) is calculated as:

$$\Delta H = \frac{1}{2.75} C L \left(\frac{L}{S_e} q_d\right)^{1.75} D^{-4.75} \left(1 + \frac{l_e}{S_e}\right) \quad (7)$$

where: C , polyethylene roughness coefficient varying with water temperature, it is assumed $C = 0.505$ for $10^\circ\text{C} < T < 30^\circ\text{C}$ (Ju et al., 2015); L , lateral length (m); S_e , emitter spacing; q_d , design emitter discharge; D , internal lateral diameter (mm); l_e , equivalent length due to local head losses at emitter insertion (Juana et al., 2002).

Calculation of the maximum length of a paired lateral involves a high degree of mathematical complexity and, for this reason, has only recently been tackled (Baiamonte et al., 2015) (Ju et al., 2015).

As pointed out previously, Baiamonte et al. (2015) found that the total length of paired laterals is fairly similar regardless of the slope. It is therefore possible to begin with the easy calculation of the maximum length of the lateral assuming flat ground. For this case, friction head loss (ΔH) is equal to pressure head variation (Δh_{lm}). Solving for length in equation (7), equation (8) is obtained and this allows us to calculate the maximum length of a single, flat, ground lateral (L_{max0}).

$$L_{\max 0} = \left(\frac{2.75 \Delta h_{l m} D^{4.75} S_e^{1.75}}{C q_d^{1.75} \left(1 + \frac{l_e}{S_e}\right)} \right)^{\frac{1}{2.75}} \quad (8)$$

Bearing in mind that the maximum length is the same on both sides in this case,

$$L_{\max T} \cong 2 L_{\max 0} \quad (9)$$

where: $L_{\max T}$ maximum length of paired lateral.

Based on the value of $L_{\max T}$ and the slope the BMP may be calculated solving equation (2) but, given that $L_{\max T}$ is an approximate value, the condition $\Delta h_l < \Delta h_{l m}$ cannot be assured. Therefore, calculation of the maximum length of the uphill section ($L_{\max u}$) is recommended, considering the actual slope of the ground. $L_{\max u}$ will be the length that satisfies equation (10),

$$\Delta h_{l m} = \Delta H_u + \Delta z_u \quad (10)$$

where: ΔH_u , the friction head loss of the uphill lateral, Δz_u , difference in elevation of the uphill lateral

The two terms on the right-hand side of equation (10) depend on the length which is the unknown variable. Substituting in equation (10)

$$\Delta h_{l m} = \frac{1}{2.75} C L_{\max u} \left(\frac{L_{\max u}}{S_e} q \right)^{1.75} D^{-4.75} \left(1 + \frac{l_e}{S_e} \right) + L_{\max u} S \quad (11)$$

where S is the slope of the ground (m/m)

Equation (11) can be iteratively solved with a calculator or spreadsheet.

The pressure head at the inlet of the uphill lateral is calculated using the formula of Keller and Bliesner (1990) which assures that the average head along the lateral equals the design pressure

$$h_{0 u} = h_d + 0.733 \Delta H + 0.5 L_{\max u} S \quad (12)$$

Finally, a first approximation of the maximum length of the downhill lateral ($L_{\max d}$) could be obtained using equation (13)

$$L_{\max d} \cong L_{\max T} - L_{\max u} \quad (13)$$

$L_{\max d}$ has to satisfy the pressure head variation constraint of the downhill lateral, $\Delta h_{l d} \leq \Delta h_{l m}$. If this is not the case, length values must be iteratively tested until the condition is met. $\Delta h_{l d}$ is calculated following the methodology set out in Wu, Saruwatari, and Gitlin (1983).

The design must satisfy another condition due to the hydraulics of the paired laterals, namely that the pressure head at the inlet of the uphill lateral ($h_{0 u}$) must be the same as the pressure head at the inlet of the downhill lateral ($h_{0 d}$).

Results

Determination of the maximum length for a given diameter and slope

The methodology described above will now be applied to the following case: an emitter has a $q_d = 2$ l/h, $h_d = 10$ m, $x = 0.4$ and $CV_m = 0.05$. Three emitters are positioned per plant and a subunit $EU = 0.9$ is desired. Using equation (5), $q_{min} = 1.87$ l/h, considering the emitter equation $h_{min} = 8.43$ m. Applying equation (6), $\Delta h_s = 3.9$ m and consequently, assuming $\Delta h_{lm} = \frac{2}{3} \Delta h_s$, the maximum pressure head variation along the lateral is 2.6 m.

Assuming a lateral with an internal commercial diameter $D = 16.6$ mm, with $C = 0.505$ and a emitter spacing $S_e = 0.2$ m, the equivalent length for local losses according to Watters and Keller (1978) is $l_e = 14.38 D^{-1.89}$. Other equations may be used as Bagarello et al. (1997) and Provenzano and Pumo (2004).

The maximum length of the lateral was calculated for different slopes by applying the proposed methodology (with a slope resolution of 0.01, for simplifying purposes). It can be seen from figure 2 that $L_{max T}$ for ($S \leq 0.07$) slightly diminishes with the slope, corroborating the result obtained by Baiamonte et al. (2015). $L_{max u}$ decreases as the slope increases, as would logically be expected. It was also observed that $L_{max d}$, which is the complementary distance of $L_{max u}$, increases with the slope until a point is reached where there occurs a sharp decrease ($S > 0.07$ m/m).

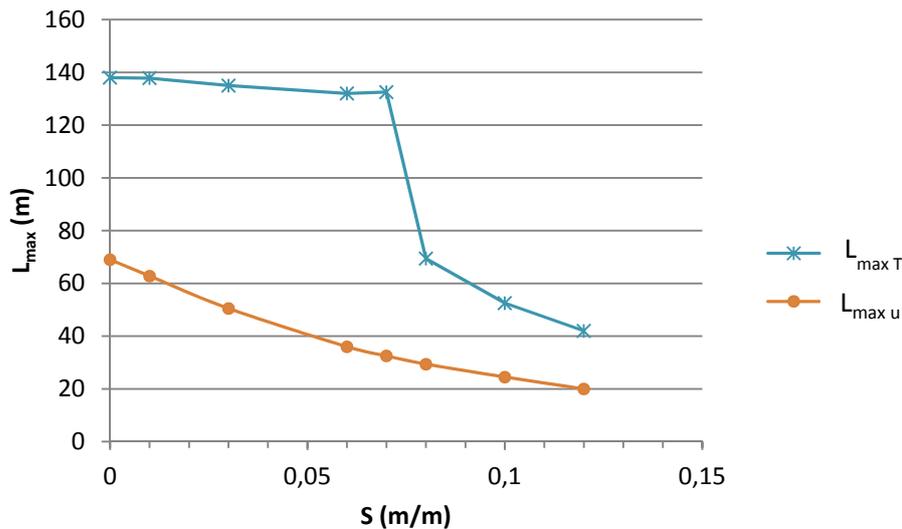


Figure 2. Variation in maximum length of paired lateral ($L_{max T}$) and uphill section ($L_{max u}$) for different slopes ($D = 16.6$ mm).

To explain the sharp decrease in the length of the lateral which takes place for $S > 0.07$, firstly an analysis is made of the process by which the $L_{max d}$ is obtained in a lateral with a slope of 0.07 m/m. The initial approximation of the length of the downhill section is obtained with equation (13), giving a result of 105 m. It can be seen in figure 3 that the pressure head variation (maximum head - minimum head) which is obtained for this length is greater than the allowable variation (2.6 m). If the length of the lateral decreases, the pressure head variation decreases and for $L = 100$ m matches the allowable variation.

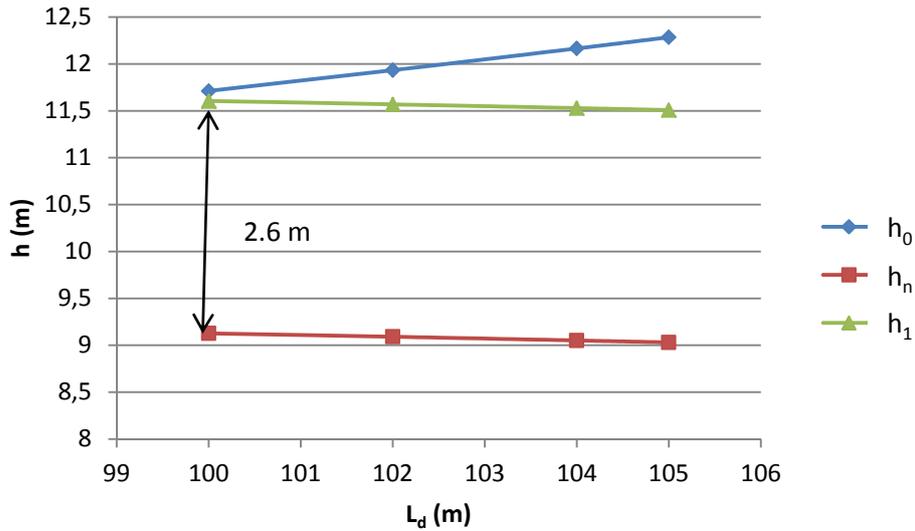


Figure 3. Inlet pressure head (h_0), minimum (h_n) and final (h_1) pressure head in a downhill lateral ($S= 0.07$ m/m) as a function of lateral length. ($D = 16.6$ mm). Allowable pressure head variation 2.6 m)

Figure 4 shows the same example, but for a slope of the lateral equal to 0.08 m/m. The length of the downhill lateral obtained from equation (13), in this case, is 109 m. In the figure, the pressure variation corresponds to the distance between the highest and the lowest line. As can be seen, the distance between the two lines is greater than 2.6 m, when $L > 60$ m. At $L = 60$ m, h_0 becomes the minimum pressure and then both lines converge. Hydraulically, this condition is met when $\Delta z_d / \Delta H_d > 2.75$ (Wu et al., 1983)

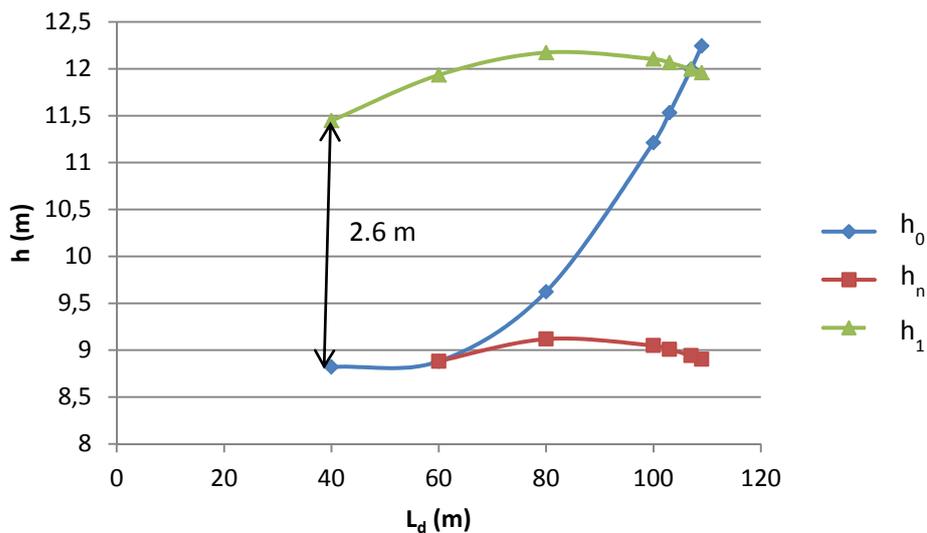


Figure 4. Inlet pressure head (h_0), minimum (h_n) and final (h_1) pressure head in a downhill lateral ($S= 0.08$ m/m) as a function of lateral length. ($D = 16.6$ mm)

The result is a considerable reduction in the length of the lateral, as was seen in figure 2. For $S > 0.08$, this situation is repeated.

As previously stated, two conditions must be satisfied in the design of a paired lateral: a) the pressure head variation in the uphill and downhill lateral sections must be lower than the established value, and b) the inlet pressure head in the uphill and downhill lateral must be the same. The first condition was considered to obtain $L_{max\ u}$ and $L_{max\ d}$. The second condition was not imposed in the design, but in Figure 5 it is seen that this condition is satisfied for all practical purposes for the range of slopes $S \leq 0.07$. However, for $S > 0.07$ it is seen that inlet pressure head in the downhill section ($h_{0\ d}$) decreases considerably, and for this reason the results are not acceptable. This decrease is due to the sudden reduction in length obtained in the downhill lateral.

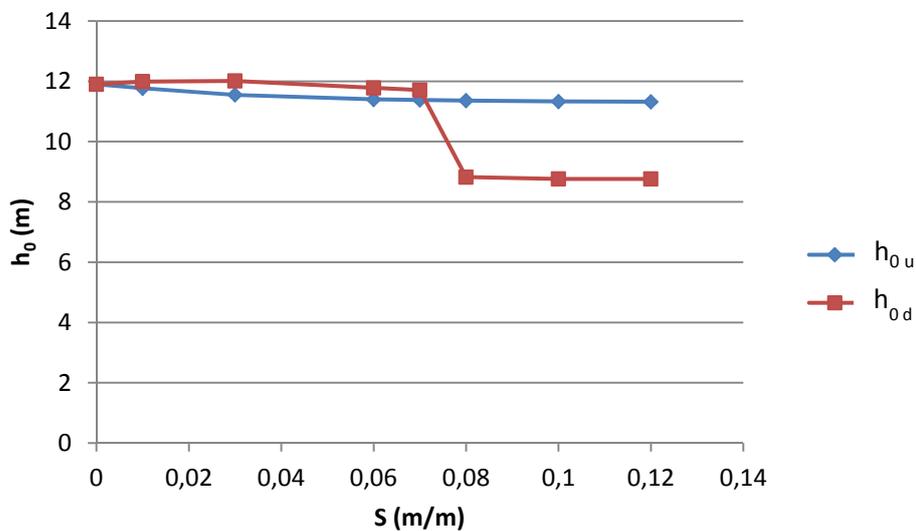


Figure 5. Inlet pressure head of uphill lateral ($h_{0\ u}$) and downhill lateral ($h_{0\ d}$) for different slopes. ($D = 16.6$ mm)

Figure 6 shows the values of $\Delta z_d / \Delta H_d$ for $L_{max\ d}$ depending on ground slopes. It can be seen that for $S = 0.07$, the value of $\Delta z_d / \Delta H_d$ reaches 1, and for steeper slopes and that thereafter there is a sudden increase in $\Delta z_d / \Delta H_d$. Considering the results of the pressure head variation and inlet pressure for the downhill lateral depending on ground slope (figures 2, 5 and 6), it can be stated that a maximum length of paired laterals exists if the condition $\Delta z_d / \Delta H_d \leq 1$ is met for $L_{max\ d}$.

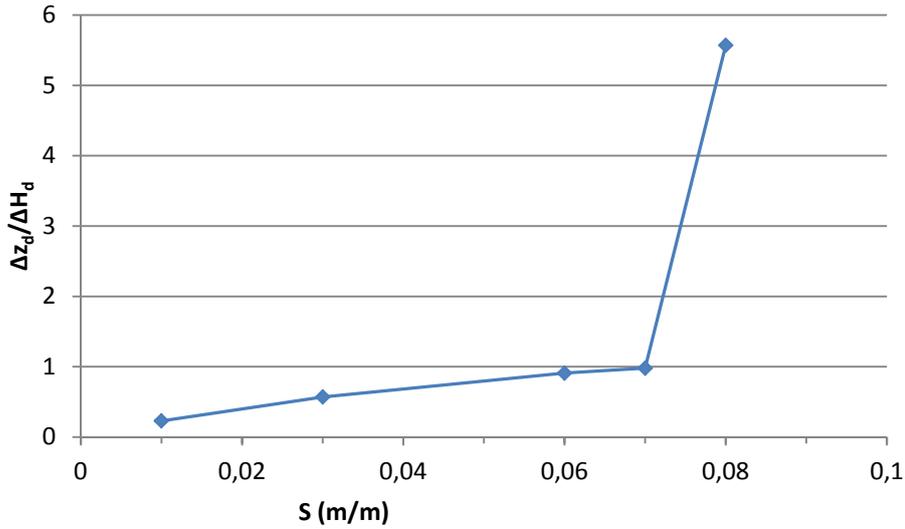


Figure 6. Ratio between the difference in elevation and the friction-related head loss at the downhill lateral ($\frac{\Delta z_d}{\Delta H_d}$) for $L_{max d}$ depending on ground slope. ($D = 16.6$ mm)

To resolve cases in which $S > 0.07$, a solution could be explored using a smaller commercial pipe diameter in order to increase friction losses and to reduce the pressure head at the end of the lateral. Figure 7 shows the results of the proposed methodology for a commercial pipe diameter of 13.2 mm. It can be seen that there are viable solutions for larger slopes than in the previous case ($S \leq 0.11$). Therefore, the lower the pipe diameter the larger the range of slopes for which acceptable results can be obtained. With respect to the condition for pressure heads of the uphill and downhill lateral, it was also verified that they are the same for $S \leq 0.11$.

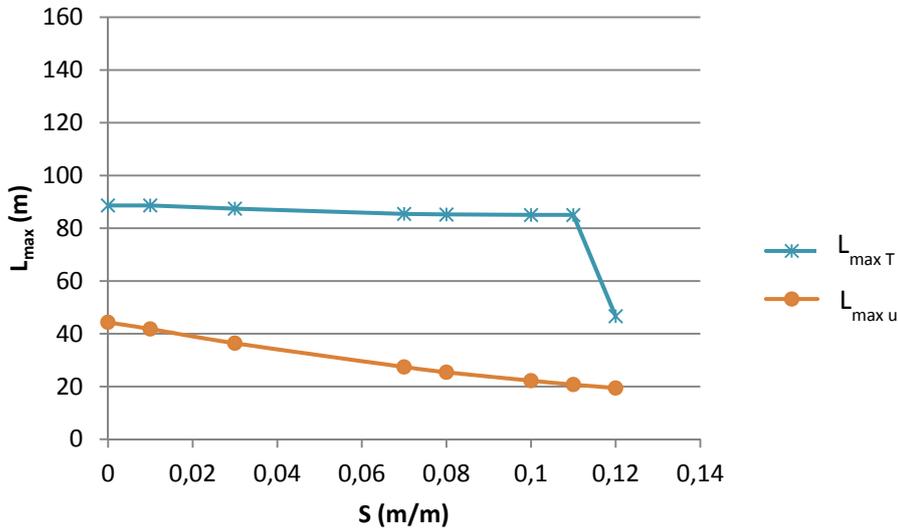


Figure 7. Variation of the maximum length of the paired lateral ($L_{max T}$) and of the uphill section ($L_{max u}$) for different slopes ($D = 13.2$ mm).

Determination of the diameter for a given length and slope

In the event that the lateral length is fixed (L_f), the proposed procedure involves searching for a lateral diameter which obtains a maximum total length greater than the fixed length (L_f). For this, equation (9) is used bearing in mind that the maximum length is reasonably constant if the condition $\Delta z_d / \Delta H_d \leq 1$ is met. Subsequently, the BMP can be calculated using equation (2).

For example, for a lateral with $S = 0.03$ and $L_f = 100$ m and with similar characteristics to those set out in the previous examples, $D = 16.6$ mm was chosen as $L_{max T (D=13.2)} = 88 \text{ m} < 100 < L_{max T (D=16.6)} = 135$ m (Figure 2 and 7 or equation (9)). Knowing $L_f = 100$ m, Δz_T and ΔH_T can be calculated and solving equation (2) a value of $BMP = 0.33$ is obtained.

Figure 8 shows the evolution of BMP and pressure head variation in the lateral for the range of lengths $L_{max T (D=13.2)} = 88 \text{ m} < L_T < L_{max T (D=16.6)} = 135$ m. It can be seen that the BMP decreases as the length decreases, and that the same occurs with respect to pressure head variation.

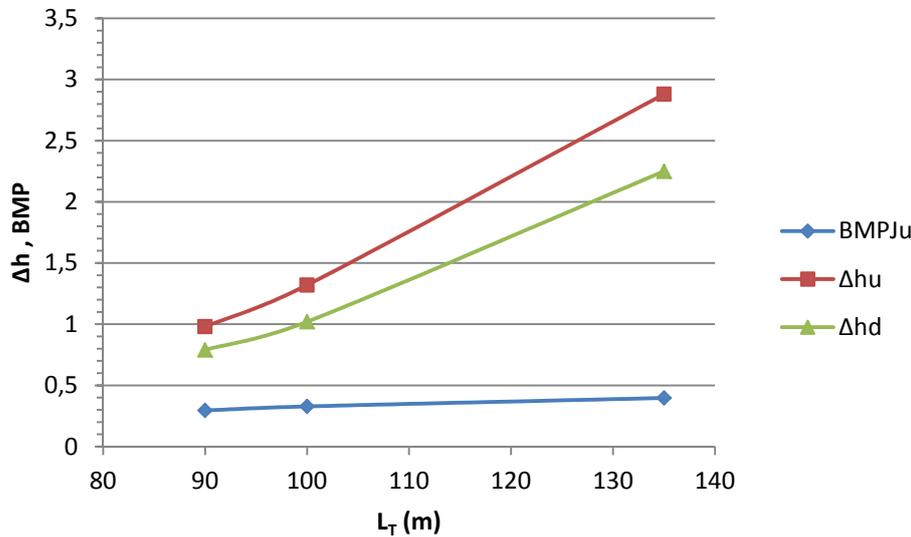


Figure 8. Evolution of the BMP and pressure head variation in the uphill and downhill lateral Δh_u , Δh_d as a function of the length of the lateral, for $D = 16.6$ mm and $S = 0.03$ m/m.

For the analysed case ($L_f = 100$ m), verification was undertaken of what was previously stated, namely that when designing an irrigation system using a fixed length and taking the diameter as the design variable, the obtained solution does not take full advantage of all the allowable pressure head variation in the lateral (2.6 m). It was also verified that the result of equation (2), proposed by Ju et al. (2015) for $L = 135$ m, gives a head variation in the uphill lateral of 2.88 m, slightly higher than the permitted value. Finally, it was observed that the pressure head variation in the uphill lateral is not the same as the variation in the downhill lateral and, given that inlet pressure head is the same, the minimum pressure heads will be different, agreeing with the observations of Kang and Nishiyama (1996).

Comparison with the method of Ju et al.

A comparison is carried out below of the results using the methodology proposed in the present paper and those using the method of Ju (Ju et al., 2015). For this purpose, it is necessary to calculate the EU of the lateral due to hydraulic causes (EU_{lh}). This index is not commonly used in the design of laterals, but can be calculated from:

$$EU_{lh} \cong \frac{q_n}{q_d} = \left(\frac{h_n}{h_d}\right)^x \quad (14)$$

where: q_n , minimum flow rate of the lateral; q_d , design emitter discharge; h_n , minimum lateral head; h_d , emitter design pressure head; x , emitter discharge exponent

In the laterals previously studied the minimum head and the design head are known and, therefore, the EU_{lh} of the uphill and downhill lateral can be calculated. Using the mean value of both and equation (3), the total length of the paired lateral was calculated and, using other equations proposed by Ju et al. (2015), the maximum length of the uphill lateral was determined.

Figure 9 represents a comparison of the results obtained with the proposed methodology and those obtained using the methodology of Ju et al. (2015). It can be seen that the two sets of results are in agreement, except for discrepancies for slopes greater than 0.07. It would appear that the method of Ju et al. (2015) was unable to detect that for these slopes the minimum pressure head is at the inlet.

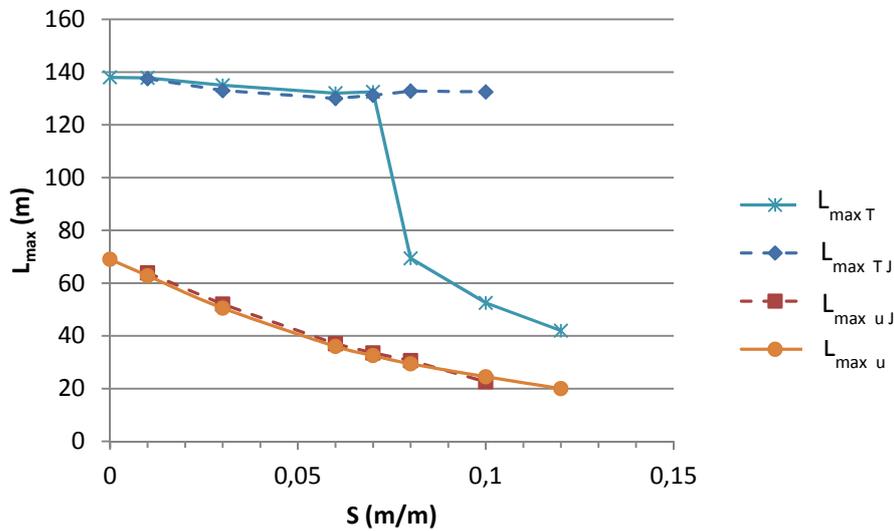


Figure 9. Comparison of the maximum length of the paired lateral and uphill lateral calculated using the proposed method (M) and the method of Ju et al. (J). ($D = 16.6$ mm)

This method has others shortcomings pointed out previously: it uses an EU index that does not correspond to regular design procedures, and it does not take into account the coefficient of variation of emitter flow due to emitter manufacturing.

Conclusions

It can be concluded from the analysed cases that given a lateral with a known diameter, the maximum length of a paired lateral when the ground is level is practically the same as when the ground is inclined. This fact has been used in the proposed design method which determines maximum length for paired laterals, knowing diameter, slope and emitter characteristics.

It was also found that there is a maximum slope beyond which there is no feasible paired lateral solution. The condition which defines the maximum slope is that in the downhill lateral the ratio between the difference in elevation and friction head loss must be less than or equal to one.

When a lateral has a slope greater than the maximum for a given diameter, the solution lies in decreasing the diameter of the lateral. If the length is fixed, it may be possible to find a commercial pipe diameter which has a maximum length longer than the fixed length. In such cases, use is not made of the full allowable head variation in the lateral.

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Notation:

BMP : Best Manifold Position, ratio of length of uphill lateral to total length of pair of laterals

C : pipe roughness coefficient

CV_m : coefficient of variation of emitter flow due to emitter manufacturing

D : internal lateral diameter (mm)

e : number of emitters per plant

EU : subunit emission uniformity

EU_{th} : lateral emission uniformity due to hydraulic causes

h_d : emitter design pressure head (m)

h_{min} : minimum subunit pressure (m)

h_n : minimum lateral pressure head (m)

h₀ : lateral inlet pressure head (m)

h_l : lateral distal end pressure head (m)

$\Delta h_{l,m}$: maximum allowable lateral pressure variation (m)

Δh_l : actual lateral pressure variation (m)

Δh_s : allowable subunit head variation (m)

ΔH : head loss due to friction (m)

$J = \frac{\Delta z_T}{\Delta H_T}$ ratio between total elevation difference and total friction head loss

L : length of lateral (m)

l_e : equivalent length due to local head losses at emitter insertion (m)

$L_{max 0}$: maximum length of a single flat ground lateral (m)

q_{min} : minimum emitter discharge in the subunit ($L h^{-1}$)

q_d : design emitter discharge ($L h^{-1}$)

S : field slope (m/m)

S_e : emitters' spacing

Δz : absolute difference in elevation between the distal ends of a lateral (m)

x : emitter discharge exponent

β_{min} : dimensionless parameter for calculating h_{min} along the paired laterals

Subscripts:

_u : uphill lateral

_d : downhill lateral

_T : total of paired lateral