Introduction

The development of appropriate technologies and design strategies to enhance modern irrigation practices, reducing energy consumption, improving water use efficiency and crop yields is imperative for sustainability (Noreldin et al. 2015). Several studies have been performed on the hydraulic design of Center-Pivot Irrigation System (CPS), with the aim to increase the uniformity of water application and to limit the peak of instantaneous precipitation rates (Valin et al. 2012, de Almeida et al. 2017, Baiamonte and Baiamonte, 2018). To ensure the uniformity of water application rate, CPS usually requires i) increasing the flow rates along the lateral, because the sprinklers farther from the pivot move faster, and therefore their instantaneous application rates must be greater. Thus, the irrigated area under a CPS expands substantially with increasing system length. Additionally, to irrigate the increased area by maintaining constant the application intensity, the manufacturers also propose: ii) to gradually decrease the spacing of equal-flow sprinklers along the Center-Pivot lateral (Howell 2003), or iii) to use semi-uniform spacing (Allen et al. 2000), which is a combination of the first two methods.

Objective

The objective of this work is to derive a CPS design procedure, allowing to set water application rates, according to a gradually decreased spacing of equal-flow sprinklers along the Center-Pivot lateral, where parameters can be set according with the site needs. First, the sprinklers’ spacing distribution corresponding to a fixed irrigated area along the radial direction is derived. According to this finding, the objective is also to suggest a simplified design procedure to determine, for the design input parameters, the maximum length of the lateral, which makes it possible to achieve the desired water uniformity in the CPS irrigated area.

Methodology (Geometric design of a Center-Pivot)

Fixing the area irrigated by the sprinklers equal for each sprinkler, \( A_j (m^2) \) according to the ratio between the sprinkler flow rate, \( q_s (m^3/s) \) and the desired rainfall intensity \( I (m/s) \):

\[
A_j = A_1 = q_s / I
\]

Deriving the annulus width \( W_a (m) \) of the first sprinkler (\( j = 0 \), Fig. 1), which can be normalized with respect the pivot lateral length \( r_0 (m) \):

\[
W_{a0} = W_0 / r_0 = 1 - \frac{1}{\sqrt{1 - r_j / r_0}}
\]

The \( W_a \) relationship, plotted in Fig. 2, only depends on one meaningful parameter:

Once \( W_{a0} \) is known, the annuli width of all of the other \( n \) sprinklers, \( W_j = W_{a0} \), can be obtained (Fig. 3) by the following recurrence relation that recursively defines a sequence of annulus width values, once the initial terms, \( r_0 = 1 \) and \( W_0 \) are known:

\[
W_j = W_{a0} - r_j - \frac{r_j}{r_j - 1} - 4 r_j - 1 W_{j-1} + 2 W_{j-2}
\]

Once determined \( W_a \), the sprinkler spacing relationship can be evaluated (Fig. 4), assuming to install the sprinklers in the middle of the annulus width:

\[
S_j = \frac{W_j + W_{j-1}}{2}
\]

Once the geometry is designed, the hydraulic design can be performed

Methodology (Hydraulic design of a Center-Pivot)

The hydraulic design follows the procedure suggested by Baiamonte and Baiamonte (2018a, b), who derived analytical solutions to facilitate the design for one lateral units and for rectangular microirrigation units.

In particular, for laterals laid in a flat field the following energy balance equation was first considered (Fig. 5):

\[
h_{j+1} = h_{\text{min}} + K \sum_{j=1}^{n} \sqrt{S_j}
\]

\( h_j \) is the ratio pressure head of the sprinkler \( j \), \( h_{\text{min}} \) and \( K \) are its minimum value and \( K \) equals:

\[
K = \frac{2.34}{C \sqrt{D}} \frac{n_{\text{max}}}{D}\text{ where: } C = \text{friction coefficient}
\]

Finally, the following relationship to design the inside diameter of the lateral \( D \) was derived:

\[
D = \frac{10.675}{K} \sqrt{\frac{n_{\text{max}}}{h_{\text{min}}}}
\]

Results

The results showed that for assigned input parameters, the lateral length is limited by a threshold value, so that for those lateral lengths longer than the threshold, it is compulsory to modify the sprinkler flow rate or the pipe diameter. Finally, for two practical cases, applications and validations of the proposed hydraulic design procedure were performed and discussed. It was shown that the main assumption of neglect the sprinkler flow rate variations provides slight relative errors of the sprinkler pressure head (RE < 3%) comparing to the corresponding calculated by the accurate SBS procedure. However, this occurrence would favour the plants’ wellbeing, because the overestimation of pressure heads allows supplying slightly higher water volumes and limits the admitted range of head pressure variability.

Conclusions

In this work, a simple procedure to design Center-Pivot irrigation systems for gradually decreased sprinkler spacing along the pivot lateral, and uniformly distributed water application rate is suggested. First, by imposing a uniform water application rate, the gradually decreased sprinkler spacing distribution associated with a compacted dimensionless group of the geometric and hydraulic input parameters, is derived. Then, according to this outcome, a simple formula for the hydraulic design of the Center-Pivot irrigation lateral is derived.

References


Centre-pivot irrigation system design for uniform water application rate

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