Centre-pivot irrigation system design for uniform water application rate

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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 of Centre-Pivot Irrigation System (CPIS), 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, 2019)

To ensure the uniformity of water application rate, CPIS 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 CPIS 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 CPIS design procedure, allowing to set favorable 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 CPIS 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_n (m^3/s) and the desired rainfall intensity i (m/s):

$$A_1 = A_2 = A_j = \frac{q_n}{i}$$

Deriving the annulus width w_0 (m) of the first sprinkler (j = 0, Fig. 1), which can be normalized with respect the pivot lateral length r_0 (m):

$$w_{*0} = \frac{w_0}{r_0} = 1 - \sqrt{1 - \frac{q_n}{i\, r_0^2}\pi^{-1}}$$

The w_{*0} relationship, plotted in Fig. 2, only depends on one meaningful parameter: $\frac{q_n}{i\, r_0^2}$

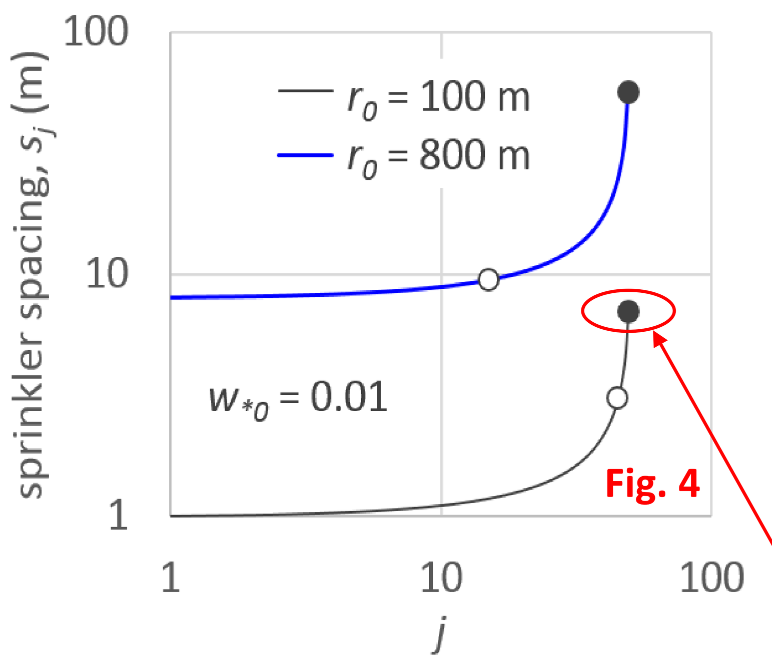
Once w_{*0} is known, the annuli width of all of the other **n** sprinklers, w_{*j} (j = 1, 2, .. **n**), can be obtained (Fig. 3) by the following recurrence relation that recursively defines a sequence of annulus width values, once the initial terms, r_{*0}, (= 1) and w_{*0} are known:

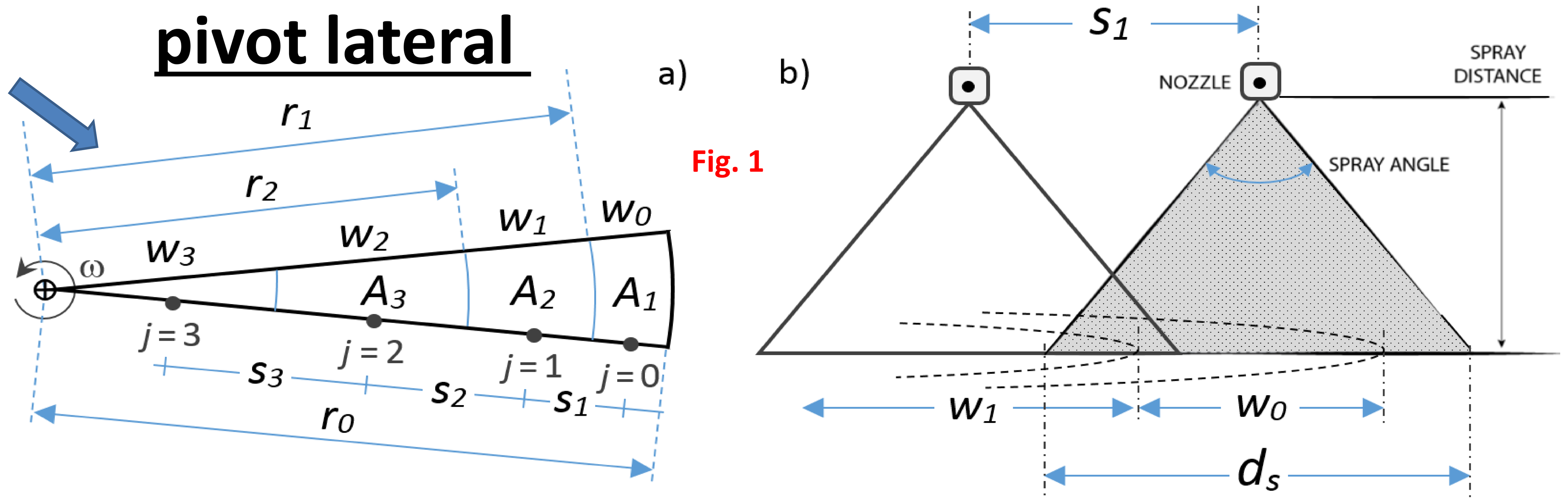
$$w_{*j} = \frac{w_j}{r_0} = r_{*j} - \sqrt{r_{*j-1}^2 - 4\, r_{*,j-1}\, w_{*,j-1} + 2\, w_{*,j-1}^2}$$

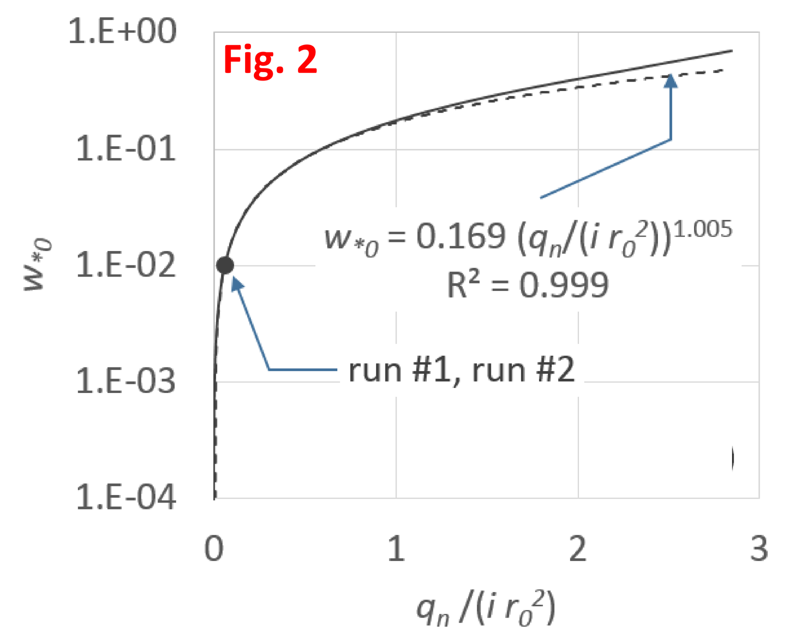
Once determined w_{*j}, the sprinkler spacing relationship can be evaluated (Fig. 4), assuming to install the sprinklers in the middle of the annulus width:

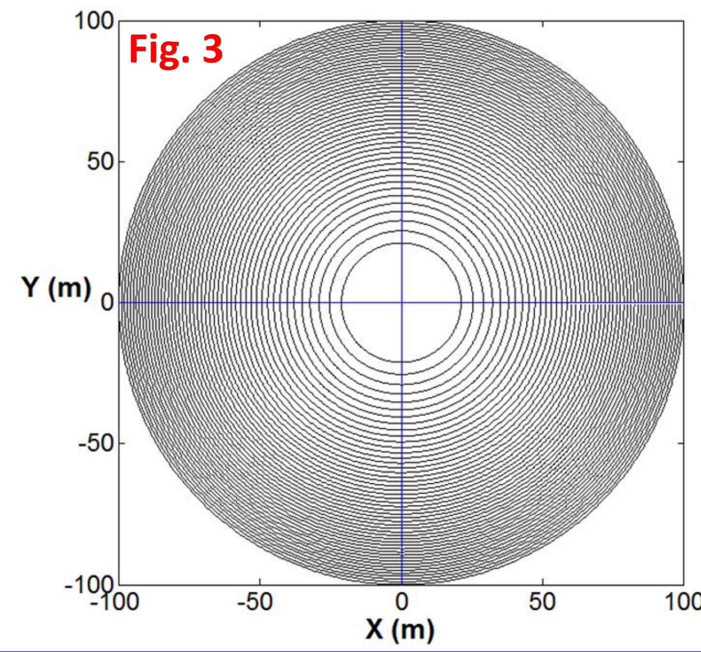
$$s_{*j} = \frac{s_j}{r_0} = \frac{w_{*j-1} + w_{*j}}{2} \qquad j = 1, 2, \dots n$$

For any assigned input parameters, the sprinkler spacing (i.e. lateral length and/or sprinklers number) is limited by a threshold value









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 (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):

$$h_{*j} = h_{*min} + K \sum_{j=1}^{j} j^{1.852}\, s_{*j}$$

where:

h_{*j} is the ratio pressure head of the sprinkler j, h_j, and r_0

h_{*min} = (1 - δ) / h_{*n} is its minimum value and **K** equals:

$$K = \frac{10.675}{C^{1.852}} \frac{q_n^{1.852}}{D^{4.871}}$$

where: C = friction coefficient

D (m) = inside lateral diameter

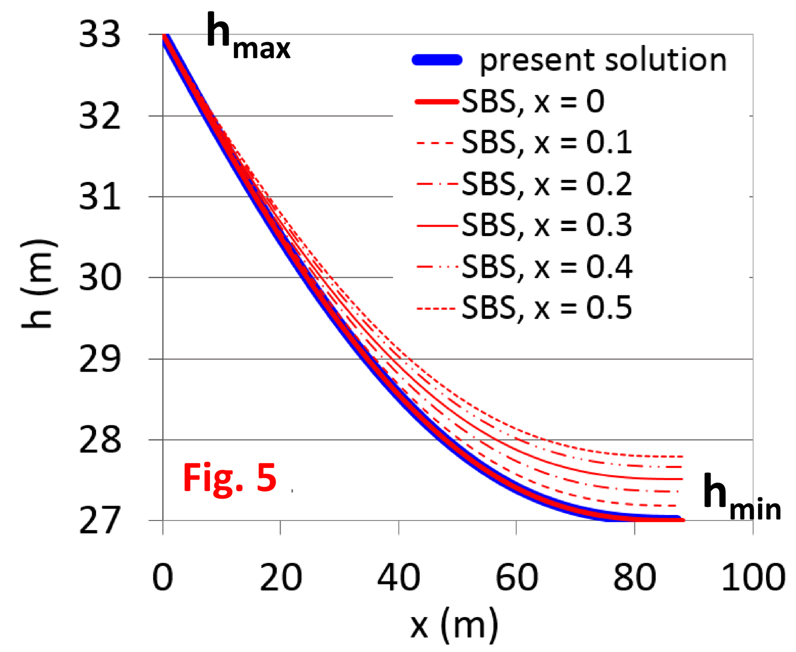
Finally, the following relationship to design the inside diameter of the lateral D was derived:

$$D = \left(\frac{10.675}{C^{1.852}} \frac{q_n^{1.852}}{2\delta h_{*n}} \sum_{j=1}^{n} j^{1.852}\, s_{*j} \right)^{1/4.871}$$

where

δ = pressure head tolerance (≅ 10%).

This solution was tested in Fig. 5, where the pressure head distribution is compared with that obtained by the exact SBS for different x ($q_n = k\, h^x$)



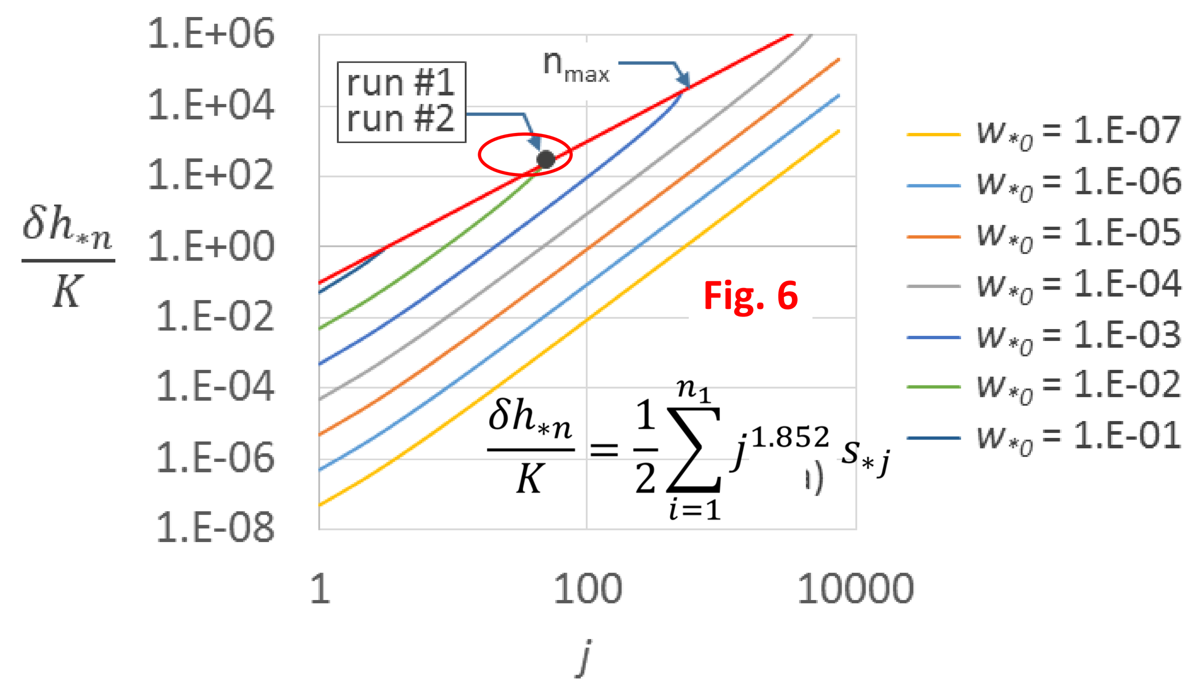


Fig. 6 shows the relationship between the dimensionless group, allows generalizing the design procedure (Baiamonte, 2020) and j. The corresponding threshold number of sprinkler n_{max} is also illustrated.

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 to neglect the sprinkler flow rate variations provide 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 pressure head 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.

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