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journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Optimisation of the design of pressurised irrigation systems for irregular shaped plots

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ARTICLE INFO

Article history:
Received 2 June 2016
Received in revised form
5 August 2016
Accepted 5 October 2016

Keywords:
Irrigation
Water-energy nexus
Pressurized irrigation system
Total water application cost
Efficiency

A software tool has been developed to support decision-making in optimising the design of pressurised irrigation systems (sprinkler and drip irrigation) for agricultural fields with sub-plots of any shape or topography. The tool determines the design with minimum total water application cost (C_T) (investment + operation). This study analysed the effect of field size, shape and slope on C_T and emission uniformity (*EU*) for drip irrigation systems for almond and pepper, as well as two possible layouts for a maize crop for permanent sprinkler irrigation systems. The minimum C_T design used polyethylene lateral pipes of 13.6 mm internal diameter at 250 kPa for drip irrigation and polyvinylchloride pipes of 46.4 mm internal diameter at 600 kPa for the permanent sprinkler irrigation systems, except in certain cases of where there were triangular plots. In the drip irrigation fields, which were more irregularly shaped and had the largest plots, the lowest C_T was achieved with regulated flow emitters which in this study had an emission exponent $x = 0.1$. This was due to their increased efficiency and therefore decreases volume requirements. The use of pressure compensating drippers is recommended for large sub-plots (>1.5 ha in the analysed cases) with irregular shape and large slopes. Under the conditions studied, the 15 × 15-m layout had a slightly lower C_T than the 18 × 18-m layout because it had greater uniformity and its increased irrigation efficiency reduced water consumption, despite having somewhat higher energy consumption and investment requirements than the 15 × 15-m layout.

1. Introduction

To support the sustainable intensification of agriculture, there is a need for low-cost, reliable, efficient irrigation systems supported by policies that recognise the trade-offs between saving water, reducing CO_2 emissions and intensifying food production (Daccache, Ciurana, Rodriguez Diaz, Knox, 2014). Consequently, optimal irrigation, from a sustainable point of view, can only be achieved by simultaneously considering environmental and economic criteria. Thus, it is necessary to develop tools and models that can contribute directly to improving water and energy use in irrigation through a holistic approach for irrigation design and management.

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http://dx.doi.org/10.1016/j.biosystemseng.2016.10.005

Nomenclature

ANOVA	analysis of the variance
AR_a	average application rate (mm h^{-1})
C_a	investment annuity (€ ha^{-1} $year^{-1}$)
C_e	energy annuity (€ ha^{-1} $year^{-1}$)
C_i	investment costs (€)
C_m	maintenance annuity (€ ha^{-1} $year^{-1}$)
CRF	capital recovery factor
C_T	total water application cost (€ ha^{-1} $year^{-1}$)
CUC	Christiansen's uniformity coefficient
CV_h	coefficient of variation of pressure head
CV_q	coefficient of variation of the flow rate in the subunit
CV_{qh}	coefficient of variation of emitter flow due to pressure variations
CV_{qmf}	manufacturer coefficient of variation of the emitters
C_w	water cost annuity (€ ha^{-1} $year^{-1}$)
D	internal pipe diameter (mm)
DE_a	distribution efficiency
D_{rs}	gross average water depth that reaches the soil surface (m^3 ha^{-1} $year^{-1}$)
e	number of emitters per plant
E_a	general application efficiency for the irrigation system
En_c	energy rate (€ kWh^{-1})
E_p	efficiency of the pumping system
EU	emission uniformity
f	friction factor of Darcy–Weisbach equation
H_0	pressure head value at the subunit intake (m kPa^{-1})
h_a	average pressure head in the system (kPa)
h_e	intake pressure head of the emitter (m)
h_{ei}	pressure head for each emitter (m)
h_f	friction losses (m)
i	annual interest rate
Jn	number of emitters to miss out
K	emission coefficient
K_s	emission coefficient of the sub-system
L	pipe length (m)
N	useful life (year)
N_p	power required (kW)
O_t	annual operating time of the irrigation system (h $year^{-1}$)
p	p-value
PE	polyethylene
PRESUD	pressurised sub-plot design
PRESUD-IR	pressurised irregular sub-plot design
PVC	polyvinylchloride
P_w	irrigation water price (€ m^{-3})
Q_0	flow rate of the pipe (m^3 s^{-1})
q_a	average emitter discharge (l h^{-1})
q_e	emission flow rate of the emitter (l h^{-1})
q_{ei}	emission flow rate for one emitter (l h^{-1})
q_{mh}	minimum emitter flow in the plot (l h^{-1})
Q_s	flow rate at the plot intake (m^3 s^{-1})
R	search radius (m)
R^2	coefficient of determination
R_e	fraction of applied water that reaches the soil surface
R_g	gross water requirement (m^3 ha^{-1} $year^{-1}$)
R_n	net crop irrigation water requirement (m^3 ha^{-1} $year^{-1}$)
S	irrigated area (ha)
S_0	slope of the plot (%)
s_e	emitter spacing along the lateral pipe (m)
s_l	lateral pipe spacing (m)
Tr	peak-use period transmission ratio
x	emission exponent
Δh	difference in pressure heads in the irrigation plot (%)
Δq	difference in emitter flow in the irrigation sub-plot (%)

The main aspects of the design and management of an irrigation system are maximising water application uniformity, minimising drift and evaporation losses, and estimating the telemetry requirements whilst reducing maintenance costs at a minimum. It is important to consider the emission uniformity (*EU*), investment and energy costs, crop response to water application uniformity (yield decreases due to non-uniform irrigation), and gross margin, among other variables. The first three variables were used to calculate the irrigation water application cost.

Solomon (1984) reported that a lack of uniformity in micro irrigation plots is mainly caused by: emitter ageing and clogging, the number of emitters per plant (*e*), the manufacturer coefficient of variation of the emitters (CV_{qmf}), pressure head variation due to differences in ground elevation and head losses in the pipes, and variations in the emission exponent (*x*).

Warrick and Yitayew (1988) presented several graphs for determining the length and diameter of lateral pipes and the intake head assuming a specific average emitter flow and water application uniformity. Kang, Yuan, and Nishiyama, 1999 developed a method for designing micro irrigation lateral pipes at a minimum cost based on the design methods of finite elements and golden-section searches. Some of the main characteristics of the system, such as lateral pipe diameters and lengths, were analysed considering uniformly and non-uniformly sloped fields. Hassanli and Dandy (2000) applied genetic algorithms to develop hydraulic calculations and designs for rectangular drip irrigation units. Zayani, Alouini, Lebdi, and Lamaddalena (2001) developed a method to design multiple outlet pipes under relatively constant outflow using the energy drop ratio approach and analytical methods. Juana, Rodríguez-Sinobas, Sánchez, and Losada (2005) developed analytical expressions relating water distribution indexes to design variables that define trapezoidal drip irrigation plots. Zayani, Hammami, Alouini, and Souissi (2013) developed an analytical method to design evenly sloping drip irrigation