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Research Paper

Optimal reservoir capacity for centre pivot irrigation water supply: Maize cultivation in Spain

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Centre pivots are one of the most widespread irrigation systems in the world. The aim was to develop a tool to optimise the design and management of the water distribution and centre pivot systems seeking to minimise water application cost per unit area (C_T), including investment (C_a), operation (C_e), and maintenance costs. With this aim, two options were considered: to feed the centre pivot 1) directly from an aquifer or 2) using a regulation reservoir. A software tool DEPIRE (design of centre pivot with regulating reservoir), was developed and implemented in MATLAB 2012b (The MathWorks Inc., Natick, MA, USA). It determines optimal flows, pipe diameters, pumps power and the volume of the regulation reservoir for any crop water requirement, different electricity rates and water availability in the tube well. With this tool, the effect of the irrigated area (S), dynamic water level (DWL) in the aquifer and the pumping flow rate on the C_T was evaluated for a maize crop in Spain. The study area representing the minor C_T was 70 ha for direct pumping from the borehole and 100 ha when using an intermediate reservoir. Incorporating a regulation reservoir generates lower C_T than direct feed from the borehole for $S > 100$ ha for any DWL. C_T increased linearly with the DWL due to a significant increase in C_e which primarily affects the cost of water extraction from the aquifer, with a smaller effect on the application cost of the irrigation system.

1. Introduction

Groundwater is the sole potable water supply for countries such as Denmark, Malta, and Saudi Arabia. It is also the most important part of total water supply in many other countries including Tunisia (95%); Belgium (83%); The Netherlands; Germany and Morocco (75%) (UNESCO, 2004). In countries with arid and semiarid climates, groundwater is also widely used for irrigation and approximately one-third of the world's landmass is irrigated by groundwater. Of the total irrigated land in the United States of America, 45% is irrigated by groundwater, 58% in Iran, 67% in Algeria and 40% in Spain. Ground water resources require high energy consumption for water abstraction. Over the 2008–2012 period energy prices in Europe increased by 4% per annum (COM, 2014). In Spain the cost of electricity increased by more than 150% since 2008 and there is a high energy dependence from irrigation because

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Nomenclature

a	adequately irrigated area (decimal)
c	coefficient of the characteristic curve of the pump in the borehole
c'	coefficient of the characteristic curve of the pump in the reservoir
C	friction coefficient for steel pipe
C'	friction coefficient for galvanised steel pipe
C_a	annual investment cost per unit area (€ ha^{-1} $year^{-1}$)
C_A	water application cost (€ m^{-3})
C_{Aa}	sum of the annual investment cost (€ ha^{-1} $year^{-1}$)
C_{Ae}	sum of the annual energy cost (€ ha^{-1} $year^{-1}$)
C_e	annual energy cost per unit area (€ ha^{-1} $year^{-1}$)
C_eB	energy costs with intermediate reservoir (€ ha^{-1} $year^{-1}$)
C_eD	energy costs in direct pumping (€ ha^{-1} $year^{-1}$)
CF	coefficient to compensate the difference of volume to the compaction level (decimal)
C_i	total investment cost (€)
C_m	annual maintenance cost (€ ha^{-1} $year^{-1}$)
C_{op}	energy costs (€)
CRF	capital recovery factor
C_T	total annual cost of irrigation water application (€)
C_{TB}	total cost with an intermediate reservoir (€ ha^{-1} $year^{-1}$)
C_{TD}	total cost with direct pumping (€ ha^{-1} $year^{-1}$)
C_w	water extraction cost (€ m^{-3})
CUCs	coefficient of uniformity of water distribution in the soil (decimal)
C_{wa}	annual investment cost of water extraction (€ ha^{-1} $year^{-1}$)
C_{wB}	water extraction cost with an intermediate reservoir (€ m^{-3})
C_{wD}	water extraction cost with direct pumping (€ m^{-3})
C_{we}	annual energy cost of water extraction (€ ha^{-1} $year^{-1}$)
D_d	distribution pipe inner diameter (mm)
D_i	pumping pipe inner diameter (mm)
DOP	optimal design of centre pivots
DOS	optimal design of borehole
D_p	centre pivot pipe inner diameter (mm)
DSS	decision support system
DWL	dynamic water level (m)
e	annual rate of escalation in energy costs (decimal)
E_a	general application efficiency by the irrigation system (decimal)
ED_a	water distribution efficiency (decimal)
ETc	crop evapotranspiration (mm)
F	freeboard (m)
$H1$	depth of excavation of reservoir (m)
$H2$	above-ground depth of reservoir (m)
H_e	sprinkler operating pressure (m)
h_f	pipe head losses (m);
h_{fd}	head loss in the distribution pipe from the reservoir to the centre pivot (m)
h_{fi}	head loss in the pumping pipe in the reservoir (m)
h_{fps}	head loss in the pumping pipe in the borehole (m)
H_g	height of the sprinkler over the ground (m)
h_{rdp}	head loss in the distribution pipe to the centre pivot (m)
h_{rds}	head loss in the distribution pipe from the borehole to the reservoir (m)
h_{rp}	head loss in the centre pivot pipe (m)
h_s	minor singular head losses (m)
HS	hydrogeological unit
H_T	pressure head required at the pump (m)
H_{Tp}	pressure head required at the pumping centre pivot (m)
H_{Ts}	pressure head required at the pumping extraction (m)
i	interest rate (decimal)
L	length of the base of the reservoir (m)
L_d	pipe length at the distribution (m)
L_i	pipe length at the pumping extraction (m)
n	lifetime (y)
N_n	crop irrigation water requirement per year (m^3 ha^{-1} $year^{-1}$)
N_p	absorbed power (kW)
N1	outside levee slope of reservoir (decimal)
N2	inside levee slope of reservoir (decimal)
P	energy rate (€ kW^{-1} $year^{-1}$)
Pa	power access price (€ kW^{-1} $year^{-1}$)
Pe	effective proportion of water that reached the soil surface (decimal)
P_t	power of the transformer (kVA)
P1	high-energy-rate period
P2	medium-energy-rate period
P3	low-energy-rate period
Q	flow rate to the reservoir (m^3 $year^{-1}$)
Q'	flow rate to the centre pivot (m^3 $year^{-1}$)
Q_0	inflow rate to the pipe (m^3 $year^{-1}$)
R	radius of centre pivot (m)
S	irrigated area (ha)
St	centre pivot spans (m)
T	monthly operation time of the pump
Ta	top width of the levees of reservoir (m)
VL	levees volume (m^3)
VT	storage volume (m^3)
Vx	excavation volume (m^3)

Greek symbols

η	efficiency of the pumping system (decimal)
ΔZ_p	elevation difference on the lateral of centre pivot (m)
ΔZ_s	elevation difference between the borehole and the reservoir (m)