



# Cost Reduction in Pressurized Irrigation Networks under a Rotation Schedule

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## Abstract

Rotation scheduling implies a reduction in pipe flows and, consequently, in network cost. This kind of scheduling is considered rigid, but the recent development of new technologies, such as Supervisory Control And Data Acquisition systems (SCADA), has allowed high-frequency irrigation (1 day or less), making it an interesting option when either designing or managing an irrigation network. In this paper, simple formulas and relevant variables are presented to easily assess the relative flow reduction in networks under a rotation schedule. The flow reduction depends on the number of outlets supplied and the probability of these being opened. The presented equations were applied to different networks, and the results obtained were accurate, with an average error of only 5%. It was observed that the ratio between relative cost reduction and the relative flow reduction had a mean value of 0.50. This ratio might be used to roughly estimate the cost reduction from the calculated relative flow reduction. The flexibility of the networks under a rotation schedule was improved by adding just one outlet flow rate to those used to size the pipes.

**Keywords** Pressurized networks · Irrigation · Scheduling · On-demand · Rotation · Economic analysis

## 1 Introduction

When designing an irrigation network, it is important to know how it will be managed. To provide an efficient water delivery system for an irrigation district, scheduling is a principal issue. In former times, canals and ditches were designed and managed under a rotation schedule. This type of irrigation scheduling is based on having groups of farms sharing the

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supplied flow rate one after another. In the 1960s in the southeast of France, a new concept called on-demand scheduling was developed in pressurized irrigation networks, allowing farmers to irrigate at any time and at a good level of service.

Pressurized irrigation networks require little maintenance and allow easy flow rate allocation and measurement of volume used (Bonnal 1963). The on-demand scheduling gives greater flexibility; however, it is more expensive than rotation scheduling, where neighboring farms do not irrigate at the same time. The rotation scheduling is less popular because it is considered to be rigid and requires the coordination of outlets. However, in recent times, rotation scheduling has become a feasible alternative due to the use of new technologies, such as SCADA systems, telemetry, and remote-control systems that facilitate farm coordination and automation. These systems are capable of sending a signal to the on-farm controller, giving a specific outlet the option to irrigate during a period. The farmer will then decide the duration of watering during this period.

Pressurized irrigation networks can provide high irrigation frequencies, even on a daily basis, which means that they are able to adapt well to different weather conditions, thereby improving irrigation efficiency and overcoming one of the main problems of rigid irrigation scheduling.

Some authors have been studying the influence of irrigation scheduling on conduit capacity. Clemens (1986) determined the canal capacity required to meet various levels of demand using simulated demand patterns for hypothetical surface irrigation conditions. Farmani et al. (2007) developed a genetic algorithm for designing and managing pressurized irrigation networks under a rotation or demand schedule, seeking to minimize costs and to improve the level of service. Rodríguez Díaz et al. (2009), Moreno et al. (2010), and Jimenez-Bello et al. (2010) have proposed tools to reduce energy costs in irrigation networks by optimizing the rotation schedule. Lapo et al. (2017) developed a hybrid model that includes linear programming to determine diameters and genetic algorithms to identify the best rotation configuration.

This article is focused on estimating capital invest reduction that could be achieved in gravity-fed irrigation networks managed by rotation rather than on-demand scheduling. To achieve this goal, the link between the flow reduction and investment cost is analyzed.

## 2 Methodology

### 2.1 Flow Reduction

In order to calculate the flows in a network, the first step is to allocate the outlets' flow rates ( $d$ ) and calculate the probability of these being opened ( $p$ ). Monserrat (2009) proposed a methodology to determine both ( $d$ ) and ( $p$ ) related to the irrigation system and farm characteristics.

In pressurized irrigation set-ups, it is unusual to water the whole farm at a time, so it is common practice to divide it into smaller zones to reduce unit area costs (€/ha). Monserrat (2009) proposed the use of the optimum irrigation block area ( $A_b$ ) based on economic analysis. The flow rate and the time needed to water the whole farm can be calculated easily once the on-farm irrigation system is defined, and the block size is determined.

Montserrat (2009) proposed Eq. (1) to calculate the maximum number of irrigation blocks ( $n_{b \max}$ ) in which a farm can be divided into based on known design variables.

$$n_{b \max} = \left\lceil \frac{q_{rg} t_{on} r_{op}}{q_{sg} 24} \right\rceil_w \tag{1}$$

where  $q_{rg}$  is the unit flow rate applied by the on-farm irrigation system ( $l \text{ s}^{-1} \text{ ha}^{-1}$ );  $t_{on}$  is the number of hours per day the network supplies water (it can be less than 24 h for multiple reasons, such as electricity tariff and adverse weather conditions);  $r_{op}$  is the operation index that is, available irrigation days during a certain period of time (e.g., 9/10, it is always less or equal than one, this considers that in a period of time, on some days will not be possible to water due to maintenance or adverse weather conditions);  $q_{sg}$  is the continuous gross specific discharge to supply crop water needs ( $l \text{ s}^{-1} \text{ ha}^{-1}$ ); and  $_w$  means the integer part.

Note that Eq. 1 only depends on variables that are defined during design. Variables such as the time needed to water an irrigation block or the irrigation frequency are not needed.

The number of irrigation blocks ( $n_b$ ) that a farm can be divided into can be calculated using Eq. (2).

$$n_b = \left\lceil \frac{A_p}{A_b} \right\rceil_w + 1; n_b \leq n_{b \max} \tag{2}$$

where  $A_p$  is the size of the farm (ha); and  $A_b$  is the size of the optimum on-farm irrigation block (ha).

To calculate the flow reduction in a pressurized irrigation network scheduled under rotation, we first analyzed the simplest case scenario, which is farms of the same size, what we called homogeneous farms.

### 2.1.1 Homogeneous Farms

**Rotation Schedule** Farms are usually divided into blocks for economic purposes and are scheduled under rotation. If a pressurized irrigation network is scheduled in the same way, the neighboring farms supplied by the irrigation network will never irrigate at the same time, they will irrigate one after another.

The number of farms that can be irrigated under a rotation ( $n_{pr}$ ) depends on the maximum number of blocks ( $n_{b \max}$ ) and was calculated using Eq. (3).

$$n_{pr} = \frac{n_{b \max}}{n_b} \tag{3}$$

A section's discharge of a rotation scheduled network ( $Q_r$ ) that supplies  $N$  farms can be calculated by Eq. (4).

$$Q_r = \left[ \left( \frac{N}{n_{pr}} \right)_w + 1 \right] d \tag{4}$$

For example, for a section delivering 10 farms when  $n_{pr} = 4$ , its capacity should be  $3 \cdot d$ .

**On-Demand Schedule** In this case, the farm outlet is also characterized by flow rate ( $d$ ) and the probability of an outlet being opened ( $p$ ) is calculated as the quotient of outlet operation time ( $n_b t_b$ , where  $t_b$  is block operation time) by the irrigation cycle time ( $n_b \max t_b$ ). The probability of an outlet being opened ( $p$ ) can be expressed using Eq. (5), (Monserrat 2009), which is the inverse of Eq. (3).

$$p = \frac{n_b t_b}{n_b \max t_b} = \frac{1}{n_{pr}} \quad ; \quad q = 1 - p \tag{5}$$

where  $q$  is the probability of an outlet being closed.

The expected flow in a section of the network can be calculated using Eq. (6) (Clément 1966). Note that this equation has been verified by other authors (CTGREF 1974; Lamaddalena and Sagardoy 2000; Monserrat et al. 2004) and is only valid for homogeneous farms.

$$Q_d = N p d + U \sqrt{N p q d^2} \tag{6}$$

where  $N$  is the number of farms supplied by the network section,  $p$  is the probability of an outlet being opened, and  $U$  is the value of the standard normal variable for the level of service (the probability of  $Q$  being less or equal than  $Q_d$ ).

For homogenous farms, the result of Eq. (6) must be a multiple of ( $d$ ), something which is unusual. To accomplish the aforementioned condition, Eq. (7) was used to calculate the expected flows in the on-demand network section.

$$Q_d = \left[ \left[ N p + U \sqrt{N p q} \right]_w + 1 \right] d \tag{7}$$

Equation (8) was obtained from Eqs. (4) and (7), which allows the calculation of the relative flow reduction of a rotation schedule in relation to on-demand schedule:

$$\frac{\Delta Q}{Q} = \frac{Q_d - Q_r}{Q_d} = 1 - \frac{Q_r}{Q_d} = 1 - \frac{[N p]_w + 1}{[N p + U \sqrt{N p q}]_w + 1} \tag{8}$$

Note that the above equation only depends on two variables, ( $N$ ) and ( $p$ ).

### 2.1.2 Heterogeneous Farms

Considering that the supplied volume must be equal to the volume used, it can be demonstrated that the area that the outlet flow rate ( $d$ ) can irrigate is  $A_b n_b \max$ .

Equation (4) was transformed into Eq. (9) for rotation scheduling.

$$Q_r \left[ \left( \frac{\sum_i A_{p_i}}{A_b n_{bmax}} \right)_w + 1 \right] d \tag{9}$$

Equations 9 and 10 assume that discharges allocated to all plots are the same but not the probability; this is possible when the farm size is smaller than  $A_b n_{bmax}$  as demonstrated in Monserrat (2009). If bigger plots exist, their discharge should be added to Eq. 9 or 10.

For the on-demand scheduling, Eq. (7) was transformed into Eq. (10).

$$Q_d = \left[ \left[ \sum p_i + U \sqrt{\sum p_i q_i} \right]_w + 1 \right] d \tag{10}$$

These equations were applied to a real pressurized irrigation network at Algerri-Balaguer district (Spain), called Network 2, which is fed by an elevated reservoir. Table 1 shows the main characteristics of Network 2, the total delivery area, the number of farms, and the variability of the farm size.

The on-farm irrigation system is sprinkler-based, so it has been considered that the unit flow rate for the sprinklers systems ( $q_{rg}$ ) is  $15.4 \text{ l s}^{-1} \text{ ha}^{-1}$  (Monserrat 2009), the number of hours farmers can irrigate a day ( $t_{on}$ ) is 16 h, the operation index ( $r_{op}$ ) is 1, the optimum size of the on-farm irrigation block ( $A_b$ ) is estimated as 0.5 ha, and the gross water need ( $q_{sg}$ ) is  $0.6 \text{ l s}^{-1} \text{ ha}^{-1}$ .

The outlet flow rate ( $d$ ) was allocated following the methodology proposed in Monserrat (2009). When the size of the farm ( $A_p$ ) is  $\leq 8.5$  ha, the outlet flow rate ( $d$ ) is 7.72 l/s. When the size of the farm ( $A_p$ ) is  $> 8.5$  ha, the outlet flow rate ( $d$ ) is  $0.91 \cdot A_p$  l/s.

### 2.2 Economic Savings

From a designer’s point of view, it would be interesting to estimate the achievable cost reduction with a rotation schedule. In order to estimate cost reduction, three particular cases of existing pressurized irrigation networks, and three theoretical networks (Table 2) were analyzed. In fact, the existing networks are three branches of a network, assumed independent and illustrated in Fig. 1. Network 2 was described previously.

The irrigation system and crop data are the same as Network 2 (refer to the info provided before Table 1). The theoretical networks (4, 5, and 6) are linear (that is, with plots aligned in one line), assuming homogeneous plots and the same total network area of 48 ha (Table 2).

Considering the data of outlet elevations, required pressures, section’s length, and pipe database, the diameters were sized using the GESTAR software (Aliod and González 2007), which provides the optimal solution for the irrigation network. Only the pipe’s cost was considered. The flows were calculated using an Excel spreadsheet.

**Table 1** Main characteristics of the Network 2

Network	Area (ha)	N	$A_{p\text{ avg}}$ (ha)	CV (%)	$p_{\text{avg}}$ (Eq. 5)
2 best centered	484.9	183	2.65	155	0.35

**Table 2** Basic data for networks

Network	Total Area (ha)	$N$	$A_{p\text{ avg}}$ (ha)	CV (%)	$p_{\text{ avg}}$
1	350.4	66	5.31	121	0.65
3	387.7	148	2.62	215	0.35
4	48	96	0.5	0	0.06
5	48	24	2	0	0.24
6	48	12	4	0	0.48

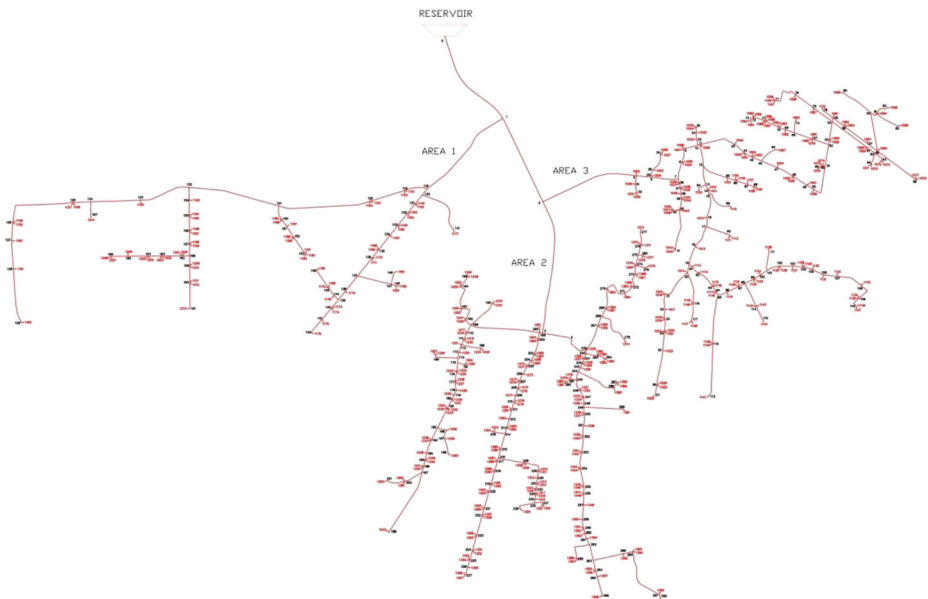
## 3 Results

### 3.1 Flow Reduction

#### 3.1.1 Homogeneous Farms

Figure 2 shows the results obtained using Eq. (8) when  $(p)$  is between 0.1 and 0.7. The considered level of service for the on-demand scheduling was 95% ( $U = 1.65$ ). The maximum relative flow reduction was achieved when only a few farms were supplied, being around 50% or more. The flow reduction increased when  $(p)$  decreased because of smaller farms are considered (Eqs. 2 and 5).

The probability  $(p)$  is independent of the irrigation frequency because it does not appear in Eq. (5). The person responsible for managing the irrigation network will decide the frequency, taking into consideration the soil characteristics and the crops grown in the area. The farmer will calculate the time needed for irrigation based on this frequency. It is also important to mention that the number of farms that can be irrigated under a rotation schedule does not depend on the frequency (Eq. 3).



**Fig. 1** Sketch of the three irrigation networks (red marks are outlets, and black marks are nodes)

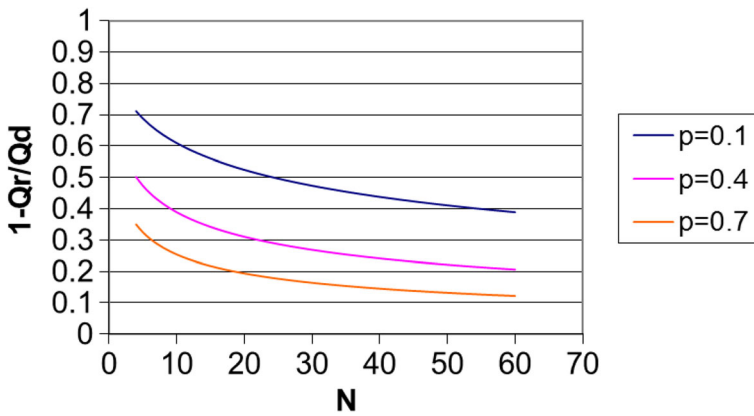


Fig. 2 Relative flow reduction at the network head under a rotation schedule based on the number of farms supplied ( $N$ ) and the probability of the outlets being opened ( $p$ )

### 3.1.2 Heterogeneous Farms

Figure 3 shows the relative reduction in the section’s flows for Network 2 under different hypotheses. Figure 3a compares the estimated reduction using Eq. 8 (assuming homogeneous farms) with the relative reduction using a manual procedure to calculate flows under a rotation schedule (Alduan and Monserrat 2009). Note that Eq. 8 tends to overestimate the flow reduction because the points are below the bisection line. It has been observed that differences between estimated and real section’s discharges are bigger at the ending sections, and lower in those close to the water source.

Figure 3b shows a better correlation than Fig. 3a, being the average error between the estimation and the calculation only 0.05.

The effect of increasing the network operating time from 16 to 24 h and the flow rate of the on-farm irrigation system ( $q_{fg}$ ) from 15.44 to 20 l s<sup>-1</sup> ha<sup>-1</sup> was assessed using Eq. (8).

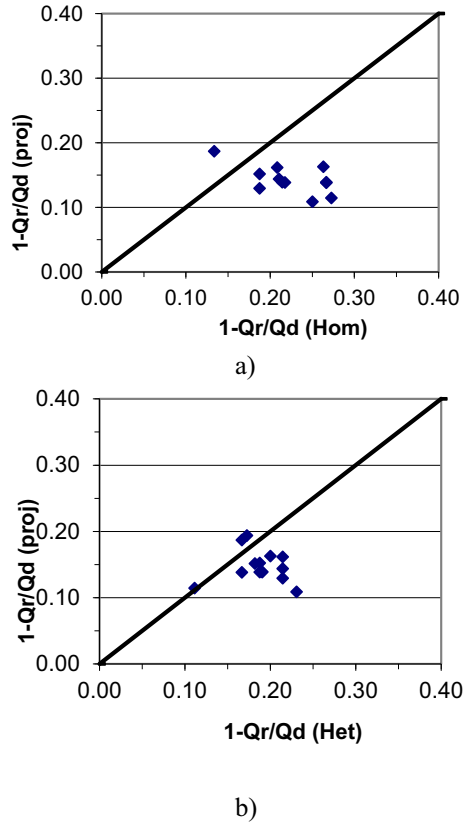
Table 3 shows that when the probability ( $p$ ) decreases, the flow reduction increases (but not as much as the probability).

### 3.2 Economic Saving

Table 4 shows that the average relative flow reduction is higher in Networks 2 and 3 than in Network 1 due to it supplying smaller farms. This is consistent with what was outlined previously. The flow reduction for Networks 4, 5, and 6 are similar even though the characteristics of the networks are different. Network 4 supplies small farms, but many, whereas Network 6 supplies big farms but fewer.

Analyzing the relative cost reduction, two groups of networks can be defined. On one side, Networks 1, 2, and 3, with low-cost reduction, and on the other, Networks 4, 5, and 6 with a higher-cost reduction. These results can be accounted for by the fact that the first group of networks is big, which implies big diameters at the beginning of the network, with higher relative cost, as could be seen in Fig. 4. This implies the flow reduction at the ending sections, by rotation scheduling, is not very relevant to the cost reduction. Whereas the other network’s group has a smaller area, in which a flow reduction has a higher impact on cost.

**Fig. 3** Comparison of flow reduction calculated with the proposed equations and manually (proj), assuming homogeneous farms (a) and heterogeneous farms (b). Network 2



Regarding the ratio between cost reduction and flow reduction, this ranges between 0.26 and 0.63 (mean, 0.50). This ratio might be used to roughly estimate the cost reduction from the relative flow reduction.

Figure 4 shows that the impact of large diameters in the total network’s cost is much higher than those of small diameters. A variation in relative cost for one diameter is related to a total length variation for this diameter because the pipe’s cost is the same. In the rotation schedule, an important reduction in the 800 and 500 mm length was observed. A subsequent increase in the length of smaller diameters to compensate for this reduction can also be observed.

Figure 5 shows the comparison between the expected flows under a rotation schedule and the on-demand schedule for Networks 1–2–3 joined as a whole. The average flow decrease under a rotation schedule was 28%. The reduction decreases when the flows are high, which is consistent with what was observed in Fig. 2.

**Table 3** Flow reduction in Network 2

Network	<i>N</i>	$t_{on} = 16 \text{ h}, q_{rg} = 15,44 \text{ s}^{-1} \text{ ha}^{-1}$		$t_{on} = 24 \text{ h}, q_{rg} = 20 \text{ l s}^{-1} \text{ ha}^{-1}$	
		$p_{avg}$	$1-Q_{0r}/Q_{0d}$ (Eq. 8)	$p_{avg}$	$1-Q_{0r}/Q_{0d}$ (Eq. 8)
2	183	0.35	0.14	0.18	0.19



**Table 4** Average relative flow reduction and relative cost reduction

Network	$(\Delta Q/Q)_{avg}$	$\Delta C/C$	$\Delta C/C / (\Delta Q/Q)_{avg}$
1	0.12	0.05	0.41
2	0.19	0.09	0.49
3	0.20	0.05	0.26
4	0.38	0.24	0.63
5	0.35	0.21	0.60
6	0.32	0.20	0.62

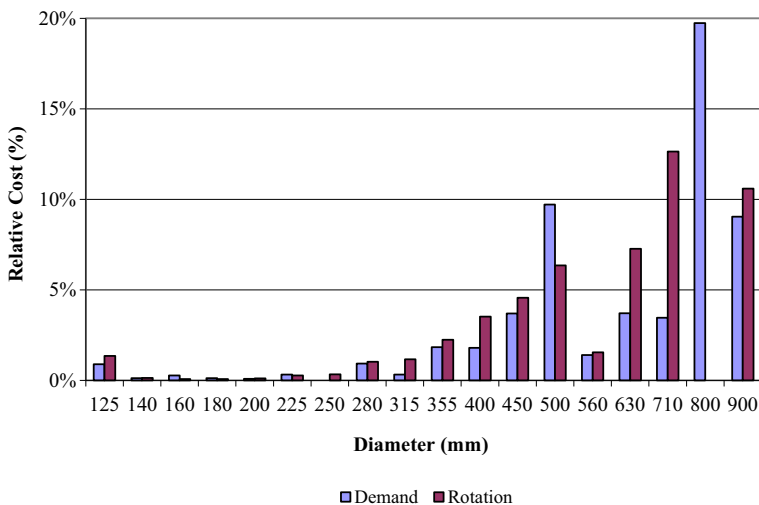
The achieved cost reduction is around 15%, with a cost to flow reduction ratio of 0.53. Garcia Asín et al. (2011) assessed cost reduction related to different irrigation scheduling (on-demand and rotation) in a network supplying 122.4 ha. From their results, the cost and flow reduction ratio was 0.66, which is similar to the data shown in Table 4.

### 3.3 Heterogeneous Crops

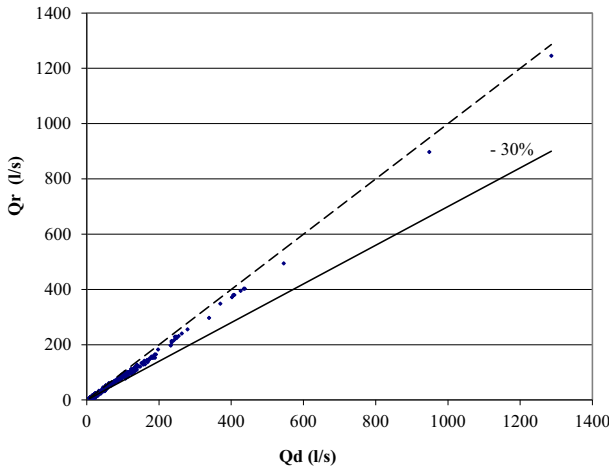
The variability of crops and, therefore, the variability in water requirements in an irrigation area could be high. The results shown above were obtained, calculating flows based on the average water needs of the irrigation area.

To analyze the effect of having heterogeneous crops, three different water requirements (0.3, 0.6, and 0.9 l s<sup>-1</sup> ha<sup>-1</sup>) were assigned randomly to different farms without exceeding the average water needs.

The expected flows in the network were calculated for this scenario and compared with the calculated flows, considering the average water requirements. Figure 6 shows that the maximum increase in flows for heterogeneous crops is equal to the flow rate of one outlet. Thus the flexibility of the network was increased considerably by adding only the flow rate of one outlet to those used to size the pipes under a rotation schedule. The cost of the network increased by only 3%.



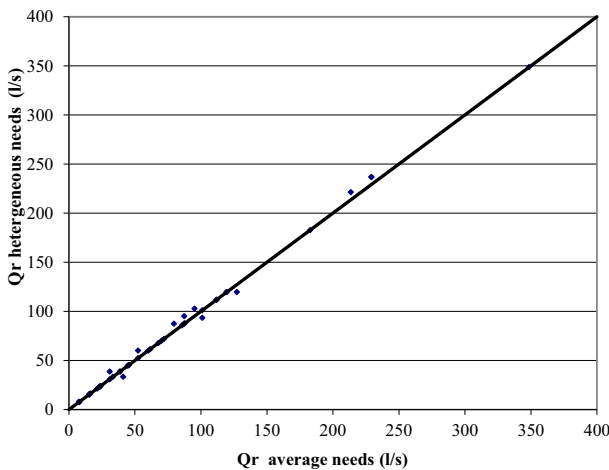
**Fig. 4** Relative cost for the different diameters for on-demand and rotation schedule



**Fig. 5** Comparison of the flows achieved under rotation ( $Q_r$ ) and on-demand ( $Q_d$ ) schedules. Bisection line (dashed), 30% flow reduction (continuous line)

### 4 Conclusions

The relative reduction in section’s flow with rotation respect on-demand scheduling could be estimated with simple formulas assuming average plot sizes. More precision could be achieved if real plot sizes are taken into account. Relative flow reduction is higher in sections that supply few and small plots. As the number of supplied plots increases, relative flow reduction decreases. The presented equations were applied to different networks, and the results obtained were very accurate, with an average error of just 5%. The average network’s cost reduction, when managed under a rotation schedule, was about 14%. Higher cost reduction might be achieved in smaller networks.



**Fig. 6** Comparison between the flows calculated considering average needs and those calculated considering heterogeneous needs

An average ratio of 0.50 was found between the cost reduction and the flow reduction for the different analyzed networks. This ratio might be used to roughly estimate the cost reduction from the relative flow reduction.

The flexibility of the network is increased by only adding the flow rate of one outlet to those used to size the diameters of the network. This solution covered the issue of having different crops with different water needs, and although it increased cost, the magnitude of the increase was small.

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**Data Availability** All the data used for this study can be provided by the authors upon request.

## Compliance with Ethical Standards

**Conflict of Interest** None.

## Glossary

$()_w$	means to round down.
$A_b$	is the optimum on-farm irrigation block (ha).
$A_p$	is the size of the farm (ha).
$d$	is the flow rate of an outlet ( $l\ s^{-1}$ ).
$N$	is the number of farms supplied.
$n_b$	is the number of on-farm irrigation blocks.
$n_{b\ max}$	is the maximum number of on-farm irrigation blocks.
$n_{pr}$	is the number of farms under a rotation schedule.
$p$	is the probability of an outlet being opened.
$q$	is the probability of an outlet being closed.
$Q_d$	is the flow for on-demand networks ( $l\ s^{-1}$ ).
$Q_r$	is the flow for networks under a rotation schedule ( $l\ s^{-1}$ ).
$q_{rg}$	is the flow rate of the on-farm irrigation system ( $l\ s^{-1}\ ha^{-1}$ ).
$q_{sg}$	is the water requirements of the crops ( $l\ s^{-1}\ ha^{-1}$ ).
$r_{op}$	is the operation index.
$t_{on}$	is the time the network is working a day (h).

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