RESEARCH ARTICLE

Adaptation of irrigation networks to climate change: Linking robust design and stakeholder contribution

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Abstract

Agriculture is a particularly sensitive sector to the potential impacts of climate change. Thus, irrigation infrastructure is required to be robust to cope with these potential threats. The objective of this research is designing more robust irrigation networks, considering cost and stakeholder contribution. To that end, the investigation was addressed in three phases: a sensitivity analysis to understand the effectiveness of the distinct variables, a cost-effectiveness analysis assessing their efficiency, and a global study of the most efficient variables to provide an insight into their function. The sensitivity analysis indicates that the networks oversized by means of the coefficient of utilisation or the factor of safety, behave better than those oversized via the continuous specific discharge; moreover, the degree of freedom has been shown ineffective. The cost-effectiveness analysis shows that the coefficient of utilisation and the factor of safety are the most efficient variables, as they introduced safety margin oversizing fewer network elements and to a lesser extent than the continuous specific discharge. It also shows that stakeholder contribution, conveyed as a reduction of the degree of freedom, plays an important role in the network's adaptive capacity to change. The global study of these variables reveals the subtlety of the coefficient of utilisation, which is the variable that better reproduces the farmer behaviour during demand increase scenarios. In conclusion, the results identify the coefficient of utilisation as the variable which provides the safest margins and reveal the importance of stakeholder contribution in absorb the demand increase in a better manner.

Additional key words: Clément's First Formula; coefficient of utilisation; degree of freedom; demand increase; discharge determination; factor of safety; stakeholder contribution.

Abbreviations used: DF (degree of freedom); FC (farmer collaboration); k (factor of safety); OQ (operation quality); q (continuous specific discharge); r (coefficient of utilisation of the network); U (standard normal variable).

Introduction

Records obtained over the past decades have shown that there has been a gradual increase in mean temperatures. Climate models predict that such a growing tendency could not only continue but also influence other climate variables, such as frost and rainfall (IPCC, 2013). The close relationship between climate and agriculture makes agriculture particularly sensitive to the potential impacts of climate change (Moriondo *et al.*, 2010; Iglesias *et al.*, 2012). Climate change may lead to modifications in cropping patterns, crop water requirements and, among others, the seasonal distribution of water demand. As these are determinants of effective water demand, impact may affect the quality of irrigation (Rodríguez-Díaz *et al.*, 2007a; Daccache *et al.*, 2010a; Pérez-Urrestarazu *et al.*, 2010; Maeda *et al.*, 2011). Besides climate change, there are other determinants that could also lead to variations in the cropping pattern and modify water requirements, such as: the agricultural markets evolution, the agricultural and hydraulic policy or the introduction of new laws and standards (Berbel & Gutiérrez, 2006; Gianoccaro & Berbel, 2011; Dury *et al.*, 2012; Rinaudo *et al.*, 2013).

The aforementioned may adversely affect the performance of irrigation networks as a consequence of the consequent total or seasonal demand increase. One way of adapting irrigated agriculture to climate change is the design of robust infrastructure (Iglesias *et al.*, 2011). The irrigation network design is required to consider this, given that demand greater than the existing at the design period may have to be met during the operational life. Therefore, the design should provide safety margin for backing future service changes (Granados, 2013). Such a cushion should be added during the project phase, as once the network is in operation resolving performance problems becomes more complex, inopportune and expensive (Lamaddalena & Sagardoy, 2000).

Computing of the peak design flows is one phase of the design process where safety margins should be introduced. One model designed to compute the discharges that has been widely used is that proposed by Clément in 1966. Its first generalised formula (Clément's First Formula) has been contrasted in several studies that considered it appropriate for the design of on-demand irrigation networks, although it should be noted some of its base assumptions show certain degrees of inaccuracy (Abadía, 2003; Monserrat *et al.*, 2004; Íniguez-Covarrubias *et al.*, 2007; Rodríguez-Díaz *et al.*, 2007b).

The abovementioned discharges were defined on the basis of: cropping patterns, service conditions and water requirements. All these factors are collected through the irrigation variables; that is to say, the continuous specific discharge, degree of freedom, operation quality, and safety coefficients (Granados, 1986; Labye *et al.*, 1988; Lamaddalena & Sagardoy, 2000).

The *continuous specific discharge* (q) is the flow which should be supplied continuously during the total operating time of the network to provide crop water requirements. This value is usually referred to as the peak season and average cropping pattern.

The *degree of freedom* (DF) is the ratio between the operating time of the network (t) and the required time that the farmer has to open the hydrant to meet the demands of the average cropping pattern during the peak season (t') (Granados, 1986) (Eq. [1]). For a DF=1, in satisfying water requirements the farmer would be obliged to irrigate continuously. Hence, this represents a level of comfort afforded to the farmers that permits them to organise their activities. The DF is usually assigned by being based on the size of the plot. Large plots have a lower DF than small plots. That is to say, farmers with small plots are granted more time to manage their irrigation.

$$DF = \frac{t}{t'} \qquad [1]$$

The *operation quality* (OQ) is the statistical probability used for selecting the design flow. It represents the percentage of the discharge demanded by the network that does not exceed the design flow.

The safety coefficients are the variables for oversizing the network which enable it to cope with larger demand during operation. The following two safety coefficients have been traditionally used: the *coefficient of utilisation of the network* (r) and the *factor of safety* (k). The first, a specific coefficient for on-demand irrigation networks (proposed by Clément in 1966), has been widely used. The coefficient of utilisation is the ratio between the time in which the network satisfies the demands (t") and the operating time of the network (t) (Granados, 1986) (Eq. [2]). Furthermore, the factor of safety is a typical multiplier that linearly increases the discharges which result from Clément's First Formula.

$$r = \frac{t''}{t} \qquad [2]$$

The discharge determination process consists of the following: allocating the hydrant discharge, determining the probability of utilisation of the hydrants and calculating discharge by means of a statistical formula.

The first step is the determination of the flows allocated to each plot i which is the hydrant discharge (d_i). Allocation is established by being based on two irrigation variables: the continuous specific discharge and the DF, and the plot area (A_i) (Eq. [3]). The product of the continuous specific discharge and the area represents the continuous flow for attending the average water requirements of the cropping pattern. As the DF oversizes the discharges, the farmers are not obliged to irrigate continuously during the peak season.

$$d_i = qA_iDF_i \qquad [3]$$

The second step is the calculation of the probability of utilisation of each hydrant (p_i) (Eq. [4]). The probability that a hydrant is open is a function of the time allowed to provide the required volume of water demanded by the crop. This time is influenced by two variables: the DF and the coefficient of utilisation. The first increases the hydrant discharge that provides farmers with time to address demand, while the second oversizes the network to enable it to supply the water requirements in a smaller time than the total operating one. If these parameters are not introduced the probability would be 1; however, if they are taken into account the probability decreases, given by:

$$p_i = \frac{1}{DF_i r} \qquad [4]$$

The third step consists in the computation of the design flows. Flows are computed by means of Clément's First Formula (Clément, 1966) (Eq. [5]):

$$Q = \sum_{i=1}^{n} p_i d_i + U \sqrt{\sum_{i=1}^{n} p_i d_i^2 (1 - p_i)} \qquad [5]$$

where Q is the flow rate of the section under consideration, which supplies n plots downstream; and U is the standard normal variable, which is a function of the operation quality. The first term of Clément's First Formula represents the mean (μ) and the second term the standard deviation (σ) (Clément, 1966) (Eq. [6]).

$$Q = \mu + U \cdot \sigma \qquad [6]$$

Clément's First Formula results may be directly multiplied by a factor of safety to oversize the design flows (Granados, 2013) (Eq. [7]).

$$Q = \sum_{i=1}^{n} p_i d_i + U \sqrt{\sum_{i=1}^{n} p_i d_i^2 (1 - p_i)} \; k \qquad [7]$$

The application of this formula directly involved the use of two irrigation variables: the operation quality and the factor of safety.

As may be observed, all the irrigation variables intervene in the discharge determination process. Thus, all could influence the resulting design flows and all may be used for oversizing the network. Nonetheless, each variable may influence discharges in distinct ways and to a different extent. Consequently, the safety margins are added with distinct costs and varying degrees of effectiveness for meeting increases in future demand (Granados, 2013).

The objective of this research is adding knowledge of the role and influence of each variable and determining which may improve the robustness of the network effectively and efficiently. In this context, *effectively* means that the network oversize helps for satisfying demand increments; and *efficiently* implies that such effectiveness is achieved by using the minimum possible resources. A deeper understanding of this could help in the design of robust irrigation infrastructures which, it might be argued, could satisfactorily cope with demand increases deriving from climate change or other determinants.

Material and methods

The research was addressed in the three following phases (Fig. 1): i) Performing a sensitivity analysis to determine the effectiveness of the safety margins added by the different variables; ii) Conducting a cost-effectiveness analysis of the groups that had previously shown a better performance with the objective of studying their efficiency; iii) Analysing the variables which offered the best cost-effectiveness ratio, with a detailed study of their influence in distinct parts of the network (head, intermediate, and tail sections).

Sensitivity analysis

A sensitivity analysis was performed to evaluate the ability of the irrigation variables for improving system robustness, that is to say, their effectiveness. The study involved calculation and analysis of eight cases: a base-case in which the network was designed without any safety margin and seven cases in which margins were introduced via distinct irrigation variables. The safety margin was considered as the relative discharge increment in design conditions with respect to the base-case ($\Delta Q1$) (Eq. [8]). The analysis of each case was performed under the following two scenarios: Q1, studied the flow rates under the design conditions, and Q2, the flow rates under a 40% increase in the initial estimates.
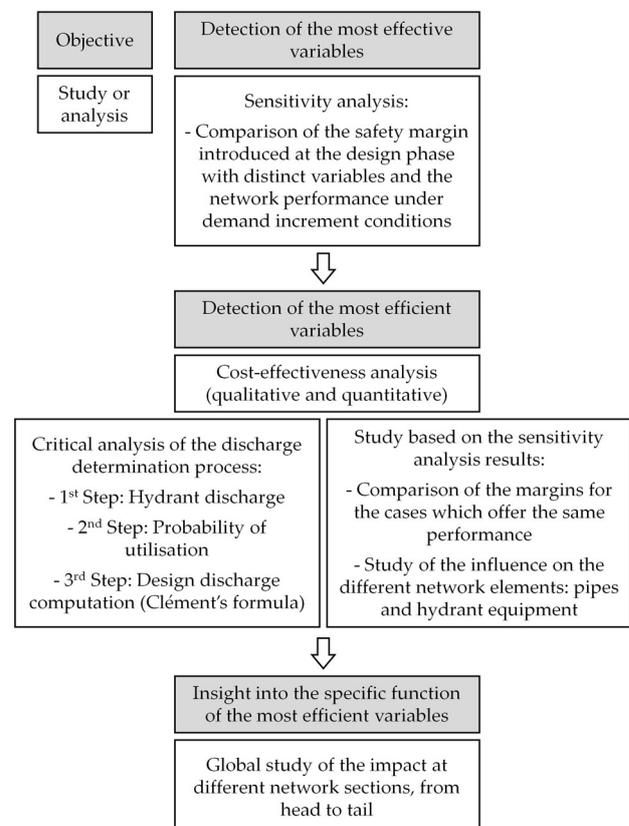

Figure 1. Methodology.

The comparison of the cases in relation to the base one (Q1 *vs*. Q1-base) allowed the variables for oversizing the network to be examined. In addition, comparison of the results obtained from each scenario (Q1 *vs*. Q2) showed how this oversize could cope with greater demands and thus determine the effectiveness of using each variable.

$$\Delta Q1 = \frac{Q1 - Q1\text{base}}{Q1\text{base}} \cdot 100 \qquad [8]$$

Climate change is one of the drivers which may lead to demand increases. Several studies have evaluated the impact of climate change on irrigation water requirements. Döll (2002) conducted a global-scale analysis and concluded that by 2070 net irrigation requirements would raise from 5 to 8%. The study also highlighted a large spatial variability with increases of up to 30% in certain areas. Fischer *et al*. (2007) provided insight into impacts at regional scale, quantifying the increase for developed regions from 36% to 45% by 2080. Other authors analysed the impact at a basin or irrigation district scale. For instance, Rodríguez-Díaz *et al*. (2007a) predicted an increase of seasonal demand from 15% to 20% by 2050 in the Guadalquivir River Basin in Spain, Daccache *et al*. (2010a) a 27% demand increment by 2050 in the Sinistra Ofanto irrigation district in Italy, and Pérez-Urrestarazu *et al*. (2010) foresaw a 33% increase by 2050 and 45% by 2080 in the Fuente Palmera irrigation district in Spain, considering no adaptation in the cropping pattern.

In this study, scenario Q2 assessed the network performance under increased demand conditions. The network performance was assessed by using the deficit between the design conditions and the demand increment situation (Eq. [9]). In this framework, the selected 40% increase represents an extreme climate change projection that was purposely chosen to highlight the difference among cases studied.

$$Deficit = \frac{Q2 - Q1}{Q1} \cdot 100 \qquad [9]$$

Here an irrigation network that supplies 100 homogeneous plots of area A has been analysed. The continuous specific discharge was q (the resulting value for the average cropping pattern during the peak season). The other irrigation variables were set within the usual ranges of design in the professional practice (IRYDA, 1985; Labye *et al*., 1988; Lamaddalena & Sagardoy, 2000).

Table 1 shows the characteristics of the eight cases analysed. Case 1-base overlooks the respective safety margin. Cases 2, 3, 5 and 7 are characterised because each variable was modified by 20%: Case 2 used a coefficient of utilisation equal to 20/24, that when applied in the denominator of Equation 4 becomes equivalent to a multiplayer of the value 24/20 (*i.e*. 1.20); Case 3 a continuous specific discharge equal to 1.2·q; Case 5 a DF=3.6; and Case 7 a factor of safety equal to 1.2. On another note, cases 2, 4, 6 and 8 are characterised because they provide the same design discharge, with it been oversized by using distinct variables. Case 2 used a coefficient of utilisation 20/24, Case 4 a continuous specific discharge 1.168·q, Case 6 a DF=7.83 and Case 8 a factor of safety 1.168.

In addition, it may be also observed how the variables change as demand increases from the design conditions (Q1) to the demand increment conditions (Q2): (i) the continuous specific discharge became 1.4·q, since an increase of 40% was analysed; (ii) the DF reduces as demand rises; once the network is built and in operation, should a farmer need a greater volume of water the only

Table 1. Sensitivity analysis. Characteristics of the cases studied.

Case	Basic descriptor of the case	Scenario Q1 (design conditions)				Scenario Q2 (40% demand increment)			
		q	DF	r	k	q	DF	r	k
1-base	No margins	q	3	1	1	1.4·q	2.14	1	1
2	r = 20/24	q	3	20/24	1	1.4·q	2.14	1	1
3	q = 1.2 · q	1.2 · q	3	1	1	1.4·q	2.57	1	1
4	q = 1.168 · q	1.168 · q	3	1	1	1.4·q	2.50	1	1
5	DF = 3.6	q	3.6	1	1	1.4·q	2.57	1	1
6	DF = 7.83	q	7.83	1	1	1.4·q	5.59	1	1
7	k = 1.2	q	3	1	1.2	1.4·q	2.14	1	1
8	k = 1.168	q	3	1	1.168	1.4·q	2.14	1	1

All cases were analysed with an operation quality OQ=96% (U=1.75).

alternative would be to maintain the hydrant open for a longer duration as the hydrant discharge is constant; (iii) the coefficient of utilisation of the network became equal to 1, given that the Q2 scenario analysed the network response when the safety margin was consumed; (iv) the factor of safety, in a similar way, became 1 when evaluating the Q2 scenario; (v) the operation quality remained constant in both scenarios. This is the variable that statistically characterises the service. In Clément's First Formula it influences the standard deviation (Eq. [6]), that is to say, the dispersion of the open hydrants of the sample. Consequently, its influence is more significant in the sections that supply a small number of plots, and less significant in the trunk mains which serve a greater number of plots (Monserrat *et al.*, 2013). If the value of the operation quality increases, the resulting flow rate will be greater and the network would be oversized. This additional margin, though, does not provide robustness to the system, given that the increase in demand would be served by sacrificing the quality of the service (Granados, 2013).

Cost-effectiveness analysis

The sensitivity analysis shows the variables effectiveness to improve the network robustness. Apart from this, it is also necessary to assess the respective efficiency, that is to say, the economic impact of each variable in achieving a given effectiveness. For such a reason a cost-effectiveness analysis has been carried out. This consists of both a critical examination of the design process and a study based on the results of the sensitivity analysis.

The critical analysis of the design process was carried out with the aim of determining which of the network elements (trunk mains, distribution mains, service pipes and hydrant equipment) are affected by each variable. It consisted of the examination of the discharge allocation process, at the head and tail sections, in relating the variables with the design discharges of the different elements.

The cost-effectiveness study is based on cases 2, 3 and 8 of the previous sensitivity analysis, in which design discharges were oversized by means of the coefficient of utilisation, continuous specific discharge and factor of safety, respectively. These cases were selected because they provided the same network performance when demand increased. Not a single case in which the DF was used for adding a safety margin was selected for the study, since this variable was shown to be ineffective in addressing the demand increase, as further explained in the results and discussion sections.

In line with the objective of the study, the results of the sensitivity analysis (design discharges at the head section) were complemented with the calculation of the design discharges at a terminal section which supplied one plot, and with the determination of a parameter which characterised the stakeholder contribution to adaptation, named *farmer collaboration* (FC). Accordingly, the discharge allocation for one plot was calculated with Eq. [3] (as it coincides with the hydrant provision) and farmer collaboration computed as the percentage reduction of the DF (Eq. [10]).

$$FC = \frac{DF_{Q1} - DF_{Q2}}{DF_{Q1}} \cdot 100 \qquad [10]$$

Study of the safety factors function

The coefficient of utilisation and the factor of safety are shown as the most effective and efficient variables in increasing network robustness. In order to acquire deep knowledge of the specific function performed by each, their effect has been evaluated in various cases and sections located along the network from head to tail.

Therefore, this study analysed a network that supplies water to 400 homogeneous plots, evaluated under the following two scenarios: the first having resulted from oversizing the network by using the coefficient of utilisation (Qr); and the second having arisen from oversizing it with the factor of safety (Qk). Accordingly, calculations were performed for three cases: Case 'a' in which both variables were selected so that the introduced margin matches in the head section (the section which supplies the 400 plots); Case 'b' in which the variables were selected in order to include the same margin at an intermediate section (with supply to 100 plots); and Case 'c' in which the variables were adjusted at the tail (supply of 10 plots). The relative discharge variation (ΔQ_{rel}) among the abovementioned scenarios was also determined (Eq. [11]), as a complement for explaining the impact of these variables along the network.

$$\Delta Qrel = \frac{Qk - Qr}{Qr} \cdot 100 \qquad [11]$$

The rest of the variables were selected by using the same criteria as in the sensitivity analysis. Therefore, it was assumed that the plots have an area A=A, the continuous specific discharge is q=q, the DF=3 and the operation quality is OQ=96% (U=1.75). Table 2 summarises the values of the variables used.

Table 2. Study of the safety factors function. Characteristics of the cases studied.

Case	Basic descriptor of the case	Scenario Qr		Scenario Qk	
		r	k	r	k
a	Adjustment at the head section (400 plots)	20/24	1	1	1.182
b	Adjustment at an intermediate section (100 plots)	20/24	1	1	1.168
c	Adjustment at the tail section (10 plots)	20/24	1	1	1.129

All cases were analysed for a continuous specific discharge q=q, a degree of freedom DF=3, and an operation quality OQ=96% (U=1.75).

Table 3. Results of the sensitivity analysis.

Case	Discharge rate at head section		Relative discharge increment ($\Delta Q1$)	Deficit
	Scenario Q1 (design conditions)	Scenario Q2 (40% demand increment)		
1-base	124.75·Aq	166.16·Aq	0 %	33.2 %
2	145.72·Aq	166.16·Aq	16.8 %	14.0 %
3	149.70·Aq	170.71·Aq	20.0 %	14.0 %
4	145.71·Aq	170.00·Aq	16.8 %	16.7 %
5	128.21·Aq	170.71·Aq	2.7 %	33.1 %
6	145.73·Aq	192.49·Aq	16.8 %	32.1 %
7	149.70·Aq	166.16·Aq	20.0 %	11.0 %
8	145.72·Aq	166.16·Aq	16.8 %	14.0 %

Results

Sensitivity analysis

The results of the eight cases studied in the sensitivity analysis are shown in Table 3. Regarding the discharge evolution for Case 1-base (without safety margins), it could be observed that adjustment of the DF, from 3 (in scenario Q1) to 2.14 (in scenario Q2), help to meet the increased demand. With this adjustment the discharge under such a demand increase scenario is Q2=166.16·Aq and the deficit is 33.2%. In another sense, if this adjustment was not made (that is to say, there is no stakeholder contribution), the Q2 discharge would be computed with a DF=3. Thus, it would have been Q2=174.75·Aq, with a 40% deficit (identical to the demand increase considered).

The results of cases 2, 3, 5 and 7 (each with an irrigation variable modified by 20%), show that discharges under design conditions (scenario Q1) are greater than that of Case 1-base; with increases that range from 2.7% to 20.0%. This indicates that all the irrigation variables could be used to oversize the network to different extents. It is also noted that the mar-gins helped to relieve the rise in demand, reducing the 33.2% deficit of Case 1-base to values to 11% (Case 7). Nonetheless, Case 5 (with the DF increased by 20%), did not produce any benefit to the network, with the deficit being 33.1%.

Cases 2, 4, 6, and 8 analysed networks with the same Q1 (*i.e.* equally oversized at the study section). The variables were selected to introduce the same margin in the design scenario ($\Delta Q1$=16.8%). The contrast identified in these cases is enlightening, given that it shows that effectiveness varies from one case to another. The deficit that arises in scenario Q2 (a 40% demand increase) is 14% for Case 2 and Case 8, 16.7% for Case 4 and 32.1% for Case 6. This indicates that the margins introduced by the coefficient of utilisation and the factor of safety behave in a better manner (that is to say, they were more efficient) than those introduced by the continuous specific discharge or the DF. This last shows a limited contribution to palliating the deficit that arises in scenario Q2.

Figure 2 represents the results of cases 1-base, 2, 4, 6 and 8, complementing the interpretation of the numerical values of Table 3. The points located above the diagonal indicate that the network is unable to meet the
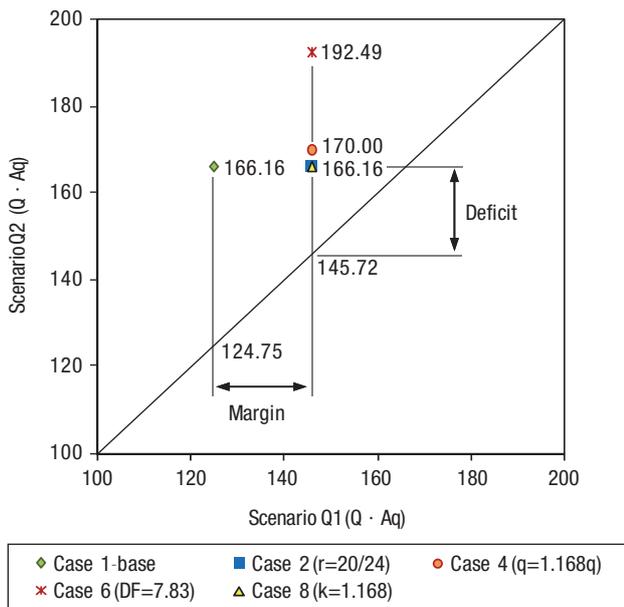
Figure 2. Sensitivity analysis. Comparison under scenarios Q1 (design conditions) and Q2 (40% demand increase).

Table 4. Results of the cost-effectiveness study.

Case	Head section (100 plots)		Hydrant (1 plot)		Farmer collaboration (FC)
	ΔQ1	Deficit	ΔQ1	Deficit	
2	16.8 %	14.0 %	0%	0%	28.7 %
3	20.0 %	14.0 %	20%	0%	14.3 %
8	16.8 %	14.0 %	0%	0%	28.7 %

ΔQ1: Relative discharge increment

demands of the scenario Q2. In such cases, the vertical distance between the point and diagonal represents the deficit. In the half below the diagonal the supply is fully satisfied, with the distance representing the surplus. Given that the Case 1-base serves as a reference, it could be observed that the other cases shifted to the right (a greater discharge in scenario Q1). This shift represents the safety margin introduced during the discharge determination phase. The points which represent cases 2, 4, 6 and 8 are located on the same vertical (Q1=145.72·Aq), which indicates that the margin introduced is equal in all of them. Nevertheless, as they are not located on the same horizontal this margin does not perform equally when demands grow. The points which are vertically closer to the diagonal have a smaller deficit which indicates that the introduced margin was more effective in coping with the demand increment. These points correspond to Case 2 and Case 8, in which the network was oversized by means of the coefficient of utilisation and the factor of safety. Moreover, it is also shown that the behaviour of the margin introduced via the continuous specific discharge (Case 4) is less effective and that the margin provided by the DF (Case 6) is ineffective.

Cost-effectiveness analysis

The critical analysis of the calculation process gives a first approximation of how the variables intervene in the design discharge determination at distinct network points, directly related with the sizing of the network components and the cost.

As a result of this analysis it has been observed that the use of the continuous specific discharge or the DF affects the hydrant discharge allocation directly and linearly (Eq. [3]). Consequently, these variables have an impact on all network elements, from tail to head: that is to say, hydrant equipment, terminal pipes, distribution mains and trunk mains. On another note, the use of the coefficient of utilisation or the factor of safety does not influence the hydrant discharge allocation. Thus, neither the hydrant equipment nor the terminal pipes (which are sized by assuming that the hydrants located downstream are open, *i.e.* Q=d) could be oversized by these variables. These variables influence only the probability of utilisation of the hydrants (Eq. [4]) and the statistical adjustment (Eq. [7]), affecting only the design of the distribution and trunk mains. Hence, the safety margin provided with the coefficient of utilisation or the factor of safety will lead to fewer oversized elements than the margin provided with the continuous specific discharge or the DF.

The design discharges, for cases in which the network was oversized by means of the coefficient of utilisation, continuous specific discharge or factor of safety, under the condition that a certain performance is required for a given demand increase, are presented in Table 4. These results complement the aforementioned reasoning. As can be observed, the relative discharge increment (ΔQ1) of Case 2 and Case 8 is smaller than that of the Case 3, for both the head and the terminal section; while the performance under the demand increment conditions is equal for the three cases, either at the head or at the terminal section.

Focussing on the terminal section, it can be seen that the use of the coefficient of utilisation or the factor of safety do not oversize the network elements (*i.e.* the relative discharge increment is 0%), whereas the 20% increment of the continuous specific discharge is directly transferred to the design discharge at this section, as explained in the critical analysis.

All the outcomes indicate that improving the network safety through the coefficient of utilisation or the factor of safety is more economical than by means of the continuous specific discharge, as they oversize fewer elements of the network and do so to a lesser extent. This efficiency is not only related to the use of the coefficient of utilisation or the factor of safety, but also to stakeholder contribution. The farmer collaboration required to address the demand increase scenario is 28.7% for Case 2 and Case 8, and 14.3% for Case 3. This result also concurred with the critical analysis findings, since the variables that do not affect the hydrant allocation and provide no more comfort to farmers, require their collaboration when demand increases. Such collaboration is conveyed as a reduction of the DF.

Study of the safety factors function

Table 5 summarises the results for the three cases analysed. It presents discharges per plot for the head section (supplying 400 plots) an intermediate section (100 plots) and a tail section (10 plots), for both scenarios Qr and Qk, as well as the relative discharge variation between both (ΔQ_{rel}).

It can be observed that the margins provided by each variable vary from one part of the network to another. The margins increased by around 50% from head to tail in all cases. This effect responds directly to the statistical adjustment carried out by Clément's First Formula (Eq. [5]), in which the number of supplied plots rises as the standard deviation decreases. Thus, for a significantly large number of plots the standard deviation tends to zero and the discharge value tends to the mean discharge value. This effect could also be observed in Figure 3, which depicts the results of cases 'a', 'b' and 'c' and includes as a reference the discharges for a design without margins (r=1 and k=1).

The results also show that the margins behave differently in the various points of the network depending on which variable has been used. The relative discharge variation between the scenarios is zero (Qr=Qk) at the

head in Case 'a', the intermediate section in Case 'b' and the tail in Case 'c', because the variables were selected to introduce the same margins in those points. However, the relative discharge variation diverges from the set-point, with the difference being greater as the distance increases. In addition to this, it should be noted that the differences do not have the same sign when they near the head or the tail. The differences are negative upstream from the set-point, which indicates that for a significant number of plots the coefficient of utilisation provides a greater margin than the factor of safety. In contrast, the differences are positive downstream which means that for a small number of plots the coefficient of utilisation introduces a smaller margin than the factor of safety.

Discussion

The study has some limitations that should be considered when interpreting the following discussion. It was limited to branched on-demand irrigation networks which end in hydrants that supply plots. Furthermore, it was assumed that water is billed according to consumption and flow is restricted in the hydrant. Both are considered necessary conditions for providing an organised service, namely avoidance of water wastage and imbalances in the operating pressures (Daccache *et al.*, 2010b). In networks where these are not met, the statistical models may not fit the farmer behaviour. If water consumption is not charged, farmers may open a given hydrant for a longer time than that required. Then, if flow is uncontrolled while the most favourable plots would take greater pressure than required the unfavourable areas could suffer significant drops in pressure. Moreover, networks which serve a large number of small plots, with considerable degrees of freedom may behave like those in which the flow is uncontrolled. In such cases the application of stochastic methods for determining the flow rates is advised (Khadra & Lamaddalena, 2006; Moreno *et al.*, 2007). In pressurised irrigation networks with hourly energy pricing, the probability of utilisation of the hydrants

Table 5. Results of the study of the safety factors function.

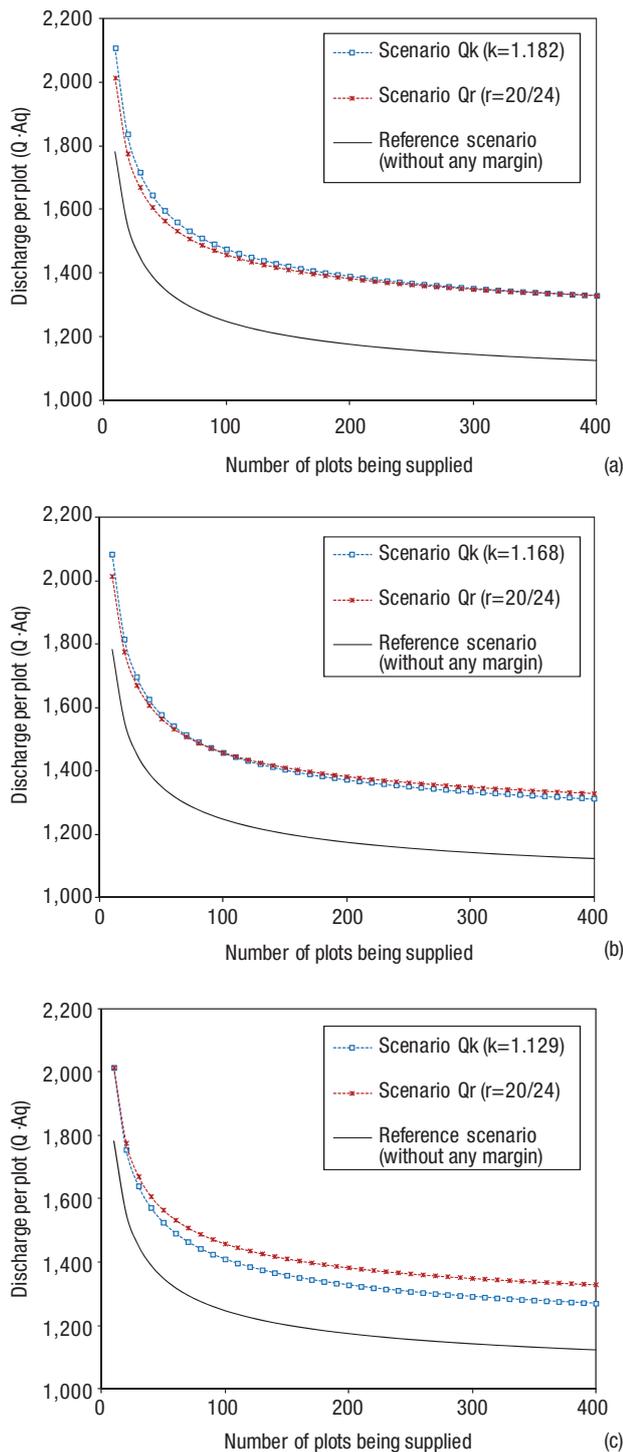| Case | Discharge per plot (Scenario Qr) | | | Discharge per plot (Scenario Qk) | | | Relative discharge variation (ΔQ_{rel}) | | |
	Head section	Inter. section	Tail section	Head section	Inter. section	Tail section	Head section	Inter. section	Tail section
a	1.329Aq	1.457Aq	2.013Aq	1.329Aq	1.475Aq	2.107Aq	0.0%	2.4%	4.7%
b	1.329Aq	1.457Aq	2.013Aq	1.313Aq	1.457Aq	2.082Aq	−1.2%	0.0%	3.4%
c	1.329Aq	1.457Aq	2.013Aq	1.269Aq	1.408Aq	2.013Aq	−4.5%	−3.4%	0.0%

Figure 3. Study of the safety factors function. Discharges per plot along the network. Case a: Adjustment at the head section (400 plots). Case b: Adjustment at an intermediate section (100 plots). Case c: Adjustment at the tail section (10 plots).

that looped networks and networks with star topology, with several supply sources, are beyond the scope of this paper, given that they should be calculated by using other methodologies (Reca *et al*., 2002). Notwithstanding the above, it could be reasoned that the results provide relevant information for designing more robust irrigation networks, considering cost and stakeholder contribution.

The research shows the influence of the irrigation variables on the determination of the design discharges. The network design should always consider the possibility that, at some time during operation, water consumption may rise as a consequence of climate change or because of other circumstances that may lead farmers to grow a more demanding crop. In order to cope with such a scenario, both a robust network and the stakeholder contribution are required.

The sensitivity analysis confirms that the network could be oversized acting on the irrigation variables during the discharge determination phase. It also shows that the margins provided by each variable are not equally effective when a scenario of increasing demand arises. The results show that the coefficient of utilisation and the factor of safety are the most appropriate tools available to efficiently oversize the network. It is noticeable that networks oversized by means of these variables behave better when demands increase than those oversized with the continuous specific discharge or the DF (Fig. 2). The effectiveness of each variable as a tool used to introduce margins is related to their specific function: the continuous specific discharge aim seeks to characterise the water requirements of the cropping pattern, the DF offers comfort to farmers, and the safety factors include a surplus in design to address unexpected events.

The sensitivity analysis also shows that the DF plays an important role in the network's adaptive capacity to change. Its reduction in attending the increment of demand has a beneficial effect on the network performance. It should be noted that as a network in operation cannot be easily modified this would require additional resources. Accordingly to this, when farmers increase water consumption the only way to satisfy it is by irrigating during a longer time. As a consequence of this, the probability of utilisation of the hydrant increases, which in Clément's First Formula is reflected as an increase in the mean and a reduction in standard deviation (Eq. [6]). The mean discharge increases linearly with the consumption increment, while the standard deviation decreases exponentially as the population increases. Physically, this means that there would be an increment in farmers irrigating simultaneously and that demand will coincide in the terminal pipes. This effect would be diluted in the trunk mains

may be highly influenced and differ substantially from the uniform one. In such cases the probability must be computed, with it being disaggregated in homogeneous time periods according to the electricity tariffs (Pulido-Calvo *et al*., 2003). Furthermore, it should be noted

where the mean increase would be partially balanced by the standard deviation reduction. Thus, as more terminals are designed in consideration of simultaneity ($Q=\sum d_i$) the more robust the network will be.

In summary, if a farmer meets demand by irrigating for greater duration efficiency improves, given that this produces a tempering effect on the discharge rates. The increment of the irrigation time, depriving a part of the initial DF, may be assumed by the farmer if the service does not deteriorate. That is to say, the flow rate and the pressure remain adequate. Thus, this variable must be set by considering that the farmer will sacrifice time when a more demanding scenario is present.

It is clear that the potential increase could also be addressed by increasing hydrant allocation. In such a case, when demand rises the farmers would not be required to cooperate, since they would be in the original design conditions. As the hydrant allocation is a direct function of the continuous specific discharge and the DF (Eq. [3]), it could be oversized by modifying these variables, which is something usually performed in professional practice. Modification of these variables is equivalent to designing the network for a more demanding cropping pattern than that resulting from agronomic studies or affording the farmers with a greater, and unreasonable, DF. Either one case or the other alters the conditions which result in the previous studies and leads to a less effective network. Additionally, the cost-effectiveness study shows that oversizing the discharges by using the continuous specific discharge or the DF influences the entire hydraulic system: hydrant equipment, terminal pipes, distribution mains and trunk mains. Given that, the use of the coefficient of utilisation or the factor of safety affects only the distribution and trunk mains, they are a more efficient (cheaper) option.

Therefore, within the recommendations for designing a robust and efficient network, the selection of the continuous specific discharge and DF should agree with the cropping pattern provided by the agronomic study and to an appropriate and medium comfort level for the farmer.

In the study of the function of the coefficient of utilisation and the factor of safety it was observed that while the first produced an increase in the mean and a decrease in the standard deviation, the second increased both linearly and equally (Eq. [7]). The results have shown such an effect which suggests that the coefficient of utilisation could better oversize the network as it reproduces better the conditions that arise when demand increases, *i.e.* increment of the irrigation time and simultaneity in the terminal pipes.

Some authors have identified the use of the coefficient of utilisation as an adjustment parameter of farmer behaviour in statistical distribution (CTGREF, 1977; Clément & Galand, 1979; Lamaddalena & Ciollaro, 1993; Lamaddalena & Sagardoy, 2000). Others, such as Monserrat *et al*. (2004) have indicated that this variable has a physical meaning as introduced by Clément in 1966. This study provides an insight into the coefficient of utilisation, its action and its physical meaning. The coefficient of utilisation is a subtle safety factor. Such subtlety comes from the peculiar way of introducing the safety margin, correcting the probability of utilisation of the hydrants (Eq. [4]). As it oversizes the network, it can supply demand in less time than in the available operational one. This is a virtual reduction of the network operation time, as it remains functional for the total time. Hence, the margin consists of a virtual time cushion which is automatically mobilised when the water requirement increases.

This cushion has a particular way to develop in the discharge determination process, given that it is linked to the probability of utilisation of the hydrants. The coefficient of utilisation virtually reduces the network operating time which, in turn, increases the probability of utilisation of the hydrants. This increment in the probability influences the statistical adjustment of Clément's First Formula (Eq. [5]), producing an increment in the mean and a decrement in the standard deviation (Eq. [6]). This distribution of the margin fits the network behaviour when this has to meet higher demands. In such a case, farmers are required to irrigate for more time. As the hydrant discharge is fixed and controlled by a flow limiter, more farmers would irrigate simultaneously, hence the dispersion will be reduced which would coincide with the adjustment provided by the coefficient of utilisation.

On another note, the safety factor is unable to match this behaviour. As can be seen in Figure 3, the curves that represent discharges in scenarios Qr and Qk intersect at the adjustment point and then diverge with different signs upstream or downstream from such a point. If the margin was adjusted at the tail section (Case 'c') the upstream sections would be undersized (meaning less effectiveness), while if the adjustment was made at the head section (Case 'a') the downstream discharges would be oversized (less efficiency).

In conclusion, this paper has provided an insight into the specific role of each irrigation variable. Among them the coefficient of utilisation is recommended as the best for improving network robustness towards potential demand increases. Results show that the coefficient of utilisation is the variable that offers not only the best cost-effectiveness relationship but also that which best suits statistical adjustment to the process that occurs when farmers are required to satisfy greater water requirements. Additionally, the study has

highlighted the importance of farmer collaboration in the adaptation process. Such cooperation, considered a reduction of the degree of freedom, benefits the operation and abates the peak demands that are diluted over time.

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