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(Article begins on next page)

Irrigation Science

Improving management scenarios of water delivery service in collective irrigation systems: a case study in Southern Italy --Manuscript Draft--

Manuscript Number:	IRSC-D-18-00006R3
Full Title:	Improving management scenarios of water delivery service in collective irrigation systems: a case study in Southern Italy
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Abstract:	The performance of water delivery service in collective irrigation networks can be enhanced by improving measures ranging from a better water allocation to more expensive structural works. In any case, the efficacy of these measures must be simulated prior to their actual implementation and evaluated using quantitative performance indicators. The aim of this study is a strategic analysis of the water delivery service to understand whether a better water allocation is possible in collective irrigation systems by implementing improving measures at lower cost compared to structural works. To this goal, the performance of three water delivery systems was evaluated in Calabria (Southern Italy) over four irrigation seasons, using the indicators of adequacy, efficiency, dependability and equity developed by Molden and Gates (1990). Subsequently, three scenarios for improving irrigation management (replacement of sprinkler methods with micro-irrigation, an arranged-demand water delivery service together with an irrigation advisory service, and a combination of both actions) were simulated and evaluated. Furthermore, two new indicators ("User Satisfaction Index" and "Water Exploitation Index"), measuring satisfaction of irrigation service users and water use levels, were proposed and applied. In the current situation poor adequacy, reliability and equity of water delivery service with low user satisfaction together with fair efficiency in exploiting the limited irrigation resources were detected. The simulation of an arranged demand distribution and irrigation advisory service was found to be more efficacious and favourite to the system users than the replacement of current sprinkler systems with micro-irrigation. The combined adoption of these scenarios is advisable, in order to assure the optimal performance in water delivery systems and to make the collective service more adequate and efficient for both irrigation users and managers.
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Author Comments:	AUTHORS' REPLY TO THE COMMENTS OF THE EDITOR Dear Prof. Chávez, thanks a lot for the acceptance of our paper. We have considered Your valuable

	comments and addressed them in the revised text. You will find below the revision notes replying to each comment. As You required, all changes made to the MS are reported in the tracked submission. Moreover, we have uploaded a clean and updated version with the exact content.
Response to Reviewers:	C: Line 141: evapotranspiration of what crop? Grass reference? Please specify R: The reported values are related to potential evapotranspiration. We have specified it in the text. C: Line 143-144: same as above R: We have specified it in the text also at these lines. C: Line 278-279: it is indicated that only the irrigation efficiency changed but that the irrigation scheduling remained the same. This statement may not be true because drip irrigation applies small amounts of water at a higher frequency than surface or sprinkler irrigation. Therefore, to apply the required amount of water (for a given crop) the irrigation duration will need to be longer. In this case, a larger number of fields may be operated simultaneously and the irrigation schedule will have to change to accommodate the new low system flow and different irrigation application duration. In general, localize irrigation will have a higher irrigation frequency, not allowing much soil water deficit in the crop root zone due to the low flows and to avoid potential water stress in crops in case of failure in any part of the system. Please add a discussion regarding the implication of varied irrigation scheduling due to drip adoption and how a more frequent irrigation affects the scenarios. R: Thanks for this consideration, which allows us to clarify the sentence. First, we have further clarified in the Method section (see lines 157-158 of the revised MS with tracked changes) that the total irrigation requirements of crops are calculated at the farm hydrant, considering the efficiency values of the irrigation method used in the farm in the net requirements evaluated for the crop. Only farms/users with a single outlet and single crop were considered, as we have reported in the previous MS (see lines 166-168); of course, the water delivered was measured at the farm hydrant as well, in order to make the comparison with the water required possible (sub-section 2.3). In the scenario “1” we have replaced the current sprinkler irrigation with micro-irrigation at farm level for some crops. Under this scenario the irrigation water distribution method remains on demand and does not change to scheduled irrigation. Therefore, at the collective system level we can not talk about irrigation scheduling. What can change is the farm-level irrigation method, but this relates to the farmer behaviour in carrying out irrigation in his farm, which goes beyond the goal of this study. In general, since micro-irrigation lowers water losses in crop irrigation compared to sprinkler method (and therefore lower water volume to be applied), we do not think that each farmer should modify irrigation scheduling and, in any case, they can easily implement the new scheduling, since in the majority of farms small reservoirs are available to modulate frequency and duration of irrigation operations. We have thoroughly rewritten these sentences in the revised text, in order to clarify and adding more discussion, as You required. C: Line 289 “All the simulated scenarios kept the same seasonal volumes of delivered water per crop.” How is it possible to deliver the same volumes of water per crop if the irrigation system efficiency has been improved (changed)? Justify, discuss. R: From the Editor’s comment, we have realised that also this sentence was not clear in the previous MS version. We meant that the irrigation service delivers each year (irrigation season) the same water volume to each hydrant. Presumably, the word “crop” is misleading, then we have replaced it with “hydrant” in the revised text. C: Page 9: in the results section, sub-section 3.1 total irrigation requirement (with CROPWAT), it seems that percent of water delivered per year (season) per crop type

does not include precipitation. This needs to be verified. Some deliveries are simple too low to sustain economic production that are not believable (despite the fact that farmers may use other sources of water). If effective precipitation has been accounted for in CROPWAT, please clarify accordingly.

R: Yes, we have accounted for the effective precipitation in CROPWAT. We have clarified this in the revised text.

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Improving management scenarios of water delivery service in collective irrigation systems: a case study in Southern Italy

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Abstract

The performance of water delivery service in collective irrigation networks can be enhanced by improving measures ranging from a better water allocation to more expensive structural works. In any case, the efficacy of these measures must be simulated prior to their actual implementation and evaluated using quantitative performance indicators. The aim of this study is a strategic analysis of the water delivery service to understand whether a better water allocation is possible in collective irrigation systems by implementing improving measures at lower cost compared to structural works. To this goal, the performance of three water delivery systems was evaluated in Calabria (Southern Italy) over four irrigation seasons, using the indicators of adequacy, efficiency, dependability and equity developed by Molden and Gates (1990). Subsequently, three scenarios for improving irrigation management (replacement of sprinkler methods with micro-irrigation, an arranged-demand water delivery service together with an irrigation advisory service, and a combination of both actions) were simulated and evaluated. Furthermore, two new indicators ("User Satisfaction Index" and "Water Exploitation Index"), measuring satisfaction of irrigation service users and water use levels, were proposed and applied.

In the current situation poor adequacy, reliability and equity of water delivery service with low user satisfaction together with fair efficiency in exploiting the limited irrigation resources were detected. The simulation of an arranged demand distribution and irrigation advisory service was found to be more efficacious and favourite to the system users than the replacement of current sprinkler systems with micro-irrigation. The combined adoption of these scenarios is advisable, in order to assure the optimal performance in water delivery systems and to make the collective service more adequate and efficient for both irrigation users and managers.

Keywords: water delivery system; performance indicators; farmer satisfaction; water exploitation; irrigation management; collective irrigation.

1. INTRODUCTION

One of the core objectives of collective irrigation management is the appropriate delivery of water resources in order to meet crop irrigation requirements. The success of an irrigation-water-delivery system can be measured by how well it meets the objectives of delivering an adequate and dependable supply of water in an equitable and efficient manner to users served by the system (Molden and Gates 1990). However, often water delivery systems suffer from problems such as capacity lower than peak demand, irregular delivery rates and low irrigation efficiency and uniformity (Nam et al. 2016). This is also due to the lack of an appropriate allocation plan for distribution of water resources to different crops. This allocation plan and corresponding water delivery need to be prepared to achieve the set objectives of a more adequate, efficient, reliable and equitable irrigation service (Pérez-Urrestarazu et al. 2009). In general, it is useful to

1 evaluate the actual performance and simulate the future behaviour of an irrigation scheme before an implementing a
2 new or an improved allocation plan. This enables the irrigation authorities make an accurate prediction of the
3 performance of the irrigation plan when the plan is put in actual operation; this evaluation can be done with the help of
4 historical and generated data series related to water supply and demand (Gorantiwar and Smout 2005). Similar studies
5 providing information on the degree of variability of irrigation performance are essential to realistically assess the
6 potential for improvements in irrigation management (Lorite et al. 2004b).

7
8 Several Authors (e.g. Molden and Gates 1990; Malano and Burton 2001) have defined sets of indicators that
9 characterize irrigation service performance, intending to quantify the system ability to achieve the objectives established
10 for an irrigation area (Lorite et al. 2004a). The literature shows that quantitative indicators such as efficiency, adequacy,
11 equity, and dependability of irrigation supplies are the most important to describe the health of an irrigation system
12 (Hamid et al. 2011). Investigations on water delivery performance have been carried out in many areas worldwide to
13 diagnose deviations from the expected performance (e.g. Molden and Gates 1990, in Sri Lanka; Vandersypen et al.
14 2006, in Mali; Kazbekov et al. 2009, in Kyrgyzstan; Hamid et al. 2011, in Sudan; Wellens et al. 2013, in Burkina Faso;
15 Nam et al. 2016, in South Korea). In Mediterranean semi-arid areas the papers of Molden and Gates (1990) in Egypt,
16 Unal et al. (2004), Akkuzu et al. (2007) and Korkmaz et al. (2009) in Turkey and Zaccaria and Neale (2014) in Italy can
17 be mentioned. However, few of these studies have compared the current performance of the studied water delivery
18 service with simulated future scenarios for improving irrigation services. Vice versa, the implementation of systematic
19 activities assessing the current and future performance of an irrigation service is a prerequisite to characterize the
20 variability in water allocation among farmers, especially in those contexts where water resources for irrigated
21 agriculture are scarce (such as in semi-arid or arid areas). In these cases, as farmers demand improvements in the
22 availability and reliability of water supplies, the number of pressurized irrigation networks arranged on demand is
23 increasing (Rodríguez-Díaz et al. 2004). If these systems (designed to deliver water with flow rates and pressures
24 required by on-farm irrigation systems, Pérez Urrestarazu et al. 2009) can overloaded, farmers may be required to cut
25 supplies and delay or postpone irrigation (Rodríguez Díaz et al. 2007). Therefore, improving management measures are
26 needed in these collective irrigation systems, targeted to a better allocation of the water resources.

27
28 Improving the irrigation management often requires structural works in the supply networks, such as construction of
29 water withdrawal works in supplying water courses, increase of the size of storage reservoirs, replacement of conveying
30 pipelines to increase their diameter. These works require a noticeable money expenditure, which forces WUAs to
31 collect additional funds, often by increasing water fees paid by the associated farmers. Sometime less expensive
32 measures would be possible, such as a more rational water allocation (that is, a distribution based on the actual
33 irrigation requirement of crops) or changes towards more efficient farm irrigation systems, whose costs would be lower
34 than structural works, thus keeping the same volumes of delivered water per ~~farm crop~~. The efficacy of these measures
35 can be evaluated before their actual implementation by simulating as many improving management scenarios in terms
36 of improved adequacy, efficiency, reliability and equity of the water delivery service, by the adoption of the related
37 performance indicators of Molden and Gates (1990).

38
39 This study evaluates the actual and future performances of three on-demand water delivery systems in Calabria
40 (Southern Italy) using records collected over four irrigation seasons; in these irrigation schemes proposals for improving
41 collective irrigation (at lower costs compared to infrastructural works) have been evaluated. In more detail, the
42 adequacy, efficiency, dependability and equity of water delivery have been quantified at farm scale for the major crops,
43 using the four indicators developed by Molden and Gates (1990). On the basis of this diagnosis, three different
44 scenarios, including an improved water allocation service and/or changes towards more efficient farm irrigation
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systems, have been simulated and their effects on water allocation have been evaluated through the performance indicators. Finally, two new indicators for quantifying user satisfaction and water exploitation in the irrigation schemes are proposed (with the scope to integrate the original set of Molden and Gates 1990). The aim of this study is a strategic analysis of the water delivery service rather than an evaluation of the system operation (requiring a hydraulic simulation of the network functioning with predictions of pressures and discharges in pipelines and outlets), since we intend to assess under the current and the simulated scenarios the irrigation water consumptions by farmers compared to the required amounts for crop growth and production.

2. MATERIAL AND METHODS

2.1 Description of the study area

In Calabria (Southern Italy) agriculture is by far the most important economic sector. In this region, where 11 Water Users Associations operate, the performance of collective irrigation services is generally poor, due to inadequate water delivery, with low farmer satisfaction (Zema et al. 2015; 2018b). Currently, in spite of well known problems of water distribution, in none of the other water delivery systems in Calabria, a quantitative evaluation of the agricultural water allocation in time and space has been performed: water managers fail to give the same importance to measuring operations as to other management operations (Zema et al. 2018a; 2018b). Only in three water delivery systems of the Water Users Association "Tirreno Catanzarese" water-use records are available for individual land parcels and this availability of water delivery data measurements in the cultivated areas allows the evaluation of the collective irrigation performance and the effects of improved management actions on a quantitative basis.

The three investigated water delivery systems fall within the Water Users Association "Tirreno Catanzarese", which covers an area of 85602 hectares (856 km²) in the western part of Calabria (Figure 1). The irrigated area (1479 ha) covers 32.6% of the command area (4540 ha). The main crops are olives, citrus and other fruits, vegetables (mainly tomatoes, aubergines and onions), gardens, forage, maize, and are mainly irrigated with sprinkler systems. The irrigation resource is supplied from surface water bodies and delivered to farmers by pressurized pipelines (about 75% of the network total length) or canals (25%). Water is distributed on demand and charged to users on water unit volumes effectively delivered. These volumes are measured in farms by the automated system "Acquacard®", which also allows data recording and storage.

The three investigated water delivery systems are called "Angitola Terzo Distretto a Monte Ferrovia" (abbreviated to "Angitola 3DMF"), "Angitola Sesto Distretto a Monte Ferrovia" ("Angitola 6DMF") and "Savuto". The water network was built in 1985 and currently delivers irrigation water to over 2000 farms (Table 1).

In the water delivery system "Angitola 3DMF" the irrigated area is 117 ha and the command area 190 ha. Water from Lake Angitola is pumped to a 4000 m³ reservoir. The water is then delivered by gravity in pressured pipelines (PVC, 9.9 km of total length).

The water delivery system "Angitola 6DMF" covers an irrigated area of 86 ha over a command area of 200 ha. Water from Lake Angitola is pumped to a 2000 m³ reservoir. The water is then delivered by gravity in pressured pipelines (asbestos cement, total length of 10.6 km).

The water delivery system "Savuto" has the largest irrigated (411 ha) and command (900 ha) areas. Water from the Savuto river is pumped to a 22000 m³ reservoir. The water is then delivered by gravity in pressured pipelines (2.6-km main conduit of steel and 49.1-km distributing pipelines of asbestos cement).

The three water delivery systems were designed by probabilistic criteria targeted to fulfil simultaneously no more than 20% of the served hydrants; therefore, these systems are not able to allocate water simultaneously to the whole area.

The agricultural district served by the analysed water delivery systems mainly consists of small and often family-run farms. Therefore, the irrigation requirement of crops is mainly determined by approximate criteria (very often simply by visually estimating the soil water content) instead of by quantifying it using scientific methods (i.e. by measuring the soil water content and/or by a quantitative water balance of crops).

2.2 Estimation of the total/net irrigation requirements

In Calabria, the climate is typically semi-arid, with mild, wet winters and hot, dry summers (Bombino et al. 2007). Precipitation is concentrated mainly in late autumn and early spring; therefore the irrigation requirement of crops is high in summer (essentially coinciding with the irrigation season) and very low in the coldest season.

Following Unal et al. (2004) and Korkmaz et al. (2009), the net irrigation requirement of each crop (that is the quantity of water exclusive of precipitation required for normal crop production) was estimated using the software CROPWAT 8.0 (Clarke et al. 1998; FAO 2009). Using this software, the water balance was performed daily for each crop over four irrigation seasons (from April to September).

The daily meteorological data required by CROPWAT (maximum and minimum temperatures, precipitation, relative humidity, wind speed and daylight) were measured at the meteorological station of Lamezia Terme (geographical coordinates 38.908304° N, 16.25358° E, falling in the perimeter of the Water Users Association "Tirreno Catanzarese"). In the monitored calendar years (2008-2011) the minimum temperature was -3.3 °C (February) and the maximum 44.0 °C (September), while the mean precipitation and potential evapo-transpiration rate were 892 mm year⁻¹ and 4.1 mm day⁻¹ respectively. In the irrigation season, the mean temperature recorded in the observation period was in the range 15.1 - 30.1 °C. The mean precipitation and potential evapo-transpiration rate were 47.5 mm month⁻¹ (with the lowest values, close to zero, recorded in July) and 5.7 mm day⁻¹ (with a peak of 7.5 mm day⁻¹ in September) respectively. Since the observations of precipitation and temperature show a limited variability (CV < 27%) among the irrigation seasons, the changes in the irrigation districts as a function of weather conditions (e.g. farmers' behaviour, irrigation requirement and scheduling, etc.) can be considered small.

In relation to the crop data, the root depth and crop coefficients for calculating evapo-transpiration (estimated by Penman-Monteith model) were derived from FAO guidelines (Doorenbos and Kassam 1986); the farm cultivation practices (Table 2) were identified by interviewing a sample of 30 farmers (two persons for each crop in each WDS, selecting the owners of medium sized farms). In general dates and operations were almost homogenous among the farms and the WDS.

Soil hydrological parameters, in the absence of direct measurements, were estimated using the Pedo Transfer Function of Saxton et al. (1986) on the basis of the soil texture reported by the Soil Map of the Calabria Region (ARSSA, 2003). The soils of the studied area, generally homogenous, are mainly sandy loam (65% of sand, 22% of silt and 13% of clay, Carta dei Suoli della Regione Calabria, ARSSA, 2003); the saturated hydraulic conductivity is 17.5 mm h⁻¹.

The total irrigation requirement of each crop (henceforth indicated as "water required") was calculated at the farm outlet (hydrant) from the net irrigation requirement considering farm irrigation efficiency: for sprinklers the value of 0.70 was assumed, while the values of 0.85 (sprayers) and 0.95 (drippers) were considered for micro-irrigation, accordingly to the CROPWAT guidelines (Clarke et al. 1998; FAO 2009). Finally, daily data of total irrigation requirement were aggregated at monthly scale.

2.3 Collection of the water delivery data

The water volumes delivered to users (henceforth indicated as "water delivered" or "water delivery") were measured by "Acquacard®" at the farm hydrants. Acquacard provides user name and code, irrigated crop and area, and delivered daily volume. Only farms/users with a single outlet and single crop were considered. About 20% of samples were ignored as giving anomalous or not useful data, for example, fields with an area of zero hectares or farms with more than one crop/hydrant/irrigation method. The integrity and reliability of the data used were assured by the recent system testing by the installer company.

Subsequently, such data were classified per water delivery system, year (irrigation season), month and irrigated crop.

2.4 Description of the performance indicators

For the month "j" of each irrigation season and farm outlet "i", the water delivered (WD_{ij} , [$m^3 \text{ ha}^{-1} \text{ month}^{-1}$]) and the water required per unit area (WR_{ij} , [$m^3 \text{ ha}^{-1} \text{ month}^{-1}$]) were considered.

The ratios between these two values ($a_{ij} = WD_{ij}/WR_{ij}$ or its reciprocal $e_{ij} = WR_{ij}/WD_{ij}$) are the elements of two matrices of the "m x n" order, where "m" is the number of farm outlets in a hydraulically independent irrigation system "R" (each of the three water delivery systems) and "n" is the number of the months of period "T" (in our study the four irrigation seasons). On the basis of the elements " a_{ij} " and " e_{ij} " of the two matrices, the indicators of Molden and Gates (1990) of adequacy (AD), efficiency (EF), dependability (DE) and equity (EQ) were evaluated in each of the three water delivery systems. Adequacy, efficiency, dependability and equity are the performance objectives taken into consideration when evaluating irrigation water delivery (Nam et al. 2016). Besides the studies of Molden and Gates (1990), the literature provides ample information about these indicators together with calculation methods and equations (e.g. Vandersypen et al. 2006; Akkuzu et al. 2007; Kazbekov et al. 2009; Korkmaz et al. 2009; Hamid et al. 2011). Here, their meaning and aim are summarised.

The indicator of adequacy " $AD_{R,T}$ " of an irrigation system "R" throughout a period "T" assesses to what extent delivered water met irrigation requirements (Molden and Gates 1990) or, in other words, whether the irrigation service delivers to a farm a water volume "adequate" for irrigation requirement (Akkuzu et al. 2007; Korkmaz et al. 2009; Hamid et al. 2011). In particular, if $AD_{R,T} < 1$, the irrigation requirement is not satisfied by the water delivery system and the irrigation service is "inadequate".

The indicator of efficiency " $EF_{R,T}$ " of an irrigation system "R" throughout a period "T" answers the question of whether there is excessive delivery of water in relation to the crop needs (Molden and Gates 1990); it measures the "efficiency" in water conservation in an irrigation system (Vandersypen et al. 2006; Akkuzu et al. 2007; Korkmaz et al. 2009). In particular, if $EF_{R,T} < 1$, there is a surplus of delivered water compared to required volume and thus the delivery service is not "efficient".

The indicators of adequacy " $AD_{R,T}$ " and efficiency " $EF_{R,T}$ " of an irrigation system "R" over a period "T" are given by the formulas (Jahromi and Feyen, 2001; Kazbekov et al., 2009):

$$AD_{R,T} = \frac{1}{n} \sum_{j=1}^n \left(\frac{1}{m} \sum_{i=1}^m p_{ij} \right) \quad [1]$$

assuming $p_{ij} = a_{ij}$, if $a_{ij} \leq 1$, otherwise $p_{ij} = 1$, if $a_{ij} > 1$

$$EF_{R,T} = \frac{1}{m} \sum_{j=1}^m \left(\frac{1}{n} \sum_{i=1}^n q_{ij} \right) \quad [2]$$

being $q_{ij} = e_{ij}$, if $e_{ij} \leq 1$, otherwise $q_{ij} = 1$, if $e_{ij} > 1$.

Dependability indicates the temporal uniformity in the ratio of amounts of water delivered to amounts of water required (Molden and Gates 1990). The indicator of dependability ($DE_{R,T}$) of an irrigation system "R" throughout the irrigation season "T" measures temporal uniformity (i.e. over the irrigation season) of the relative amount of water delivered to the different farm outlets (Kazbekov et al. 2009); in other words, $DE_{R,T}$ is an index of the irrigation system's ability to deliver water at the desired time compared to a specific requirement (Vandersypen et al. 2006; Korkmaz et al. 2009). A value of $DE_{R,T}$ close to zero indicates an irrigation service uniform in time and, therefore, "dependable" throughout the irrigation season (Molden and Gates 1990; Korkmaz et al. 2009).

For an irrigation system "R" consisting of "m" outlets, the indicator of dependability over the irrigation season "T" ($DE_{R,T}$) can be calculated by the following formula:

$$DE_{R,T} = \frac{1}{m} \sum_{i=1}^m CV_T(a_{ij}) \quad [3]$$

where CV_T is the coefficient of variation over the time "T" (i.e. the "n" months of the irrigation season) of the indicator of adequacy " a_{ij} " (Jahromi and Feyen, 2001; Kazbekov et al., 2009).

Equity addresses the extent of fairness of water distribution among users (Molden and Gates 1990). The indicator of equity ($EQ_{R,T}$) of an irrigation system "R" throughout the irrigation season "T" measures the spatial variability (i.e. among the different farm outlets) of the relative amount of water delivered during the irrigation season (Molden and Gates 1990; Vandersypen et al. 2006); in other words, $EQ_{R,T}$ is an index of the irrigation system's ability to deliver the water evenly among all the users in the irrigation season compared to a given requirement (Molden and Gates 1990; Hamid et al. 2011). A value of $EQ_{R,T}$ close to zero indicates an irrigation service uniform in space and, therefore, "equitable" among the users (Molden and Gates 1990; Korkmaz et al. 2009).

During the "n" months of the irrigation season "T" the indicator of equity ($EQ_{R,T}$) was calculated by the following formula:

$$EQ_{R,T} = \frac{1}{n} \sum_{j=1}^n CV_R(a_{ij}) \quad [4]$$

where CV_R is the coefficient of variation of the indicator of adequacy " a_{ij} " in the irrigation system "R" (Jahromi and Feyen, 2001; Kazbekov et al., 2009).

Of course, it is practically impossible to achieve the ideal values for all the indicators considered; thus, the standard values reported by Molden and Gates (1990) were adopted as acceptance limits:

- $AD_{R,T}$ good if ≥ 0.90 , fair in the range $0.80 - 0.89$ and poor if < 0.80
- $EF_{R,T}$ good if ≥ 0.85 , fair in the range $0.70 - 0.84$ and poor if < 0.70
- $DE_{R,T}$ good if ≤ 0.10 , fair in the range $0.11 - 0.20$ and poor if > 0.20
- $EQ_{R,T}$ good if ≤ 0.10 , fair in the range $0.11 - 0.25$ and poor if > 0.25 .

The desirable values of the adequacy indicator suggested by Molden and Gates (1990) do not include the irrigation inefficiency, according to the calculation method; therefore, values of one could lead to a slight deficit irrigation.

The high aggregation level of the ratios $a_{ij} = WD_{ij}/WR_{ij}$ or its reciprocal $e_{ij} = WR_{ij}/WD_{ij}$ (averaged in time and space) adopted by the performance indicators of Molden and Gates (1990) complies with the main goal of WUA managers, which are interested on the general operation quality of water delivery system rather than a detailed analysis of irrigation behaviour of the single farmers in the different time steps of an irrigation season. This is the main approach of this study, targeted to a synthetic but comprehensive measure of management efficacy of water delivery systems and not to a full evaluation of the variability of the performances in the irrigation districts at farm scale.

2.5 Description of the new performance indicators proposed

In this study two new indicators are suggested. As reported above, if a_{ij} is equal or higher than 1, the water delivered to a farm satisfies the water required or it is in excess. The sum of all occurrences " $a_{ij} \geq 1$ " accounts throughout all the time periods of an irrigation season (in our study the number of months) the number of farmers which receive the adequate water volume for crop irrigation (not measured by the $DE_{R,T}$ indicator, which globally indicates how much water delivered matches irrigation requirement). In such way, this sum gives the incidence of the periods in which a share of the irrigation system users is globally satisfied for the adequate water delivery. From the point of view of WUA managers, this index can be considered as a feedback measure of the users' opinion about the water delivery service performance.

Furthermore, if e_{ij} is equal or higher than 1, no surplus of delivered water compared to volume required is observed. The sum of all occurrences " $e_{ij} \geq 1$ " accounts throughout all the time periods of an irrigation season the number of farmers which irrigate crops using the entire water delivered by the service (without considering whether this volume is sufficient or not, whose measure is given by the AD indicator). In other terms, under these situations the delivered water is completely supplied to plants and thus the irrigation resource is exploited with the maximum efficiency, giving WUA managers an indication about the global level of irrigation water use. Thus, a new index can be added to $EF_{R,T}$, taking into consideration only those situations for which irrigation water is fully exploited and measures their incidence throughout the irrigation season and on the total number of farmers.

Therefore, for the irrigation system "R" and throughout the irrigation season "T" a "User Satisfaction Index" (USI, [%]) and a "Water Exploitation Index" (WEI, [%]) of the water delivery can be defined as follows:

$$USI_{R,T} = \frac{1}{m \ n} \sum_{j=1}^n \sum_{i=1}^m r_{ij} \times 100 \quad [5]$$

$$WEI_{R,T} = \frac{1}{m \ n} \sum_{j=1}^n \sum_{i=1}^m s_{ij} \times 100 \quad [6]$$

where:

$r_{ij} = 1$, if $a_{ij} \geq 1$, otherwise $r_{ij} = 0$, in equation [5]

$s_{ij} = 1$, if $e_{ij} \geq 1$, otherwise $s_{ij} = 0$, in equation [6]

Of course, the sum of $USI_{R,T}$ and $WEI_{R,T}$ is equal to 100.

2.5 Analysis of the performance indicators currently and under improved management scenarios

In the current situation (in the following indicated "scenario 0"), for each farm supplied with irrigation water in the three studied water delivery systems, WD_{ij} , WR_{ij} and their ratios (a_{ij} and e_{ij}) were calculated monthly for each irrigated crop (from April to September) throughout each of the four irrigation seasons. After this, the indicators $AD_{R,T}$, $EF_{R,T}$, $DE_{R,T}$ and $EQ_{R,T}$ were calculated at an annual scale (grouping the "n" months of each irrigation season) and the related mean values were derived.

Subsequently, three possible management scenarios, aiming at improving the unsatisfactory performance of the analysed water delivery services, were evaluated through the six indicators (the set of Malano and Burton, 1991, and the new indices USI and WEI) above mentioned. These simulation activities may be considered by the irrigation managers and users as a preliminary analysis of the feasibility of the planned interventions.

In a first scenario ("1"), the water delivery service was improved by simulating micro-irrigation (by sprayers or drippers) farm systems in replacement of the current sprinkler irrigation for vegetables, citrus and olive groves as well as other orchards; the collective delivery service will continue to distribute irrigation water on demand as in the current scenario. The water saving provided by micro-irrigation compared to sprinkler systems is well known, since micro-irrigation lowers water losses in crop irrigation. The migration from sprinklers to drippers simply consists of a change in the irrigation efficiency of the farm method. At farm level, in some cases the farmers could need modifying the frequency and duration of irrigation operations, compared to the previous sprinkler system. This can be allowed by the availability of small reservoirs/tanks (installed in most farms), disconnecting the farm and collective systems.

In the second scenario ("2"), to increase system dependability, the following management actions were simulated:

- a "limited rate arranged-demand" water distribution method (Merriam et al. 2007) (in the following simply indicated as "arranged demand"), in replacement of the current on-demand method;
- an irrigation advisory service, based on the water balance of crops, which suggests irrigation requirements to users using internet or SMS.

Finally, a third combined scenario ("3") includes both improvement measures mentioned above.

All the simulated scenarios kept the same seasonal volumes of delivered water per farm hydrant. In scenarios 2 and 3, the irrigation water volumes to be delivered to each farm by the irrigation network were estimated as the product of the water delivered in each irrigation season by a monthly coefficient; this latter was calculated as the ratio between the monthly and the seasonal irrigation requirements calculated by CROPWAT. For example, if CROPWAT estimates for July a monthly irrigation requirement equal to 42% of the seasonal value, then the water delivered to the farm in the same month is the 42% of the seasonal delivered volume.

The water delivery planned in scenarios 2 and 3 simulates a "limited rate arranged-demand" (Merriam et al. 2007) or a "semi-demand" water distribution method in which the irrigator requests a specific volume of water and flow rate (Mateos et al. 2002) to be arranged with WUA management. More specifically, under this arranged demand method (less restricted than a rotational schedule and thus more appreciated by users), the farmer requests a specific water volume and flow rate to be supplied on one or several days, following the suggested time and volume for crop irrigation. The WUA managers check if the requests can be satisfied by the operational flow and delivery sequence selected, and the sector assignments. If not (that is, when the limitation of simultaneity under 20% is not respected due to the low flow capacity of the collective network), water is made available within a few days (generally 2-7 days) of his request (Anwar et al., 2006) or new manager-farmer arrangements will have to be made (Mateos et al. 2002). Under the "semi-demand" water distribution method of scenarios 2 and 3, the control of the water network is partly shifted from the farmers (as in the "on-demand" water delivery systems) to the WUA managers (as in the "fixed rotation" methods); therefore, having the general overview of the hydraulic functioning of the delivery systems, the WUAs managers are able to avoid - or, at least, reduce as much as possible - peaks of irrigation demand from farmers and the subsequent risk of exceeding the water delivery capacity due to simultaneity. On the whole, the planned management actions let the farmers replenish the water content into soil in a timely manner, and the WUA managers plan the irrigation operations properly. These planned actions should deliver a more adequate water volume to farmers only when irrigation is effectively needed (thus assuring more system dependability), and, furthermore, should modify the inappropriate irrigation programs of the majority of farms, thus aiming to provide a more rational and opportune exploitation of irrigation water.

The effects on the water delivery systems of the above mentioned scenarios were evaluated by the six performance indicators above. The statistical significance of the differences in the performance indicators among the different

scenarios were analysed by an analysis of variance (ANOVA) applied to the evaluated crops by XLSTAT software ($p < 0.05$).

3. RESULTS

3.1 Analysis of the total irrigation requirements

CROPWAT estimated the same annual irrigation requirement for each crop in the three water delivery systems, accounting also for the effective precipitation: this happened because the soil characteristics are homogenous and the climate data, showing low variability throughout the observation period, were surveyed in a unique meteorological station.

As detailed below, the water delivered to the crops was found to vary from farm to farm.

3.1.1 Water delivery system "Angitola 3DMF"

The water delivered to citrus groves was on average $5700 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ against an average irrigation requirement of $6100 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$. In olive groves $3100 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ were delivered, while the water required was $5600 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$. Therefore, 95% (citrus) and 52% (olives) of the annual irrigation requirement was satisfied. For vegetables, which have a much higher irrigation requirement ($8000 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) compared to orchards, on average only $3100 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ were delivered and therefore only 39% of their annual irrigation requirement was satisfied (Figure 2).

3.1.2 Water delivery system "Angitola 6DMF"

For orchards (citrus, olives and other fruits), which have an average irrigation requirement between 5600 and $7500 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$, annual water delivery was highly variable (from a minimum of $1500 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ for olives to a maximum of $11000 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ for other fruits). Thus, 19% (olives) and 84% (citrus) of the annual irrigation requirement was satisfied. However, the water delivered was greatly in excess for the other orchards (150% of the annual requirement). The monitored irrigation system delivered to vegetables total water of $5500 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ (69% of the water required, equal to $8000 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$). Finally, an annual water delivery ($18600 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) exceeding by over 100% the corresponding requirement ($8900 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) was found for the irrigated gardens (Figure 2).

3.1.3 Water delivery system "Savuto"

For citrus groves, a surplus of 25% in water delivery ($7600 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) was detected on average in comparison to the irrigation requirement ($6100 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$). Conversely, for the only orchard in the studied water delivery systems the irrigation requirement ($7500 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) was not met, the water delivered being nearly zero. Only $3300 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ of irrigation water were delivered annually to vegetables, thus only 41% of the requirement ($8000 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) was satisfied. In farms cultivating other cereals, water delivery was $4800 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$, about 66% of the water required ($7400 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$). For forage, the water delivered was $3600 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$, 41% of the requirement (equal to $8900 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$). Finally, gardens showed an irrigation requirement of $8900 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$, of which 34% was delivered ($3000 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) (Figure 2).

A comparison of the water delivered to crops (averaged over the three water delivery systems) recorded in this study was made with the latest available data reported by ISTAT (2010) for Calabria region. In the three water delivery systems, olive groves, orchards (other than citrus) and forage crops received less water than the regional statistical values (orchards $10400 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$, olives $5900 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$, forage $14900 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$), while vegetables were over-irrigated with reference to a regional mean of $2400 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$.

On the whole, as regards the average data analysed in the three water delivery systems, it can be noticed:

- the irrigation requirement of the few irrigated olive groves (only three in the studied water delivery systems) was satisfied only partly (19-52%) (presumably, the farmers believe that full irrigation for this crop is not appropriate due to the low water productivity and other agronomical limitations);
- conversely, the water delivered to citrus groves almost met or exceeded the irrigation requirement in all the water delivery systems (WD/WR in the range 84-125%);
- in the water delivery system "Angitola 6DMF" orchards were supplied with more water than citrus and olive groves;
- in this latter water delivery system there was a clear imbalance between irrigation of gardens (WD/WR over 200%) and orchards (WD/WR of about 150%) compared to the other crops (water delivery much lower than irrigation requirement by over 70%);
- the average water delivery to vegetables met the irrigation requirement by only 40-70%.

3.2. Analysis of the current performance indicators

3.2.1 Water delivery system "Angitola 3DMF"

The analysis of the water delivery performance highlighted poor adequacy (mean AD = 0.57) and dependability (mean DE = 0.43), but good efficiency (mean EF = 0.92), water exploitation level (WEI = 74%) and equity (mean = 0.09) during the monitoring period of four years. Globally, user satisfaction was very low, as shown by the average USI index equal to 26% (Figures 3a and 4).

In relation to each analysed crop, the irrigation requirement of vegetables and olives was satisfied only in part (AD < 0.52, confirming the outcomes reported in section 3.1) and the temporal uniformity of the relative amount delivered was poor (DE = 0.44 for olives and 0.58 for vegetables). Water delivery adequacy (0.77) and dependability (0.25) in citrus groves were almost satisfactory, since the values of these indicators were slightly lower than the acceptance limits (0.80 and 0.20 respectively) (Figure 3a).

3.2.2 Water delivery system "Angitola 6DMF"

Mean adequacy (0.55), dependability (0.49) and equity (0.33) of the irrigation service over the monitored irrigation periods were far from the acceptance limits (0.80, 0.20 and 0.25 respectively), while the efficiency in water resource exploitation (0.82) was generally fair (Figure 3b), as confirmed by a WEI of 68.7%. User satisfaction (measured by USI), even though again low (31%, Figure 4), was the highest among the studied water delivery systems.

Detailing these results for each irrigated crop, the adequacy was poor for olive groves (0.27), but fair for gardens (0.73). The minimum dependability was observed for vegetables (0.69, with a high variability, shown by the significant standard deviation). The temporal uniformity of the collective irrigation service was fair only for gardens (DE = 0.19). However, these latter, together with orchards, showed a very low equity of service (0.63 and 0.57 respectively) (Figure 3b).

3.2.3 Water delivery system "Savuto"

The estimation of the performance indicators, averaged over the monitoring period, showed: (i) very poor adequacy (0.44) and dependability (0.62); (ii) good efficiency (EF = 0.90) and water exploitation (WEI = 82.3%); (iii) fair equity (0.13) (Figure 3c). The users are little satisfied with the irrigation service performance, the mean USI being equal to 18% (Figure 4).

Concerning the different crops, the water delivered was adequate only for citrus groves ($AD = 0.83$). A very low amount was delivered to maize ($AD = 0.15$). The irrigation efficiency was high (> 0.83) for all crops, except for citrus groves ($EF = 0.69$). The temporal uniformity of water delivery was always poor ($DE > 0.39$) and under the limit of acceptance (0.20) only for citrus ($DE = 0.17$). The spatial uniformity of water delivery was unsatisfactory only for citrus groves ($EQ = 0.44$) (Figure 3c).

3.3. Analysis of the performance indicators under improved management scenarios

In order to support future actions to improve the studied water delivery systems, the improved management scenarios, simulated and evaluated by the performance indicators, should allow adequate water to be delivered, as much as possible, when required (as indicated by the water balance of crops) and, thus, avoid water waste or conversely shortage.

Figures 5a, b, c and d and Figures 6a and b compare the values of the six performance indicators for the water delivery systems under the simulated scenarios, while Table 4 reports the related variations compared to the current status ("scenario 0").

The replacement of the sprinkler systems with farm micro-irrigation ("scenario 1") increases water delivery adequacy on average by 11.3% with a maximum of 14.3% in the water delivery system "Angitola 3DMF" (Table 4). Nevertheless, the water volume delivered is still lower than the irrigation requirement, the adequacy being in the range 0.48-0.65 (Figure 5a), thus well below the acceptance limit of 0.80; water delivery equity is also decreased (increase of EQ indicator of 37.4%) (Table 4).

The introduction of an arranged demand water delivery mode together with the irrigation advisory service ("scenario 2"), whose benefits in improving irrigation management under water scarce agriculture, have widely reported (e.g. Lorite et al. 2007; Montoro et al. 2011), induces a noticeable improvement in service temporal uniformity, as shown by the average decrease in the indicator of dependability (-56.2%) (Table 4). Thanks to these measures, water delivery over time becomes fair in the water delivery system "Angitola 3DMF" ($DE = 0.11$) and close to the limit of 0.20 in "Angitola 6DMF" ($DE = 0.26$) (Figure 5c). Moreover, also service efficiency felt the effects of these improvements (Figure 5b), as shown by the increased value of EF (4.2%); also equity in water distribution increases ($EQ = -22.1\%$) (Table 4).

Scenario "3", combining the previous scenarios ("1", introduction of micro-irrigation, and "2", arranged demand water delivery + irrigation advisory service), allows a simultaneous increase in adequacy (on average +8.2%), efficiency (+0.4%) and dependability (by 59.5%) of water delivery despite a slight worsening of its equity (by 3.3%) (Table 4).

Compared to the current management (scenario "0"), through the introduction of the improving measures under scenario "3" it can be noticed:

- dependability becomes good in the water delivery system "Angitola 3DMF" and is closer to the limit of acceptance (0.20) in the other water delivery systems;
- efficiency, previously good in the water delivery systems "Angitola 3DMF" and "Savuto", slightly further improves in these systems and remains fair in "Angitola 3DMF";
- in all the investigated water delivery systems adequacy noticeably increases, even though remaining far from the acceptance limit of 0.80 (the maximum value of this performance indicator, equal to 0.64, is recorded in the water delivery system "Angitola 3DMF");
- equity, essentially constant, is still fair in the water delivery systems "Angitola 3DMF" and "Savuto", but remains poor in "Angitola 6DMF".

Finally, scenario "3" induces an appreciable improvement in user satisfaction towards the water delivery service performance, as shown by the increase of the USI index (on average by 10.6% in the studied water delivery systems with a maximum of 13.1% in "Angitola 3DMF" and "Angitola 6DMF") (Figure 6a). Conversely, a slight decrease in the WEI index is observed (on average by 3.6% with a minimum of 0.6% in the water delivery system "Savuto") (Figure 6b).

4. DISCUSSIONS

The analysis carried out for the current situation of the three studied water delivery systems revealed that according to the performance standards adopted, the adequacy, dependability and equity of the water delivery were generally unsatisfactory, while its efficiency was adequate. The average values of the six performance indicators monitored showed systemic problems that are discussed below.

Firstly, the water volume delivered was never sufficient to satisfy the irrigation requirements of crops (as shown by the poor indicator of adequacy), with the exception of citrus groves in the water delivery systems "Angitola 3DMF" and "Savuto" (mainly served by micro-irrigation systems); the data about olive grove irrigation may be affected by the simultaneous presence of young (irrigated) and old (not irrigated) trees inside the same farm. Korkmaz et al. (2009) assume that the fact that adequacy is poor in periods when irrigation requirement is high shows that there is a shortage of resource in the system. In peak irrigation period, the water delivery systems analysed in this study are not able to allocate water simultaneously to all the requiring farms and this generates problems of insufficient water volumes delivered. This is due to the generally insufficient capacity of the hydraulic infrastructure to allocate water simultaneously to the whole area in an equitable measure, such as: (i) the small size of storage reservoirs of WDS "Angitola 3DMF" and "Angitola 6DMF"; (ii) limitations in the water distribution network (low section of pipelines), which lead to insufficient water delivery due to problems of farmer simultaneous demand; (iii) use of inadequate farm irrigation systems, such as sprinklers and low-efficiency systems, which determine water waste. Moreover, the individual irrigation programs of the farmers do not appear suitable for the management of the water delivery services. Since the users did not report a reduction in crop yield, it may be deduced that farmers irrigated crops with additional resources, such as groundwater and/or potable water, often without authorization (as sometimes reported by local authorities); unfortunately, these unregulated supplies can not be properly quantified. However, the fair value of the indicator of efficiency and water exploitation indicated that the available water volume, delivered to the crops in the three water delivery systems, was properly used for irrigation. One should note that this irrigation efficiency relates to the WDS, but it does not include the water conveyance system. Since the water diverted from the source could be significantly higher, the values of the efficiency indicators should be multiplied by 0.8 or 0.9 (typical values in pressurized systems).

Secondly, as shown by the poor indicator of dependability, the service was not able to deliver water at the desired time, and thus the irrigation service was not uniform over time. This may be attributable to a farmers' lack of knowledge about times of supplying irrigation water to crops: in other words, often crops were irrigated when not necessary or, conversely, in some periods the irrigation requirement remained unsatisfied, regardless of a scheduled hydrological balance.

Finally, few cases (i.e. irrigation of gardens and orchards in the water delivery system "Angitola 6DMF" and citrus groves in "Savuto", irrigated by sprinklers) of very low spatial uniformity in water delivery to the irrigated farms were recorded, since the indicator of equity was poor. Some Authors (Abernethy 1986; Khepar et al. 2000; Gorantiwar and Smout 2005) have argued that the equitable distribution of water is also necessary for maximizing productivity.

1 However, equity of water delivery is a difficult objective to measure because there are many factors that determine the
2 meaning of a "fair share" and because a fair share is often interpreted subjectively (Molden and Gates 1990): this is the
3 reason why the problem of equity improvement was not analysed in depth in those situations in which a low spatial
4 uniformity of water delivery was recorded.

5 Therefore, the performed analysis suggests to both service managers and users the need for substantial changes either in
6 the system infrastructure or management procedures. Since the cost of irrigation network modification may be
7 unsustainable for the analysed WUA, management actions are planned. These improvements should be planned on the
8 basis of the results of water delivery performance in the studied irrigation services. This confirms that performance
9 evaluation of irrigated areas is needed not only to assess the productivity of water at various scales, but also to propose
10 improvements in irrigation management (Molden and Sakthivadivel 1999; Lorite et al. 2004b).

11 In this case of poor adequacy and dependability in water delivery systems, the comparison of the evaluated scenarios
12 shows that the replacement of sprinklers with micro-irrigation (scenario "1") produces lower improvements in water
13 delivery performance compared to arranged-demand distribution + irrigation advisory systems (scenario "2"). As a
14 matter of fact, scenario "1" induces a slight increase of water delivery adequacy (on the average 11.3%) and
15 dependability (9.7%) in spite of a decrease of efficiency (3.9%) and equity (25.9%). Instead, scenario "2" increases
16 slightly efficiency (on the average 4.2%) but noticeably dependability (56.2%) and equity (22.1%) of water delivery,
17 although worsening adequacy (by 4.5%) (Table 4). This latter performance may be a problem, since it reduces the
18 already poor water delivery compared to irrigation requirement, but the decrease is limited. Moreover, scenario "2"
19 assures a higher user satisfaction (on the average 33.3%) - poor in the current situation, - while scenario "1", as
20 expected, is the action targeted to the maximum water saving (74.9%), which however is currently fair (Figure 6). The
21 combination of the two scenarios (micro-irrigation and arranged-demand distribution + irrigation advisory service) is
22 the optimal choice, since its introduction simultaneously increases water delivery adequacy (on the average 8.2%),
23 efficiency (0.4%) and noticeably dependability (59.5%) - this latter more than in the single scenarios, - in spite of a
24 limited decrease of equity (3.3%) (Table 4); user satisfaction (27.7%) and water efficiency (72.3%) levels are halfway
25 and thus a compromise among the efficacy of the scenarios "1" and "2" (Figure 6).

26 From the simulation of improved management scenarios and the related evaluations by performance indicators, it
27 emerges that the amount of water, insufficient to satisfy the irrigation requirement, must be considerably increased
28 through further improvements, in order to assure a higher water availability during the entire irrigation season. This may
29 be achieved, for example, by diverting additional volumes from water courses and lakes, pumping groundwater from
30 wells or using reclaimed wastewater. Another choice may be the adoption of deficit irrigation (that is, an optimization
31 strategy with irrigation is limited and water delivery is not proportional to irrigation requirements). Deficit irrigation has
32 been widely investigated as a valuable strategy for dry regions (English 1990; Pereira et al. 2002; Fereres and Soriano
33 2007); however, since this inevitably results in plant drought stress and consequently in production loss, farmers in
34 Calabria may be restive in its implementation, because in general they show a low tolerance to the consequent reduction
35 of the economic value of agricultural yield.

36 Overall, the present study must be considered as the preliminary step of a more complete evaluation, which should also
37 include other detailed technical and economic analyses of the entire irrigation system (such as the supplying,
38 conveyance and distribution elements of the network). As a matter of fact, prior to the practical implementation of some
39 of these scenarios to improve the water delivery service performance, water managers must carry out careful hydraulic
40 analysis of the entire irrigation system (which should predict the network functioning and simulate pressures and
41 discharges in pipelines and hydrants) and economic evaluations of the proposed improving alternatives.

4. CONCLUSIONS

This study was targeted to understand whether a better allocation of irrigation water is possible by implementing improving measures at lower cost compared to structural works in collective irrigation service of Southern Italy. To this goal, the performance of the collective irrigation service in three Water Users Associations in Calabria was analysed through the indicators of adequacy, efficiency, dependability and equity of the water delivery integrated by two new indicators proposed (User Satisfaction and Water Exploitation Indices). Moreover, simulating improved scenarios, the gaps between the potential performance and the current management were identified.

The almost poor performance of water delivery currently identified suggested the simulation of the effects of some improvements, such as the replacement of farm sprinkler irrigation with micro-irrigation, the introduction of an arranged demand water delivery service together with the installation of an irrigation advisory service for farmers, or a combination of both actions. These improvements are easily to be implemented without the adoption of heavy actions, such as structuring works of the water supply network to increase water availability at scheme level, or expensive systems for automated remote control for centralised water delivery. Among the experimented management scenarios, the introduction of arranged demand distribution and irrigation advisory service not only is more favourite to the service users, but was also found to be more efficacious than the replacement of current sprinkler systems with micro-irrigation. In this case of poor service adequacy and dependability, the combined adoption of these scenarios is advisable, in order to assure the maximum performance in the analysed water delivery systems; it simultaneously increases three of the four water delivery performances and lets the collective service be more adequate and efficient for irrigation users and managers.

However, the simulated management scenarios were not sufficient to significantly modify the performance of the water delivery service. More specifically, in spite of the appreciable improvements in irrigation water allocation among farmers, in the case of chronicle or heavy scarcity of irrigation water (as in the case of many semi-arid zones devoted to water-fed agriculture of the Mediterranean environment), these improving actions should be integrated by other measures, such as deficit irrigation, heuristic water distribution methods, diversion of additional water volumes.

Overall, this study contributes to the diffusion of diagnostic and simulation tools in the collective irrigation sector of the Mediterranean basin, in order to promote a more productive and efficient use of water resources and a sustainable irrigated agriculture. However, a wide consolidation of this rational approach in irrigation water management should overcome many constraints, limiting the efficacy of these monitoring and planning activities (as also in the case of our study): (i) a higher reliability in estimating the crop irrigation requirements (e.g., by remote sensing based on actual water content of soils in real time) without relying on approximate methods; (ii) reduction of the time scale for the available water delivery data (this would allow the calculation of the ratio "water delivered/water required" on a decadal, a weekly or, better, a daily scale, leading to a more detailed and efficient water allocation plan among the irrigated farms); (iii) economic evaluation of the simulated scenarios, providing a cost/benefit analysis; (iv) a social analysis of farmers' perceptions towards the improving actions (for instance based on the "USI" index proposed in this study), since the farmer's satisfaction and thus their acceptance of water taxation could influence the financial performance of the collective organisations. If such limitations are overcome, this diagnostic and planning may be helpful in view of a more rational and opportune exploitation of irrigation water. Our strategic study must be integrated by other detailed technical and economic analyses of the water network operations, prior to the practical implementation of the planned scenarios.

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TABLES

Table 1 – Main characteristics of the water delivery systems “Angitola 3DMF”, “Angitola 6DMF” and “Savuto”.

Characteristics		Water delivery system		
		Angitola 3DMF	Angitola 6DMF	Savuto
Area (ha)	Command	190	200	900
	irrigated	117	96	411
Number of users		104	476	1554
Average farm size (ha)		1.1	0.2	0.3
Main crops		Vegetables and citrus	Vegetables, citrus and fruits	Vegetables
Water source		Lake Angitola		Savuto river
Year of construction		1985		
Water network length (km)		9.9	10.6	51.7
Water delivery conduit		Pressured pipelines		
Conduit material (% on total length)		Asbestos cement	PVC	Steel (5%), asbestos cement (95%)
Water distribution method		On demand		
Water charging method		Delivered water volume		

Table 2 – Crop data related to the water delivery systems “Angitola 3DMF”, “Angitola 6DMF” and “Savuto”.

Crop		Planting date	Harvesting date	Irrigated area (%)		
				Angitola 3DMF	Angitola 6DMF	Savuto
Olives ^(*)		-	-	0.2	18.9	0.0
Citrus ^(*)		-	-	60.9	41.1	6.7
Other fruits ^(*)		-	-	0.0	6.5	1.7
Vegetables	Tomato ^(**)	10-20 April	June/September	38.9	32.4	86.2
	Aubergine ^(**)	10-20 April	June/September			
	Onion ^(**)	10-20 March	June/August			
Maize and other cereals		1-10 May	October	0.0	0.5	0.9
Forage		10-30 October	August/September		0.0	4.1
Gardens ^(*)		-	-		0.5	0.9

Notes: (*) Trees and gardens are perennial; (**) Planting and harvesting dates refer to open field crops (excluding greenhouses).

Table 3 – Number of farm outlets for water delivery measurement in the water delivery systems “Angitola 3DMF”, “Angitola 6DMF” and “Savuto”.

Crop	Water delivery system		
	<i>Angitola 3DMF</i>	<i>Angitola 6DMF</i>	<i>Savuto</i>
<i>Olives</i>	1	2	-
<i>Citrus</i>	13	34	4
<i>Other fruits</i>	-	4	1
<i>Vegetables</i>	13	38	111
<i>Maize</i>	-	-	5
<i>Other cereals</i>	-	-	4
<i>Gardens</i>	-	4	3
<i>Forage</i>	-	-	2

Table 4 - Variation (%) of the irrigation performance in the water delivery systems “Angitola 3DMF”, “Angitola 6DMF” and “Savuto” under improved management compared to scenario "0".

Water delivery system	Micro-irrigation	Arranged demand	Arranged demand + micro-irrigation
<i>Adequacy</i>			
<i>Angitola 3DMF</i>	14.3	-4.6	11.0
<i>Angitola 6DMF</i>	9.2	-3.8	6.3
<i>Savuto</i>	10.5	-5.0	7.4
Mean	11.3	-4.5	8.2
<i>Efficiency</i>			
<i>Angitola 3DMF</i>	-3.8	4.7	1.2
<i>Angitola 6DMF</i>	-4.2	3.5	-0.6
<i>Savuto</i>	-3.6	4.4	0.7
Mean	-3.9	4.2	0.4
<i>Dependability</i>			
<i>Angitola 3DMF</i>	-13.0	-73.2	-76.8
<i>Angitola 6DMF</i>	-8.3	-46.6	-49.1
<i>Savuto</i>	-7.8	-48.9	-52.7
Mean	-9.7	-56.2	-59.5
<i>Equity</i>			
<i>Angitola 3DMF</i>	37.4	-34.2	-0.1
<i>Angitola 6DMF</i>	16.4	-6.9	8.6
<i>Savuto</i>	23.9	-25.1	1.5
Mean	25.9	-22.1	3.3

FIGURE CAPTIONS

Figure 1 – Location of the studied water delivery systems (Calabria, Southern Italy).

Figure 2 – Current annual water required (“WR”) and delivered per unit of irrigated area (“WD”) in the water delivery systems “Angitola 3DMF” (a), “Angitola 6DMF” (b) and “Savuto” (c).

Figure 3 – Current indicators (average values and standard deviations) of adequacy (“AD”), efficiency (“EF”), dependability (“DE”) and equity (“EQ”) in the water delivery systems “Angitola 3DMF” (a), “Angitola 6DMF” (b) and “Savuto” (c).

Figure 4 - Current User Satisfaction (“USI”) and Water Exploitation (“WEI”) Indices in the water delivery systems “Angitola 3DMF”, “Angitola 6DMF” and “Savuto”.

Figure 5 – Indicators of adequacy (a), efficiency (b), dependability (c) and equity (d) in the water delivery systems “Angitola 3DMF”, “Angitola 6DMF” and “Savuto” (the red and green lines show the limits "poor" and "good" respectively).

Figure 6 - User Satisfaction (“USI”, a) and Water Exploitation (“WEI”, b) Indices in the water delivery systems “Angitola 3DMF”, “Angitola 6DMF” and “Savuto”.

Figure 1



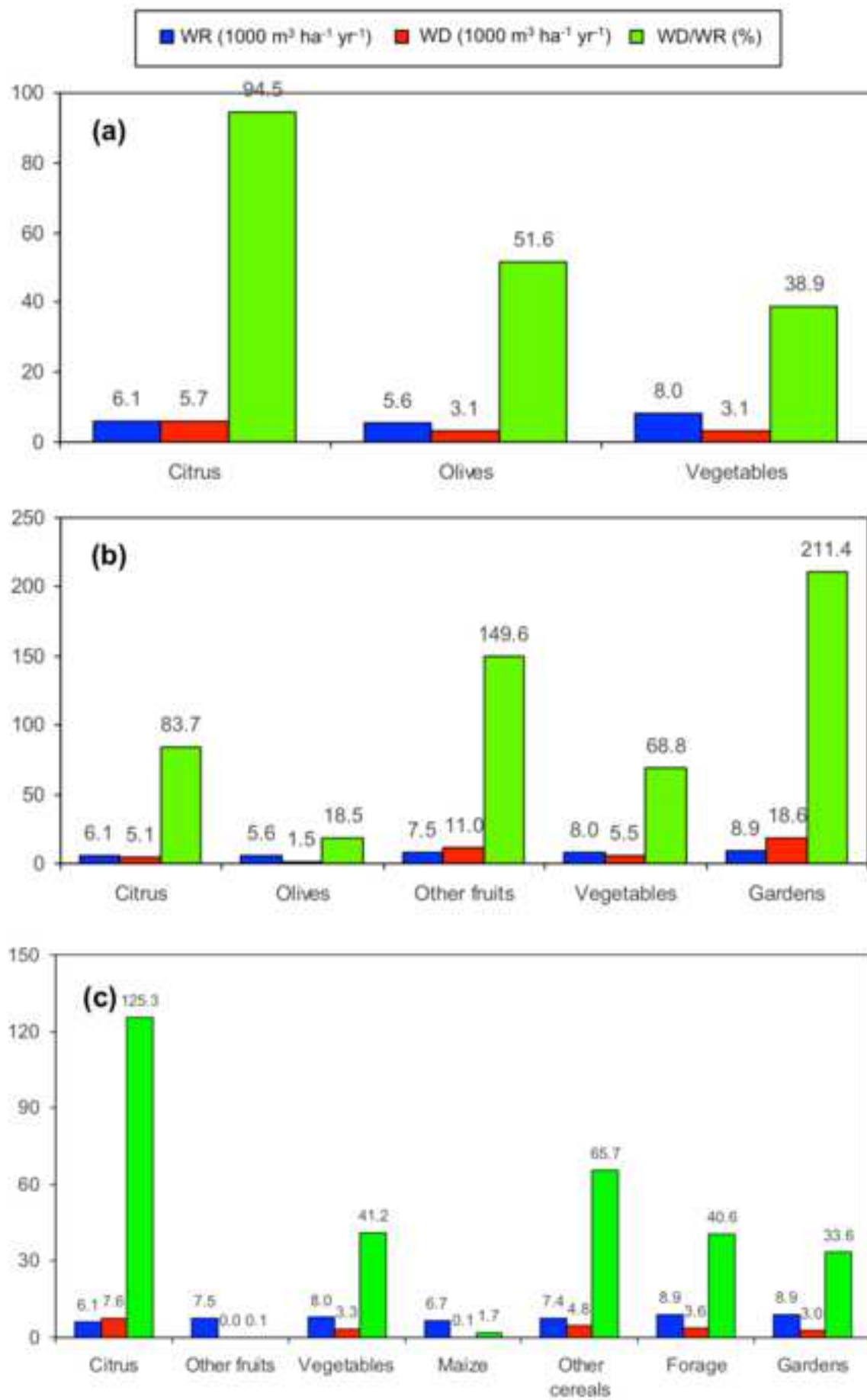


Figure 3

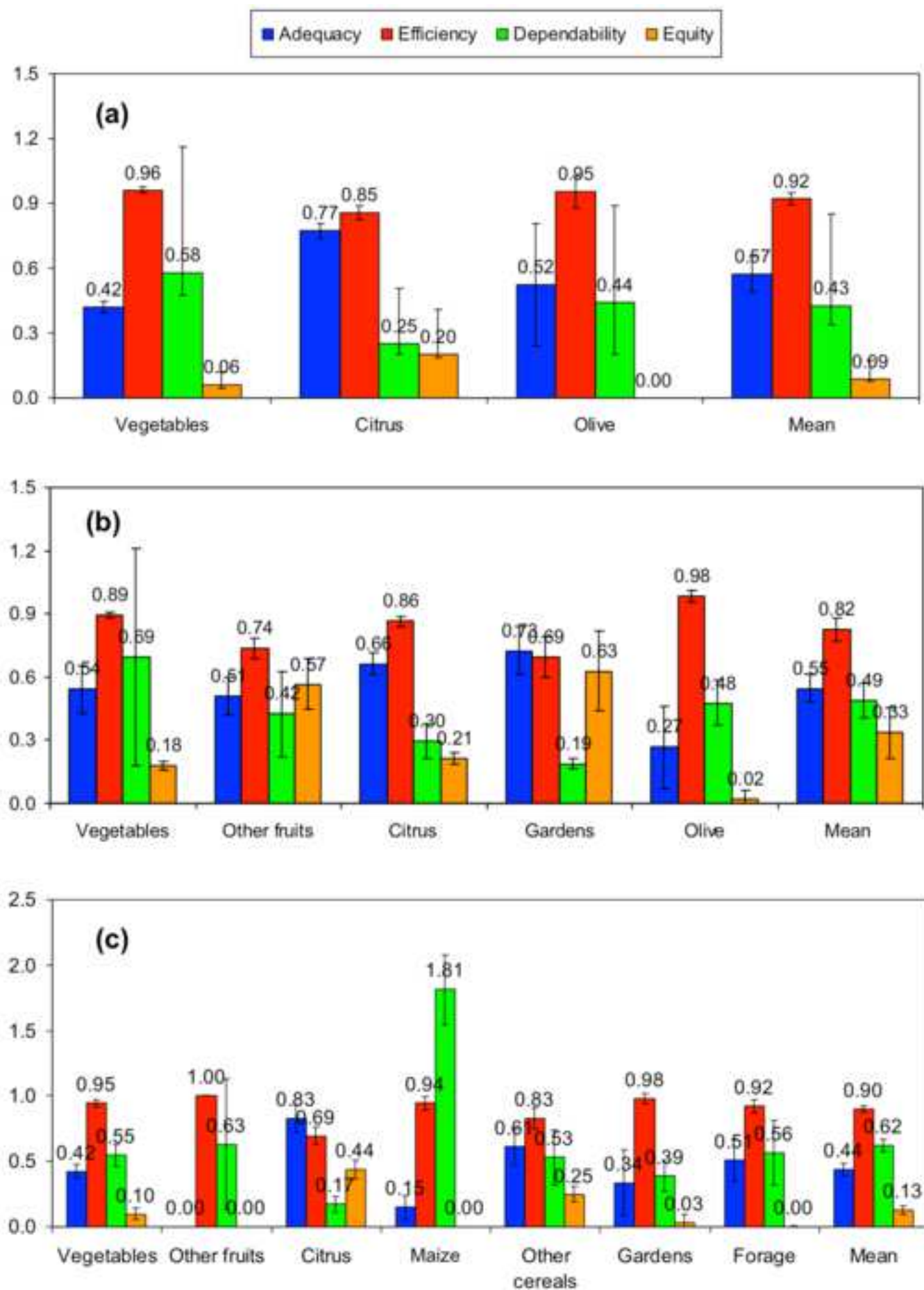
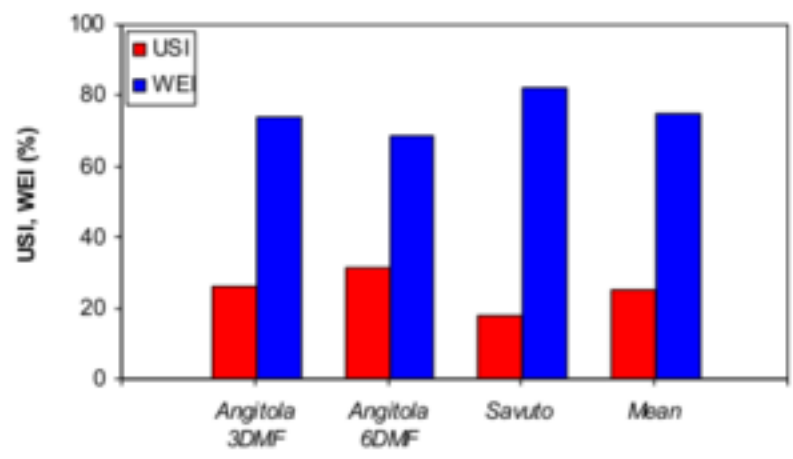
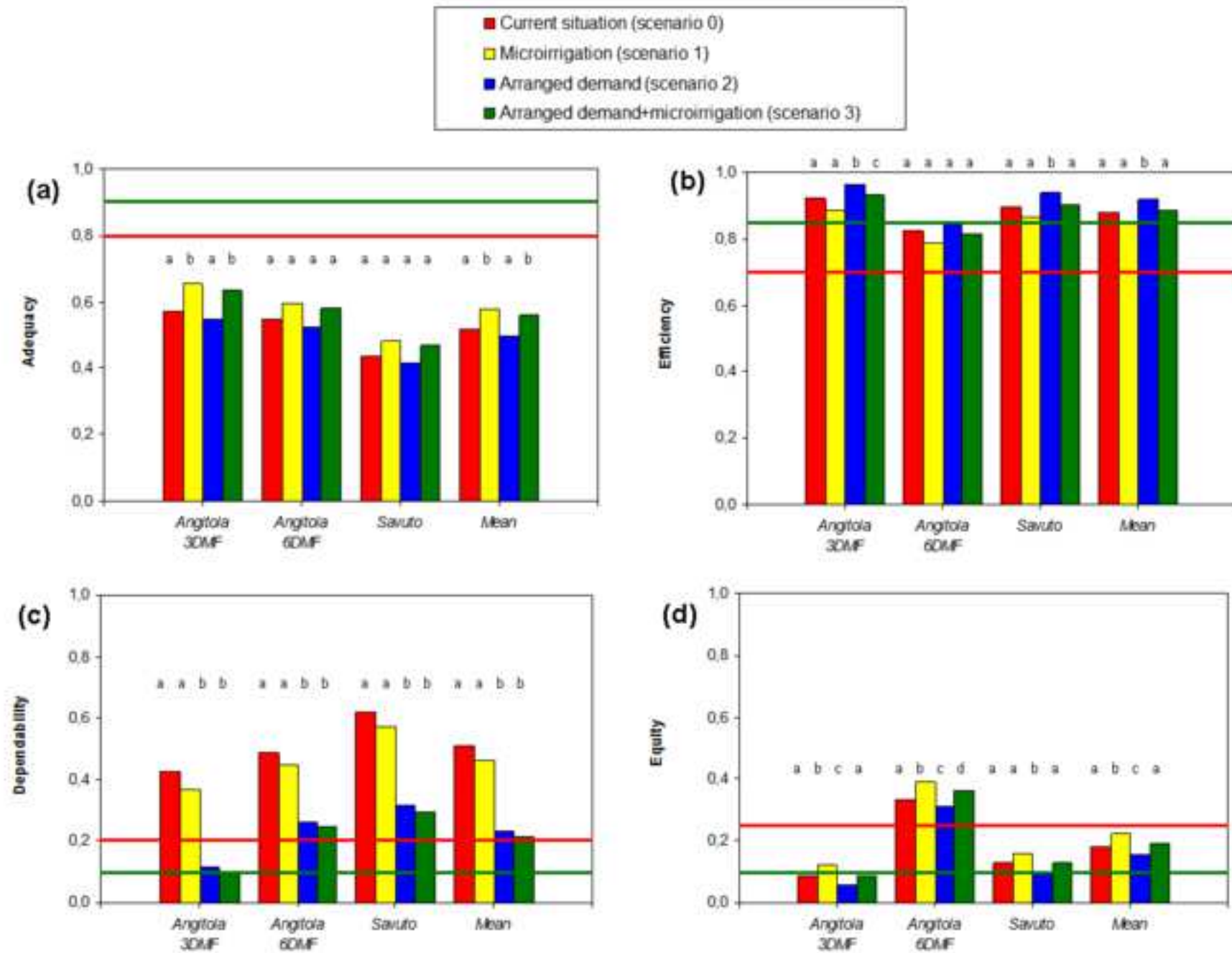
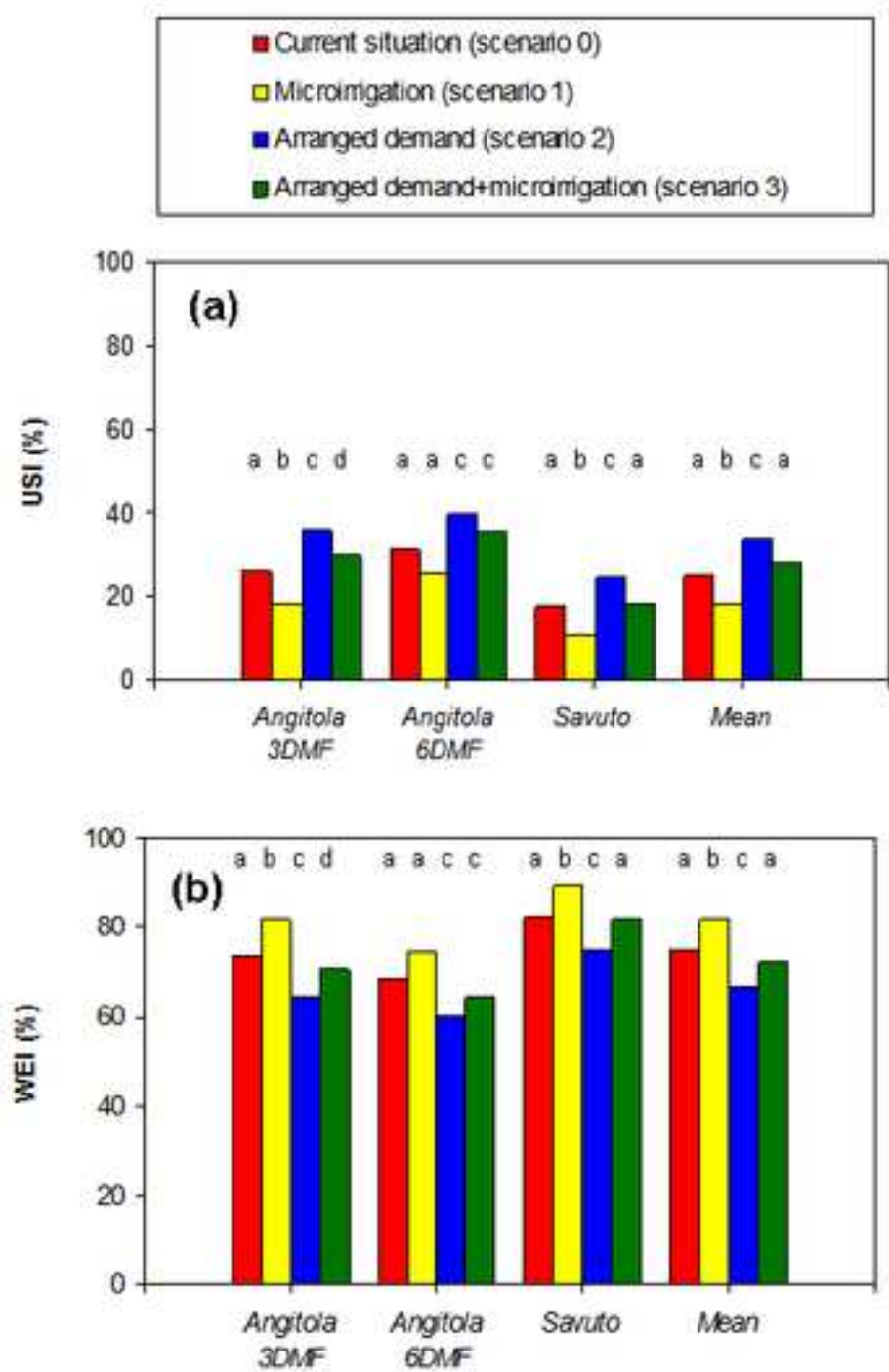
[Click here to access/download;Figure;Figure 3.tif](#)

Figure 4







AUTHORS' REPLY TO THE COMMENTS OF THE EDITOR

Dear Prof. Chàvez,

thanks a lot for the acceptance of our paper. We have considered Your valuable comments and addressed them in the revised text. You will find below the revision notes replying to each comment. As You required, all changes made to the MS are reported in the tracked submission. Moreover, we have uploaded a clean and updated version with the exact content.

C: Line 141: evapotranspiration of what crop? Grass reference? Please specify

R: The reported values are related to potential evapotranspiration. We have specified it in the text.

C: Line 143-144: same as above

R: We have specified it in the text also at these lines.

C: Line 278-279: it is indicated that only the irrigation efficiency changed but that the irrigation scheduling remained the same. This statement may not be true because drip irrigation applies small amounts of water at a higher frequency than surface or sprinkler irrigation. Therefore, to apply the required amount of water (for a given crop) the irrigation duration will need to be longer. In this case, a larger number of fields may be operated simultaneously and the irrigation schedule will have to change to accommodate the new low system flow and different irrigation application duration. In general, localize irrigation will have a higher irrigation frequency, not allowing much soil water deficit in the crop root zone due to the low flows and to avoid potential water stress in crops in case of failure in any part of the system. Please add a discussion regarding the implication of varied irrigation scheduling due to drip adoption and how a more frequent irrigation affects the scenarios.

R: Thanks for this consideration, which allows us to clarify the sentence. First, we have further clarified in the Method section (see lines 157-158 of the revised MS with tracked changes) that the total irrigation requirements of crops are calculated at the farm hydrant, considering the efficiency values of the irrigation method used in the farm in the net requirements evaluated for the crop. Only farms/users with a single outlet and single crop were considered, as we have reported in the previous MS (see lines 166-168); of course, the water delivered was measured at the farm hydrant as well, in order to make the comparison with the water required possible (sub-section 2.3).

In the scenario “1” we have replaced the current sprinkler irrigation with micro-irrigation at farm level for some crops. Under this scenario the irrigation water distribution method remains on demand and does not change to scheduled irrigation. Therefore, at the collective system level we can not talk about irrigation scheduling. What can change is the farm-level irrigation method, but this relates to the farmer behaviour in carrying out irrigation in his farm, which goes beyond the goal of this study. In general, since micro-irrigation lowers water losses in crop irrigation compared to sprinkler method (and therefore lower water volume to be applied), we do not think that each farmer should modify irrigation scheduling and, in any case, they can easily implement the new scheduling, since in the majority of farms small reservoirs are available to modulate frequency and duration of irrigation operations. We have thoroughly rewritten these sentences in the revised text, in order to clarify and adding more discussion, as You required.

C: Line 289 “All the simulated scenarios kept the same seasonal volumes of delivered water per crop.” How is it possible to deliver the same volumes of water per crop if the irrigation system efficiency has been improved (changed)? Justify, discuss.

R: From the Editor’s comment, we have realised that also this sentence was not clear in the previous MS version. We meant that the irrigation service delivers each year (irrigation season) the same water volume to each hydrant. Presumably, the word “crop” is misleading, then we have replaced it with “hydrant” in the revised text.

C: Page 9: in the results section, sub-section 3.1 total irrigation requirement (with CROPWAT), it seems that percent of water delivered per year (season) per crop type does not include precipitation. This needs to be verified. Some deliveries are simple too low to sustain economic production that are not believable (despite the fact that farmers may use other sources of water). If effective precipitation has been accounted for in CROPWAT, please clarify accordingly.

R: Yes, we have accounted for the effective precipitation in CROPWAT. We have clarified this in the revised text.

Improving management scenarios of water delivery service in collective irrigation systems: a case study in Southern Italy

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Abstract

The performance of water delivery service in collective irrigation networks can be enhanced by improving measures ranging from a better water allocation to more expensive structural works. In any case, the efficacy of these measures must be simulated prior to their actual implementation and evaluated using quantitative performance indicators. The aim of this study is a strategic analysis of the water delivery service to understand whether a better water allocation is possible in collective irrigation systems by implementing improving measures at lower cost compared to structural works. To this goal, the performance of three water delivery systems was evaluated in Calabria (Southern Italy) over four irrigation seasons, using the indicators of adequacy, efficiency, dependability and equity developed by Molden and Gates (1990). Subsequently, three scenarios for improving irrigation management (replacement of sprinkler methods with micro-irrigation, an arranged-demand water delivery service together with an irrigation advisory service, and a combination of both actions) were simulated and evaluated. Furthermore, two new indicators ("User Satisfaction Index" and "Water Exploitation Index"), measuring satisfaction of irrigation service users and water use levels, were proposed and applied.

In the current situation poor adequacy, reliability and equity of water delivery service with low user satisfaction together with fair efficiency in exploiting the limited irrigation resources were detected. The simulation of an arranged demand distribution and irrigation advisory service was found to be more efficacious and favourite to the system users than the replacement of current sprinkler systems with micro-irrigation. The combined adoption of these scenarios is advisable, in order to assure the optimal performance in water delivery systems and to make the collective service more adequate and efficient for both irrigation users and managers.

Keywords: water delivery system; performance indicators; farmer satisfaction; water exploitation; irrigation management; collective irrigation.

1. INTRODUCTION

One of the core objectives of collective irrigation management is the appropriate delivery of water resources in order to meet crop irrigation requirements. The success of an irrigation-water-delivery system can be measured by how well it meets the objectives of delivering an adequate and dependable supply of water in an equitable and efficient manner to users served by the system (Molden and Gates 1990). However, often water delivery systems suffer from problems such as capacity lower than peak demand, irregular delivery rates and low irrigation efficiency and uniformity (Nam et al. 2016). This is also due to the lack of an appropriate allocation plan for distribution of water resources to different crops. This allocation plan and corresponding water delivery need to be prepared to achieve the set objectives of a more adequate, efficient, reliable and equitable irrigation service (Pérez-Urrestarazu et al. 2009). In general, it is useful to

42 evaluate the actual performance and simulate the future behaviour of an irrigation scheme before an implementing a
 43 new or an improved allocation plan. This enables the irrigation authorities make an accurate prediction of the
 44 performance of the irrigation plan when the plan is put in actual operation; this evaluation can be done with the help of
 45 historical and generated data series related to water supply and demand (Gorantiwar and Smout 2005). Similar studies
 46 providing information on the degree of variability of irrigation performance are essential to realistically assess the
 47 potential for improvements in irrigation management (Lorite et al. 2004b).

48 Several Authors (e.g. Molden and Gates 1990; Malano and Burton 2001) have defined sets of indicators that
 49 characterize irrigation service performance, intending to quantify the system ability to achieve the objectives established
 50 for an irrigation area (Lorite et al. 2004a). The literature shows that quantitative indicators such as efficiency, adequacy,
 51 equity, and dependability of irrigation supplies are the most important to describe the health of an irrigation system
 52 (Hamid et al. 2011). Investigations on water delivery performance have been carried out in many areas worldwide to
 53 diagnose deviations from the expected performance (e.g. Molden and Gates 1990, in Sri Lanka; Vandersypen et al.
 54 2006, in Mali; Kazbekov et al. 2009, in Kyrgyzstan; Hamid et al. 2011, in Sudan; Wellens et al. 2013, in Burkina Faso;
 55 Nam et al. 2016, in South Korea). In Mediterranean semi-arid areas the papers of Molden and Gates (1990) in Egypt,
 56 Unal et al. (2004), Akkuzu et al. (2007) and Korkmaz et al. (2009) in Turkey and Zaccaria and Neale (2014) in Italy can
 57 be mentioned. However, few of these studies have compared the current performance of the studied water delivery
 58 service with simulated future scenarios for improving irrigation services. Vice versa, the implementation of systematic
 59 activities assessing the current and future performance of an irrigation service is a prerequisite to characterize the
 60 variability in water allocation among farmers, especially in those contexts where water resources for irrigated
 61 agriculture are scarce (such as in semi-arid or arid areas). In these cases, as farmers demand improvements in the
 62 availability and reliability of water supplies, the number of pressurized irrigation networks arranged on demand is
 63 increasing (Rodríguez-Díaz et al. 2004). If these systems (designed to deliver water with flow rates and pressures
 64 required by on-farm irrigation systems, Pérez Urrestarazu et al. 2009) can overloaded, farmers may be required to cut
 65 supplies and delay or postpone irrigation (Rodríguez Díaz et al. 2007). Therefore, improving management measures are
 66 needed in these collective irrigation systems, targeted to a better allocation of the water resources.

67 Improving the irrigation management often requires structural works in the supply networks, such as construction of
 68 water withdrawal works in supplying water courses, increase of the size of storage reservoirs, replacement of conveying
 69 pipelines to increase their diameter. These works require a noticeable money expenditure, which forces WUAs to
 70 collect additional funds, often by increasing water fees paid by the associated farmers. Sometime less expensive
 71 measures would be possible, such as a more rational water allocation (that is, a distribution based on the actual
 72 irrigation requirement of crops) or changes towards more efficient farm irrigation systems, whose costs would be lower
 73 than structural works, thus keeping the same volumes of delivered water per ~~farm~~ **crop**. The efficacy of these measures
 74 can be evaluated before their actual implementation by simulating as many improving management scenarios in terms
 75 of improved adequacy, efficiency, reliability and equity of the water delivery service, by the adoption of the related
 76 performance indicators of Molden and Gates (1990).

77 This study evaluates the actual and future performances of three on-demand water delivery systems in Calabria
 78 (Southern Italy) using records collected over four irrigation seasons; in these irrigation schemes proposals for improving
 79 collective irrigation (at lower costs compared to infrastructural works) have been evaluated. In more detail, the
 80 adequacy, efficiency, dependability and equity of water delivery have been quantified at farm scale for the major crops,
 81 using the four indicators developed by Molden and Gates (1990). On the basis of this diagnosis, three different
 82 scenarios, including an improved water allocation service and/or changes towards more efficient farm irrigation

systems, have been simulated and their effects on water allocation have been evaluated through the performance indicators. Finally, two new indicators for quantifying user satisfaction and water exploitation in the irrigation schemes are proposed (with the scope to integrate the original set of Molden and Gates 1990). The aim of this study is a strategic analysis of the water delivery service rather than an evaluation of the system operation (requiring a hydraulic simulation of the network functioning with predictions of pressures and discharges in pipelines and outlets), since we intend to assess under the current and the simulated scenarios the irrigation water consumptions by farmers compared to the required amounts for crop growth and production.

2. MATERIAL AND METHODS

2.1 Description of the study area

In Calabria (Southern Italy) agriculture is by far the most important economic sector. In this region, where 11 Water Users Associations operate, the performance of collective irrigation services is generally poor, due to inadequate water delivery, with low farmer satisfaction (Zema et al. 2015; 2018b). Currently, in spite of well known problems of water distribution, in none of the other water delivery systems in Calabria, a quantitative evaluation of the agricultural water allocation in time and space has been performed: water managers fail to give the same importance to measuring operations as to other management operations (Zema et al. 2018a; 2018b). Only in three water delivery systems of the Water Users Association "Tirreno Catanzarese" water-use records are available for individual land parcels and this availability of water delivery data measurements in the cultivated areas allows the evaluation of the collective irrigation performance and the effects of improved management actions on a quantitative basis.

The three investigated water delivery systems fall within the Water Users Association "Tirreno Catanzarese", which covers an area of 85602 hectares (856 km²) in the western part of Calabria (Figure 1). The irrigated area (1479 ha) covers 32.6% of the command area (4540 ha). The main crops are olives, citrus and other fruits, vegetables (mainly tomatoes, aubergines and onions), gardens, forage, maize, and are mainly irrigated with sprinkler systems. The irrigation resource is supplied from surface water bodies and delivered to farmers by pressurized pipelines (about 75% of the network total length) or canals (25%). Water is distributed on demand and charged to users on water unit volumes effectively delivered. These volumes are measured in farms by the automated system "Acquacard®", which also allows data recording and storage.

The three investigated water delivery systems are called "Angitola Terzo Distretto a Monte Ferrovia" (abbreviated to "Angitola 3DMF"), "Angitola Sesto Distretto a Monte Ferrovia" ("Angitola 6DMF") and "Savuto". The water network was built in 1985 and currently delivers irrigation water to over 2000 farms (Table 1).

In the water delivery system "Angitola 3DMF" the irrigated area is 117 ha and the command area 190 ha. Water from Lake Angitola is pumped to a 4000 m³ reservoir. The water is then delivered by gravity in pressured pipelines (PVC, 9.9 km of total length).

The water delivery system "Angitola 6DMF" covers an irrigated area of 86 ha over a command area of 200 ha. Water from Lake Angitola is pumped to a 2000 m³ reservoir. The water is then delivered by gravity in pressured pipelines (asbestos cement, total length of 10.6 km).

The water delivery system "Savuto" has the largest irrigated (411 ha) and command (900 ha) areas. Water from the Savuto river is pumped to a 22000 m³ reservoir. The water is then delivered by gravity in pressured pipelines (2.6-km main conduit of steel and 49.1-km distributing pipelines of asbestos cement).

The three water delivery systems were designed by probabilistic criteria targeted to fulfil simultaneously no more than 20% of the served hydrants; therefore, these systems are not able to allocate water simultaneously to the whole area.

124 The agricultural district served by the analysed water delivery systems mainly consists of small and often family-run
125 farms. Therefore, the irrigation requirement of crops is mainly determined by approximate criteria (very often simply by
126 visually estimating the soil water content) instead of by quantifying it using scientific methods (i.e. by measuring the
127 soil water content and/or by a quantitative water balance of crops).

128

129 2.2 Estimation of the total/net irrigation requirements

130 In Calabria, the climate is typically semi-arid, with mild, wet winters and hot, dry summers (Bombino et al. 2007).
131 Precipitation is concentrated mainly in late autumn and early spring; therefore the irrigation requirement of crops is high
132 in summer (essentially coinciding with the irrigation season) and very low in the coldest season.

133 Following Unal et al. (2004) and Korkmaz et al. (2009), the net irrigation requirement of each crop (that is the quantity
134 of water exclusive of precipitation required for normal crop production) was estimated using the software CROPWAT
135 8.0 (Clarke et al. 1998; FAO 2009). Using this software, the water balance was performed daily for each crop over four
136 irrigation seasons (from April to September).

137 The daily meteorological data required by CROPWAT (maximum and minimum temperatures, precipitation, relative
138 humidity, wind speed and daylight) were measured at the meteorological station of Lamezia Terme (geographical
139 coordinates 38.908304° N, 16.25358° E, falling in the perimeter of the Water Users Association "Tirreno Catanzarese").
140 In the monitored calendar years (2008-2011) the minimum temperature was -3.3 °C (February) and the maximum 44.0
141 °C (September), while the mean precipitation and **potential** evapo-transpiration rate were 892 mm year⁻¹ and 4.1 mm
142 day⁻¹ respectively. In the irrigation season, the mean temperature recorded in the observation period was in the range
143 15.1 - 30.1 °C. The mean precipitation and **potential** evapo-transpiration rate were 47.5 mm month⁻¹ (with the lowest
144 values, close to zero, recorded in July) and 5.7 mm day⁻¹ (with a peak of 7.5 mm day⁻¹ in September) respectively. Since
145 the observations of precipitation and temperature show a limited variability (CV < 27%) among the irrigation seasons,
146 the changes in the irrigation districts as a function of weather conditions (e.g. farmers' behaviour, irrigation requirement
147 and scheduling, etc.) can be considered small.

148 In relation to the crop data, the root depth and crop coefficients for calculating evapo-transpiration (estimated by
149 Penman-Monteith model) were derived from FAO guidelines (Doorenbos and Kassam 1986); the farm cultivation
150 practices (Table 2) were identified by interviewing a sample of 30 farmers (two persons for each crop in each WDS,
151 selecting the owners of medium sized farms). In general dates and operations were almost homogenous among the
152 farms and the WDS.

153 Soil hydrological parameters, in the absence of direct measurements, were estimated using the Pedo Transfer Function
154 of Saxton et al. (1986) on the basis of the soil texture reported by the Soil Map of the Calabria Region (ARSSA, 2003).
155 The soils of the studied area, generally homogenous, are mainly sandy loam (65% of sand, 22% of silt and 13% of clay,
156 Carta dei Suoli della Regione Calabria, ARSSA, 2003); the saturated hydraulic conductivity is 17.5 mm h⁻¹.

157 The total irrigation requirement of each crop (henceforth indicated as "water required") was calculated **at the farm outlet**
158 **(hydrant)** from the net irrigation requirement considering farm irrigation efficiency: for sprinklers the value of 0.70 was
159 assumed, while the values of 0.85 (sprayers) and 0.95 (drippers) were considered for micro-irrigation, accordingly to
160 the CROPWAT guidelines (Clarke et al. 1998; FAO 2009). Finally, daily data of total irrigation requirement were
161 aggregated at monthly scale.

162

2.3 Collection of the water delivery data

The water volumes delivered to users (henceforth indicated as "water delivered" or "water delivery") were measured by "Acquacard®" at the farm outlets (hydrants). Acquacard provides user name and code, irrigated crop and area, and delivered daily volume. Only farms/users with a single outlet and single crop were considered. About 20% of samples were ignored as giving anomalous or not useful data, for example, fields with an area of zero hectares or farms with more than one crop/hydrant/irrigation method. The integrity and reliability of the data used were assured by the recent system testing by the installer company.

Subsequently, such data were classified per water delivery system, year (irrigation season), month and irrigated crop.

2.4 Description of the performance indicators

For the month "j" of each irrigation season and farm outlet "i", the water delivered (WD_{ij} , [$m^3 ha^{-1} month^{-1}$]) and the water required per unit area (WR_{ij} , [$m^3 ha^{-1} month^{-1}$]) were considered.

The ratios between these two values ($a_{ij} = WD_{ij}/WR_{ij}$ or its reciprocal $e_{ij} = WR_{ij}/WD_{ij}$) are the elements of two matrices of the "m x n" order, where "m" is the number of farm outlets in a hydraulically independent irrigation system "R" (each of the three water delivery systems) and "n" is the number of the months of period "T" (in our study the four irrigation seasons). On the basis of the elements " a_{ij} " and " e_{ij} " of the two matrices, the indicators of Molden and Gates (1990) of adequacy (AD), efficiency (EF), dependability (DE) and equity (EQ) were evaluated in each of the three water delivery systems. Adequacy, efficiency, dependability and equity are the performance objectives taken into consideration when evaluating irrigation water delivery (Nam et al. 2016). Besides the studies of Molden and Gates (1990), the literature provides ample information about these indicators together with calculation methods and equations (e.g. Vandersypen et al. 2006; Akkuzu et al. 2007; Kazbekov et al. 2009; Korkmaz et al. 2009; Hamid et al. 2011). Here, their meaning and aim are summarised.

The indicator of adequacy " $AD_{R,T}$ " of an irrigation system "R" throughout a period "T" assesses to what extent delivered water met irrigation requirements (Molden and Gates 1990) or, in other words, whether the irrigation service delivers to a farm a water volume "adequate" for irrigation requirement (Akkuzu et al. 2007; Korkmaz et al. 2009; Hamid et al. 2011). In particular, if $AD_{R,T} < 1$, the irrigation requirement is not satisfied by the water delivery system and the irrigation service is "inadequate".

The indicator of efficiency " $EF_{R,T}$ " of an irrigation system "R" throughout a period "T" answers the question of whether there is excessive delivery of water in relation to the crop needs (Molden and Gates 1990); it measures the "efficiency" in water conservation in an irrigation system (Vandersypen et al. 2006; Akkuzu et al. 2007; Korkmaz et al. 2009). In particular, if $EF_{R,T} < 1$, there is a surplus of delivered water compared to required volume and thus the delivery service is not "efficient".

The indicators of adequacy " $AD_{R,T}$ " and efficiency " $EF_{R,T}$ " of an irrigation system "R" over a period "T" are given by the formulas (Jahromi and Feyen, 2001; Kazbekov et al., 2009):

$$AD_{R,T} = \frac{1}{n} \sum_{j=1}^n \left(\frac{1}{m} \sum_{i=1}^m p_{ij} \right) \quad [1]$$

assuming $p_{ij} = a_{ij}$, if $a_{ij} \leq 1$, otherwise $p_{ij} = 1$, if $a_{ij} > 1$

$$EF_{R,T} = \frac{1}{m} \sum_{j=1}^m \left(\frac{1}{n} \sum_{i=1}^n q_{ij} \right) \quad [2]$$

being $q_{ij} = e_{ij}$, if $e_{ij} \leq 1$, otherwise $q_{ij} = 1$, if $e_{ij} > 1$.

Dependability indicates the temporal uniformity in the ratio of amounts of water delivered to amounts of water required (Molden and Gates 1990). The indicator of dependability ($DE_{R,T}$) of an irrigation system "R" throughout the irrigation season "T" measures temporal uniformity (i.e. over the irrigation season) of the relative amount of water delivered to the different farm outlets (Kazbekov et al. 2009); in other words, $DE_{R,T}$ is an index of the irrigation system's ability to deliver water at the desired time compared to a specific requirement (Vandersypen et al. 2006; Korkmaz et al. 2009). A value of $DE_{R,T}$ close to zero indicates an irrigation service uniform in time and, therefore, "dependable" throughout the irrigation season (Molden and Gates 1990; Korkmaz et al. 2009).

For an irrigation system "R" consisting of "m" outlets, the indicator of dependability over the irrigation season "T" ($DE_{R,T}$) can be calculated by the following formula:

$$DE_{R,T} = \frac{1}{m} \sum_{i=1}^m CV_T(a_{ij}) \quad [3]$$

where CV_T is the coefficient of variation over the time "T" (i.e. the "n" months of the irrigation season) of the indicator of adequacy " a_{ij} " (Jahromi and Feyen, 2001; Kazbekov et al., 2009).

Equity addresses the extent of fairness of water distribution among users (Molden and Gates 1990). The indicator of equity ($EQ_{R,T}$) of an irrigation system "R" throughout the irrigation season "T" measures the spatial variability (i.e. among the different farm outlets) of the relative amount of water delivered during the irrigation season (Molden and Gates 1990; Vandersypen et al. 2006); in other words, $EQ_{R,T}$ is an index of the irrigation system's ability to deliver the water evenly among all the users in the irrigation season compared to a given requirement (Molden and Gates 1990; Hamid et al. 2011). A value of $EQ_{R,T}$ close to zero indicates an irrigation service uniform in space and, therefore, "equitable" among the users (Molden and Gates 1990; Korkmaz et al. 2009).

During the "n" months of the irrigation season "T" the indicator of equity ($EQ_{R,T}$) was calculated by the following formula:

$$EQ_{R,T} = \frac{1}{n} \sum_{j=1}^n CV_R(a_{ij}) \quad [4]$$

where CV_R is the coefficient of variation of the indicator of adequacy " a_{ij} " in the irrigation system "R" (Jahromi and Feyen, 2001; Kazbekov et al., 2009).

Of course, it is practically impossible to achieve the ideal values for all the indicators considered; thus, the standard values reported by Molden and Gates (1990) were adopted as acceptance limits:

- $AD_{R,T}$ good if ≥ 0.90 , fair in the range $0.80 - 0.89$ and poor if < 0.80
- $EF_{R,T}$ good if ≥ 0.85 , fair in the range $0.70 - 0.84$ and poor if < 0.70
- $DE_{R,T}$ good if ≤ 0.10 , fair in the range $0.11 - 0.20$ and poor if > 0.20
- $EQ_{R,T}$ good if ≤ 0.10 , fair in the range $0.11 - 0.25$ and poor if > 0.25 .

The desirable values of the adequacy indicator suggested by Molden and Gates (1990) do not include the irrigation inefficiency, according to the calculation method; therefore, values of one could lead to a slight deficit irrigation.

The high aggregation level of the ratios $a_{ij} = WD_{ij}/WR_{ij}$ or its reciprocal $e_{ij} = WR_{ij}/WD_{ij}$ (averaged in time and space) adopted by the performance indicators of Molden and Gates (1990) complies with the main goal of WUA managers, which are interested on the general operation quality of water delivery system rather than a detailed analysis of irrigation behaviour of the single farmers in the different time steps of an irrigation season. This is the main approach of this study, targeted to a synthetic but comprehensive measure of management efficacy of water delivery systems and not to a full evaluation of the variability of the performances in the irrigation districts at farm scale.

239

240 **2.5 Description of the new performance indicators proposed**

241 In this study two new indicators are suggested. As reported above, if a_{ij} is equal or higher than 1, the water delivered to
 242 a farm satisfies the water required or it is in excess. The sum of all occurrences " $a_{ij} \geq 1$ " accounts throughout all the time
 243 periods of an irrigation season (in our study the number of months) the number of farmers which receive the adequate
 244 water volume for crop irrigation (not measured by the $DE_{R,T}$ indicator, which globally indicates how much water
 245 delivered matches irrigation requirement). In such way, this sum gives the incidence of the periods in which a share of
 246 the irrigation system users is globally satisfied for the adequate water delivery. From the point of view of WUA
 247 managers, this index can be considered as a feedback measure of the users' opinion about the water delivery service
 248 performance.

249 Furthermore, if e_{ij} is equal or higher than 1, no surplus of delivered water compared to volume required is observed. The
 250 sum of all occurrences " $e_{ij} \geq 1$ " accounts throughout all the time periods of an irrigation season the number of farmers
 251 which irrigate crops using the entire water delivered by the service (without considering whether this volume is
 252 sufficient or not, whose measure is given by the AD indicator). In other terms, under these situations the delivered water
 253 is completely supplied to plants and thus the irrigation resource is exploited with the maximum efficiency, giving WUA
 254 managers an indication about the global level of irrigation water use. Thus, a new index can be added to $EF_{R,T}$, taking
 255 into consideration only those situations for which irrigation water is fully exploited and measures their incidence
 256 throughout the irrigation season and on the total number of farmers.

257 Therefore, for the irrigation system "R" and throughout the irrigation season "T" a "User Satisfaction Index" (USI, [%])
 258 and a "Water Exploitation Index" (WEI, [%]) of the water delivery can be defined as follows:

$$259 \quad USI_{R,T} = \frac{1}{m \cdot n} \sum_{j=1}^n \sum_{i=1}^m r_{ij} \times 100 \quad [5]$$

$$260 \quad WEI_{R,T} = \frac{1}{m \cdot n} \sum_{j=1}^n \sum_{i=1}^m s_{ij} \times 100 \quad [6]$$

261 where:

262 $r_{ij} = 1$, if $a_{ij} \geq 1$, otherwise $r_{ij} = 0$, in equation [5]

263 $s_{ij} = 1$, if $e_{ij} \geq 1$, otherwise $s_{ij} = 0$, in equation [6]

264 Of course, the sum of $USI_{R,T}$ and $WEI_{R,T}$ is equal to 100.

265

266 **2.5 Analysis of the performance indicators currently and under improved management scenarios**

267 In the current situation (in the following indicated "scenario 0"), for each farm supplied with irrigation water in the three
 268 studied water delivery systems, WD_{ij} , WR_{ij} and their ratios (a_{ij} and e_{ij}) were calculated monthly for each irrigated crop
 269 (from April to September) throughout each of the four irrigation seasons. After this, the indicators $AD_{R,T}$, $EF_{R,T}$, $DE_{R,T}$
 270 and $EQ_{R,T}$ were calculated at an annual scale (grouping the "n" months of each irrigation season) and the related mean
 271 values were derived.

272 Subsequently, three possible management scenarios, aiming at improving the unsatisfactory performance of the
 273 analysed water delivery services, were evaluated through the six indicators (the set of Malano and Burton, 1991, and the
 274 new indices USI and WEI) above mentioned. These simulation activities may be considered by the irrigation managers
 275 and users as a preliminary analysis of the feasibility of the planned interventions.

276 In a first scenario ("1"), ~~the adequacy of the water delivery service~~ was improved by simulating micro-irrigation (by
277 sprayers or drippers) farm systems in replacement of the current sprinkler irrigation for vegetables, citrus and olive
278 groves as well as other orchards; **the collective delivery service will continue to distribute irrigation water on demand as**
279 **in the current scenario. The water saving provided by micro-irrigation compared to sprinkler systems is well known,**
280 **since micro-irrigation lowers water losses in crop irrigation. The migration from sprinklers to drippers simply consists**
281 **of a change in the irrigation efficiency of the farm method. At farm level, in some cases the farmers could need**
282 **modifying the frequency and duration of irrigation operations, compared to the previous sprinkler system. This can be**
283 **allowed by the availability of small reservoirs/tanks (installed in most farms), disconnecting the farm and collective**
284 **systems.**

285 ~~The water saving provided by micro irrigation compared to sprinkler systems is well known. The migration from~~
286 ~~sprinklers to drippers evidently consists of a change in the irrigation efficiency, since irrigation scheduling is not~~
287 ~~modified. The expected variations of pressure and flow, compared to the sprinkler systems, can be faced off by auto-~~
288 ~~compensating drippers, valves and small reservoirs/tanks installed in the farm irrigation systems, respectively; these~~
289 ~~devices also allow to match the limitation of simultaneity under 20%, disconnecting the farm and system networks each~~
290 ~~other.~~

291 In the second scenario ("2"), to increase system dependability, the following management actions were simulated:
292 - a "limited rate arranged-demand" water distribution method (Merriam et al. 2007) (in the following simply indicated
293 as "arranged demand"), in replacement of the current on-demand method;
294 - an irrigation advisory service, based on the water balance of crops, which suggests irrigation requirements to users
295 using internet or SMS.

296 Finally, a third combined scenario ("3") includes both improvement measures mentioned above.

297 All the simulated scenarios kept the same seasonal volumes of delivered water per **farm hydrant crop**. In scenarios 2 and
298 3, the irrigation water volumes to be delivered to each farm by the irrigation network were estimated as the product of
299 the water delivered in each irrigation season by a monthly coefficient; this latter was calculated as the ratio between the
300 monthly and the seasonal irrigation requirements calculated by CROPWAT. For example, if CROPWAT estimates for
301 July a monthly irrigation requirement equal to 42% of the seasonal value, then the water delivered to the farm in the
302 same month is the 42% of the seasonal delivered volume.

303 The water delivery planned in scenarios 2 and 3 simulates a "limited rate arranged-demand" (Merriam et al. 2007) or a
304 "semi-demand" water distribution method in which the irrigator requests a specific volume of water and flow rate
305 (Mateos et al. 2002) to be arranged with WUA management. More specifically, under this arranged demand method
306 (less restricted than a rotational schedule and thus more appreciated by users), the farmer requests a specific water
307 volume and flow rate to be supplied on one or several days, following the suggested time and volume for crop
308 irrigation. The WUA managers check if the requests can be satisfied by the operational flow and delivery sequence
309 selected, and the sector assignments. If not **(that is, when the limitation of simultaneity under 20% is not respected due**
310 **to the low flow capacity of the collective network)**, water is made available within a few days (generally 2-7 days) of
311 his request (Anwar et al., 2006) or new manager-farmer arrangements will have to be made (Mateos et al. 2002). Under
312 the "semi-demand" water distribution method of scenarios 2 and 3, the control of the water network is partly shifted
313 from the farmers (as in the "on-demand" water delivery systems) to the WUA managers (as in the "fixed rotation"
314 methods); therefore, having the general overview of the hydraulic functioning of the delivery systems, the WUAs
315 managers are able to avoid - or, at least, reduce as much as possible - peaks of irrigation demand from farmers and the
316 subsequent risk of exceeding the water delivery capacity due to simultaneity. On the whole, the planned management

actions let the farmers replenish the water content into soil in a timely manner, and the WUA managers plan the irrigation operations properly. These planned actions should deliver a more adequate water volume to farmers only when irrigation is effectively needed (thus assuring more system dependability), and, furthermore, should modify the inappropriate irrigation programs of the majority of farms, thus aiming to provide a more rational and opportune exploitation of irrigation water.

The effects on the water delivery systems of the above mentioned scenarios were evaluated by the six performance indicators above. The statistical significance of the differences in the performance indicators among the different scenarios were analysed by an analysis of variance (ANOVA) applied to the evaluated crops by XLSTAT software ($p < 0.05$).

3. RESULTS

3.1 Analysis of the total irrigation requirements

CROPWAT estimated the same annual irrigation requirement for each crop in the three water delivery systems, **accounting also for the effective precipitation**: this happened because the soil characteristics are homogenous and the climate data, showing low variability throughout the observation period, were surveyed in a unique meteorological station.

As detailed below, the water delivered to the crops was found to vary from farm to farm.

3.1.1 Water delivery system "Angitola 3DMF"

The water delivered to citrus groves was on average $5700 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ against an average irrigation requirement of $6100 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$. In olive groves $3100 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ were delivered, while the water required was $5600 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$. Therefore, 95% (citrus) and 52% (olives) of the annual irrigation requirement was satisfied. For vegetables, which have a much higher irrigation requirement ($8000 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) compared to orchards, on average only $3100 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ were delivered and therefore only 39% of their annual irrigation requirement was satisfied (Figure 2).

3.1.2 Water delivery system "Angitola 6DMF"

For orchards (citrus, olives and other fruits), which have an average irrigation requirement between 5600 and $7500 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$, annual water delivery was highly variable (from a minimum of $1500 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ for olives to a maximum of $11000 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ for other fruits). Thus, 19% (olives) and 84% (citrus) of the annual irrigation requirement was satisfied. However, the water delivered was greatly in excess for the other orchards (150% of the annual requirement). The monitored irrigation system delivered to vegetables total water of $5500 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ (69% of the water required, equal to $8000 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$). Finally, an annual water delivery ($18600 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) exceeding by over 100% the corresponding requirement ($8900 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) was found for the irrigated gardens (Figure 2).

3.1.3 Water delivery system "Savuto"

For citrus groves, a surplus of 25% in water delivery ($7600 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) was detected on average in comparison to the irrigation requirement ($6100 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$). Conversely, for the only orchard in the studied water delivery systems the irrigation requirement ($7500 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) was not met, the water delivered being nearly zero. Only $3300 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ of irrigation water were delivered annually to vegetables, thus only 41% of the requirement ($8000 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$) was satisfied. In farms cultivating other cereals, water delivery was $4800 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$, about 66% of the water required ($7400 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$). For forage, the water delivered was $3600 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$, 41% of the requirement (equal to 8900 m^3

358 ha⁻¹ year⁻¹). Finally, gardens showed an irrigation requirement of 8900 m³ ha⁻¹ year⁻¹, of which 34% was delivered
359 (3000 m³ ha⁻¹ year⁻¹) (Figure 2).

360 A comparison of the water delivered to crops (averaged over the three water delivery systems) recorded in this study
361 was made with the latest available data reported by ISTAT (2010) for Calabria region. In the three water delivery
362 systems, olive groves, orchards (other than citrus) and forage crops received less water than the regional statistical
363 values (orchards 10400 m³ ha⁻¹ year⁻¹, olives 5900 m³ ha⁻¹ year⁻¹, forage 14900 m³ ha⁻¹ year⁻¹), while vegetables were
364 over-irrigated with reference to a regional mean of 2400 m³ ha⁻¹ year⁻¹.

365 On the whole, as regards the average data analysed in the three water delivery systems, it can be noticed:

- 366 - the irrigation requirement of the few irrigated olive groves (only three in the studied water delivery systems) was
367 satisfied only partly (19-52%) (presumably, the farmers believe that full irrigation for this crop is not appropriate due to
368 the low water productivity and other agronomical limitations);
- 369 - conversely, the water delivered to citrus groves almost met or exceeded the irrigation requirement in all the water
370 delivery systems (WD/WR in the range 84-125%);
- 371 - in the water delivery system "Angitola 6DMF" orchards were supplied with more water than citrus and olive groves;
- 372 - in this latter water delivery system there was a clear imbalance between irrigation of gardens (WD/WR over 200%)
373 and orchards (WD/WR of about 150%) compared to the other crops (water delivery much lower than irrigation
374 requirement by over 70%);
- 375 - the average water delivery to vegetables met the irrigation requirement by only 40-70%.

376

377 **3.2. Analysis of the current performance indicators**

378 *3.2.1 Water delivery system "Angitola 3DMF"*

379 The analysis of the water delivery performance highlighted poor adequacy (mean AD = 0.57) and dependability (mean
380 DE = 0.43), but good efficiency (mean EF = 0.92), water exploitation level (WEI = 74%) and equity (mean = 0.09)
381 during the monitoring period of four years. Globally, user satisfaction was very low, as shown by the average USI index
382 equal to 26% (Figures 3a and 4).

383 In relation to each analysed crop, the irrigation requirement of vegetables and olives was satisfied only in part (AD <
384 0.52, confirming the outcomes reported in section 3.1) and the temporal uniformity of the relative amount delivered was
385 poor (DE = 0.44 for olives and 0.58 for vegetables). Water delivery adequacy (0.77) and dependability (0.25) in citrus
386 groves were almost satisfactory, since the values of these indicators were slightly lower than the acceptance limits (0.80
387 and 0.20 respectively) (Figure 3a).

388

389 *3.2.2 Water delivery system "Angitola 6DMF"*

390 Mean adequacy (0.55), dependability (0.49) and equity (0.33) of the irrigation service over the monitored irrigation
391 periods were far from the acceptance limits (0.80, 0.20 and 0.25 respectively), while the efficiency in water resource
392 exploitation (0.82) was generally fair (Figure 3b), as confirmed by a WEI of 68.7%. User satisfaction (measured by
393 USI), even though again low (31%, Figure 4), was the highest among the studied water delivery systems.

394 Detailing these results for each irrigated crop, the adequacy was poor for olive groves (0.27), but fair for gardens (0.73).
395 The minimum dependability was observed for vegetables (0.69, with a high variability, shown by the significant
396 standard deviation). The temporal uniformity of the collective irrigation service was fair only for gardens (DE = 0.19).
397 However, these latter, together with orchards, showed a very low equity of service (0.63 and 0.57 respectively) (Figure
398 3b).

399

400 3.2.3 Water delivery system "Savuto"

401 The estimation of the performance indicators, averaged over the monitoring period, showed: (i) very poor adequacy
402 (0.44) and dependability (0.62); (ii) good efficiency (EF = 0.90) and water exploitation (WEI = 82.3%); (iii) fair equity
403 (0.13) (Figure 3c). The users are little satisfied with the irrigation service performance, the mean USI being equal to
404 18% (Figure 4).

405 Concerning the different crops, the water delivered was adequate only for citrus groves (AD = 0.83). A very low
406 amount was delivered to maize (AD = 0.15). The irrigation efficiency was high (> 0.83) for all crops, except for citrus
407 groves (EF = 0.69). The temporal uniformity of water delivery was always poor (DE > 0.39) and under the limit of
408 acceptance (0.20) only for citrus (DE = 0.17). The spatial uniformity of water delivery was unsatisfactory only for citrus
409 groves (EQ = 0.44) (Figure 3c).

410

411 3.3. Analysis of the performance indicators under improved management scenarios

412 In order to support future actions to improve the studied water delivery systems, the improved management scenarios,
413 simulated and evaluated by the performance indicators, should allow adequate water to be delivered, as much as
414 possible, when required (as indicated by the water balance of crops) and, thus, avoid water waste or conversely
415 shortage.

416 Figures 5a, b, c and d and Figures 6a and b compare the values of the six performance indicators for the water delivery
417 systems under the simulated scenarios, while Table 4 reports the related variations compared to the current status
418 ("scenario 0").

419 The replacement of the sprinkler systems with farm micro-irrigation ("scenario 1") increases water delivery adequacy
420 on average by 11.3% with a maximum of 14.3% in the water delivery system "Angitola 3DMF" (Table 4).
421 Nevertheless, the water volume delivered is still lower than the irrigation requirement, the adequacy being in the range
422 0.48-0.65 (Figure 5a), thus well below the acceptance limit of 0.80; water delivery equity is also decreased (increase of
423 EQ indicator of 37.4%) (Table 4).

424 The introduction of an arranged demand water delivery mode together with the irrigation advisory service ("scenario
425 2"), whose benefits in improving irrigation management under water scarce agriculture, have widely reported (e.g.
426 Lorite et al. 2007; Montoro et al. 2011), induces a noticeable improvement in service temporal uniformity, as shown by
427 the average decrease in the indicator of dependability (-56.2%) (Table 4). Thanks to these measures, water delivery over
428 time becomes fair in the water delivery system "Angitola 3DMF" (DE = 0.11) and close to the limit of 0.20 in "Angitola
429 6DMF" (DE = 0.26) (Figure 5c). Moreover, also service efficiency felt the effects of these improvements (Figure 5b), as
430 shown by the increased value of EF (4.2%); also equity in water distribution increases (EQ = -22.1%) (Table 4).

431 Scenario "3", combining the previous scenarios ("1", introduction of micro-irrigation, and "2", arranged demand water
432 delivery + irrigation advisory service), allows a simultaneous increase in adequacy (on average +8.2%), efficiency
433 (+0.4%) and dependability (by 59.5%) of water delivery despite a slight worsening of its equity (by 3.3%) (Table 4).

434 Compared to the current management (scenario "0"), through the introduction of the improving measures under
435 scenario "3" it can be noticed:

- 436 - dependability becomes good in the water delivery system "Angitola 3DMF" and is closer to the limit of acceptance
437 (0.20) in the other water delivery systems;
- 438 - efficiency, previously good in the water delivery systems "Angitola 3DMF" and "Savuto", slightly further improves in
439 these systems and remains fair in "Angitola 3DMF";

440 - in all the investigated water delivery systems adequacy noticeably increases, even though remaining far from the
441 acceptance limit of 0.80 (the maximum value of this performance indicator, equal to 0.64, is recorded in the water
442 delivery system "Angitola 3DMF");

443 - equity, essentially constant, is still fair in the water delivery systems "Angitola 3DMF" and "Savuto", but remains poor
444 in "Angitola 6DMF".

445 Finally, scenario "3" induces an appreciable improvement in user satisfaction towards the water delivery service
446 performance, as shown by the increase of the USI index (on average by 10.6% in the studied water delivery systems
447 with a maximum of 13.1% in "Angitola 3DMF" and "Angitola 6DMF") (Figure 6a). Conversely, a slight decrease in the
448 WEI index is observed (on average by 3.6% with a minimum of 0.6% in the water delivery system "Savuto") (Figure
449 6b).

450

451 **4. DISCUSSIONS**

452 The analysis carried out for the current situation of the three studied water delivery systems revealed that according to
453 the performance standards adopted, the adequacy, dependability and equity of the water delivery were generally
454 unsatisfactory, while its efficiency was adequate. The average values of the six performance indicators monitored
455 showed systemic problems that are discussed below.

456 Firstly, the water volume delivered was never sufficient to satisfy the irrigation requirements of crops (as shown by the
457 poor indicator of adequacy), with the exception of citrus groves in the water delivery systems "Angitola 3DMF" and
458 "Savuto" (mainly served by micro-irrigation systems); the data about olive grove irrigation may be affected by the
459 simultaneous presence of young (irrigated) and old (not irrigated) trees inside the same farm. Korkmaz et al. (2009)
460 assume that the fact that adequacy is poor in periods when irrigation requirement is high shows that there is a shortage
461 of resource in the system. In peak irrigation period, the water delivery systems analysed in this study are not able to
462 allocate water simultaneously to all the requiring farms and this generates problems of insufficient water volumes
463 delivered. This is due to the generally insufficient capacity of the hydraulic infrastructure to allocate water
464 simultaneously to the whole area in an equitable measure, such as: (i) the small size of storage reservoirs of WDS
465 "Angitola 3DMF" and "Angitola 6DMF"; (ii) limitations in the water distribution network (low section of pipelines),
466 which lead to insufficient water delivery due to problems of farmer simultaneous demand; (iii) use of inadequate farm
467 irrigation systems, such as sprinklers and low-efficiency systems, which determine water waste. Moreover, the
468 individual irrigation programs of the farmers do not appear suitable for the management of the water delivery services.
469 Since the users did not report a reduction in crop yield, it may be deduced that farmers irrigated crops with additional
470 resources, such as groundwater and/or potable water, often without authorization (as sometimes reported by local
471 authorities); unfortunately, these unregulated supplies can not be properly quantified. However, the fair value of the
472 indicator of efficiency and water exploitation indicated that the available water volume, delivered to the crops in the
473 three water delivery systems, was properly used for irrigation. One should note that this irrigation efficiency relates to
474 the WDS, but it does not include the water conveyance system. Since the water diverted from the source could be
475 significantly higher, the values of the efficiency indicators should be multiplied by 0.8 or 0.9 (typical values in
476 pressurized systems).

477 Secondly, as shown by the poor indicator of dependability, the service was not able to deliver water at the desired time,
478 and thus the irrigation service was not uniform over time. This may be attributable to a farmers' lack of knowledge
479 about times of supplying irrigation water to crops: in other words, often crops were irrigated when not necessary or,

conversely, in some periods the irrigation requirement remained unsatisfied, regardless of a scheduled hydrological balance.

Finally, few cases (i.e. irrigation of gardens and orchards in the water delivery system "Angitola 6DMF" and citrus groves in "Savuto", irrigated by sprinklers) of very low spatial uniformity in water delivery to the irrigated farms were recorded, since the indicator of equity was poor. Some Authors (Abernethy 1986; Khepar et al. 2000; Gorantiwar and Smout 2005) have argued that the equitable distribution of water is also necessary for maximizing productivity. However, equity of water delivery is a difficult objective to measure because there are many factors that determine the meaning of a "fair share" and because a fair share is often interpreted subjectively (Molden and Gates 1990): this is the reason why the problem of equity improvement was not analysed in depth in those situations in which a low spatial uniformity of water delivery was recorded.

Therefore, the performed analysis suggests to both service managers and users the need for substantial changes either in the system infrastructure or management procedures. Since the cost of irrigation network modification may be unsustainable for the analysed WUA, management actions are planned. These improvements should be planned on the basis of the results of water delivery performance in the studied irrigation services. This confirms that performance evaluation of irrigated areas is needed not only to assess the productivity of water at various scales, but also to propose improvements in irrigation management (Molden and Sakthivadivel 1999; Lorite et al. 2004b).

In this case of poor adequacy and dependability in water delivery systems, the comparison of the evaluated scenarios shows that the replacement of sprinklers with micro-irrigation (scenario "1") produces lower improvements in water delivery performance compared to arranged-demand distribution + irrigation advisory systems (scenario "2"). As a matter of fact, scenario "1" induces a slight increase of water delivery adequacy (on the average 11.3%) and dependability (9.7%) in spite of a decrease of efficiency (3.9%) and equity (25.9%). Instead, scenario "2" increases slightly efficiency (on the average 4.2%) but noticeably dependability (56.2%) and equity (22.1%) of water delivery, although worsening adequacy (by 4.5%) (Table 4). This latter performance may be a problem, since it reduces the already poor water delivery compared to irrigation requirement, but the decrease is limited. Moreover, scenario "2" assures a higher user satisfaction (on the average 33.3%) - poor in the current situation, - while scenario "1", as expected, is the action targeted to the maximum water saving (74.9%), which however is currently fair (Figure 6). The combination of the two scenarios (micro-irrigation and arranged-demand distribution + irrigation advisory service) is the optimal choice, since its introduction simultaneously increases water delivery adequacy (on the average 8.2%), efficiency (0.4%) and noticeably dependability (59.5%) - this latter more than in the single scenarios, - in spite of a limited decrease of equity (3.3%) (Table 4); user satisfaction (27.7%) and water efficiency (72.3%) levels are halfway and thus a compromise among the efficacy of the scenarios "1" and "2" (Figure 6).

From the simulation of improved management scenarios and the related evaluations by performance indicators, it emerges that the amount of water, insufficient to satisfy the irrigation requirement, must be considerably increased through further improvements, in order to assure a higher water availability during the entire irrigation season. This may be achieved, for example, by diverting additional volumes from water courses and lakes, pumping groundwater from wells or using reclaimed wastewater. Another choice may be the adoption of deficit irrigation (that is, an optimization strategy with irrigation is limited and water delivery is not proportional to irrigation requirements). Deficit irrigation has been widely investigated as a valuable strategy for dry regions (English 1990; Pereira et al. 2002; Fereres and Soriano 2007); however, since this inevitably results in plant drought stress and consequently in production loss, farmers in Calabria may be restive in its implementation, because in general they show a low tolerance to the consequent reduction of the economic value of agricultural yield.

Overall, the present study must be considered as the preliminary step of a more complete evaluation, which should also include other detailed technical and economic analyses of the entire irrigation system (such as the supplying, conveyance and distribution elements of the network). As a matter of fact, prior to the practical implementation of some of these scenarios to improve the water delivery service performance, water managers must carry out careful hydraulic analysis of the entire irrigation system (which should predict the network functioning and simulate pressures and discharges in pipelines and hydrants) and economic evaluations of the proposed improving alternatives.

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529 **4. CONCLUSIONS**

This study was targeted to understand whether a better allocation of irrigation water is possible by implementing improving measures at lower cost compared to structural works in collective irrigation service of Southern Italy. To this goal, the performance of the collective irrigation service in three Water Users Associations in Calabria was analysed through the indicators of adequacy, efficiency, dependability and equity of the water delivery integrated by two new indicators proposed (User Satisfaction and Water Exploitation Indices). Moreover, simulating improved scenarios, the gaps between the potential performance and the current management were identified.

The almost poor performance of water delivery currently identified suggested the simulation of the effects of some improvements, such as the replacement of farm sprinkler irrigation with micro-irrigation, the introduction of an arranged demand water delivery service together with the installation of an irrigation advisory service for farmers, or a combination of both actions. These improvements are easily to be implemented without the adoption of heavy actions, such as structuring works of the water supply network to increase water availability at scheme level, or expensive systems for automated remote control for centralised water delivery. Among the experimented management scenarios, the introduction of arranged demand distribution and irrigation advisory service not only is more favourite to the service users, but was also found to be more efficacious than the replacement of current sprinkler systems with micro-irrigation. In this case of poor service adequacy and dependability, the combined adoption of these scenarios is advisable, in order to assure the maximum performance in the analysed water delivery systems; it simultaneously increases three of the four water delivery performances and lets the collective service be more adequate and efficient for irrigation users and managers.

However, the simulated management scenarios were not sufficient to significantly modify the performance of the water delivery service. More specifically, in spite of the appreciable improvements in irrigation water allocation among farmers, in the case of chronicle or heavy scarcity of irrigation water (as in the case of many semi-arid zones devoted to water-fed agriculture of the Mediterranean environment), these improving actions should be integrated by other measures, such as deficit irrigation, heuristic water distribution methods, diversion of additional water volumes.

Overall, this study contributes to the diffusion of diagnostic and simulation tools in the collective irrigation sector of the Mediterranean basin, in order to promote a more productive and efficient use of water resources and a sustainable irrigated agriculture. However, a wide consolidation of this rational approach in irrigation water management should overcome many constraints, limiting the efficacy of these monitoring and planning activities (as also in the case of our study): (i) a higher reliability in estimating the crop irrigation requirements (e.g., by remote sensing based on actual water content of soils in real time) without relying on approximate methods; (ii) reduction of the time scale for the available water delivery data (this would allow the calculation of the ratio "water delivered/water required" on a decadal, a weekly or, better, a daily scale, leading to a more detailed and efficient water allocation plan among the irrigated farms); (iii) economic evaluation of the simulated scenarios, providing a cost/benefit analysis; (iv) a social

analysis of farmers' perceptions towards the improving actions (for instance based on the “USI” index proposed in this study), since the farmer's satisfaction and thus their acceptance of water taxation could influence the financial performance of the collective organisations. If such limitations are overcome, this diagnostic and planning may be helpful in view of a more rational and opportune exploitation of irrigation water. Our strategic study must be integrated by other detailed technical and economic analyses of the water network operations, prior to the practical implementation of the planned scenarios.

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TABLES

Table 1 – Main characteristics of the water delivery systems “Angitola 3DMF”, “Angitola 6DMF” and “Savuto”.

Characteristics		Water delivery system		
		Angitola 3DMF	Angitola 6DMF	Savuto
Area (ha)	Command	190	200	900
	irrigated	117	96	411
Number of users		104	476	1554
Average farm size (ha)		1.1	0.2	0.3
Main crops		Vegetables and citrus	Vegetables, citrus and fruits	Vegetables
Water source		Lake Angitola		Savuto river
Year of construction		1985		
Water network length (km)		9.9	10.6	51.7
Water delivery conduit		Pressured pipelines		
Conduit material (% on total length)		Asbestos cement	PVC	Steel (5%), asbestos cement (95%)
Water distribution method		On demand		
Water charging method		Delivered water volume		

658 Table 2 – Crop data related to the water delivery systems “Angitola 3DMF”, “Angitola 6DMF” and “Savuto”.

Crop		Planting date	Harvesting date	Irrigated area (%)		
				Angitola 3DMF	Angitola 6DMF	Savuto
Olives ^(*)		-	-	0.2	18.9	0.0
Citrus ^(*)		-	-	60.9	41.1	6.7
Other fruits ^(*)		-	-	0.0	6.5	1.7
Vegetables	Tomato ^(**)	10-20 April	June/September	38.9	32.4	86.2
	Aubergine ^(**)	10-20 April	June/September			
	Onion ^(**)	10-20 March	June/August			
Maize and other cereals		1-10 May	October	0.0	0.5	0.9
Forage		10-30 October	August/September		0.0	4.1
Gardens ^(*)		-	-		0.5	0.9

659 Notes: (*) Trees and gardens are perennial; (**) Planting and harvesting dates refer to open field crops (excluding greenhouses).

660 Table 3 – Number of farm outlets for water delivery measurement in the water delivery systems “Angitola 3DMF”,
661 “Angitola 6DMF” and “Savuto”.

Crop	Water delivery system		
	<i>Angitola 3DMF</i>	<i>Angitola 6DMF</i>	<i>Savuto</i>
<i>Olives</i>	1	2	-
<i>Citrus</i>	13	34	4
<i>Other fruits</i>	-	4	1
<i>Vegetables</i>	13	38	111
<i>Maize</i>	-	-	5
<i>Other cereals</i>	-	-	4
<i>Gardens</i>	-	4	3
<i>Forage</i>	-	-	2

662

663 Table 4 - Variation (%) of the irrigation performance in the water delivery systems “Angitola 3DMF”, “Angitola
664 6DMF” and “Savuto” under improved management compared to scenario "0".

Water delivery system	Micro-irrigation	Arranged demand	Arranged demand + micro-irrigation
<i>Adequacy</i>			
<i>Angitola 3DMF</i>	14.3	-4.6	11.0
<i>Angitola 6DMF</i>	9.2	-3.8	6.3
<i>Savuto</i>	10.5	-5.0	7.4
Mean	11.3	-4.5	8.2
<i>Efficiency</i>			
<i>Angitola 3DMF</i>	-3.8	4.7	1.2
<i>Angitola 6DMF</i>	-4.2	3.5	-0.6
<i>Savuto</i>	-3.6	4.4	0.7
Mean	-3.9	4.2	0.4
<i>Dependability</i>			
<i>Angitola 3DMF</i>	-13.0	-73.2	-76.8
<i>Angitola 6DMF</i>	-8.3	-46.6	-49.1
<i>Savuto</i>	-7.8	-48.9	-52.7
Mean	-9.7	-56.2	-59.5
<i>Equity</i>			
<i>Angitola 3DMF</i>	37.4	-34.2	-0.1
<i>Angitola 6DMF</i>	16.4	-6.9	8.6
<i>Savuto</i>	23.9	-25.1	1.5
Mean	25.9	-22.1	3.3

665

666 **FIGURE CAPTIONS**

667
668 Figure 1 – Location of the studied water delivery systems (Calabria, Southern Italy).

669
670 Figure 2 – Current annual water required (“WR”) and delivered per unit of irrigated area (“WD”) in the water delivery
671 systems “Angitola 3DMF” (a), “Angitola 6DMF” (b) and “Savuto” (c).

672
673 Figure 3 – Current indicators (average values and standard deviations) of adequacy (“AD”), efficiency (“EF”),
674 dependability (“DE”) and equity (“EQ”) in the water delivery systems “Angitola 3DMF” (a), “Angitola 6DMF” (b) and
675 “Savuto” (c).

676
677 Figure 4 - Current User Satisfaction (“USI”) and Water Exploitation (“WEI”) Indices in the water delivery systems
678 “Angitola 3DMF”, “Angitola 6DMF” and “Savuto”.

679
680 Figure 5 – Indicators of adequacy (a), efficiency (b), dependability (c) and equity (d) in the water delivery systems
681 “Angitola 3DMF”, “Angitola 6DMF” and “Savuto” (the red and green lines show the limits "poor" and "good"
682 respectively).

683
684 Figure 6 - User Satisfaction (“USI”, a) and Water Exploitation (“WEI”, b) Indices in the water delivery systems
685 “Angitola 3DMF”, “Angitola 6DMF” and “Savuto”.