Science of the Total Environment 633 (2018) 271–284

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Identifying efficient agricultural irrigation strategies in Crete

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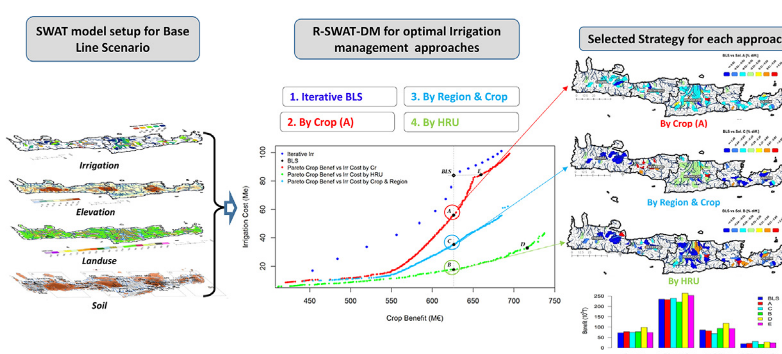
HIGHLIGHTS

- A simulation-optimization framework for optimal identification of agricultural management strategies was applied to Crete
- Three spatial management approaches were analyzed to point out different levels of integration of optimal solutions
- Results suggests that more efficient management of water can be achieved without impacting current agricultural benefit
- Water saving solutions could be identified for each crop, highlighting in which crops to best reduce or increase irrigation
- The proposed framework shows great flexibility to provide solutions to different types of stakeholders

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 26 July 2017
Received in revised form 10 November 2017
Accepted 14 March 2018
Available online 22 March 2018

Keywords:
Best Management Practices
Multi-objective optimization
R-SWAT-DM
Irrigation
Water scarcity

ABSTRACT

Water scarcity and droughts are a major concern in most Mediterranean countries. Agriculture is a major user of water in the region and releases significant amounts of surface and ground waters, endangering the sustainable use of the available resources. Best Management Practices (BMPs) can mitigate the agriculture impacts on quantity of surface waters in agricultural catchments. However, identification of efficient BMPs strategies is a complex task, because BMPs costs and effectiveness can vary significantly within a basin. In this study, sustainable agricultural practices were studied based on optimal allocation of irrigation water use for dominant irrigated crops in the island of Crete, Greece. A decision support tool that integrates the Soil and Water Assessment Tool (SWAT) watershed model, an economic model, and multi-objective optimization routines, was used to identify and locate optimal irrigation strategies by considering crop water requirements, impact of irrigation changes on crop productivity, management strategies costs, and crop market prices. Three spatial scales (crop type, fields, and administrative regions) were considered to point out different approaches of efficient management. According to the analysis, depending on the spatial scale and complexity of spatial optimization, water irrigation volumes could be reduced by 32%–70% while preserving current agricultural benefit. Specific management strategies also looked at ways to relocate water between administrative regions (4 prefectures in the case of Crete) to optimize crop benefit while reducing global water use. It was estimated that an optimal reallocation of water could reduce irrigation water volumes by 52% (148 Mm^3/y) at the cost of a 7% (48 M€) loss of agricultural income, but maintaining the current agricultural benefit (626.9 M€). The study showed how the identification of optimal, cost-effective irrigation management

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https://doi.org/10.1016/j.scitotenv.2018.03.152
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strategies can potentially address the water scarcity issue that is becoming crucial for the viability of agriculture in the Mediterranean region.

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1. Introduction

Water is a key resource for sustainable development in most Mediterranean countries, where water scarcity and droughts are a major concern (EEA, 2015). Satisfying raising and conflicting water demands while maintaining sufficient volumes and good water quality standards is a major challenge at the global scale, but even more in the Mediterranean region, where water resources are already subject to over-exploitation in response to demographic and economic pressures and climatic variability (Koutroulis et al., 2013; Panagopoulos et al., 2014; Parry et al., 2007). Agriculture is the most water demanding economic sector, especially in Greece where irrigation accounts for about 88% of total water abstraction (EUROSTAT, 2016). The European Union 2020 strategy (EU, 2010) sets resource efficiency targets that require identifying cost effective measures and management strategies to be included in the Programmes of Measures (PoMs) of the River Basin Management Plans (RBMPs) established in the Water Framework Directory (European Union, 2000). The identification of efficient water saving strategies in all economic sectors, and in particular in agriculture (EEA, 2012), is an essential task towards achieving the strategic water target of sustainable water exploitation.

The improvement of water management requires an efficient use of water for irrigation, where efficient means to use less water to produce more, or at the same level of productivity. This improvement can be achieved by increasing the effectiveness of irrigation technologies, e.g. reducing water losses in the supply system or upgrading irrigation methods, etc., or by increasing water productivity, i.e. by enhancing the outcome of irrigation water. In the case of the island of Crete (Greece) efficient irrigation technology is already applied in most of the agricultural farms (about 81% according to EUROSTAT (2017)) and, specifically for tree fruit crops, low-volume drip and microsprinkler irrigation systems have become the standard irrigation method in Crete (Kourgialas and Karatzas, 2015). Further increasing water demands means that inefficient water use will have to be eliminated in the near future, which calls for sufficient adoption of irrigation-efficient Best Management Practices (BMPs). Unfortunately, the implementation of many, but uncoordinated BMPs in a watershed may not ensure that water saving targets at the watershed outlet are achieved (Emerson et al., 2005) because interactions between BMPs may significantly affect their individual performances at a watershed scale. On the other hand, large and widespread interventions may not be necessary: Harrell and Ranjithan (Harrell and Ranjithan, 2003) emphasized that a small number of strategically allocated BMPs could achieve the same results as a multitude of BMPs dispersed throughout the watershed.

The identification and design of efficient strategies require an understanding of the water cycle within a basin, and careful consideration of competing water demands with their economic and social impacts. Hydrological models are valid tools to consider the biophysical processes linked to the water cycle at the basin scale (Haas et al., 2017; Jang et al., 2017; Krysanova and White, 2015; Liu et al., 2016; Panagopoulos et al., 2014; Volk et al., 2016; Wang et al., 2017). However, assessment of the economic impacts of BMPs strategies requires coupling hydrological models to other economic and optimization tools.

Evolutionary optimization methods such as genetic algorithms (Goldberg, 1989) are popular in spatial optimization (Arabi et al., 2006; Chatterjee, 1997; Gitau et al., 2004; Lautenbach et al., 2013; Maringanti et al., 2009; Srivastava et al., 2002; Veith et al., 2004). The most popular method of spatial optimization is dynamic linking of a watershed simulation model with an optimization algorithm (Bekele and Nicklow, 2005; Cho et al., 2004; Kalcic et al., 2014; Nicklow et al., 2010; among many others), wherein simulation model outputs are used to estimate the objective functions of the optimization algorithm. Interest has grown in spatial optimization of conservation practices using genetic algorithms and the hydrologic model Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Neitsch et al., 2011). SWAT is a watershed model commonly used to simulate the impact of land use and land management on water quantity and water quality. Many studies have focused either on using a single objective function for optimization that combines BMP effectiveness with cost (Chatterjee, 1997; Srivastava et al., 2002), or on sequential optimization of effectiveness and cost as separate objective functions (Gitau et al., 2004; Veith et al., 2004), i.e. constraining one objective function during optimization of the other. In addition, most works were conducted in relatively small watersheds or in simplified model representation (e.g., Bekele and Nicklow, 2005; Maringanti et al., 2009) where the search space for optimal solutions is relatively narrow resulting in efficient implementation of the optimization algorithms.

Multi objective optimization has been shown how agricultural efficiency at Country level in Africa could be improved (Pastori et al., 2017). A tool to perform multi-objective optimization at catchment level that links a catchment scale model with economic analysis and optimization routines in R software (R-SWAT-DM) was presented in Udias et al. (2016a). The tool was applied to quantify potential reduction in nitrate by smart fertilization schemes in the Upper Danube (Udias et al., 2016b).

The overall goal of this work was to develop a simulation/optimization framework to identify cost-effective irrigation management strategies, i.e. which achieved optimal crop productivity; and assess the potential impact of reduced water use on agricultural productivity. In this study, the hydrological SWAT model was used to simulate crop productivity, water demand, and diffuse nutrient emissions in a watershed. The specific tasks of the study were: (1) set up the SWAT model to simulate crop productivity under current and alternative scenarios; (2) integrate the SWAT model with a genetic algorithm multi-objective optimization routine and an economic evaluation model; (3) apply the framework to the case of Crete in order to identify optimal spatial allocation of irrigation BMPs; and (4) run a scenario analysis of reduced water availability.

2. Materials and methods

2.1. Study area

The island of Crete is the largest island of Greece and the fifth in the Mediterranean, covering an area of 8336 km^2 (Fig. 1).

Crete is characterized by a dry semi-humid Mediterranean climate with dry and warm summers and humid and relatively cold winters. Mean annual rainfall decreases from west to east and from north to south, but increases with altitude (MEDIWAT, 2013), ranging between 300 mm in coastal areas and 2000 mm in headwaters of the White Mountains. For the period 1983–2009, the mean annual precipitation was estimated around 965 mm, of which 40% contributed to evapotranspiration, 53% to infiltration and 7% to surface runoff (Malagò et al., 2016). The mean annual temperature ranges from 18.5° in the west to 20° in the south, and decreases with altitude.

The island is divided into four administrative prefectures, namely from east to west: Lasithi (1810 km^2), Heraklion (2626 km^2), Rethymno (1487 km^2) and Chania (2342 km^2; Fig. 1). Crete has about 2870 km^2 of

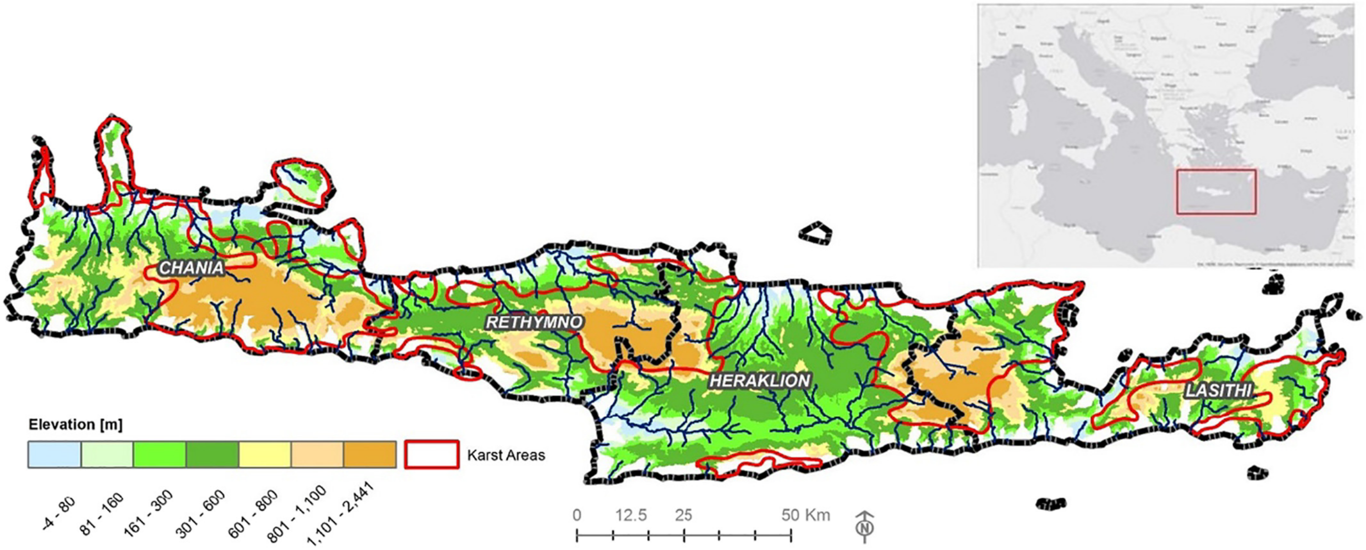

Fig. 1. Location of the island of Crete in Europe (insert), and the spatial distribution of elevation (m) and karst areas from geological map, with the four main administrative prefectures.

agriculture land, of which about 45% (1225 km^2) is irrigated. The Heraklion prefecture holds the largest share of irrigated area, around 600 km^2, followed by Lasithi and Chania with around 300 km^2 each, while only 93 km^2 are irrigated in Rethymno (Table 1). The total demand for irrigation water is about 283 Mm^3/y.

The main crops are olives, grapes, and vegetables (tomatoes, cucumbers, onions, potatoes, watermelons and melons), citrus, fruits and potatoes. Olive is a cash crop of great importance for Crete (43% of agricultural area) and may be considered a strategic crop in all of the Mediterranean region because it is adaptable to water scarcity, although it maximizes yields with high rainfall and/or irrigation water (Iniesta et al., 2009; Martínez-Cob and Faci, 2010; Moriana et al., 2003; Palese et al., 2010; Palomo et al., 2002). The majority (84%) of irrigated land in Crete is currently cultivated for olives (Table 1), whereas other irrigated crops include vegetables, grape, citrus and some cereals. The other major land use is pasture, which occupies about 3720 km^2 (45% of total areas of Crete).

2.2. The R-SWAT decision making framework

The decision support tool R-SWAT-DM (Udias et al., 2016a) is a framework developed to help stakeholders in the selection of efficient agricultural BMPs related to water and nutrient resources at watershed level. It includes the following main components: (1) a watershed model (SWAT) for simulation the hydrologic water cycle and crop growth under management scenarios; (2) a component to link the hydrological model to the R software (R Core Team, 2011); (3) an economic module to estimate costs and benefits associated with the scenarios; (4) an optimization engine to search for optimal, trade-off scenarios according to environmental and socioeconomic objectives. The framework can model crop productivity, water and nutrient demands, and assess environmental impacts to surface and groundwater bodies. In what follows the development of each component for the application to the island of Crete is described.

Table 1
Regional distribution of pasture and agricultural land (km^2) in the island of Crete. Olive and grape areas are part of the agricultural land.
(Agriculture Statistics of Greece, 2009.)

Region	Pasture	Agricultural land		Olive		Grape	
		All	Irrigated	All	Irrigated	All	Irrigated
Chania	1075	680	266	476	221	20	7
Heraklion	921	1295	592	825	511	195	25
Lasithi	879	433	274	283	235	24	5
Rethymno	844	460	93	256	73	19	3

2.3. The agro-hydrological modelling of island of Crete using SWAT

The SWAT model (Arnold et al., 1998) is a semi-distributed, process-based model that simulates the daily water balance, crop yields, sediments, nutrients and pesticide in a basin. SWAT integrates all relevant eco-hydrological processes including water flow, surface runoff, percolation, lateral flow, groundwater flow, evapotranspiration, transmission losses, nutrient transport and turn-over, vegetation growth, land use, and water management. Watersheds are divided into spatially linked subbasins; the subbasins are subdivided into Hydrological Response Units (HRUs) with unique soil/land use and slope characteristics. The simulation of watershed hydrology is divided into two main phases: the land phase and the routing phase, which controls the amount of water, sediment, and nutrients into the main stream network. The land phase is solved at HRU level, which determines water flow and nutrient load outputs; these outputs are routed through the subbasin and then, in the water phase, through the stream network till the watershed outlet.

For application to Crete, SWAT was modified and coupled to a karst-flow model in order to take into account the specific karst-springs water processes of the island (KSWAT; Malagò et al., 2016). Here we provide only a short description of the model set up and the calibration/validation, while all detail can be found in Malagò et al. (2016).

SWAT subbasins were delineated using the ArcSWAT interface with a Digital Elevation Model of 25 m pixel size EU-DEM; (Bashfield et al., 2011). Subbasins and streams were defined using a drainage area threshold of 1000 ha resulting in 352 subbasins with an average area of 19 km^2 covering 6700 km^2 (Fig. 2).

The climate data included 69 stations with daily data for precipitation and 21 stations for temperature from 1961 to 2009. Monthly statistics of solar radiation, wind speed and relative humidity were calculated using the pan European high-resolution gridded daily data set EFAS-METEO (Ntegeka et al., 2012) for 29 stations uniformly distributed over the island.

Land cover was derived from a 1 km raster map built from the combination of Common Agricultural Policy Regionalized Impact

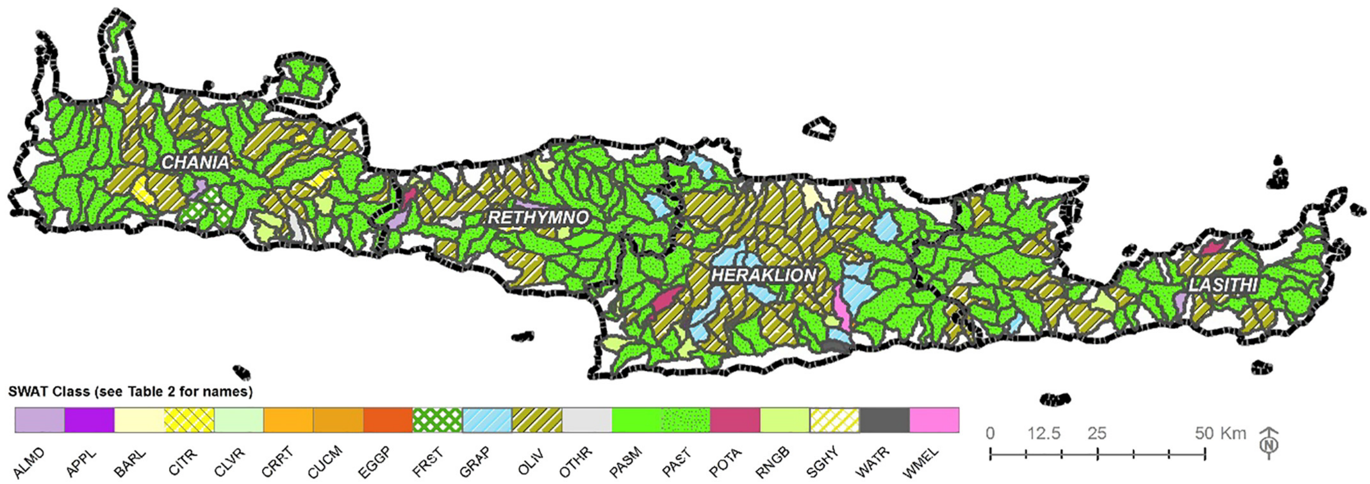

Fig. 2. Dominant landuse for the SWAT model subbasins in the four Crete Prefectures. The crop acronyms of the legend are described in Table 2.

agro-economic model (CAPRI) (Britz, 2004), HYDE 3 (Klein Goldewijk and van Drecht, 2006) and GLC (Bartholomé and Belward, 2005) for the year 2005. Land use (specifically for the use of agricultural land area by different crops) was obtained from the Agriculture statistics of Greece (Agriculture Statistics of Greece, 2009). Soil type and characteristics were defined using a 1 km soil raster map, obtained from the Harmonized World Soil Database (HWSD) (FAO et al., 2009). From the combination of land use and dominant soils, 502 HRUs were defined with an average area of 13 km^2.

Table 2
Crete Baseline Scenario information related to the crop area and applied fertilization rates. Average observed yields are derived from EUROSTAT, 2016.

Crop name	CROP id.	Number of HRU	km^2	% Area	Average mineral fertilizer (kg/ha)	Average organic fertilizer (kg/ha)	Average simulated wet yield (t/ha)	Average observed yield (t/ha)	
								Crete	Greece/EU
Pasture	PAST	196	3718	55.8			0.4	na	0.1
Olive	OLIV	101	1840	27.6	3.8	12.6	1.6	1.6[a]	1.2/2.7
Grape	GRAP	27	257	3.9	4.2	13.9	12.6	na	11.5/8
Grass	RNGB CLVR	28	217	3.3	1.5	0.1	1.3	na	na
Sorghum	SGHY	14	73	1.1	123.6	0.0	4.9	4.9	3.6
Other agriculture	AGRR	16	59	0.9	1.5	0.1	0.2	na	na
Potatoes	POTA	11	59	0.9	1.9	52.6	24.8	25.7	27.6
Citrus	CITR	13	58	0.9	8.5	27.7	23.0	na	25.2
Almond	ALMD	12	57	0.9	2.9	9.7	3.1	na	12.5 (oils)
Pasture managed	PASM	4	57	0.9	55.4	15.6	3.1	na	
Tomatoes	TOMA	9	27	0.4	20.9	71.2	18.8	na	37.4 (veg.)
Carrots	CRRT	8	25	0.4	12.9	44.0	23.5	na	37.4 (veg.)
Watermelons	WMEL	6	22	0.3	17.5	163.4	10.5	na	37.4 (veg.)
Green beans	GRBN	6	20	0.3	1.5	8.3	2.0	na	na
Spring wheat	SWHT	4	20	0.3	40.5	40.0	2.6	1.2	2.5
Barley	BARL	4	18	0.3	18.4	14.3	2.4	4.9	2.75
Cucumbers	CUCM	5	13	0.2	17.5	163.4	17.3	na	na
Oats	OATS	5	12	0.2	29.3	17.8	2.6	0.9	
Sunflower	SUNF	6	10	0.1	0.0	0.0	0.1	na	2
Onions	ONIO	4	7	0.1	12.9	44.0	43.7	na	37.4 (veg.)
Cereals grain	GRSG	4	5	0.1	42.6	15.6	2.1	na	2.2
Fruits	APPL	2	5	0.1	2.9	9.7	9.7	na	12.5
Cabbages	CABG	4	5	0.1	12.9	44.0	28.9	na	37.4 (veg.)
Alfalfa	ALFA	1	2	0.0	1.5	8.3	1.7	na	na
Eggplant	EGGP	1	1	0.0	17.5	163.4	2.9	na	na
Urban areas	URHD	5	7	0.1					
Water bodies	WATR	3	17	0.3					
Forest	FRST	3	58	0.9					
Total		502	6669	100					

Average calculated for the whole island, including non-fertilized agricultural areas.
[a] Peloponnese area.

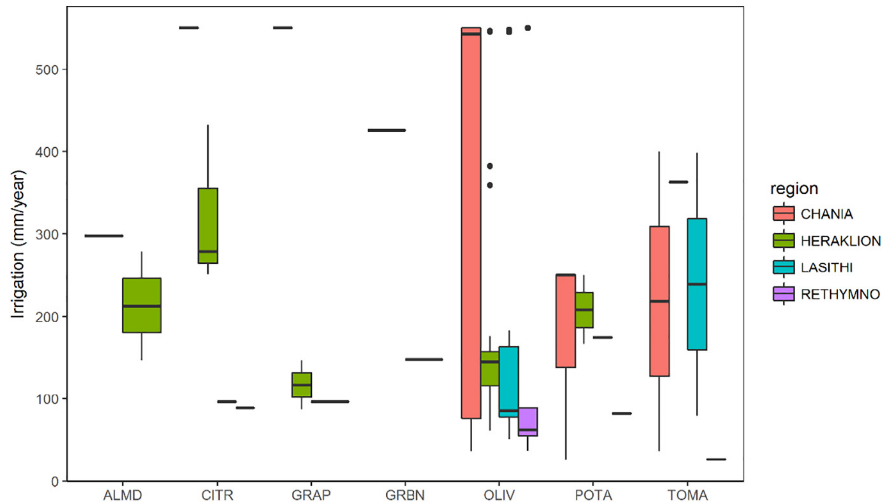

Fig. 3. Box plot of HRU current irrigation volumes by crop and prefecture for Baseline Scenario (BLS). In some crop/prefectures only one HRU is simulated, thus the boxplot becomes a single line. Total volumes are shown in Fig. 12.

Crop management practices included planting, fertilization, irrigation and harvesting. The timing of plant sowing and harvesting were simulated through daily heat unit concept (Gilmore and Rogers, 1958). Heat units are calculated based on the PHU (Potential Heat Units) program (PHU, 2007) using long term minimum/maximum temperatures, optimum and minimum plant growing temperatures and the average number of days for the plant to reach maturity (Bouraoui and Aloe, 2007). Application rates of manure and mineral fertilizers were retrieved from CAPRI (Britz and Witzke, 2008). Irrigated areas and volumes were obtained from the Agriculture statistics of Greece (Agriculture Statistics of Greece, 2009; Table 1).

The KSWAT adapted model allows representing the main karst features (i.e. sinkholes and fast infiltration in the soil), while the karst-flow model was used for quantifying the karst spring's discharges. KSWAT was applied to simulate the daily discharge of 47 springs in the period 1983–2009 and the monthly streamflow in the period 1980–2009.

The calibration proceeded in two sequential steps: the calibration of annual crop yields and the calibration/validation of streamflow and spring discharges (Malagó, 2016). Average crop yields were calibrated against Country statistics (EUROSTAT, 2016). Comparison of long term modeled and reported by Eurostat yield productivity is given in Table 2. For the calibration and validation of streamflow 15 and 7 gauging stations were used respectively. With calibration, about 64% of the calibrated gauging streamflow and >70% of calibrated springs reached satisfactory percentage bias (values in the range ± 25%; (Moriasi et al., 2007)). The baseline (BLS) is defined as the calibrated setup of SWAT for the period 1980–2009.

2.4. Best Management Practices

Irrigation, constrained by water availability, and mineral fertilization strategies were considered in the work. As irrigation methods used in Crete are generally very efficient (Kourgialas and Karatzas, 2015), we used a drip irrigation scheme in SWAT model by dividing the total irrigation volume into daily applications not exceeding 10 mm of water each. An increase of irrigation volume is achieved by raising the number of applications and not the application rate: this ensures an effective, albeit expensive, use of water that can be reasonable for Crete, where drip irrigation is widespread. HRU mean annual irrigation volumes applied per crop and prefecture are shown in Fig. 3. Irrigation volumes for olive were highly variable, and peaked in Chania, which was also the prefecture with the most intensively irrigated vegetables (TOMA and POTA).

Average mineral and organic fertilization rates in the BLS are reported in Table 2. Organic fertilization is quite limited, at least in dominant crops (olive, grape, pasture and grassland, citrus), and was not changed in alternative management strategies. Mineral fertilization was changed only for those crops and regions that were already fertilized under current management. In this case, management scenarios changed application rates while the total number of applications by year was not modified.

2.5. Optimization objectives

R-SWAT-DM explores the outcomes of management strategies, starting from the Baseline Scenario (BLS), which reflects the current situation of Crete as implemented in SWAT. For each alternative management strategy, the framework communicates with the SWAT model through ASCII files and/or R wrapper functions, modifying model input files and reading outputs files.

The user can run single or combined simulations of spatially explicit management practices, or iterative simulations whereby all management practices of one type are changed simultaneously

Table 3
Crete crop selling prices, management costs and gross margin reported values for 2004. The fixed cost included: total cost of machinery, labor and seed.

Crop category	Avg. sell. price[a] (€/tons)	Min. sell. price[a] (€/tons)	Max. sell. price[a] (€/tons)	Fixed cost[b] (€/ha)	Gross margin (rep. 2004)[a] (€/tons)
Pasture and grass areas	180			30	25
Olive	1820	1190	2080	1250	2000–3000
Grape	535	400	675	4500	3000
Sorghum and grains	145	135	220	400	255
Citrus	485	200	810	4500	4500
Potatoes	450	312	538	200	6950
Almonds	2227	1417	3083	2400	2100
Tomatoes and vegetables	524	436	645	400	4400
Green beans	1558	1015	1976	400	3250
Soft wheat	186	135	235	30	290
Barley	177	137	225	150	280
Apples	607	363	672	3000	2100

[a] Reported in Eurostat Statistics Database (EUROSTAT, 2016).
[b] Fixed cost was estimated based on crop income from reported data – gross margin reported.

step-wise in a fixed range of values. Alternatively, the user can run a multi-objective optimization process. In this case, he/she should define the environmental or water availability objectives and management practices to be considered. Once the simulation and/or optimization process has finished, the user can analyze and compare the management scenario outputs graphically and statistically. The framework can also generate maps with detailed spatial information about any selected scenario.

A logical approach for targeting water availability control practices should be to propose a multi-objective problem following the next equation:

$$\begin{cases} \text{minimize Irrigation volume or Irrigation cost} \\ \text{maximize Farmers Global benefit(s)} \end{cases} \tag{1}$$

Under this or other similar formulations, the objective functions are often incommensurable, i.e. they cannot be measured with the same scale, and conflicting. Thus, optimal solution(s) for each objective could substantially differ from the optimal solution(s) for the other objectives. Multi-objective optimization approaches can identify a set of non-dominated solutions that define a Pareto-optimal front. Non-dominated solutions are set of solutions in the search space that are better than any other solution in one or more objective (Srinivas and Deb, 1994). Any improvement in one objective among Pareto-optimal solutions will essentially result in the degradation of at least another objective (Pareto, 1971).

For this study, the two objectives selected were the miniminization of the water cost and the maximization of the farmers benefit (see Section 2.4)

- *Total irrigation water volume*

The total irrigation volume was computed by the sum of the water applied to each HRU of the study region:

$$\sum_{i=1}^{ns}\sum_{j=1}^{nt} W_{ij} * Aj \tag{2}$$

where:

nt: number of time-steps in the simulation period.
ns: number of HRU.
Wij: irrigation water applied (mm) to HRU "i" and simulation time-step "j".
Aj: irrigate area (ha) in HRU "j".

Alternatively, the first objective in (1) could be defined as minimizing the total irrigation cost, computed as follow:

$$\sum_{i=1}^{ns}\sum_{j=1}^{nt} W_{ij} * A_j * \mathrm{WCost}_{ij} \tag{3}$$

where:

nt: number of time-steps in the simulation period.
ns: number of HRU.
WCost_{ij}: water cost (€/m^3) in HRU "i" and simulation time-step "j".

- *Farmers benefit*

Farmers benefit for different management strategies was estimated as total gross margin, and set as a function of crop yield and market price, fertilizer cost, irrigation water cost, standard operational cost, and fixed costs (including seeds cost, tillage operations, machinery, grain drying, labor, etc.). For each alternative management scenario, total gross margin was estimated as:

$$B_1^{mp} = \sum_{i=1}^{HRU}\sum_{j=1}^{crop}\left(Y_{ij}^{mp} * Up_j - Fc_{ij}^{mp} * Qf_{ij}^{mp} - Qw_{ij}^{mp} * Wc - Oc_j\right) * A_{ij} \tag{4}$$

where:

B_1^{mp}: agricultural total benefit for the BMP.
Y_{ij}^{mp}: yield (T/ha) of crop j in HRU i under an irrigation pattern.
Aij: area (ha) of crop j in HRU i.
Upj: unit price (€/T) of crop j (Table 3).
Qf_{ij}^{mp}: quantity of fertilizer applied (kg/ha) to crop j in HRU i under an irrigation pattern.
Fc_{ij}^{mp}: unit cost of fertilizer (€/kg) of crop j in HRU i under an irrigation pattern.
Wc: irrigation cost per water unit (€/mm), constant across HRUs.
Qw_{ij}^{mp}: irrigation quantity (mm/ha) for crop j in HRU i under an irrigation pattern.
Oc_j: fixed operational management cost (including the labor, machinery, etc.) in €/ha for the crop j (Table 3).

Crop management costs were assumed constant throughout the simulation period and independent from the annual yield. The average crop yield for the period 1990–2010 of each HRU under management

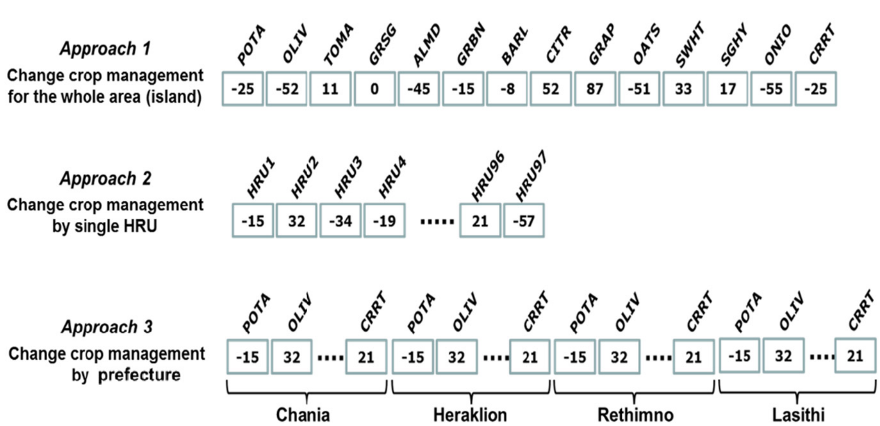

Fig. 4. Schema of the management strategies (chromosome) combining alternative decision units (genes) for the three decision approaches (crop, HRU, crop & prefecture) taken into consideration. The values represent the rate of increasing (positive values) or decreasing (negative values) irrigation volume applied in each decision unit (gene). A value of zero represents no variation.

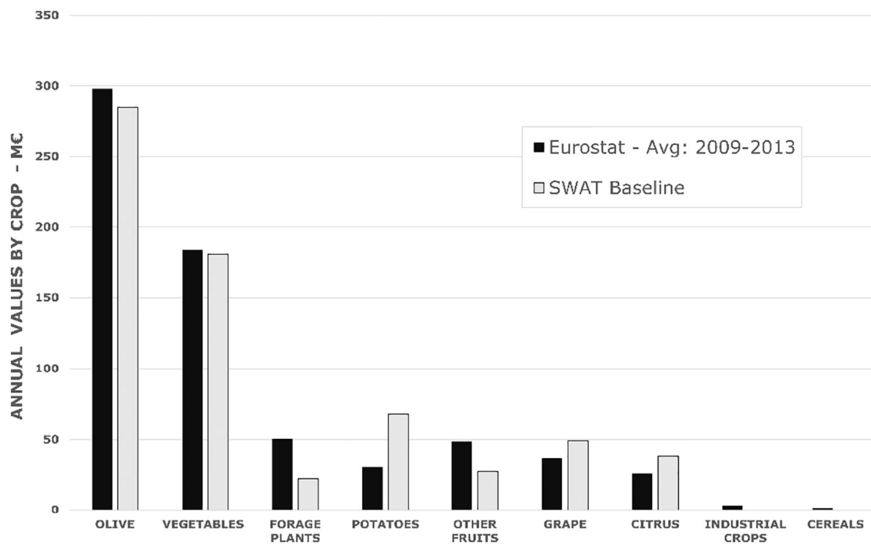

Fig. 5. Crete mean annual crop benefit M€ - Eurostat (5 years average, 2009–2013) vs baseline.

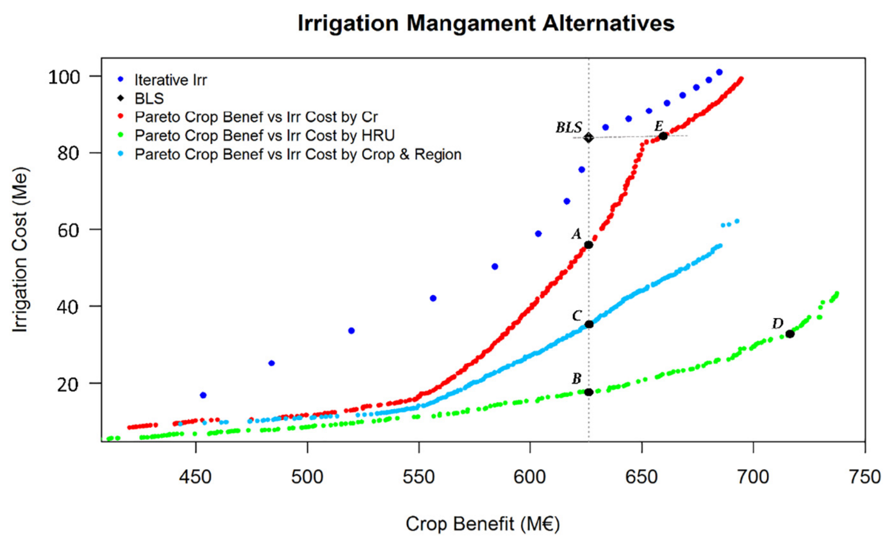

Fig. 6. Pareto front strategies according to the minimum irrigation cost and maximum crop benefit objectives. Efficient strategies of irrigation rates applied at crop level are in red, at HRU level are in green, and at crop/prefecture level are in light blue. The blue dark points correspond to an iterative 5% irrigation rate change applied to all HRUs. The black dot indicates Baseline Scenario (BLS). Strategies BLS, A, B, C, D, E are described in Table 4.

scenarios was assessed with SWAT. Table 3 includes crop average, minimum and maximum market prices (EUROSTAT, 2016) in the study region, the operational costs and gross margin as reported for the year 2004 (EUROSTAT, 2016).

The cost of water per cubic meter can vary greatly between regions, catchment, and even within the same catchment, depending on the management agency and the altitude (Chartzoulakis et al., 2001). In this analysis, water cost was set according to elevation: 0.01 € at elevation <80 m, 0.13 till 160 m, 0.35 till 600 m, and 0.60 for elevations >600 m (Chartzoulakis et al., 2001).

Nutrients N, P and K are applied with several fertilizer products (anhydrous ammonia, nitrogen solutions 30%, urea 44–46, ammonium nitrate, sulfate of ammonium, super phosphate 20%, etc.) containing different forms and percentages of the elements. The total cost of the fertilization was estimated based on the quantity (kg) of elementary N, P and K present in the applied fertilizers. The cost per kg of N P and K was estimated from annual data from 2000 to 2013 (USDA, 2015), and estimated at 1.21 €/kg of N, 2.8 €/kg of P, and 0.97€ /kg of K.

2.6. Multi-objective optimization method

Since the shape of the objective function cannot be assumed a priori as smooth or differentiable, gradient approaches such as quasi-Newton

Table 4
Short description of the management strategies analyzed.

Strategy	Identified solution	Short description
Current	BLS	Baseline Scenario
Approach 1	A	Same benefit than BLS minimizing irrigation at crop management resolution
Approach 1	E	Same irrigation cost than BLS maximizing benefit at crop management resolution
Approach 2	B	Same benefit than BLS minimizing irrigation at HRU management resolution
Approach 2	D	Point coming from the same Pareto frontier than B but close to the highest benefit
Approach 3	C	Same benefit than BLS minimizing irrigation at crop management resolution by prefecture

Table 5
Crop irrigation area (km^2) and rate changes from the BLS to achieve 1.A and 1.E strategies.

STR	Pota	Oliv	Toma	Grsg	Almd	Grbn	Barl	Citr	Grap	Oats	Swht	Sghy	Onio	Crrt
Area	33	1040	49	3	4	3	16	13	40	10	5	7	5	1
A	88%	−36%	−20	−90	86	34	−76	72	88	−90	−70	−90	−44%	6%
E	84%	10%	20	20%	44%	10%	−54	−28	88%	−90	30%	−90%	−48%	80%

Table 6
Economic indicators for some hypothetical irrigation management strategies in Crete.

Strategy	Production		Irrigation				Income	Benefit	
	All (1)	Oliv (1)	Rate	Volume		Cost	(1)	(1)	(2)
			(1)	All (1)	Oliv (1)	(1)			
	$10^3 \times$ T	$10^3 \times$ T	(mm/ha)	(Mm^3)	(Mm^3)	(M€)	(M€)	(M€)	(M€)
BLS	154.3	85.5	229.1	283.0	234.9	83.9	663.0	412.3	626.2
A	146.8	75.7	156.6	193.4	150.7	56.1	635.9	413.0	626.9
C	144.1	72.3	109.5	135.2	102.6	35.2	614.6	412.6	626.5
B	136.3	69.2	68.3	84.4	54.6	17.7	594.7	410.2	624.1
D	161.4	89.9	123.6	152.7	115.2	34.9	709.1	507.4	721.3
E	160.1	87.5	231.7	286.1	243.6	83.8	694.3	443.7	657.6

(1): Only irrigated HRU. (2): Irrigated and non-irrigated HRU.
Note: For the BLS, the Crete total Income is 1141 M€ (irrigated and non-irrigated HRU).

methods cannot be applied (Nocedal and Wright, 1999). Conversely, gradient free methods such as evolutionary algorithms can be applied. The R-SWAT-DM integrates the evolutionary algorithm nsga2R package (Tsou, 2013) because preliminary tests showed it performed slightly better than other methods. The nsga2R package implements the non-dominated sorting genetic algorithm NSGA-II (Deb, 2001), which is among the most commonly used multi-objective global optimization methods and it has been applied successfully in several watershed management applications (Bekele and Nicklow, 2005; Nicklow and Muleta, 2001; Udias et al., 2016b; Udías et al., 2012). The procedure starts with an initial population of solutions that are typically generated randomly. The fitness of individual solution in successive generations increases through selection, crossover, and mutation. The procedure stops when a set of predefined termination conditions is met.

The multi-objective optimization module simulates individuals of a population as chromosomes (scenarios), which are composed of building blocks called genes (Fig. 4). The gene is the smallest management unit. A chromosome thus represents a particular management strategy, i.e. a unique combination of irrigation BMPs (BMP combination) implemented in its genes. In this study, three management approaches were considered, leading to different number genes (decision units) for each chromosome:

- *Approach 1*: agricultural management is defined per crop, independently from its spatial location (14 genes, one per crop).
- *Approach 2*: agricultural management is defined per irrigated HRU (97 genes).
- *Approach 3*: agricultural management is defined per crop for each administrative prefecture (Chania, Heraklion, Rethimno and Lasithi; 56 genes, one per crop/prefecture combination).

The NSGA-II results are very sensitive to the operational parameters that define the search algorithm: population size, number of generations, crossover probability, and mutation rates. In order to search effectively for near-optimal solutions, the best NSGA-II operational parameters need to be estimated. This task was performed by using a nonlinear sensitivity analysis (Maringanti et al., 2009), in which different values of the NSGA-II operational parameters were modified one at a time. A good performance was found with a population size similar

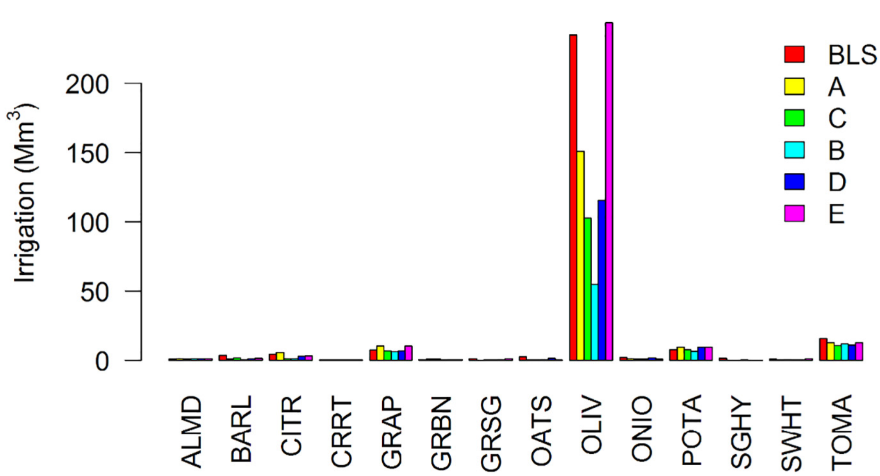

Fig. 7. Total irrigation volume by crop for the six selected strategies.

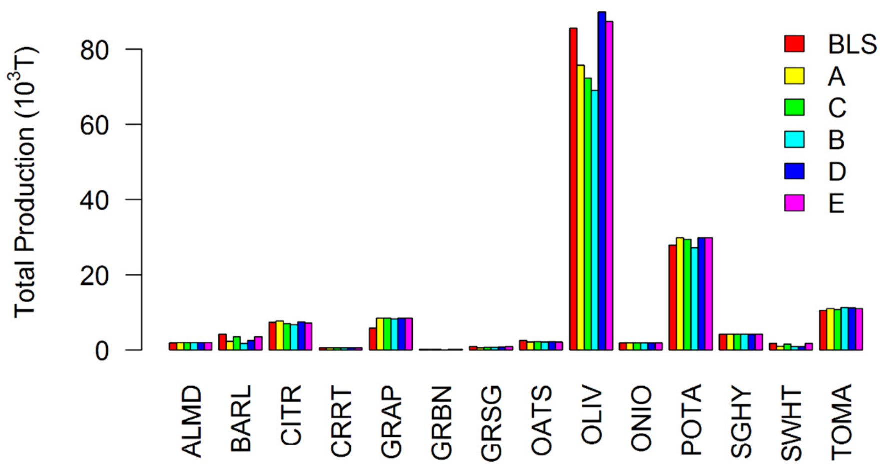

Fig. 8. Total production (T/year) by crop in irrigated HRU for the six selected solutions.

to the number of genes of the simulation, 100 generations, crossover probability of 0.9, and mutation probability of 0.1.

3. Results and discussions

Fig. 5 compares annual average crop benefits reported by Eurostat (2009–2013) with farmers' benefits estimated using R-SWAT-DM for BLS (Eq. (4)). Olive is the main source of agricultural income, generating 44% of total agricultural crop production, followed by vegetables, potatoes and grapes.

The R-SWAT-DM framework was applied to analyze different irrigation scenarios for several crop and administrative regions. A preliminary analysis was performed simulating iterative 5% incremental changes in the irrigation rate applied to all HRUs starting from the BLS (dark blue dots in Fig. 6). Each dot is the result of an increase or decrease of 5% in the amount of irrigation water applied with respect to the previous iterative dot. The iterative simulations showed that the crop benefit increases with the applied irrigation volume. At low irrigation rates (left part of the curve, crop benefit below the BLS benefit), a 5% irrigation increase produces a more than proportional crop benefit increase, because at these low rates, crops are very reactive to water applications. Instead, close to the baseline (both left and right side), a 5% changes in irrigation rates generate a less than proportional change in crop benefit: at these irrigation rates, crop water stress is generally low, and crop productivity is near to its potential. The slope of the curve to the right of the BLS point (irrigation increment) has a different shape (Fig. 6). This is because we introduced a maximum limit of water that can be applied to each HRU to avoid very high unsustainable irrigation schemes.

Fig. 6 shows the Pareto fronts that minimize irrigation cost (Eq. (2); directly linked to irrigation water use) vs total crop benefit for the three management decision levels (decisions per crop, per HRU and crop/prefecture combinations), in comparison with the baseline (BLS) conditions.

The management strategies identified in the three Pareto fronts are all more efficient than the iterative irrigation strategies, i.e. optimal allocation of irrigation is more efficient than systematic changes applied uniformly. The most efficient strategies occur at the smallest spatial management decision units (*Approach 2*, HRU level). However, implementation of management solutions identified with this approach requires a large effort and high operational complexity, as strategies changes field by field. On the other side, solutions identified with the *Approach 1* (crop level) are less efficient in water saving, but they can be implemented very easily, as the same crop solution is valid everywhere, and strategies can be transferred locally with less practical and political difficulties. The *Approach 3* (crop management by prefecture) could represent a balanced compromise between searching for efficient water saving solutions but reducing implementation burdens. Adoption of crop efficient solutions tailored per prefecture can also ensure simplicity of knowledge transfer, and equal treatments among farmers' communities.

In order to analyze more in detail different optimal solutions, we compared selected Pareto strategies to the baseline management (Table 4; Fig. 6). Strategies "*A*", "*B*" and "*C*" are efficient solutions

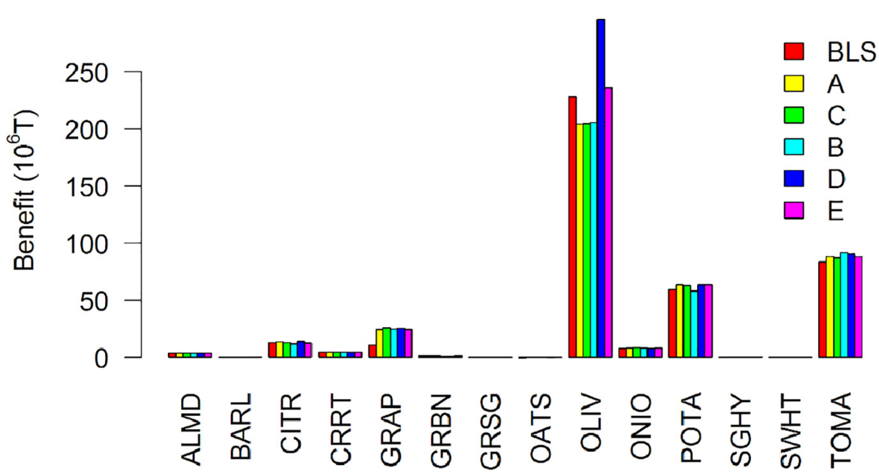

Fig. 9. Total benefit in irrigated HRU by crop for the six selected strategies.

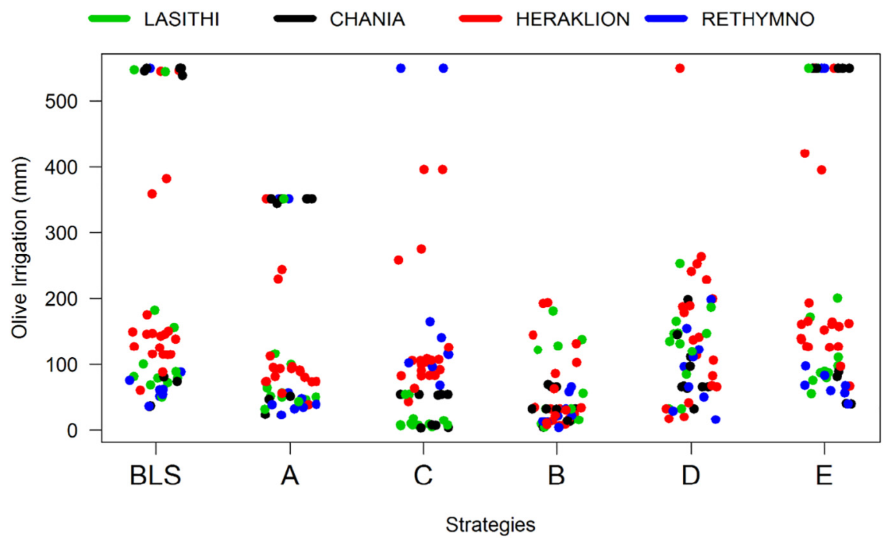

Fig. 10. Dot plot for irrigation quantity used for olive in each HRU for different strategies. Colors indicate the prefecture of the HRUs.

under the three decision approaches that attain the same farmers benefit than BLS. In addition, point "*E*" is an irrigation strategy that potentially allows increasing farmers' benefit while maintaining the current water irrigation use. Finally, point "*D*" was arbitrarily selected from the *Approach 3* (by HRU) Pareto front as an example of management strategy that potentially allows achieving a very high crop benefit (increasing it by 15%) while reducing irrigation water use compared with the baseline.

Solution "*A*" (by crop) is very simple and it mainly consists of reducing water irrigation in olive (by 36%; Table 5); this would result in 84 Mm^3 of water saving and about 26 M€ avoided cost. According to SWAT simulations, the large reduction of irrigation in olive would entail a reduction of olive production of about 11% (from 85.5 to 75.7 thousand tons per year, Table 6) corresponding approximately to 24 M€ loss of olive crop benefit. For other crops, the "*A*" strategy envisage increases or decreases of irrigation rates, which are in some cases noticeable (Table 5), but generally with a small impact on total income because of the much smaller cultivated areas. With this strategy, it would be possible to reduce the total water cost by almost a third (31.6% reduction of total irrigation volume, 90 Mm^3) without losing crop profits (Fig. 6 and Table 6). By comparing cost and income for BLS and solution A (Table 6) it can be appreciated that the important loss of crop income (27.1 M€; 663.0–635.9) is counterbalanced by savings in irrigation cost (27.8 M€; 83.9–56.1).

Solution "*B*" could potentially cut current irrigation cost by about 80% (and 70% of irrigation volume; amounting to 199 Mm^3) by maintaining at the same time the current benefit. This impressive reduction could be achieved by modifying irrigation in each HRU. Also in this case, most of the water savings occur in olive crop HRUs, which accounted for 77% (180 Mm^3) of water reduction achieved under this strategy. The importance of water saving in olive is because it is the most extensively cultivated and irrigated crop of the island, so that even small reductions can permit important savings, and because it is sometime over-irrigated in regions of high water availability.

Differences in irrigation volumes, crop yields, and total benefit for each crop under baseline and selected scenarios can be appreciated in Figs. 7, 8 and 9.

Fig. 7 shows the importance of irrigation in olive groves compared with all other crops, and the high reductions in irrigation volume that can be achieved with strategies "*A*", "*B*", "*C*" and "*D*" in comparison to the current situation.

Fig. 8 shows that changes in total crop production under the different management solutions are relatively small, up to a maximum reduction of 15% for olive under solution "*C*". In terms of benefit (Fig. 9), the loss for olive in solutions "*A*", "*B*" and "*C*" is large, but it is compensated by an increase of benefit generated by other crops, mainly grape, vegetables (TOMA), and potatoes.

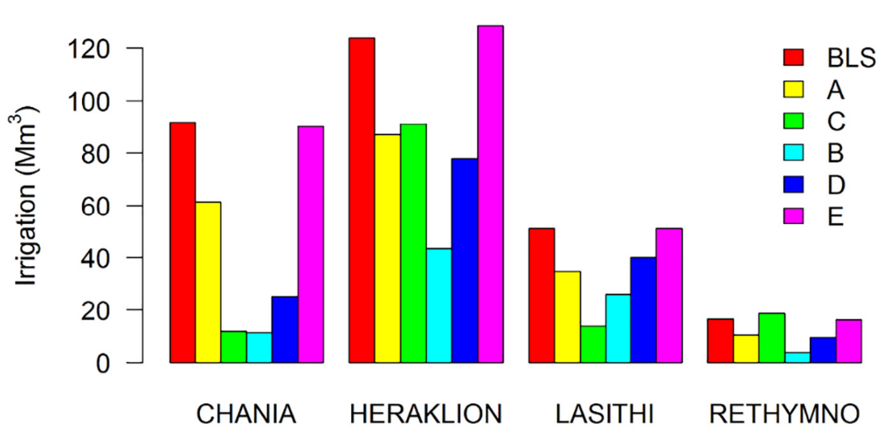

Fig. 11. Total irrigation by region for the six selected strategies.

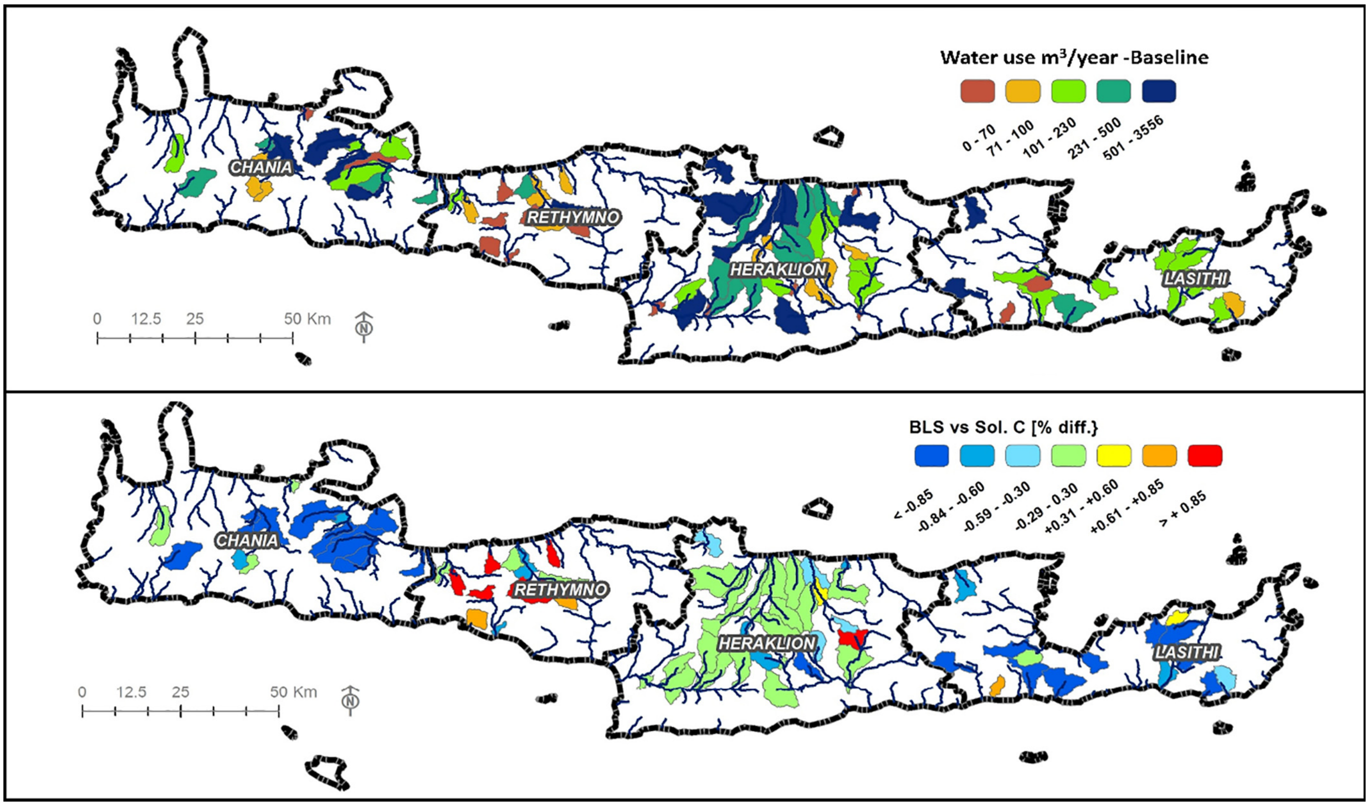

Fig. 12. Spatial distribution of the irrigation water use in the Baseline Scenario (upper) and irrigation percentage variation between baseline and scenario "*C*" (lower).

With solution "*E*" the total irrigation cost does not change, but modifying irrigation volumes by crop could increase the benefit by 7% (around 30 M€). According to this strategy, the irrigation rate in olive should increase by about 10% (Table 5), with a 4% increase of irrigation volume for olive from current 234.9 Mm^3 to 243.6 (Table 6 and Fig. 7).

In force of the maximum HRU irrigation rate threshold imposed in the model, HRUs that already receive very high irrigation rates under current management do not receive more water. This constrain causes the change in shape of the Pareto front at irrigation rates higher than point "*E*" (Fig. 6). This aspect can be better appreciated in the dot plot of Fig. 10, when looking at solutions of the "BLS" and "*E*" strategies: in all HRUs where the irrigation rates in olive are already high (550 mm), no variation of irrigation rate is applied.

Strategy "*D*" reduces the irrigation cost by about 58% and brings an increase of the global crop benefit of about 15% respect to "*BLS*" (Table 6). Once again, the most important contribution to the benefit increase comes from net savings in olive crop (Fig. 9), where important water cost savings are realized with limited loss of crop yields.

Strategies "*B*" and "*D*" are clear examples of exploiting the capacity of olive to produce good yields under limited water stress. Albeit limited, individual olive producers could legitimately consider crop production losses inacceptable. Solutions that ask some farmers to reduce water use while allowing others to increase it for an overall larger community benefit generate complex political and societal issues. All stakeholders should participate to the debate on if, where, and how to implement apparently unequal treatments. Clearly, compensation systems could be considered in this type of strategies.

Finally, "*C*" strategy (Fig. 6 and Table 6) belongs to the Pareto front of the crop by prefecture approach. While maintaining the same benefit of BLS, solution "*C*" could achieve a 53 M€ (60%) reduction of irrigation cost and a 148 Mm^3 (52%) reduction of irrigation volume. The reduction in water volume in olive would amount to 132 Mm^3 (90%). The

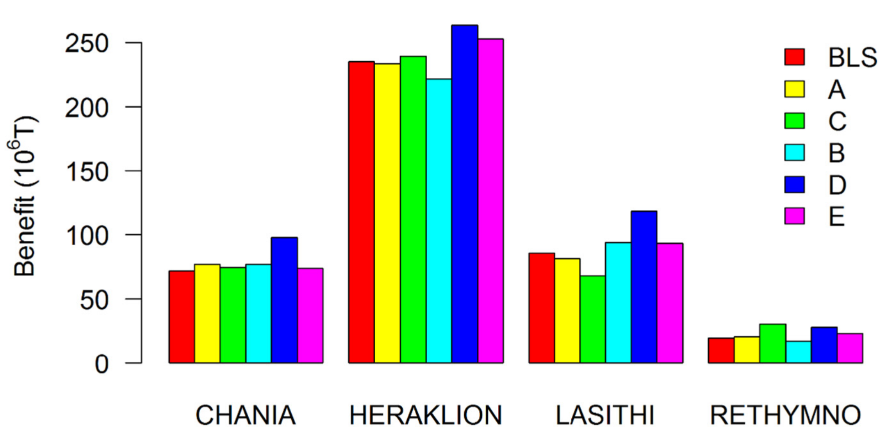

Fig. 13. Total benefit in irrigated HRU by prefecture for the six selected strategies.

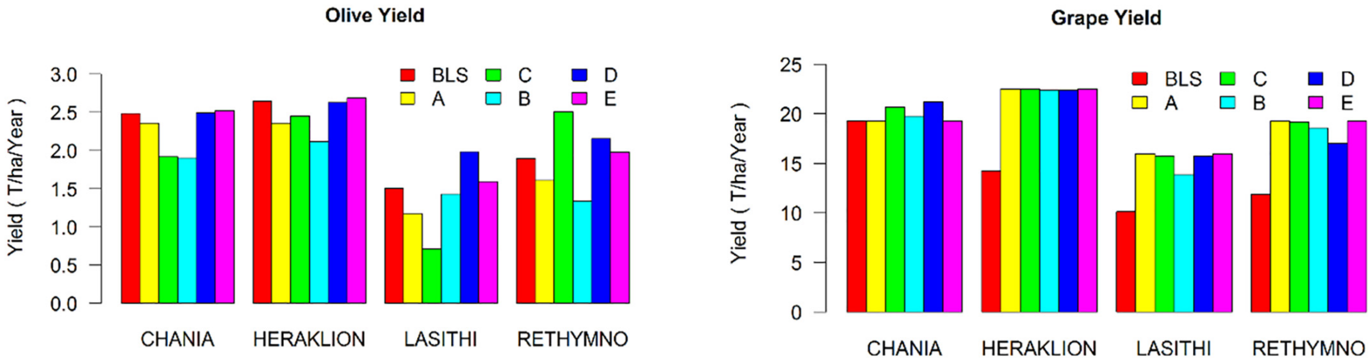

Fig. 14. Wet Crop yield by region for the selected strategies for olive (left) and grape (right).

prefecture of Heraklion has the largest irrigated agricultural area followed by Lasithi, Chania, and Rethymno (Table 1). However, water irrigation use in Chania is almost double that in Lasithi, and almost eight times that in Rethymno (Fig. 11). This is partially because there is more olive in Chania than in Lasithi and Rethymno, but probably also because water availability is higher in Chania (46% of Crete) than in Heraklion (25%), Rethymno (20%) and Lasithi (9%). In Chania, current irrigation rates are high (Figs. 11 and 12): indeed, most of the HRUs with high annual irrigation rates for olive belong to Chania (black spots in Fig. 10).

Under solutions that reduce water uses (strategies "*B*", "*C*" and "*D*" in Fig. 11), reductions of irrigation rates are heterogeneous across prefectures: the most important reductions occur in Chania (almost 85% of BLS for strategies "*B*" and "*C*"). At the opposite, according to strategy "*C*" (crop optimization by prefecture) irrigation volumes would slightly increase in Rethymo (Figs. 11 and 12), i.e. the prefecture that is the poorest in water.

Although current global benefit is maintained under strategies "*A*"–"*C*" (Table 6), locally there can be important changes; for example local benefits would be reduced under strategy "*C*" in Lasithi and under strategy "*B*" in Heraclion (Fig. 13). It is also of note that preservation of benefits is mainly due to a reduction of water cost (26.9 M€ for strategy "*A*" and 49 M€ for strategy "*C*") but implies corresponding reductions of gross income for some crops (Table 6): 27.8 M€ for strategy "*A*" and 48.7 M€ for strategy "*B*". In both cases, about 95% of the income reduction occurs for olive production (Fig. 9).

The average annual olive yield (Fig. 14 left) varies considerably across prefectures. According to BLS, average yield is about 2.5–2.7 tons/ha in Chania and Heraklion and 1.6–1.8 tons/ha in Lasithi and Rethymno. Olive yields are quite sensitive to irrigation volumes used under different scenarios in all the regions (Fig. 13 left). Grape yield variability is also clearly affected by water irrigation scenarios in all the four prefectures (Fig. 13 right). Olive and grape yield sensitivity to irrigation is more than sufficient to generate important benefits for crop production to offset the irrigation costs in several scenarios and prefectures. For example, the "*C*" strategy reduces quite significantly the yield of olive in the region of Lasithi (Fig. 14 left) while increasing the yield of grape (Fig. 14 right). The combination of these factors together with the abatement of irrigation costs allows maintaining the same benefit of baseline.

4. Summary and conclusions

Sustainable water use is a prerequisite to enhance resource efficiency in Europe as defined within the EU 2020 strategy objectives (EU, 2010). Improving water saving in all sectors, and particularly in the agricultural one (EEA, 2012), requires to adopt cost effective management strategies within the Programmes of Measures (PoMs) of the River Basin Management Plans (RBMPs). This pressing need is particular crucial in the agricultural areas of the Mediterranean region in response to the growing demands of water use from other sectors for an already scarce, but essential, resource.

In this study an integral simulation-optimization framework (R-SWAT-DM) for optimal identification of agricultural management strategies was applied to the island of Crete, analyzing trade-offs between minimizing irrigation water use and total benefit. The optimization process was able to identify solutions that, by compensating losses that may occur for some crops in some regions with gains for more productive crops in other prefectures, could achieve important reduction of water use while preserving total agriculture benefits and production.

A prominent feature of the framework is its flexibility. Different, equally optimal, solutions could be identified at the scale of interest of different stakeholders. Three levels of spatial resolution were analyzed to show potential gains under different levels of implementation complexity. With the simplest approach, i.e. targeting crops, the best water saving strategies pointed at reducing irrigation in olive and increasing in vegetables and grapes. The crop approach could reduce water irrigation by around 32% (90 Mm^3). This approach could be appealing for example to a national manager who could be more interested in solutions that can be more easily implemented or monitored. However, the most efficient solutions were found by defining site-specific strategies that considered local condition (the HRU level). This approach could be of interest to farmers who search for locally relevant solutions. This site-specific approach could potentially lead to reducing water irrigation by about 70%, saving 199 Mm^3 of water annually. Such high detailed strategies however would require high skills in precision agriculture and could be politically hard to implement, not least because of real or perceived social inequalities. The crop-by-prefecture approach appeared to be a balanced compromise that combined simplicity of implementation with consideration of local geography. The approach could suit prefecture water management agencies. In this case, an optimal water saving strategy would reduce irrigation in olive and grapes in Chania (87%) and Lasithi (72%), and to a smaller extent in Heraklion (27%), whereas irrigation could be increased in Rethymno (13%). The net result of this reallocation of water would maintain farmers global benefits, but would entail a 7% income reduction for a 52% water saving (148 Mm^3).

The analysis suggests that more efficient management of water can be achieved without losing current agricultural production and benefits. The projected impact of the water stress on crop yields should be verified in the field. In the majority of optimal solutions, irrigation rates (and crop production) would be reduced in olive. This is because the olive is less sensitive to water stress than other predominantly irrigated crops of Crete (vegetables and grapes). Despite its water stress resistance, olive quantitative and qualitative production depends on proper irrigation management. Reducing irrigation could potentially bring larger yield losses in dry years, an aspect that was not fully considered in this analysis. Thus, the use of irrigation in olive remains agronomically valid, especially in dry years. Also, the feasibility of water transfers across prefectures should be assessed properly. Despites these limitations, the large potential water savings highlighted in the analysis indicate that cost-effective optimal irrigation strategies should be searched and implemented in water scarce regions like the Mediterranean area.

Abbreviations

BLS	Base Line Scenario
BMP	Best Management Practices
EC	European Commission
FAO	Food and Agriculture Organization
JRC	Joint Research Centre
HRU	Hydrological Response Unit
MCDM	Multi-Criteria Decision Making
MOEA	Multi Objective Evolutionary Algorithm
RBMPs	River Basin Management Plans
R-SWAT-DM	Soil Water Assessment Tool Decision Making package in R software
WFD	Water Framework Directive
SWAT	Soil and Water Assessment Tool
PoMs	Programmes of Measures

Acknowledgments

This work has received funding from the European Union Seventh Framework Programme for Research, Technological Development and Demonstration under grant agreement No. 603629 project “Globaqua”.

Conflicts of interest

The authors declare no conflict of interest.

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