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Identifying efficient agricultural irrigation strategies in Crete

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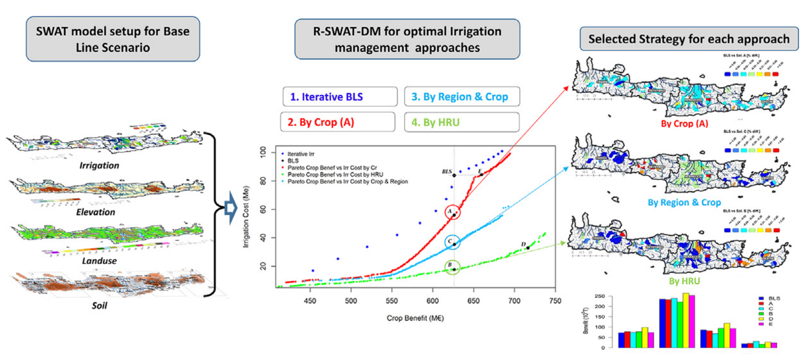
HIGHLIGHTS

- 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



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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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strategies can potentially address the water scarcity issue that is becoming crucial for the viability of agriculture in the Mediterranean region.

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