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Assessing the cost-effectiveness of irrigation water management practices in water stressed agricultural catchments: The case of Pinios

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ABSTRACT

Agricultural water use in the Mediterranean region is significant, causing serious threats to water bodies that may not be able to reach the 'good status' required by the Water Framework Directive. This study uses the Soil and Water Assessment Tool (SWAT) model and a simple economic component developed in order to estimate the cost-effectiveness (CE) of six agricultural Best Management Practices (BMPs) in reducing irrigation water abstractions in the water scarce Pinios catchment in central Greece. Deficit irrigation, precision agriculture, waste water reuse, conveyance efficiency improvement and their combinations were evaluated and their CE was calculated for each Hydrologic Response Unit (HRU) separately and for the entire catchment. The results at the HRU scale are presented comprehensively on a map, demonstrating the spatial differentiation of CE ratios across the catchment. Based on the analysis, a catchment management solution of affordable total cost would include waste water reuse in areas adjacent to treatment installations, deficit irrigation in the least water deficient areas as well as precision agriculture in the most deficient ones. Conveyance losses reduction through the construction of piped irrigation networks was necessary for considerably decreasing groundwater overexploitation. However, since conveyance loss reduction entails significant costs, the resulting CE is not favorable. The methodology presented aims to facilitate decision making for agricultural water management by enabling modelers to combine process-based hydrological models with rapid and reliable cost estimations and use cost effectiveness metrics to identify and prioritize suitable irrigation water management practices. However, existing SWAT limitations are also discussed and the need for improving the accuracy of the representation of such practices in the future is highlighted.

1. Introduction

Agriculture is a significant water user in the European Union (EU), reaching up to 80% of the total abstractions in parts of the Mediterannean region (Wriedt et al., 2009). Especially in Greece, irrigation of crops accounts for virtually all agricultural water use, which in some cases has reached unsustainable levels (EEA, 2012). Sustainable water exploitation of aquatic systems is, inter alia, a prerequisite for achieving 'good status' for surface and groundwater as required by the Water Framework Directive (WFD) (Directive, 2000/60/EC). Towards this end, EU Member States are required to establish a cost-effective Program of Measures (PoMs) in each river basin appropriate to water quantity and quality pressures identified in the River Basin Management Plans (RBMPs). Parts of these measures referring to the agricultural sector are known as 'Best Management Practices' (BMPs) (Cherry et al., 2008).

For the estimation of BMPs' cost-effectiveness (CE) in reaching multiple environmental targets at the river basin scale, highly sophisticated models are widely used. Such models are considered irreplaceable in terms of making quick water quality predictions under agricultural management changes due to their relatively fast simulation runs and increased number of watch points. Between

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several existing models, the Soil and Water Assessment Tool (SWAT) is a prominent process-based model, which is considered a robust, interdisciplinary tool appropriate for agricultural management simulation (Gassman et al., 2007; Neitsch et al., 2009).

Recent examples of water management SWAT studies focus on estimating crop water productivity under alternative policy scenarios and water scarcity conditions (Faramarzi et al., 2010; Feng and Baoguo, 2010). Santhi et al. (2005) used SWAT to investigate the water savings in irrigation projects in Texas, USA, by examining crop change scenarios and irrigation water conveyance efficiency improvement. Masih et al. (2011) on the other hand, have used SWAT to investigate the impact of agricultural changes on basin streamflow in Iran. An interesting point in that study was the effort to simulate various in situ water harvesting systems and conservation techniques such as: micro-basins, terracing, bunds and mulching, with the purpose to increase soil water retention and foster plant water availability. Such interventions were indirectly represented in SWAT by increasing the Available Water Capacity (AWC) of soils. There are also studies where the SWAT code and the existing parameters could not adequately simulate specific irrigation systems. A representative recent example is the study of Xie and Cui (2011), who improved the irrigation function of ponds and reservoirs in order to reliably simulate irrigation in paddy rice fields of China, while another is this of Dechmi et al. (2012), who adjusted the model's code to appropriately simulate irrigation water returns and total streamflow in intensively irrigated areas from outside sources.

Despite those and possibly a few additional SWAT studies on agricultural water use, the water management module of SWAT has not been systematically examined for a range of practices and interventions, contrary to large sets of pollution mitigation practices, whose simulation has been adequately reported in recent studies (e.g. Arabi et al., 2008; Panagopoulos et al., 2011, 2012). Therefore, one of the major purposes of this paper is to provide guidance on how a wide range of agricultural water management BMPs could be represented at the river basin scale, taking advantage of model improvements incorporated in the most recent version of SWAT at the time of this research (ArcSWAT 2009 Version 93.7b), but also taking into consideration model representation inaccuracies that still exist. Moreover, the study contributes to the reporting on CE analysis with water management BMPs implementation, a topic of significant interest for water deficient southern European countries (Estrela and Vargas, 2012), on which only few peer-reviewed studies have been published (Berbel et al., 2011). The model and approach are tested in the largest irrigated area in Greece, the water scarce Pinios catchment, which has been selected for conducting the EU funded project '*i-adapt*' (www.i-adapt.gr), the Greek pilot project on the development of prevention activities to halt desertification in Europe.

2. Methodology

2.1. SWAT model description

A catchment in the GIS-based SWAT environment is divided into subbasins and subsequently into Hydrologic Response Units (HRUs), which represent the different combinations of land use and soil types. The processes associated with water and sediment movement, crop growth and nutrient cycling are modeled at the HRU scale. Hydrological processes include surface runoff/infiltration, evapotranspiration, lateral flow, percolation, and return flow. The model considers a shallow unconfined aquifer, which contributes to the return flow and a deep confined aquifer acting as a source or sink. Agricultural management practices, such as planting, harvesting, tillage, irrigation, grazing and nutrient applications can be simulated with specific dates. Irrigation and fertilization can be additionally applied automatically according to crop water and nutrient stress. The crop growth component of SWAT is a simplified version of the Erosion Productivity Impact Calculator (EPIC) model (Williams, 1995), which is capable of simulating a wide range of crop rotation, grassland/pasture systems, and trees. In the SWAT model, potential crop growth and yield are usually not achieved as they are inhibited by temperature, water and nutrient stress factors. As far as the irrigation routine is concerned, SWAT uses as potential irrigation sources: (a) the river, (b) a reservoir, (c) the shallow aquifer, (d) the deep aquifer or (e) an unlimited source outside the catchment. Compared to the older versions, SWAT 2009, used in this study, promises to represent more accurately the reality as the excess irrigation water applied to the HRUs does not return to the source, while new parameters have been added, with the purpose to simulate irrigation inefficiencies during water transport and application to the HRUs (Neitsch et al., 2009).

2.2. Study area

The study is focusing at the Pinios basin (~10,600 km^2), covering almost entirely the River Basin District (RBD) of Thessaly in central Greece as shown in Fig. 1. The mean annual river flow at the outlet is reported close to 80 m^3/s and the mean annual precipitation is approximately 700 mm (Evangelou et al., 2011). The catchment is the most important agricultural producer in Greece, with fertile soils but drought climate during summer (Vasiliades et al., 2011). These conditions inversely affect both the natural vegetation and the agriculture of the region resulting in irrigation cutbacks, overexploitation of groundwater and significant losses of crop yields (Evangelou et al., 2011).

Agriculture represents the 90–95% of the annual water demand of the area, with irrigated land (200,000 ha) covering half of the total cultivated area (400,000 ha). Cotton is the main crop cultivated (~150,000 ha), followed by much smaller areas of corn and alfalfa. Irrigation water is abstracted mostly from groundwater sources; however, overexploitation has been a common practice for years leading to ever lower groundwater levels, making water more expensive to extract (deep pumping) and enhancing saline water intrusion in coastal areas (Evangelou et al., 2011; Loukas et al., 2007). It has also been estimated that the collective irrigation networks which are comprised of open canals in the study area, are characterized by significant conveyance losses and sub-optimal management of irrigation water (Mouratiadou and Moran, 2007).

2.3. Model setup and calibration

The modeling study is comprised of two different simulation periods: (a) the historical period of 1975–1994 with available river flows for calibrating the model and (b) the future period 2011–2027, used as the baseline for testing irrigation BMPs. For the second period, the weather generator of SWAT (Neitsch et al., 2009) was used to produce meteorological time-series based on historical statistical measures derived from the existing stations. A crucial difference in water management between these two periods is that within the past (calibration) period crop areas were less, while irrigation water requirements could be totally satisfied by deep pumping and aquifer overexploitation. On the other hand, in nowadays and due to extremely high groundwater depths, deep pumping is not a viable practice and has been drastically reduced, while irrigated areas have been almost doubled (Makropoulos and Mimikou, 2012).

The Pinios SWAT model setup was initiated with the use of a 25 m × 25 m DEM to delineate the study area (10,599 km^2) and the river network with the catchment being divided in 49 subbasins