Sustainable agricultural water management in Pinios river basin using remote sensing and hydrologic modeling

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Abstract

The Pinios river basin is a major agricultural area in Greece, which faces environmental issues with water scarcity and nutrient pollution. Recent Earth Observation satellite data and ground truth information were combined to produce an updated land use map, focusing on irrigated crop areas. A process-based hydrological model (SWAT) was set up using the produced land use map. The model was calibrated and validated using observed streamflows and nutrient concentrations at selected gauging stations. Four irrigation and nutrient management practices related to resource efficiency (i.e. deficit irrigation, reduced fertilization, combination of deficit irrigation and fertilization, precision agriculture) were modelled and simulated. The sustainability of the management practices was assessed using indicators to quantify their impacts on the water-energy-land-food nexus of the river basin.

Keywords: agricultural water management; Pinios; remote sensing; SWAT; water efficiency; nexus;

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1. Introduction

Agriculture is a major water user for Europe accounting for 22.5% of total freshwater abstractions. In southern Europe agricultural abstractions account for 46% on average, while in certain southern river basin districts they reach up to 80%, causing serious water quantity issues [1]. Furthermore, areas with intensive agricultural activity suffer from water quality degradation, which is associated with N and P emissions from fertilizers [2]. As a result, irrigated agriculture is considered a key driver for both water scarcity and drought and nutrient pollution. Climate change is expected to deteriorate the situation, unless mitigation and adaptation measures are implemented [3, 4]. Several European policies support the effort to increase resource efficiency of water and fertilizers to alleviate these environmental pressures. The EU 2020 Strategy [5] for smart, sustainable and inclusive growth and the Roadmap to a Resource Efficient Europe [6] frame the vision for a low-carbon, innovative and sustainable economy through the promotion of resource efficiency. In addition, water saving and water protection measures are required to be integrated in the Programmes of Measures (PoMs) of the national River Basin Management Plans (RBMPs) in line with the Water Framework Directive (WFD) [7], with the ultimate goal of achieving good status for surface and groundwater bodies.

However, decisions about farming practices may influence not only water quantity and quality status, but also other environmental components in a catchment, as well as societies and the economy. Designing and implementing measures for sustainable management of water resources in agriculture requires an integrated approach addressing the water-energy-land-food nexus [8, 9] and also taking into account rural development, economic growth and social cohesion. Especially in the Mediterranean, agriculture is considered a significant economic sector, because of its traditionally high contribution to growth and employment. For example, the gross added value of crop production in EU is estimated at 1.6% of the total economy, whereas in Spain and Greece it reaches 2.5% and 3.8% respectively [10]. In addition, the agricultural sector accounts for 5.2% of the total EU labour force on average, whereas this share rises up to 9% in Italy and Spain or even 20% in Poland [11].

The Soil and Water Assessment Tool (SWAT) is considered a prominent process-based model, which serves as a robust and interdisciplinary tool for the simulation of agricultural catchment management [12]. It has been used in a broad range of studies for designing water-related measures in agricultural catchments [13, 14, 15]. Recent studies have also focused on coupling remote sensed products and SWAT to analyse the impacts of land use change or agricultural management practices [16, 17, 18, 19].

The Pinios river basin is a key agricultural area in central Greece facing issues with both water scarcity and nutrient pollution. The current study focuses on the assessment of the sustainability of alternative agricultural management practices to deal with these issues. The methodology that is followed combines remote sensing and image interpretation, GIS processing, hydrologic modeling and simulation of agricultural management practices using SWAT, analysis of impacts on the water-energy-land-food nexus and development of nexus-related indicators.

2. Methodology

2.1. Study area

The Pinios river basin (~10600 km$^2$) lies in central Greece, covering most of the area of the Thessaly River Basin District (RBD). The central part of the river basin is covered by a large fertile plain, where cotton, winter wheat, maize and alfalfa are mainly cultivated. The average annual rainfall and reference evapotranspiration are approximately 700 mm and 1400 mm respectively, while the observed average annual streamflow at the catchment outlet is approximately 80 m$^3$/s. Irrigated agriculture takes up 90-95% of the total water use and approximately 50% of the total agricultural land. Taking into account the official and unauthorised abstractions from illegal boreholes, the primary water source is groundwater by far. Overexploitation of groundwater has led to higher costs for pumping from greater depths and seawater intrusion in coastal aquifers. Surface water is mainly abstracted from the Plastiras reservoir, which is considered an outside source because it collects water from the RBD of Western Greece, the Smokovo reservoir and Karla, which is a lake restored in recent years. Irrigation infrastructure includes collective systems with open trenches and canals, which are responsible for very high conveyance losses (30-50%). The conveyance efficiency of the urban distribution network is also very low, as losses reach up to 40%. Since the 1980s, payments to the farmers under the
Common Agricultural Policy (CAP) have led to intensive farming of subsidised crops. As a result, the use of fertilizers and pesticides has grown rapidly causing problems with diffuse pollution. The plain of Thessaly is officially characterized as a Nitrate Vulnerable Zone (NVZ). According to the 1st RBMPs reported to the European Commission, the ecological status of the majority of the water bodies was found to be below good condition [20, 21].

2.2. Remote sensing, image interpretation and GIS processing

Remote sensing and image interpretation techniques can be used to derive information in spatial and temporal resolution that was previously not available. This can be applied in ungauged basins, where no ground information exists, or in poorly gauged basins, where the spatial or temporal coverage of monitoring is unsatisfactory. Earth observation techniques can support the acquisition of high-resolution land use data to meet two kinds of needs. The need for frequent update of land use information at higher temporal resolution than national and European statistics (e.g. Corine Land Cover, National Agricultural Census) and the need for near-to-farm-level spatial information to identify detailed crop patterns and farm-based management practices.

For this study, satellite multispectral high spatial resolution data (Landsat 8/OLI-TRS, 30 m) were acquired for the period June-September 2013. Using ERMapper software a mosaic of images covering the total area of the Pinios river basin was first created. Then, the plain of Thessaly, where most of the irrigation takes place, was isolated and the appropriate RGB band composite for image interpretation was developed. This product was inserted in eCognition, which is an object-based image analysis software. Bottom-up multiresolution segmentation was implemented focusing on the homogeneity criteria of shape and colour to produce polygon features. Supervised hierarchical classification was carried out for the various land use classes using the Nearest Neighbour algorithm. The main crops that were chosen to be classified are cotton, corn, alfalfa, winter wheat, tomato and sugar beet. Information derived from the OPEKEPE database, which is the Greek organization for paying subsidies to farmers, was used to develop two independent sets of training and test regions. The classification accuracy was evaluated using a confusion matrix and suitable statistical indices. The best classification showed Overall Accuracy and Kappa Index of Agreement equal to 0.67 and 0.6 respectively. Accuracy was very high for cotton, corn, alfalfa and winter wheat, which are the most predominant cultivations, but very low for tomato and sugar beet, which cover only small and scattered areas. Using ArcGIS the land classes of tomato and sugar beet were merged with neighbouring crop classes. Then, the new product was combined with the Corine Land Cover map of the region to produce the updated land use map of the river basin for 2013.

2.3. Hydrologic and crop growth modelling

The SWAT model, which is developed by the USDA Agricultural Research Service, is a physically-based, basin-scale, continuous-time model that operates on a daily time step. In the GIS-based SWAT environment a watershed is divided into multiple sub-watersheds, which are subsequently further divided into hydrologic response units (HRUs). The HRUs represent areas with homogeneous land use, management, soil characteristics and slope [12]. The processes associated with water and sediment transport, crop growth and nutrient cycling, including the agricultural management practices, are modelled at HRU level. 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 applying a user-defined schedule. Additionally, irrigation and fertilization can be triggered automatically for pre-defined thresholds of soil water deficit and plant N stress respectively. Irrigation needs are met with water abstractions from model elements acting as water sources: rivers, reservoirs, aquifers or outside sources. Irrigation inefficiencies, such as conveyance losses from the source to the field or additional water application losses on-site, can also be simulated with SWAT. In the crop growth module temperature, water and nutrient stress may act as limiting factors, hence lowering the actual compared to the potential yields [22].

Relevant datasets for the Pinios river basin were collected from various sources, such as the Greek Ministry of Environment & Energy, the Public Power Corporation, the National Institute of Geology and Mineral Exploration,
the National Institute of Soil Mapping and Classification, Eurostat and previous studies conducted in the Pinios river basin. Information included topography, geology/hydrogeology, climate/hydrometeorology, water supply/demand/consumption, water efficiency, management practices, administration and socio-economic affairs. The GIS maps for land use, soil and topography (DEM - Digital Elevation Model) were used as input to ArcSWAT to divide the Pinios catchment into subcatchments and HRUs. The schematization led to 49 subcatchments and 848 HRUs. Each HRU was linked to a shallow aquifer by default. The dams of Plastiras, Smokovo, Gyrtoni and Karla were added in the model. Irrigation and fertilization management follows a user-defined schedule for cotton, corn, alfalfa and winter wheat (Table 1).

The model was calibrated (1976-1985) and validated (1986-1995) using observed monthly streamflows at two gauging stations: Ali Efenti and Amygdalia. The calibrated parameters included 10 model variables, which represent hydrological processes or hydrological properties of soils. The Nash-Sutcliffe coefficient was very high (0.635-0.878) indicating good fitting of the model. However, the Mean value bias (6.85-23.16) revealed a tendency of the model to underestimate the observed water volumes, especially for high monthly peaks. The model was also calibrated (1984-2004) using observed seasonal nutrient loads at two gauging stations: Keramidi and Ydatopyrgos. The data was scarce and of poor quality, so no validation was carried out. The calibrated parameters included 10 model variables, which represent N and P processes. A satisfactory correlation was found between the observed and simulated seasonal loads of N, especially for low values (<500 \(10^6\) kg). For bigger loads, there was a clear tendency of the model to underestimate the observed values. The respective correlation for P was found very weak. Generally, the calibration was assisted by international literature and previous experience in SWAT parameters for the basin [23, 24]. During calibration the irrigated land was reduced by 40% and all dams and reservoirs, except for Plastiras, were set inactive to account for the historical conditions in the catchment.

### Table 1. Conventional agricultural management practices.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Annual irrigation (mm)</th>
<th>Annual fertilization (kg N/ha)</th>
<th>(kg P/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cotton</td>
<td>570</td>
<td>195</td>
<td>31</td>
</tr>
<tr>
<td>corn</td>
<td>620</td>
<td>214</td>
<td>48</td>
</tr>
<tr>
<td>alfalfa</td>
<td>740</td>
<td>0</td>
<td>46</td>
</tr>
<tr>
<td>winter wheat</td>
<td>40</td>
<td>131</td>
<td>16</td>
</tr>
</tbody>
</table>

### Table 2. Scenarios for efficient agricultural management practices.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
<th>Crops to be applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (REF)</td>
<td>Conventional farming</td>
<td>cotton, corn, alfalfa</td>
</tr>
<tr>
<td>Deficit Irrigation (DI)</td>
<td>-30% in irrigation doses</td>
<td></td>
</tr>
<tr>
<td>Reduced Fertilization (RF)</td>
<td>-30% in fertilization doses</td>
<td></td>
</tr>
<tr>
<td>Combined Deficit Irrigation &amp; Reduced Fertilization (DIRF)</td>
<td>-30% in irrigation and fertilization doses</td>
<td>cotton, corn, alfalfa</td>
</tr>
<tr>
<td>Precision Agriculture (PA)</td>
<td>Automated irrigation and fertilization</td>
<td>only cotton</td>
</tr>
</tbody>
</table>

### 2.4. Baseline and Scenarios for efficient agricultural management practices

The baseline scenario uses the updated land use map of 2013 (see 2.2), while all dams and reservoirs are set active to account for current conditions. The overall conveyance efficiency in irrigation is set equal to 25%.

Four alternative scenarios focusing on efficient irrigation and fertilization practices were examined, with the aim of improving water quantity and quality in the catchment. All scenarios (Table 2) were simulated over a 20 year period using the calibrated SWAT model in two versions.

Since irrigation abstraction can be implemented only from one source in SWAT, this source was chosen to be the shallow aquifers. The first model version assumes very high initial depths of the shallow aquifers to allow for abstractions from non-renewable groundwater resources (unsustainable water management – actual conditions), while
the second model version assumes limited initial depths of the shallow aquifers to prohibit abstractions from non-renewable groundwater resources (sustainable water management – ideal conditions). Such depths for sustainable water management have been estimated using hydrogeological analysis and can be found in relevant literature for the catchment [20]. The comparison of the two versions of simulations allows for the estimation of the renewable and non-renewable groundwater resources for irrigation abstraction.

2.5. Analysis of impacts on the water-energy-land-food nexus and development of nexus-related indicators

The relationships between water, energy, land and food resources at catchment scale have been analysed and indicators best reflecting each of these nexus components have been proposed. Overall, a set of indicators has been developed, which is capable of expressing the sustainability of agricultural management in the catchment. It should be noted, though, that the water-energy-land-food nexus contains high complexity, which cannot be fully reflected through this indicator set. In addition, the nexus involves all kind of relationships between the various components, whereas the selected set of indicators focuses more on the impacts of water on the other components of the nexus. Therefore, the analysis of this study is more water-oriented.

The selected indicators to express the WATER component of the nexus are the following:

- **Renewable groundwater resources for irrigation**, which is calculated as the share of the renewable groundwater resources for irrigation in the total irrigation abstractions (renewable and non-renewable) from groundwater (see 2.4);
- **simplified Water Exploitation Index**, which is the ratio between total water abstraction and total water availability in the catchment;
- **Load of NO$_3$ percolating to groundwater**, which is expressed as the average load of NO$_3$ to groundwater per unit area of HRU.

The selected indicator to express the ENERGY component of the nexus is the following:

- **Net value of water-related energy production/consumption**, which comprises of three elements: the potential production of 2nd generation bioethanol by using 30% of corn residues, the potential production of hydropower from the dams of Plastiras and Smokovo and the potential consumption of electricity for pumping in irrigated agriculture.

The food component of the nexus is conceptually extended in order to include not only edible crops (e.g. wheat, corn), but also crops for feeding animals (e.g. corn, alfalfa) and industrial crops (e.g. cotton). Hence, the selected indicator to express the FOOD/CROP PRODUCTION component of the nexus is the following:

- **Value of crop production**, which is calculated as the product of crop yields and prices.

The selected indicator to express the LAND component of the nexus is the following:

- **Erosion intensity**, which is the average sediment yield per unit area of HRU.

3. Results

Using the simulations of the SWAT model and further processing, all nexus-related indicators (see 2.5) have been calculated. The summary results are illustrated in Table 3. The illustrated values represent annual averages for the whole simulation period.

A number of conclusions can be drawn by assessing the performance of all agricultural management practices per indicator. In particular, all management practices targeting at water saving (DI, DIRF, PA) enhance the use of renewable groundwater resources for irrigation purposes, while precision agriculture (PA) achieves the most sustainable use of groundwater resources. It also evident that the river basin of Pinios is suffering from serious water scarcity, which cannot be reversed even if deficit irrigation by 30% is applied (DI, DIRF). The simplified Water Exploitation Index, which does not include the influence of the outside source of Plastiras, improves significantly in these scenarios, but it is constantly kept over the critical threshold of 40% in all cases. If deficit irrigation by 30% is
applied to cotton, corn and alfalfa, then at catchment scale this would lead to 27.5% reduction in water abstractions. As a direct result, electricity for pumping would decrease significantly creating a large benefit in terms of net energy value. If reduced fertilization by 30% is applied to cotton, corn and alfalfa, then at catchment scale this would lead to 15% reduction of applied N. The comparison of simulated yields of corn and cotton for deficit irrigation and reduced fertilization reveal that the yields are more vulnerable in the former case than in the latter. In addition, precision agriculture is the most favourable technique for increasing cotton yields, thus leading to a greater value of agricultural production. Finally, the erosion intensity is similarly reduced in all scenarios, because surface runoff decreases in all cases.

Another set of conclusions can also be drawn by assessing the performance of all agricultural management practices across the whole indicator set. In particular, reduced fertilization (RF) is a non-optimal solution for all scenarios. When comparing it with its combination with deficit irrigation (DIRF) the second seems to dominate. Deficit irrigation (DI) and its combination with reduced fertilization (DIRF) show similar performance for all nexus-related indicators, except for the load of percolating NO$_3^-$, where DIRF is more effective. Precision agriculture (PA) has the best performance for the indicators related to Water and Food/Crop production. It achieves higher efficiency in the use of water and fertilizers, it raises the use of renewable groundwater resources and reduces the NO$_3^-$ load to groundwater, while it increases the value of crop production.

Table 3. Water-Energy-Land-Food nexus impacts for alternative agricultural management practices.

<table>
<thead>
<tr>
<th>Nexus Indicator *</th>
<th>REF Conventional farming</th>
<th>DI Irrigation -30%</th>
<th>RF Fertilization -30%</th>
<th>DIF Irrigation &amp; Fertilization -30%</th>
<th>PA Precision Agriculture</th>
</tr>
</thead>
<tbody>
<tr>
<td>WATER</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Renewable groundwater resources for irrigation (% of total irrigation abstractions from groundwater</td>
<td>51.3</td>
<td>62.2</td>
<td>51.3</td>
<td>62.0</td>
<td>75.6</td>
</tr>
<tr>
<td>Water Exploitation Index (simplified)</td>
<td>0.92</td>
<td>0.70</td>
<td>0.92</td>
<td>0.70</td>
<td>0.94</td>
</tr>
<tr>
<td>Load of NO$_3^-$ [kg/ha] percolating in groundwater</td>
<td>24.22</td>
<td>23.64</td>
<td>18.22</td>
<td>17.94</td>
<td>14.28</td>
</tr>
<tr>
<td>ENERGY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net value of water-related energy production/consumption [10$^6$ €]</td>
<td>2.1</td>
<td>6.5</td>
<td>1.2</td>
<td>6.1</td>
<td>2.0</td>
</tr>
<tr>
<td>LAND</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Erosion intensity [1000 kg/ha]</td>
<td>1.350</td>
<td>1.336</td>
<td>1.350</td>
<td>1.336</td>
<td>1.344</td>
</tr>
<tr>
<td>FOOD - CROP PRODUCTION</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value of crop production [10$^6$ €]</td>
<td>406.5</td>
<td>383.2</td>
<td>402.3</td>
<td>381.2</td>
<td>410.3</td>
</tr>
</tbody>
</table>

*average annual values; values showing best performance are underlined

4. Conclusions

Remote sensing and image interpretation techniques can be applied in order to enhance the spatial and temporal resolution of the available information in poorly gauged or ungauged catchments. Updated land use map products can be coupled with distributed hydrologic models, such as SWAT, to simulate catchment hydrology and agricultural management practices addressing water quantity and quality issues. The development of indicators in order to quantify the impacts of irrigation and fertilization management practices on the water-energy-land-food nexus is an integrated approach, which may assist the design of sustainable water management measures in agricultural catchments. The Pinios river basin, in central Greece, suffers from serious water scarcity and nutrient pollution. Precision agriculture, followed by deficit irrigation and the combination of deficit irrigation and reduced fertilization appear to be the management practices with the highest potential to address these environmental issues more effectively and efficiently, promoting sustainable water management in the catchment.
Acknowledgements

Parts of this research were conducted under the projects ‘Nomoteleia’ and ‘i-adapt’ (Scientific Responsible: M. Mimikou). ‘Nomoteleia’ (http://nomoteleia.eu/) was partly funded by the General Secretariat of Research & Technology of the Greek Ministry of Education, Research and Religious Affairs (ARISTEIA I project). ‘I-adapt’ (http://i-adapt.gr/) was partly funded by DG Environment of the European Commission (Pilot project on Development of Prevention Activities to Halt Desertification in Europe). We thank Dr Pol Kolokoussis for providing theoretical training and technical advice on remote sensing and image interpretation applications.

References

[21] Special Secretariat for Water, River basin management plan for the river basin district of Thessaly (GR 08), YPEKA, Athens, Greece, 2014.