



# Comparing Two Hydro-Economic Approaches for Multi-Objective Agricultural Water Resources Planning

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## Abstract

Hydro-economic models are valuable tools that can be used in irrigated agriculture in order to improve the understanding of the status quo of water resources, the role of water in agriculture, and the system behavior under changing conditions. The present paper attempts to give insights on how different water management objectives and data availability may influence the specification/application of hydro-economic modeling, as well as the reliability and interpretation of their results. A Greek rural watershed located in Central Greece (Region of Thessaly) is used as a case study application. A common hydro-economic framework for sustainable water resources management in irrigated agriculture is examined, aiming to provide a simple and understandable tool for policymakers. In this framework two hydro-economic models (HEMs) were developed to address challenges regarding data limitations, spatial analysis, and scenario-based problems (e.g. agri-economic scenarios, water policy scenarios, environmental scenarios, etc.). A set of selection criteria was then used to qualitatively compare these two models, based on their advantages and disadvantages. The results of this analysis indicate that HEMs' development must be quite flexible about their settings and must take into consideration the desired accuracy level that is likely to satisfy their main purpose/goal. The optimal approach is the one that can achieve a balance between simplicity, flexibility, accuracy and robustness.

**Keywords** Hydro-economic modeling · Water resources management · Comparison of hydroeconomic models · Modeling settings

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## 1 Introduction

The combination of economic, hydrological and engineering processes in models for decision support on irrigated agriculture issues is an increasingly developed field (Barthel et al. 2012; Sherafatpour et al. 2019). The integration of economic-productive objectives and environmental pressures into single model applications (mostly known as hydro-economic model) provides a holistic and coherent view of the studied problems. Hence, Hydro-Economic Models (HEMs) are increasingly used, in water resources management, agricultural issues, policymaking, and other fields with many extents, such as climate change, projects and planning, etc. (Blanco-Gutiérrez et al. 2013; Nakic 2017).

The main challenge in the development of a HEM is the appropriate description of the system, and for this, adequate and necessary data is needed. Defining the main components of the model and the way they will interact is a tough task, as it needs knowledge/understanding and data relative with hydrology, water infrastructure, economy, supply and demand operations in water and economic terms, and impacts or interactions with case-specific parameters (Nakic 2017). For each one of the above components the literature may be rich, but the guidance for the combined simulation is poor, since the experience is limited, and case-specific factors are the main drivers affecting the models' structure. Interdisciplinary (often complex and mathematically complicated) models have been developed to overcome the above challenges. These elements restrict the HEMs' applicability in rural areas, which usually need such tools and require the involvement of various disciplines and stakeholders.

The discussion in the international literature has been proved to be poor for the optimum way to address these issues (Alamanos et al. 2019a). Comparative studies of HEMs have been carried out using efficiency criteria (Krause et al. 2005), for example, Harou et al. (2009) described the status of HEMs and their future, Cornelissen et al. (2013) assessed the suitability of different model types for simulating scenarios of future discharge behaviour in the context of climate and land use change, and Bekchanov et al. (2015, 2017) provided a review of HEMs' features and applications. But to our knowledge no study has compared the performance of the same model under various conditions or tested various approaches to examine modeling practices.

The present paper attempts to give insights on the most appropriate way to build a HEM, better exploit the available data depending on the desirable outputs, and discuss how the selection of a HEM and the various management priorities may affect water use decisions in agricultural areas. A Greek rural watershed, located in Central Greece, is used as a case study application. Firstly, a HEM was developed, as a first attempt using a simpler approach and limited data to address the main issues and to estimate the basic hydro-economic parameters (Alamanos et al. 2019b). Then, the (water) policy targets are increased, and more issues and hydro-economic parameters are addressed (i.e. full cost of water), leading to a more comprehensive and detailed HEM (Alamanos et al. 2020). The two modeling versions apply to different situations of: data availability (a limited-data and versus an extended-data version), scope (a simple versus an integrated version), and different required estimated hydro-economic parameters. Both versions were developed to address the above presented challenges, and to solve practical difficulties and facilitate their applicability. This work presents briefly the two versions of HEMs and compares them, quantitatively, mainly through their common outputs rather than their methodological structure which has been presented in our previous work, and qualitatively, in an attempt to provide useful insights in HEMs' development and use. Then, the results and the performances of the two HEM versions were compared under general and

specific modeling criteria allowing a justified evaluation. The results of the analysis will, hopefully, help future modelers: (a) considering broader points of view and goal-based approaches, as well as (b) deciding if a simpler or a more detailed approach is more suitable for their purposes and needs.

Other objectives of this study are: to show how flexible should be the settings of a model, depending on the needs of the required results and the data availability, to discuss the most appropriate–case-specific–approach, to better quantify - in a simple engineering way, hydrological and economic effects of irrigation policies and management decisions.

## 2 Study Area

Lake Karla watershed in Central Greece is a representative Mediterranean agricultural watershed (Fig. 2). Its area is about 1173 km<sup>2</sup> and almost half of its area is intensively cultivated. Irrigation consumes about 92% of the total water use in the watershed. Water resources are limited, and, continuously, deteriorate. The Mediterranean climate of the watershed is semi-arid with dry and hot summer and cold and humid winter. Drought phenomena are frequent and water scarcity is a normal condition, especially during the summer months.

In 1962 Lake Karla was drained for flood protection and more farmland, however the planned associated works were never built. Subsequently, environmental problems occurred, such as depletion of the aquifer, pollution of surface and groundwater resources, changes in the local climate, extreme events (e.g. droughts, floods, erosion), etc. These issues led to the decision of the restoration of the former Lake, in 1981, with the construction of a reservoir. The inflows to the Lake Karla reservoir are: surface runoff of the watershed and water transfer from Pinios River during the freshet winter period. The reservoir has been planned to supply irrigation water in the neighboring areas and cease the groundwater pumping from the overexploited aquifer. However, although the construction of the reservoir was completed in 2011, the reservoir does not operate because the accompanying irrigation works have been constructed only recently. As a result, the overexploited aquifer is still the main source of water supply, including a number of illegal wells, deteriorating the quantity and quality of groundwater further (Sidiropoulos et al. 2013). The responsible authorities for water management are the Local Administrations of Land Reclamation (LALRs) of Pinios and Karla. Pinios LALR uses open irrigation canals and ditches, which result in large water losses, while the Karla LALR has recently been ceased to operate. This fact indicates that the inefficient agricultural water use and management is accompanied with administrative problems, regarding infrastructure management and maintenance and financial management. As a result, land uses are not monitored, water use rates are unknown, water pricing follows an area-based system, LALRs are in great debts, intense cultivation is being continued, there is no cooperation between authorities and stakeholders, the state does not seem willing to intervene, while the harmful results of these situation to the ecosystem are expanding.

The above situation instigated our research. Firstly, A HEM combining the main water and economic parameters has been developed (Version1) for a simpler evaluation (Alamanos et al. 2019b). The data limitations lead to assumptions but provided us with a satisfactory illustration of the system. The full cost of water was expected to be incorporated into water charges from June of 2018, but there has been no change in the pricing policy yet. This measure has been seen as an “additional problem” by the local authorities, who find reasonable difficulties to address and implement it. The existing “flat-rate per area” tariff system is generally considered

as an inefficient mechanism because the applied water prices are not impacted by the actual water use (consumption). Thus, it is essential to estimate the full cost of water to use it as a better proxy for future pricing mechanisms. This new turn of things in the region lead to the need of upgrading the HEM, with the necessary modifications that would make it able to incorporate the concept of full cost of irrigation water (Version2) (Alamanos et al. 2020). The following sections present in detail and compare the two HEMs.

## 3 Methods

### 3.1 The 1st Version of HEM

During the first attempt to analyze the study case, we encountered the problem of data availability. The development of a HEM was something new in the study area (Figure1). Hydrological, land use, economic data, were necessary but the recordings were incomplete. Another important difficulty during that time was the lack of stakeholders' cooperation. Thus, a first version of HEM (2016) was developed providing estimations of water balance, irrigation water cost, profits from agriculture, and irrigation water values. These estimations rely on some assumptions about the key variables. An important goal of this first attempt was to underline the purposes and the advantages of a HEM approach and, thus, to raise awareness among the responsible authorities about the importance of applying continuous monitoring systems.

In order to estimate irrigation water demand, the CROPWAT model (FAO 2015) and the Blaney-Criddle method (Blaney and Criddle 1962) for the estimation of crop evapotranspiration were used. Irrigation water requirements were refined/adjusted in order to take into account the precipitation, the local network losses and the actual irrigation methods' efficiency, as found from recent field surveys in the area (Tzabiras et al. 2016). As water availability was already known, the calculation of the water balance was possible. A simple economic model was also developed to estimate the profits, based on gross revenue values, as well as on total production costs. The "Net Income Change" method was used to approximate the irrigation water value (Heady 1952). This method compares the net profits between the baseline (Business as usual – BAU) Scenario with a rainfed (non-irrigated) scenario, holding all the other factors constant. Rainfed crops were used to replace the existing water consuming crops in a way that maximizes the profit and met the cultivation constraints (Latinopoulos 2006). Thus, the only difference in the net profit between the two conditions (scenarios) can be solely attributed to the use of irrigation water (Gibbons 1986). The detailed structure and the results of Version1 HEM has been presented in an earlier paper (Alamanos et al. 2019b).

The following assumptions were made in the first version of the hydro-economic model:

- Land uses were classified using satellite remote sensing (Spiliotopoulos et al. 2015) from available images of 2007 (before the construction of the reservoir) and 2012 (after the construction of the reservoir). Four main crops were considered in this analysis (Fig.2): alfalfa, corn, winter wheat and cotton.
- Data from the design studies of Pinios pumping stations and Karla's reservoir withdrawals were used to estimate water availability. Recent studies were also used to determine the available groundwater renewable volume (Sidiropoulos et al. 2013).

- Agro-economic estimations were made by using statistical data from local/regional agencies (e.g. data concerning crops' yields, production costs, product prices, etc).
- A simple and easy-to-use method, which was already applied in another Greek watershed (Latinopoulos 2006), was selected to estimate the value of irrigation water. This method aims at indirectly estimating the value of irrigation water as the net income received by a farmer, per unit of water applied. The selection and use of this method is further justified by the lack of data concerning water contribution in the production process in the study area.

In this context, the following strategy has been employed to overcome the data availability limitations:

- Cross-checking of the presently available (statistical) databases (from the Hellenic Statistical Authority) for land uses and agro-economic results. In this context, several surveys and studies have been conducted in the broader area for the same purpose (i.e. studies related to the efficient use/allocation of irrigation water or to the cost of irrigation water).
- Dividing the watershed into zones (or sub-areas) to deal with the problem of "aggregated data", using only the four major crop cultivations in the study area, and to provide a spatial context for the estimation of water cost and water value. These zones were based on soil and geo-hydrological characteristics (e.g. hydraulic conductivity of groundwater for defining pumping zones) (Sidiropoulos et al. 2013). Furthermore, this zoning system makes also possible to detect various management practices applied in each zone.
- Comparing the existing databases of CROPWAT on soil and cropping data to the estimated/calculated values of irrigation water demand.
- Various scenarios (e.g. water pricing scenarios, optimizing factors as utilities or production costs, climate or product prices scenarios based on extreme observed data, etc.) have been modelled and their results were analysed and compared. This approach can be proved useful for ensuring some model's settings, and particularly for indicating sensitive variables, improving thus the decision-making processes.

### 3.2 The 2nd Version of HEM

A few months after the development of the 1st version of our HEM (2016), the Greek Payment Authority of Common Agricultural Policy (GPACAP 2016) finally responded to the authors' requests and provided us with more accurate and official crop data for the year 2015. Furthermore, a basis for cooperation with the Local Administrations of Land Reclamation (LALRs) has been established providing us with more detailed agro-economic data (subsidies, costs of fertilizers, herbicides, seeds, sprays, defoliant, as well as harvesting costs, pumping costs, oil, labor and planting cost, mechanical operation, and depreciation costs), which were included in the latest version of HEM (Version 2) (Fig. 1). The above data were verified from new data retrieved by some farmers of the watershed and researchers.

At that period, it was already late for the LALRs to incorporate the full cost of water to their bills, according to the Water Framework Directive-WFD (EC 2000/60). As a consequence, the regional Water Resources Management Plan had referred to the study area as of "unknown condition" (Ministry of Environment 2012), and until today, no change has been observed regarding the cost of water. On the basis of these new conditions the authors created a more detailed and analytical version of the existing HEM, building it towards the valuation of the full cost of irrigation water in the watershed.

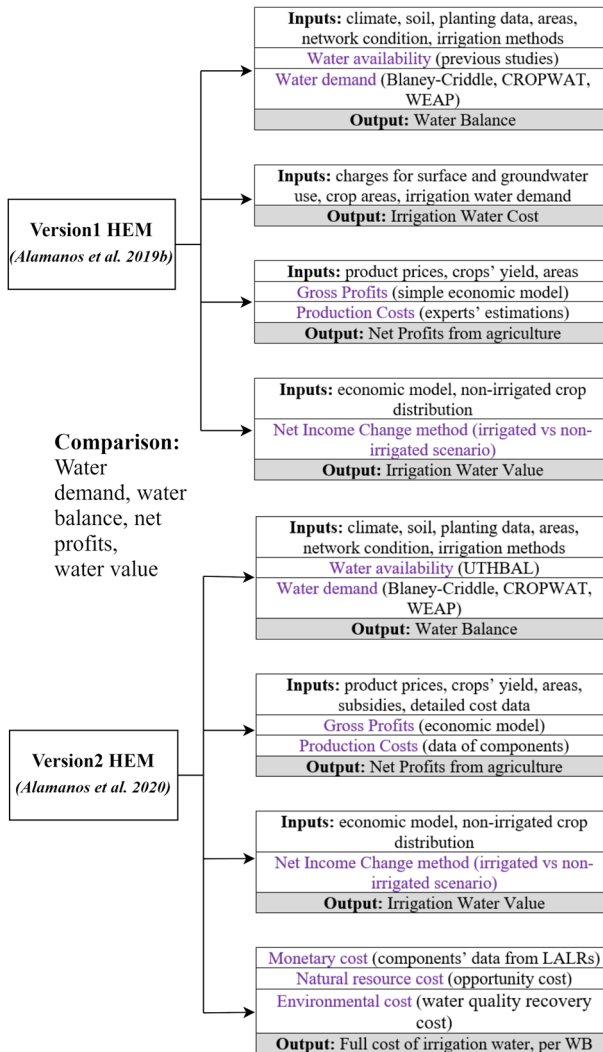


Fig. 1 Comparison of the structure, parameters, inputs and outputs of Version1 and Version2 HEM

This second version of HEM can provide the water agencies with results, which are mainly related to water balance, net profits from agricultural activity, and full cost of irrigation water. The assumptions used in Version1 were avoided in Version2. Briefly, in this new version, each farm has a crop code, so the cultivated crops were classified in 11 categories which were then used to calculate irrigation water requirements. That led to the following methodological differentiation from Version1: The water availability was estimated using the hydrological model UTHBAL (Loukas et al. 2007), and thus, a more precise water balance was found. UTHBAL calculates, among other variables, the surface runoff and the groundwater recharge, explicitly, the renewable surface water and groundwater resources. The economic model also became more detailed than in Version1 since the gross profits and production costs components are now more accurately calculated. It should be also noted that the full cost of irrigation water was found as the sum of the following costs:

- Monetary (direct) cost of the water supply company/ies (sum of capital costs, maintenance and operation costs and administrative cost).
- Natural resource cost. This component is related to the damage or the negative impact due to the water scarcity or the resource misallocation. During the first version, it was estimated as the opportunity cost (i.e. lost profits) of exploring the water resources faster than their natural rate of renewal (WATECO 2002). This opportunity cost was found as the profit difference of the existing and a new cultivating plan, expressing a better water-use allocation (Tietenberg and Lewis 2011; Alamanos et al. 2020).
- Environmental cost. It was considered equal to the watershed's recovery cost, i.e. equal to the cost of restoring water quality to its original condition (quality standards). Namely, the decontamination cost that is needed to bring the environment back to its original state (WATECO 2002; Greek Ministry of Environment 2012) was calculated using depollution cost-functions from the literature.

The detailed structure and the results of Version2 HEM has been presented in an earlier paper (Alamanos et al. 2020).

### 3.3 Application and Comparison of HEMs

Figure 1 illustrates the conceptual structure and parameters of the two versions of HEM, with emphasis on their inputs, intermediate steps, and outputs.

To make possible the comparison between the two HEM versions, the following strategy was employed in this study:

- The data of 2015, which were obtained for the second version, were inserted as input data in Version1, keeping all the other parameters unchanged. Thus, the comparison of the results of two versions of HEM were referred to the same year and conditions, and the differences should be only due to the assumptions of the first version, as mentioned above.
- Water values were calculated in Version2, by using the same method as in Version1, but with more detailed data.
- A series of common management scenarios were developed. The scenarios aimed to the reduction of irrigation water demand and/or to efficient irrigation water use in the watershed. Briefly, the following scenarios were analyzed:
  - Scenario1: Baseline – BAU (current situation). The Karla reservoir is not active yet, so the main supply sources are the groundwater aquifer and the Pinios River.
  - Scenario1a: Reducing water irrigation losses on Scenario 1, through continuous repair and maintenance of the surface irrigation and groundwater network of Pinios LALR.
  - Scenario1b: Replacing sprinklers with drip irrigation, when applicable.
  - Scenario2: Future Situation (operation of the reservoir and the new Lake Karla irrigation network). The main difference between this scenario and Scenario1 is that the new irrigation network is operated serving the areas around the Lake Karla reservoir. In the baseline scenario (Scenario1) these areas around the Lake Karla reservoir are irrigated by groundwater pumping.
  - Scenario2a: In the future scenario (reservoir operation), 25% of cotton crops will be replaced with winter wheat.



- Scenario2b: In the future scenario (reservoir operation) 20% of cotton crops will be replaced with winter wheat (10%) and maize (10%).
  - Scenario2c: In the future scenario (reservoir operation) water irrigation losses will be reduced, as described in Scenario 1a.
  - Scenario2b: In the future scenario (reservoir operation) sprinklers will be replaced with drip irrigation, as described in Scenario 1b.
- The two HEM versions were applied by using the same models, in order to consider the same modeling assumptions and compare and find the differences in the results of the HEMs due to the structure of the two HEMs. In this study, the Water Evaluation and Planning system (WEAP) ([weap21.org](http://weap21.org)) was used, based on the results of other models applied in the area (Loukas et al. 2014; Alamanos et al. 2019a). It is worth noting that WEAP is capable of simulating both hydrologic and economic aspects, by operating as a management tool, which can compare different management scenarios.

The features of Version1 and 2, and their differences are highlighted, and compared point by point, in Table 1 and Fig. 2.

## 4 Results

This section aims to articulate the key features and differences of the two HEMs by comparing them across their common (hydrological and economic) outputs under the same management scenarios (as summarized in Table2 and presented in Fig. 3), as well as by assessing a set of hydro-economic modelling (qualitative) evaluation criteria (Table 3).

The results of Table 2 are encouraging for the two HEMs and indicate significant improvements in both water demand and unmet demand, for the selected water management scenarios. The economic output (i.e. net profits) differences between the two HEM versions, under the same scenarios, are mainly due to the different input data and models' structure, usually resulting in higher prices in Version1. The opposite outcome is only observed in those scenarios which impose changes in cropping patterns (e.g Scen.2a, 2b). It should be also noted that scenarios suggesting technical measures (e.g. reducing irrigation losses, implementing drip irrigation, etc.), do not affect profits, but entail an implementation cost.

Water values are in general relatively low in the studied watershed, compared to other similar cases in Greece (Latinopoulos 2005, 2006; Greek Ministry of Environment 2012). When water requirements are decreasing, or net profits are increasing, the value of irrigation water tends to increase. The only parameter that seems to affect both (value) mechanisms is the crop distribution, being thus a key factor in irrigation water management. One thing that is evident from this table is that water values are significantly lower in Version2 than in Version 1. The reason for this is that Version2 uses more detailed data, which allows the per-farm calculation of water demands and profits. Consequently, more detailed data revealed significantly higher water demand, and lower profits, compared to the preliminary aggregated version.

On the other hand, the annual fertilizer requirements are higher in the “simplified” Version1, as compared to the “detailed” Version2. However, in general, the results of the two versions of HEMs with respect to fertilizers are comparable and follow the same patterns under the various management scenarios. It should be noted that both models indicate a



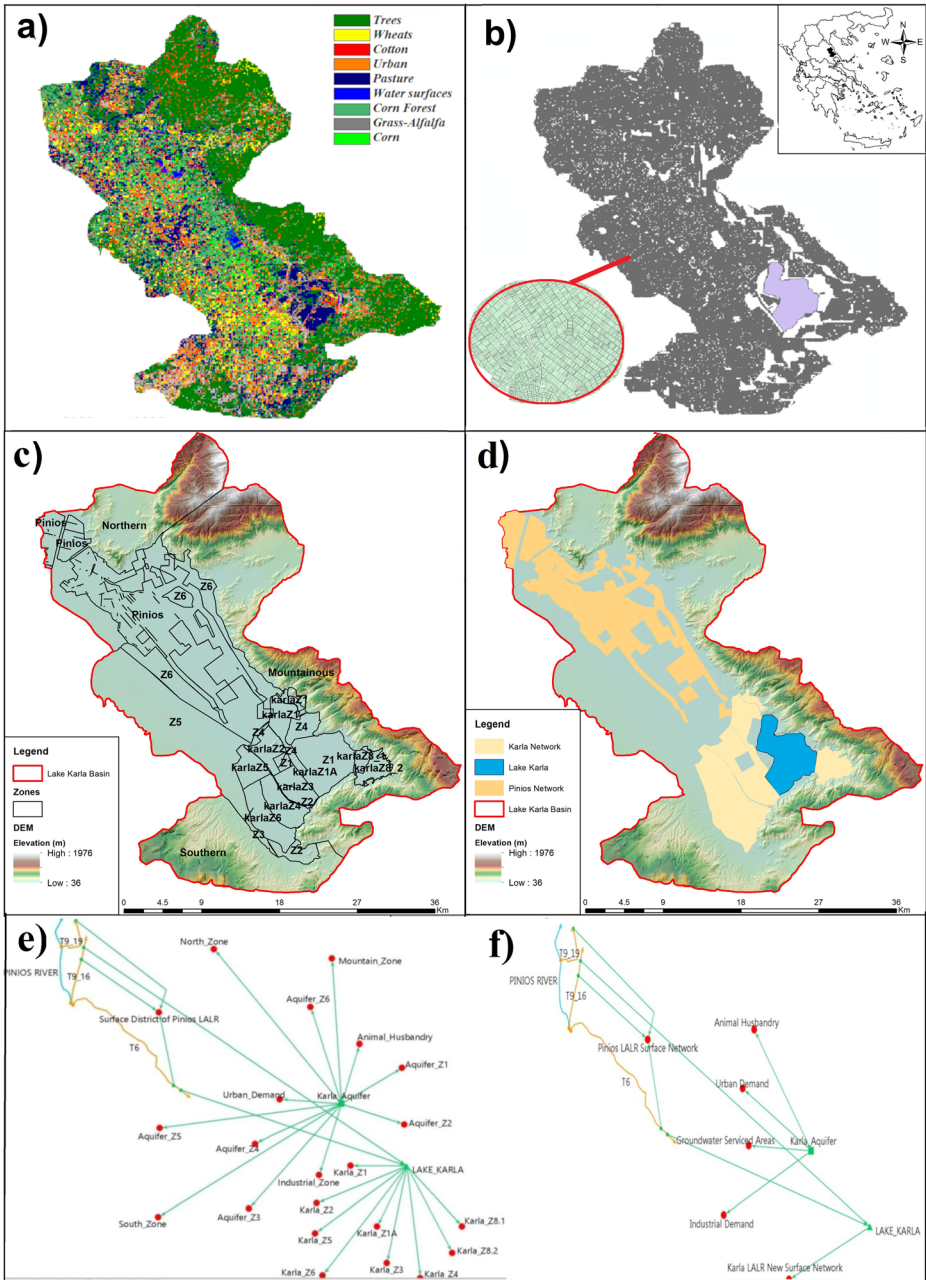
**Table 1** Characteristics of the two HEMs' versions

Version 1	Version 2
Model building and data use	
Incomplete data and recordings (hydrological and economic). Thus, the scope was a preliminary understanding of the system.	Complete and reliable official data per farm. The aim was to prepare the implementation of the economic objectives of the WFD.
Desirable outputs: water balance, irrigation water cost, net profits, irrigation water value.	Desirable outputs: water balance, net profits, full cost of irrigation water.
4 main crops were used, because of limited data.	11 crops were used, as classified from official data.
The watershed is divided into 10–19 irrigation zones. The 10 zones refer to Scenario 1 (BAU, without the new irrigation zones from the reservoir), and the 19 zones refer to the reservoir operation (Scenario 2, where they will be serviced from its surface water from).	The watershed is divided into 3 zones depending on the supply source (water bodies), as it is convenient and useful to evaluate the full cost of water regarding the quantitative and qualitative degradation of each water body of the watershed.
Tools: GIS, CROPWAT, WEAP, economic model (net profits & water value).	Tools: GIS, CROPWAT, WEAP, economic model (net profits, water value, full cost of irrigation water).
Specific (and comparable) outputs	
Water Demand: Blaney-Criddle, CROPWAT, WEAP, using only the 4 crop types. Spatial resolution: total per irrigation zone. Calibr./Valid.: cross-checked from statistical databases, Greek Ministry's Management Plans, (Tzabiras et al. 2016).	Water Demand: Blaney-Criddle, CROPWAT, WEAP using 11 crop types. Spatial resolution: per farm. Calibr./Valid.: cross-checked from statistical databases, Greek Ministry's Management Plans, (Tzabiras et al. 2016)
Water availability: retrieved from previous studies. Calibr./Valid.: Oct1960-Sep2002 (runoff, ground-water recharge).	Water availability: estimated from UTHBAL. Calibr./Valid.: Oct1960-Sep2002 (runoff, ground-water recharge).
Fertilizer requirements: average fertilizer application per crop type, using only the 4 crop types. Spatial resolution: total per irrigation zone. Calibr./Valid.: cross-checked from statistical databases.	Fertilizer requirements: average fertilizer application per crop type using 11 crop types. Spatial resolution: per farm. Calibr./Valid.: cross-checked from statistical databases.
Profits: Statistical average data (crops' yields, costs, product prices). Spatial resolution: total per irrigation zone. Calibr./Valid.: verified with local experts.	Profits: first-hand data for the watershed (detailed gross profit, subsidies, and cost components). Spatial resolution: per farm. Calibr./Valid.: verified with local experts.
Water Value: "Net Income Change" method applied with 4 crop types. Spatial resolution: total per irrigation zone. Calibr./Valid.: NA	Water Value: "Net Income Change" method applied with 11 crop types. Spatial resolution: per farm. Calibr./Valid.: NA

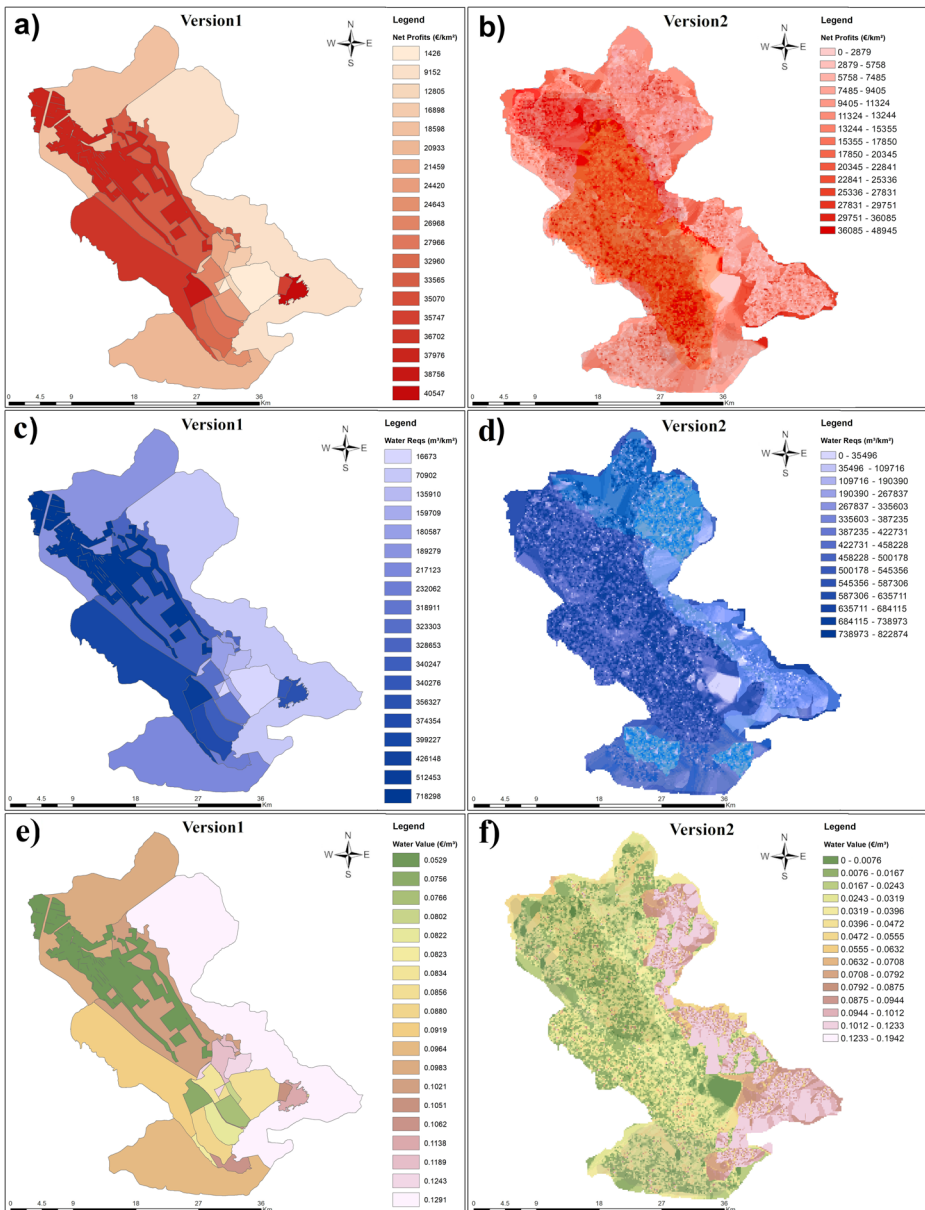
notable increase in fertilizer requirements for the case of all future (reservoir operation) Scenarios (i.e. Scenarios 2). This is mainly due to the slight increment of the cultivation area, because the new irrigation network which would withdraw surface water from the reservoir and will allow larger irrigated cultivation area.

The results for the two versions are presented in Fig. 3. In the left column (in Version1) the results are shown (estimated) per irrigation zone, while in the right column (in Version2) the results are more detailed as they are estimated at the farm-level.

Models are descriptions of the system's behavior, and even when there is literature on model-relations building, it rarely can provide the necessary guidance to support critical decisions (Myung and Pitt 2018), such as: parameterization, choice of functions, variables, required data, satisfactory description of system, and desired accuracy that satisfies the purposes of the model. In an attempt to compare also qualitatively the examined versions, a features-table was formulated, listing 17 relevant evaluation criteria. The scope of this approach is to help policymakers, in other areas with similar characteristics to formulate the most suitable to their needs HEM (by approximating their model to be as close as possible to



**Fig. 2** Version 1: Land use data as retrieved from Spiliotopoulos et al. (2015), having limited crop categories (a) led to irrigation zones to balance this ‘weakness’ with the increment of spatial detail (c). Version 2: farm level data (b) secured a more detailed analysis that allowed the formation of irrigation zones per water body for Version 2 (d). This was necessary for obtaining the full cost of water per water body, too, according to WFD. Each version was modeled then in WEAP. The software’s schematics are node-based per demand site (zone) for Version 1 (e), and for Version 2 (f)



**Fig. 3** Net profits (€/km<sup>2</sup>) for Version1(a) and Version2 (b). Water requirements (m<sup>3</sup>/km<sup>2</sup>) for Version1 (c) and Version2 (d). Water value(€/m<sup>3</sup>) for Version1(e) and Version2 (f)

one of the above presented HEMs). The criteria used in Table 3 are factors considered important for the design and the operation of HEMs' performance, namely: number of parameters, typology of variables, stakeholders' involvement, simplicity/complexity, accuracy, time for structuring it, data-collection time, input level (low, medium, high), computational power, reliability (validation potential), technical-expert support, plausibility of assumptions, management scenarios, simulation of future conditions, extension with hydrological/socio-

**Table 2** Common hydrological and economic results of the two HEMs' versions

	Water demand (hm <sup>3</sup> /y) Version1/ Version2	Unmet demand (hm <sup>3</sup> /y) Version1/ Version2	Net Profits (mil. €/y) Version1/ Version 2	Water value (€/m <sup>3</sup> ) Version1/ Version2	Fertilizers requirements (tons/y) Version1/ Version2
Scen.1	355.5 / 374.1	141.9 / 160.4	49.678 / 47.313	0.093 / 0.069	15.36 / 15.12
Scen.1a	264.2 / 284.9	112.5 / 71.2	49.678 / 47.313	0.111 / 0.093	15.36 / 15.12
Scen.1b	299.7 / 356.2	129.4 / 142.5	49.678 / 47.313	0.099 / 0.084	15.36 / 15.12
Scen.2	350.9 / 373.2	110.3 / 99.5	55.068 / 49.395	0.092 / 0.069	16.97 / 15.25
Scen.2a	319.7 / 351.8	86.2 / 78.2	45.237 / 47.328	0.080 / 0.064	16.48 / 14.56
Scen.2b	316.4 / 363.9	88.8 / 90.3	46.880 / 48.681	0.085 / 0.066	15.38 / 14.37
Scen.2c	259.5 / 284.2	46.4 / 10.5	55.068 / 49.395	0.0112 / 0.096	16.97 / 15.25
Scen.2d	292.9 / 355.3	80.7 / 81.7	55.068 / 49.395	0.098 / 0.086	16.97 / 15.25

economic variables. A simple qualitative evaluation based on a system of plus (+) and minus (-) was used, due to the fact that some criteria cannot be quantitatively evaluated. As both versions meet the selected objectives, a comparative analysis was made to identify which version performed more satisfactorily (+ vs -) than the other, for each one of the 17 criteria. Subsequently, a (+) indicates a version-approach that we would recommend for modeling the specific criterion (if both versions have a positive sign it means that this criterion is equally

**Table 3** Comparing HEMs versions' main results for the entire watershed

No.	General Criteria	Version1	Version2
1	Small number of parameters	+	-
2	Quantitative variables	+	+
3	Qualitative variables	-	-
4	Stakeholders' involvement	-	+
5	Simplicity	+	-
6	Accuracy	+	+
7	Reliability (validation potential)	-	+
8	Development time	+	-
9	Data-collection time	+	-
10	Low input level	+	-
11	Reasonable computational power	+	+
12	No need of technical-expert support	-	-
13	Plausibility of assumptions	+	+
14	Management scenarios	+	+
15	Simulation of future conditions	-	+
16	Extension with hydrological variables	-	+
17	Extension with socio-economic variables	-	+
	Specific factors		
1	Water Demand	+	+
2	Water availability	-	+
3	Water Balance	-	+
4	Profits	-	+
5	Water Value	-	+
6	Water quality (if measured per water body)	+	+
7	Usefulness at present situation	+	-
8	Usefulness in the future	-	+
9	Comprehensiveness to decision-makers	+	-

\*Detailed approaches (Version2) should be preferred for "specific outputs"-oriented results. Simplified approaches (Version1) seem more suitable for general understanding of a system, which can be used for the cases of preliminary studies

satisfied). On the other hand, a (–) indicates an inferior version with respect to this particular criterion (if both versions have a negative sign it means that this criterion is not satisfied in either version).

After having the detailed dataset needed for Version2, and knowing the system's behavior better, it will be not an assumption to consider Version2 as the most accurate-realistic representation. According to the "specific factors" of Table 3, Version2's superiority is obvious. However, this difference is not simulated or shown as "score", to be presented as an "error" or "deviation", because the main purpose/goal of Version1 HEM was totally achieved. Namely, Version1 contributed significantly to a set of specific goals such as: the understanding of the system, the magnitude of each parameter, and the identification/initial assessment of the potential improvements through the selected management scenarios. Its uncertainties, assumptions and limitations were unavoidably accepted from the very beginning, under the certain conditions, which have been already explained. Besides, by comparing the general criteria in Table 3, it seems that the two versions are quite competitive. Both Version1 and Version2 gather a score of 10/17 of positive scores (+). If all criteria are considered of equal weight, this could be an interesting outcome.

On the other hand, the second version can be considered as a "better" HEM approach because the quantitative results (i.e. more or less all the specific factors) are presented in detail. However, the final choice between the two versions should be based on the specific conditions/characteristics of the problem under consideration. In the discussion section we further comment on the role and rationale of the comparison of these two versions.

## 5 Discussion

A parameter that could not be depicted in the results comparison and the qualitative comparison of Table 3, is the scope of each model. The scope of the two versions (Version1 and Version2) are different. This is illustrated in the settings of the two models. These models were developed in a 2-year research period in the area. Starting with many limitations, Version1 aimed to provide a preliminary understanding of the system. After achieving its scope and the collection of more detailed data, Version2 aimed to prepare the ground for the implementation of the economic objectives of the WFD, providing thus the basis for more accurate HEM. As both versions have been presented thoroughly in our previous work (Alamanos et al. 2019a, b, 2020), this study tries to adjust them in an attempt to incorporate the past experience into a qualitative comparison and discussion, aiming to help future modelers on their perspectives and approaches.

In general, the two versions of HEM have achieved their goal satisfactory and are suggested for similar case-studies. From a decision-maker's perspective, before knowing the data availability and the potential difficulties of developing a HEM in a watershed scale, a trade-off between information and accuracy, or information and usefulness are common problems is such designs/decisions. Many techniques have been developed to study these relations (trade-offs); however, this is out of our scope. The reason is that this study compares different performances based on different goals, rather than different modeling techniques as means to the same end. After all, the ratio of information to usefulness is equal for both versions, as each modeling approach (HEM version) used only the necessary data to achieve its purpose.

It should be also noted that Version1 HEM does not "cancel" or revoke Version2 HEM or vice versa. On the contrary, the weaknesses of one version are usually remedied by the

strengths of the other. The two different divisions of the watershed (spatial scale of analysis) can also work complementary to each other, if a larger region is analysed in order to examine and depict the results in different spatial resolution/representations (i.e. a higher resolution for a particular area and a lower resolution for the whole study area). In other words, the hydro-economic models should be treated as flexible tools that can be controlled and adapted by the modelers (e.g. by using different settings), in order to make possible to assess different scenarios, to evaluate different goals, to accommodate different availability (e.g. imprecise and/or vague data), and make the best out of any given condition.

## 6 Conclusions

The potential of HEMs is often highlighted in the literature, but the guidance on decisions regarding the structure and the settings of the models is rare, so far. The present paper tried to show a model-building rationale, considering some dilemmas modelers often face, based on the authors' personal experience in real case applications. This research also brings up the topic of how different situations lead to different model settings and how these can be compared.

Initially, the goal was to combine hydrological, economic, and engineering goals in a data-scarce rural watershed. Ways on how to use the data, how to exploit 'strong points' and cover weaknesses-limitations through choosing different, modified or simpler outputs, were presented in Version1. Version2 was built to provide more detailed outputs, based on more precise models. A good trade-off between complexity, time, effort, and accuracy was sought, in the basis of providing the most desired/useful outcomes for (local) policy makers.

The comparison of a simple and a detailed HEM based on the assumptions, limitations, results, scope, accuracy and managerial implications, shows that overall, both approaches can meet the objectives set up, if they are developed carefully. The comparison also provides guidance to future modelers on which approach they can follow (simpler or detailed) in case that they want to focus on certain general and/or specific criteria discussed in Table 3. Some of them can be the driving factors affecting the modeling decisions of a future HEM development, so the analyst could find justified help in their evaluation to lean towards a simpler or a detailed modeling structure.

Future research ideas include the comparison of the same HEM version(s) under different assumptions (with sensitivity analyses), the estimation of costs and benefits of data collection that may increase the accuracy, to assess the impact of the different assumptions in our hydro-economic models, and how our models can be expanded and applied in different areas.

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**Data Availability** Data available after request from the authors.

## Compliance with Ethical Standards

**Conflict of Interest** None.



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