Water Policy 23 (2021) 617–632

Applying a novel framework for the estimation of the full cost of water in a degraded rural watershed

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Abstract

Water Resources Management's modern concerns include solutions on water scarcity, water quality problems and the use of economic and decision-support tools. Especially, the agricultural sector in South Europe under the requirements of the Water Framework Directive 2000/60/EC(WFD) remains a challenge. Most scholars so far doubt and criticize the implementation of the full cost of irrigation water, review papers highlight the limited progress, and fewer cases provide guidance on how to address this case. The present study applies a novel methodological framework for the estimation of the full cost of irrigation water, based on hydro-economic concepts such as: water balance, profits from agriculture, water value, water quality, monetary, opportunity and environmental costs. Originally, the method has been applied only once in a rural watershed with surface and groundwater resources. Here, a degraded Greek watershed using only groundwater resources is the study area, and the results of the two cases are compared. The model was also examined under demand management strategies and recommendations to scrutinize the effects and the applicability of the proposed measures in hydrological and economic terms. The findings give useful insights on the future management of achieving economic objectives with environmental constraints and the harmonization of Greek agriculture to the WFD.

Keywords: Almyros watershed; Full cost of irrigation water; Greece; Hydro-economic modelling; Water quality; Water value

Highlights

- A previously presented methodology for the estimation of the full cost of irrigation water is now applied in another case, proving its consistency and establishing previous findings.

doi: 10.2166/wp.2021.240

- Extension of the method and new suggestions.
- Comparison of case studies shows the method is suitable for Greek basins and water pricing analysis is required before tariff policy.
- Novel hydro-economic approach.
- Handy tool for local agencies.

Introduction

In South Mediterranean countries, irrigated agriculture is a major part of economic growth and the productive expectations are increasing. In order to meet these increasing expectations, intensification of agriculture is often adopted, and thus a number of consequences that it entails are increasingly observed: over-exploitation of water resources, quality degradation, changes in soil and land uses, greenhouse gas emissions, poor managerial control, absence of economic tools, water underpricing, incomplete works, lack of funding, infrastructure, water conservation incentives and unsustainable planning (Alamanos *et al.*, 2019). Greece is no exception as most watersheds combine both environmental and economic issues (Greek Ministry of Environment, 2012).

Integrated modelling is the most promising path to address the above issues, and the research interest focuses on combining hydrology, economics (hydro-economic modelling), water quality, and engineering for the achievement of multiple and often competitive objectives. However, integrated modelling is a complex process, as many of the above factors are subject to different units and scales, data limitations, and inherent weaknesses that end to increased uncertainties. WFD was the first legislative framework that requires the incorporation of economic tools into water management, through water costing (as a sum of monetary, resource and environmental costs) and pricing. This made the development and the application of hydro-economic tools even more questionable, causing objections and criticism (Ker Rault & Jeffrey, 2008; Berbel & Expósito, 2018). Several member-states have not discussed costing techniques or have not addressed them satisfactorily in the agricultural sector. Others claim that resource cost and environmental cost are already incorporated into the water pricing, thus there is no need to develop specific techniques and methods for assessing them separately (European Commission, 2015). Different approaches have been observed, with interesting examples and rich literature (e.g. Italy, Germany, UK, Netherlands, and Portugal) (Kochskamper *et al.*, 2016). In several cases the definition of the full water cost is based on the least-cost approach regarding recovery and maintenance measures of the water bodies' (WBs) good status, while progress still needs to be done and measures' programs are still being developed. In Greece, the costs of the 'related measures for improving the quantitative and qualitative status of WBs', were estimated by a group of experts, but until today (2020), there is no change in the costing or pricing system of irrigation water (Lazaridou *et al.*, 2020). To our knowledge, with the exception of some local-scale studies (Bithas *et al.*, 2014; Alamanos *et al.*, 2020), Greece has been slow to examine hydro-economic modelling applications for knowing the situation of its WBs and to provide solutions. Hence, the formation of integrated tools to support monitoring, rationale management and decision-making is mandatory.

This study is an attempt to address the above issues with a single simulation system, applying the framework developed by Alamanos *et al.* (2020), which uses hydro-economic and water quality factors to estimate the full cost of irrigation water. Water demand, water balance, profits, water value, direct costs, opportunity and environmental costs are estimated in an agricultural Greek watershed with degraded groundwater resources. The introduction of these techniques to local agricultural managers is also necessary (Alamanos *et al.*, 2018), as a starting point for monitoring and data collection. Under this purpose and conditions, the tools presented are simple and some parameters were estimated in order to make the situation more comprehensive. A set of measures in the form of management scenarios are proposed to present the effects of demand management to the system. The suggested methodology has already been applied successfully to another rural watershed with similar characteristics but with both surface and groundwater use (Alamanos *et al.*, 2020). The two cases are compared to discuss the methodology's efficiency, effectiveness and limitations. The results indicate the importance of modernizing established practices followed by local managers with techniques based on the principles of integrated and sustainable water demand management, establishing the methodological framework, and raising considerations about the strict implementation of the WFD.

Study area

Almyros watershed, covering an area of about 85,000 ha in Central Greece, was chosen as the study area (Figure 1) as it faces complex environmental and management challenges. The climate is Mediterranean, with an average annual temperature of 14.84 °C and rainfall of 547.55 mm (Georgiadou, 2015). The study area is coastal and uses groundwater resources exclusively to serve its needs. The aquifer extends to an area of 31,000 ha and is located in the central part of the watershed (Sidiropoulos *et al.*, 2016).

Agriculture is the dominant land use (and thus the main economic activity) in the watershed followed by domestic water use from a few small settlements, while livestock and industrial uses are minor (Georgiadou, 2015). The main crops used by the farmers are winter wheat, cotton, alfa-alfa, corn, olives, trees, and vegetables. The aquifer is overexploited as a consequence of intensified agriculture, absence of surface water reservoirs, underpricing and poor management (Sidiropoulos *et al.*, 2016). The pollution of the aquifer is the most severe problem as, being a coastal area, Almyros watershed faces the problem of salinization as seawater enters the aquifer because of the drawdown of the aquifer's level (Georgiadou, 2015). High concentrations of inorganic pollutants, and especially chlorides, have been observed in groundwater (IGME, 2010). This renders the groundwater unsuitable for irrigating crops and domestic use. In Greece, Local Agencies of Land Reclamation (LALRs) are responsible for the local irrigation management, however Almyros LALR stopped operating several years ago. Some responsibilities were transferred to the Water Supply Agency (which is responsible for domestic water), while most of LALR's responsibilities do not exist anymore. A typical example was a short pause of issuing licenses for drilling wells, resulting an increased number of illegal private (unregistered) wells opened at that time, and the absence of any initiative to manage the irrigation sector. The consequences are both environmental and economic, namely the aquifer's drawdown levels, the absence of irrigation water pricing, any information, cooperation, and incentive for water quality improvement and conservation (Myriounis, 2008; Sidiropoulos *et al.*, 2016).

The above characteristics have attracted scholars to conduct research in the area. A quantitative evaluation of surface and groundwater resources of Almyros watershed was held by Sidiropoulos *et al.* (2016), aimed at aquifer management. In another study by Myriounis (2008), the hydrogeological

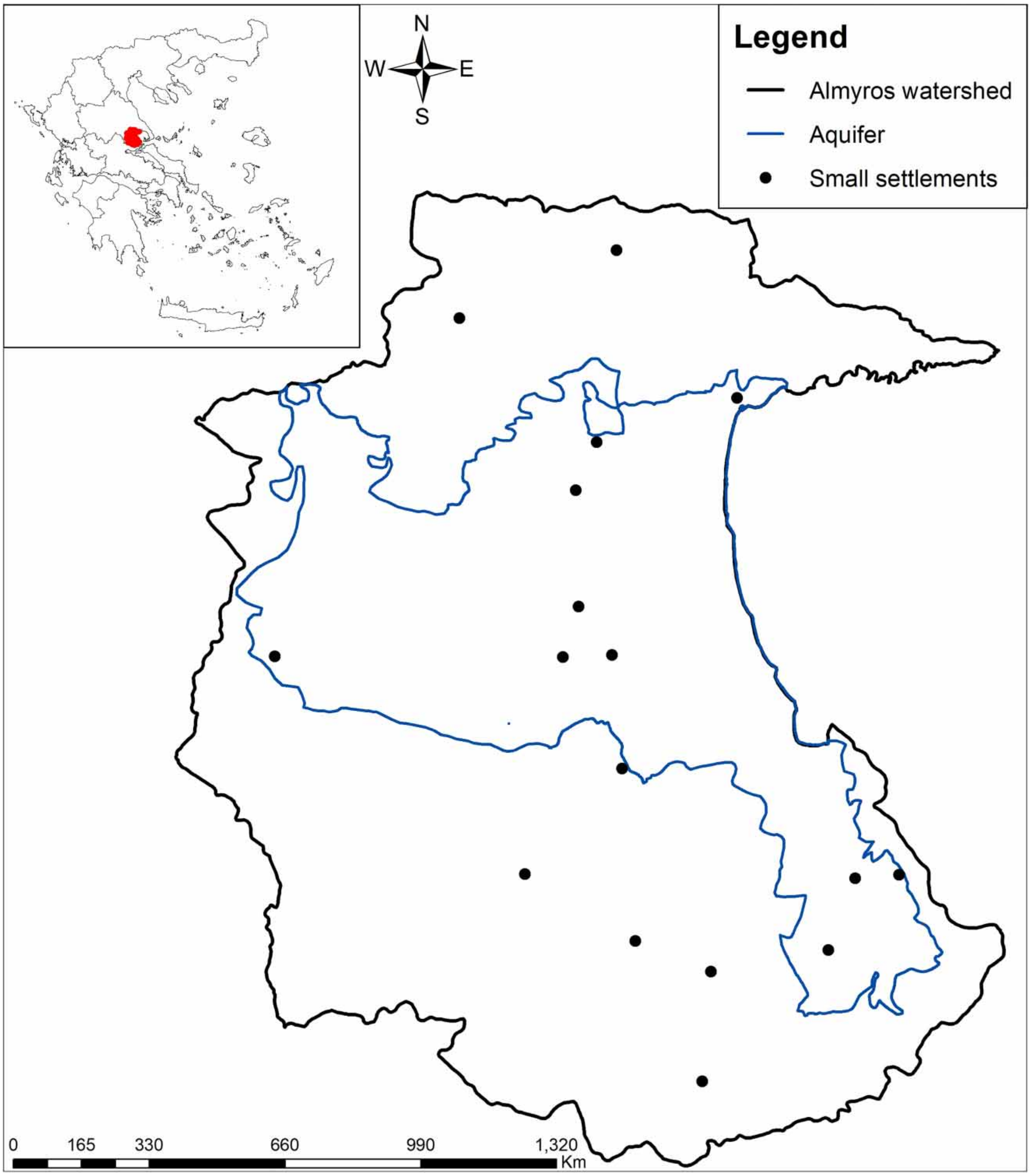

Fig. 1. The study area.

and hydro-chemical conditions were assessed, finding that seawater intrusion is related to the natural geological structure of the area and to human activities. However, this is the first time that hydro-economic and full cost of irrigation water concepts have been applied to the region.

Methods

The basic steps of the methodology are analyzed below. Its structure can be summarized in the following steps-estimations: water availability, water demand and thus water balance (hydrological model); net profits from the agricultural activities and water value (economic-logistic model); water quality assessment; full cost of water as sum of direct, resource and environmental costs (economic-optimization model); run the system under management scenarios. For each step more than one method can be applied depending on the examined watershed, and more than one tool can be used for the solution.

Water balance

Agriculture is the largest water consumer in the watershed, while urban water demand is only a small part of the total consumption. The CROPWAT model (FAO, 2015) and the Blanney–Criddle method were used for the estimation of crop water demand, using meteorological (2006–2015), soil and cropping data. Irrigation water requirements were adjusted in order to take into account the local network losses and the actual irrigation methods' efficiency, using efficiency coefficients, as found from field surveys in the area. The cultivated area's crops were classified into the following categories: corn, cotton, vineyards, winter wheat, alfalfa, trees, others and sugar-beets. For the sake of precision and completeness, urban water demand was estimated using census data, typical water consumption per capita and the reported network losses. For each water use's demand estimation, different methods can be used depending on the examined case's specific features.

Due to data limitations and the different scope of the present study, water availability data were used instead of simulating the watersheds hydrology. Recent studies' findings were used to determine the groundwater renewable volume (Myriounis, 2008; Georgiadou, 2015; Sidiropoulos *et al.*, 2016). Given the water demand and the water supply-availability, the water balance in the watershed was estimated in monthly (and annual) time steps.

Net profits from agricultural activity

For the estimation of net profits, a simple economic model was developed according to Equation (1):

$$NP = GP - TPC \tag{1}$$

where NP are the net profits, GP the gross profits, and TPC the total production costs. GP is the sum of gross revenue and subsidies. TPC is the sum of all expenditures needed to produce one unit of the crop-product (lubrication, herbicides, seed, sprays, defoliation, harvesting costs, irrigation costs, labor, oil, planting costs, maintenance, agricultural contribution and fixed costs, e.g. machinery depreciation).

Water quality

The Institute of Geology and Mineral Exploration (IGME, 2010) is responsible for monitoring the groundwater quality using a number of observation wells. Using these data, this study examined which pollutants' concentrations exceeded the allowable safety limits. The limits were considered as the established standards by World Health Organization and European Union. The possibilities of water quality improvement were also examined through the quantitative replenishment, as achieved from management scenarios discussed below. Furthermore, using the average crop fertilization requirements, the pressure due to fertilizers use was estimated for each year, and also the prospects for its mitigation through management scenarios.

Water value

The irrigation water value was approximated as an understandable measure for the local policymakers to realize the monetary units per m^3 used, and also as a comparison measure to the full cost of water, estimated below. The 'Net Income Change' method was used (Heady, 1952). This method compares the net profits between the baseline scenario and 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 meets 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). This parameter is an addition compared to the method's first application, as pricing according to the full value is an important measure of demand management (European Commission, 2000). This relation of water value with water demand (demand curve) was graphically represented in this study in order to provide a preliminary tool for proxies on future water pricing policies according to its different water values.

Full cost

The deterioration of water value maintains the mindset to treat water as an inexhaustible resource, leading to overexploitation and environmental problems. WFD established the full cost of water to face this challenge, considering monetary, natural resource and environmental costs.

Monetary-direct cost (DC). DC expresses the water supply's companies expenses to provide the necessary water infrastructure and services. In Almyros watershed, since the LALR is absent, and the water supply company does not consider any capital, operation, maintenance, or administration expenditures neither charges the irrigation water, these components are not applicable. Only investment costs could be considered if the water supply company plans any technical measures for improving the system's operation.

Resource cost (RC). RC is usually defined as lost profits due to the exploitation of water resources faster than their natural rate of renewal (WATECO, 2002). In areas with sufficient water resources water may not be allocated to its optimum use, but to other less profitable uses (Kaliabakos & Damigos, 2008). Then, RC expresses the difference between the current and the optimum water allocation (DG ECO2, 2004). Here, RC is estimated using a joint application of the two definitions: lost profits and difference between the current and the optimum water use, according to Alamanos *et al.* (2020). The foregone benefits (RCmethod1), are estimated by allocating the deficit water (as resulted from the water balance) to the existing crop distribution. Water requirements of each crop (m^3/acre) are also known, so the deficit (m^3) is allocated proportionally to the existing crop distribution, thus finding the area that could theoretically be serviced from this water amount ($Area_{def}$). The regional profits from irrigating these areas are then calculated (NP). These profits correspond to the water scarcity cost, i.e. the foregone future benefits due to the negative water balance (Equation (2)):

$$RC_{method1} = NP(Area_{def}) \tag{2}$$

The RC as opportunity cost (RCmethod2) was considered equal to the benefit differential between the existing water use and the optimum water use (as described in Table 1).

In the study of Alamanos *et al.* (2020) it was proved that the two techniques, RCmethod1 and RCmethod2, result in similar costs, and here this case is also examined as it may strengthen the finding that different definitions can converge. If the two definitions-approaches are in agreement then this can be a novel finding as it will facilitate the estimation of RC by choosing a method depending on the case and the available data.

Environmental cost (EC). EC is associated with the water quality deterioration. EC is considered equal to the cost needed to restore the water quality to its original state/condition (European Commission, 2000; Tietenberg & Lewis, 2011; Bithas *et al.*, 2014) from the major pressure of sea water intrusion and agricultural pollution. Sampling data from IGME were used to classify the water quality parameters in physicochemical parameters, conductivity measures, main inorganic compounds and pesticides. A novel element is the consideration of water replenishment to water quality, by examining the dilution of water pollutants with the corresponding volume of deficit water (according to the water balance) (Alamanos *et al.*, 2020). This consideration is necessary for avoiding double charging a part of the RC, since the cost of this deficit has already been calculated. If after the dilution, there is no pollution

Table 1. Steps and rationale of the optimization problem for $RC_{method2}$.

Current total benefit (in terms of agricultural profits), in the given area 'A', is estimated (under the status quo of a negative water balance) (NP)	
Objective function	**Description**
P (max) $= \sum_i (np_i \cdot x_i)$ where np_i represents the net profit per area of each crop.	Through linear programming, a new crop distribution (area B) is extracted in order to maximize farmers' net profit (objective function)
Constraints (area's resources and environmental capacity)	Description
Xi where $i = 1$–18	The areas of the crops were used as decision variables Xi for the main crops (i)
$\sum_i (wr_i \cdot x_i) \leq$ TWA	Water requirements for each crop (wr_i) do not exceed the total water availability (TWA), i.e. the renewables resources
$\sum_i (x_i) \leq$ Total area	Constraint for not surpassing the available cultivation area (total area)
$\sum_i (fert_i \cdot x_i) \leq$ TF	Constraint for not surpassing the already implemented fertilization (TF) from each crop's requirement in fertilizers ($fert_i$)
$\sum_i (lh_i \cdot x_i) \leq$ TLH	Constraint for not surpassing the already labor hours (TLH) from each crop's working requirement (lh_i)
$X_i \geq$ typical x_i	Constraint where the area of each crop will stay within its area range, as observed the last 10 years in the watershed, staying thus in line with its productive expectations
Constrained resources, make area B smaller than the 'baseline' area A. Throughout the same linear programming model the remaining area ($B' = A - B$) is being filled with non-irrigated (rain-feed) crops.	
The net profit (NP) difference between the optimized (opt $= B + B'$) and the existing area A (exist) is considered as the $RC_{method2}$: $RC_{method2}$ = NPopt – NPexist	

($WQ_{diluted}$ < quality standards), then it is assumed that the EC has already been estimated into the RC. If there is pollution ($WQ_{diluted}$ > quality standards), then the remediation cost ($C_{depollution}$) is calculated based on the cost that is required in order to reduce the pollutants' concentrations to levels below the environmental standard limits (Equation (3)). This calculation was done by testing several relevant cost-functions estimating depollution capital and operation costs, converted to Greek currency units (Alamanos *et al.*, 2020). The final EC's estimate occurred from the cost-functions results distance from the expected (as determined so far by the national legislation) level of environmental charges, using a minimum distance criterion (Alamanos *et al.*, 2020). Thus the acceptability of the EC estimates has been ensured without endangering the current and/or future water supply quality:

$$WQ_1 \overset{deficit}{\Longrightarrow} WQ_{diluted} \begin{cases} if\ WQ_{diluted} < quality\ standards,\ EC = 0 \\ if\ WQ_{diluted} > quality\ standards,\ EC = C_{depollution} \end{cases} \tag{3}$$

Management scenario analysis

All the above parameters were examined under four demand management scenarios, aimed at sustainable water use, more efficient operation of the existing infrastructure and of the economy (Kampragou *et al.*, 2010). These scenarios were developed after discussions with the local authorities, and the inclusion of their feedback makes the approach more complete. Scenarios refer to technical measures and crop replacement, and their results are compared:

- Scenario 1: Baseline scenario refers to the existing situation of the watershed (do-nothing-scenario).
- Scenario 2: Assumes a reduction of losses due to poor-maintained irrigation network (e.g. misconnections, aged pipelines, vegetation). It was simulated using a higher coefficient for the network's and pumping wells' efficiency. The formation of this scenario is based on the stated plans of the water utility of the region.
- Scenario 3: Improving irrigation efficiency is the goal of this scenario, so the dominant and extensive use of sprinklers is replaced with drip irrigation. This scenario is in line with a relevant State's subsidy for farmers who change their irrigation method into drip irrigation.
- Scenario 4: The Greek Ministry of Agriculture through its Management Plans and the Common Agricultural Policy (Greek Ministry of Environment, 2012, 2015) is pushing farmers towards less water-consuming crops. Considering the Ministry's recommendations and the trends in the products prices for the past 10 years, this crop replacement scenario was developed where 20% of the cotton crop is replaced with 10% wheat and 10% corn.

The scenarios' implementation costs are also included, as occurred from ad-hoc calculations, based on experts' estimations on the expected labor and installation costs assumed in the scenarios. This is a new addition compared to the method's first application as implementation costs significantly affect the decision-making, especially in areas with limited funds.

Results

Applying the methodology discussed above step-by-step, the monthly and annual water balances, farmers' net profits, water value, quality and full costs were calculated. The average urban water demand was found to be almost 3.58% of the total use, which was around 50 hm^3/year. Table 2 summarizes the results (hydrological, economic, water value, fertilizers, water quality and implementation costs for each scenario – in 2018 values).

The results are very encouraging for the potential improvements in every parameter of the system. Water deficit is decreasing with every demand management scenario, especially the ones including technical measures. Farmers' profits are changing only in Scenario 4 due to the cropping pattern change. Scenarios 2 and 3 do not affect profits but entail implementation costs. These costs are the only component (investment costs) that can be included to the DC, given the fact that they require certain expenditures that in Greece are not borne by users. The demand curve (Figure 2) shows the irrigation water value if considered as price for each Municipal District of the watershed with their average irrigation water consumption. The inelastic character of the curve in the largest range of values indicates that a pricing policy would not mainly affect the farmers' decisions on cropping patterns in terms of reducing

Table 2. Results overview.

	Scen. 1	Scen. 2	Scen. 3	Scen. 4
Water balance (hm^3/y)	–20.58	–11.23	–11.92	–18.83
Net profits (mil. €/y)	9.328	9.328	9.328	9.221
Implementation costs (mil. €)	–	0.012	0.029	0
Water value (€/m³)	0.0621	0.0728	0.0656	0.0549
Fertilizers requirements (tons/y)	1,376	1,376	1,376	1,377
No. of pollutants above allowable limits/no. of total detected pollutants	11/15	7/15	8/15	9/15
Average percentage (%) of pollutants concentrations' reduction	–	26.13	34.84	37.32
Full cost of irrigation water (€/m³)	0.0539	0.0378	0.0480	0.0513

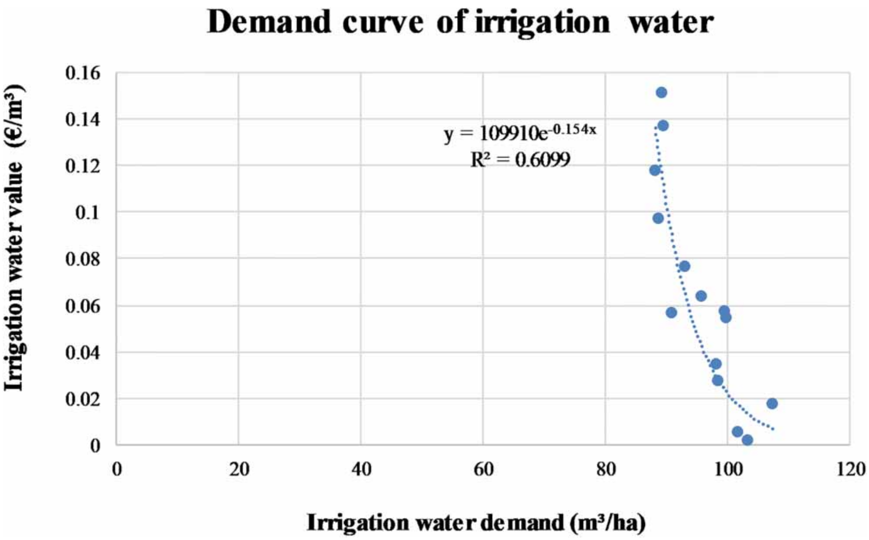

Fig. 2. The demand curve of irrigation water in Almyros watershed for the BAU Scenario 1.

water consumption. This is indicative of the scarce water resources and their importance for the local population's engagement with agricultural activities. The average value of 0.0621€/m³ is in similar (low) levels as in other rural Greek areas (Ministry of Environment, 2012). When water requirements are decreasing, or net profits are increasing, the value of irrigation water tends to increase. The lower water requirements of Scenarios 2 and 3 result in slightly higher water value, while the lower net profits of Scenario 4 due to the new crops justifies the lower water value, always compared to the BAU Scenario 1.

The annual fertilizer requirements of the watershed occurred from area-based estimations, assuming only the respective changes into the crop's areas. The qualitative status of the aquifer has been assessed using the samples of IGME, checking the number of the parameters that are above the allowable limits. The reduction in the water deficit achieved by the management scenarios translates into a larger volume of water stock, which will naturally dilute the detected pollutants. The remaining pollutants' unsafe concentrations and the decrease of the chemical parameters' concentrations (e.g. pesticides) are also encouraging regarding the implementation of demand management scenarios.

The results for the annual RC are presented in Figure 3 for both estimation methods/techniques (as described in the Methods section above). The first technique is considered more appropriate for a short-term cost estimation, as it better approximates the current situation. The second one results in lower costs than the first one, and it is considered more appropriate for a long-term cost estimation. The results of these two techniques may converge if, during the optimization process of the second technique, 'tight' cropping patterns' constraints (as compared with current ones) are placed. Besides, in most Greek rural areas these constraints are already 'strict'.

The most noticeable feature in the combined graph is that the two models converge (Figure 3), confirming the previous application of the method (Alamanos *et al.*, 2020) and the argument that these two RC definitions can be successfully combined. This can be an important insight regarding the safer choice of one of the two methods depending on the goal (short vs long-term cost estimation), and the data availability (the first method is less data-hungry).

The EC occurred from the solution of different water treatment cost-functions (as in Alamanos *et al.*, 2020), so no pollutant's concentration is above the acceptable limits (Figure 4). The final annual EC's estimation from this range of values was done by selecting the values that converge to the suggested

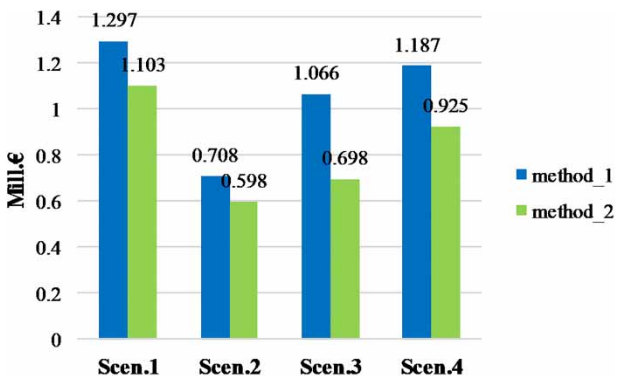

Fig. 3. Recourse costs (in million €/year), as resulted from the foregone benefits technique (method_1), and from the optimization technique (method_2).

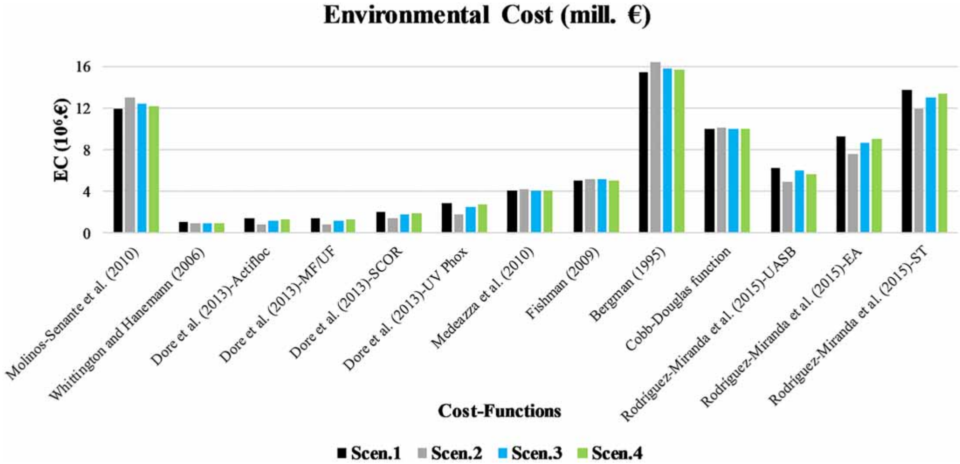

Fig. 4. Environmental cost estimations for each cost function.

Ministry's results. The EC for Scen. 1 was found to be 1.389 mill.€, 0.808 mill.€ for Scen. 2, 1.162 mill.€ for Scen. 3 and 1.281 mill.€ for Scen. 4.

The full cost of irrigation water is close, but still lower than the water value (Table 2). This fact is indicative of the mild cost estimations and the need of informing stakeholders about the real value of the environmental resources. This study's addition (water value parameter) is deemed important compared to its first application (Alamanos *et al.*, 2020) regarding its potential on stakeholders' involvement and increased understanding of the issues and challenges described.

Discussion

The proposed framework was also applied to an adjacent watershed as mentioned before. Lake Karla watershed (117,300 ha) is located above the north border of Almyros watershed. The climate and land use conditions are the same. The intensified agriculture is responsible for 94% of the water consumption in the area. Karla watershed's farmers use the overexploited aquifer as the main irrigation supply source, and River Pinios. Surface water from Pinios is also used to refill the constructed lake Karla (as a reservoir which is expected to operate). The numerous illegal wells, the (very) negative water balances, the area-based irrigation tariffs, the large debts from the users to the LALRs (and consequently from the LARLs to the State), and the continuous pollution are completing the frame. Table 3 compares the results of the full cost of irrigation water of only the aquifers of the two watersheds, for the same scenarios. The detailed procedure for Karla watershed can be found in Alamanos *et al.* (2020).

The huge groundwater resources overexploitation combined with the larger scale of Karla watershed is responsible for the high RCs. Karla's aquifer has not been found to be saline, however the excessive use of pesticides and fertilizers result in these ECs. The situation of Karla watershed is worse, resulting in almost double full water costs per m³. These findings represent the status of the majority of the country's rural regions. Most Greek rural areas have common characteristics, but the two examined cases have certain differences (regarded salinization, usage of surface water resources, projects and plans that are underway, and intensity of cultivation). The method can depict such differences in terms of RC (increased with

Table 3. The components of the full cost of irrigation water in Almyros and Karla aquifers and the total cost.

	Scen. 1	Scen. 2	Scen. 3	Scen. 4
Almyros – DC (mill. €)	0	0.012	0.029	0
Karla – DC (mill. €)	0.329	0.366	1.069	0.329
Almyros – RC (mill. €)	1.297	0.708	1.066	1.187
Karla – RC (mill. €)	20.41	17.815	18.955	19.780
Almyros – EC (mill. €)	1.389	0.808	1.162	1.281
Karla – EC (mill. €)	3.324	1.825	2.505	2.782
Almyros – full cost (€/m³)	0.054	0.038	0.048	0.051
Karla – full cost (€/m³)	0.100	0.089	0.094	0.095

deficits), EC (increased with qualitative degradation), and their connection (quantity to quality), thus enhancing its validity. In a more detailed comparison of the hydrological, economical and water quality status of more Greek agricultural watersheds (including Almyros and Karla watersheds), degradation, overexploitation and lack of proper management is observed (Angeli *et al.*, 2020). The above findings are strong signs that the proposed tool could be successfully applied across the country. The full cost of water, according to the recommendations of the WFD 2000/60 was expected to be implemented in June 2018, both in urban and irrigation water tariffs. However, no action has been observed so far, nor other measures to counter the generally bad reported status (Greek Ministry of Environment, 2012), which continues getting worse (Angeli *et al.*, 2020). In this section the effect of pricing irrigation water in order to cover the (estimated) full cost is examined. Figure 5 compares the net profits from agriculture with the full cost of irrigation water in the two cases described above.

The 'strict' implementation of the measure significantly affects the economies in both cases: the profits from agricultural activity will face a substantial decrease to reach around 25 and 50% of their original value, respectively. Thus, the importance of a pricing analysis is highlighted before the WFD is applied. This work attempted to give this insight using a simple (water value) addition, however, more systematic study is necessary. The achievement of a water pricing policy also requires education and information campaigns and a system that will ensure that these funds will become investments for the improvement of the water use efficiency.

The main limitation of the methodology's application to Almyros watershed was the absence of information on the number of unregistered wells and their effect on the water balance (here this water amount was attributed to be the balance's deficit), and the absence of cooperation (and knowledge) with the local authorities. However, the flexibility of the application of each stage of the proposed methodology allows the analyst to use different approaches (from simplistic with assumptions to more detailed models), and to reach satisfactory results (Alamanos *et al.*, 2020). The number of stages and steps involved in an integrated hydro-economic model that also estimates each component of the full cost of water under different scenarios, and compares it with another case-study application, leave limited space for continuing with a water-pricing analysis (future research-goal) and getting into the calculations' detail. However, our intention was to outline the theoretical-mathematical background of the methodology, expanding its capabilities and applicability (e.g. another watershed, adding simple but important new outputs, and comparing the results of both applications). Other additional elements of the present study are: (i) the implementation costs of the scenarios, (ii) water value (as a straightforward preliminary pricing investigation), (iii) the finding that the two RC estimation methods converge, which

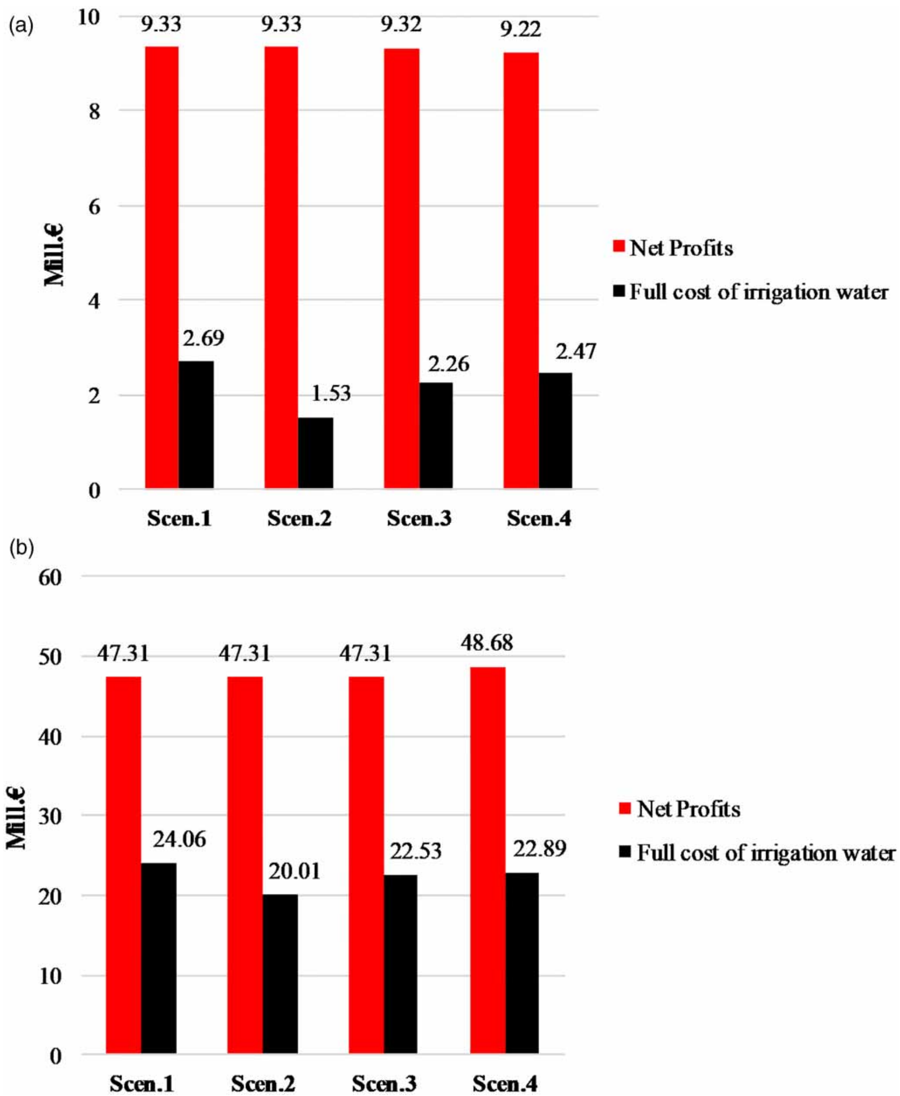

Fig. 5. Comparison of the full water cost and net profits (a) for Almyros and (b) for Karla watershed.

strengthen the argument of choosing the most appropriate method depending on each case's characteristics, (iv) the presentation of the second method for the estimation of RC in a clearer way with equations (Table 1), unlike the first application, and (v) a broader discussion on the practical applicability of the method. The results prove that this framework can provide reliable solutions, and thus it is recommended as an objective method for the full cost estimation. To quote Delli Priscoli *et al.* (2004) on the latter: 'it is an ethical obligation on scientists and engineers and other experts, who are trained and experienced in the relevant disciplines, to provide the best possible analysis of the problem'. This work's scope, analysis, proposed tools and unavoidable limitations are a step towards that direction, and provide useful insights to the relevant authorities to implement any legislation in a fair and equitable manner.

Conclusions

This research shows the potential of hydro-economic, water quality and engineering modelling approaches in degraded watersheds, to both describe their status and facilitate the implementation of economic tools (full cost) in water resources management. Some of the models' outputs were used for further analysis (e.g. water balance, profits, water quality), while others were used as explanatory purposes for local managers and stakeholders, and measures to highlight the system's situation. The performance of these factors was tested under demand-management scenarios, which proves they can contribute significantly to the overall watershed's status. These elements, combined with a more thorough description of the methodology, strengthen the framework's applicability and estimation of RC and EC, using and/or adapting different methods. Furthermore, the proposed framework avoids subjectivities and uncertainties that may occur due to other methodologies' gaps and lack of data, especially in the selection of 'related measures' and in their empirical cost estimation (especially for the case of resource and environmental costs).

The successful implementation of the proposed framework, even with limited data, encourages future applications because it is important to make a 'first step' for such areas. Several Greek watersheds were referred to as status 'unknown'. Our ongoing research's findings so far show that this can often be a bad status, so any effort to start monitoring and modelling them in an integrated way must be encouraged.

Regarding the policy extent of this work, the implementation of the River Basin Management Plans is an opportunity to apply the framework. As explained, the provision of handy and comprehensive tools for LALRs and local policymakers must be a priority at the time. An overall better understanding of our systems can be a solid basis for critical thinking on the ways that any legislation should be applied or adapted to our needs. In that context, the discussion above indicates that a detailed water-pricing analysis is necessary, and this is one of our future research plans, together with expanding the framework to more Greek and European case studies. Hydro-economic modelling is a useful vehicle towards monitoring, integrated modelling, recognition of the economic value of water, and multi-disciplinary collaboration.

Acknowledgements

We would like to thank the Associate Editor and the two anonymous reviewers for their comments and feedback that helped us improve the presentation of this work.

Data availability statement

All relevant data are included in the paper or its Supplementary Information.

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Received 16 November 2020; accepted in revised form 26 March 2021. Available online 10 May 2021