Examining the potential of an irrigation work to improve sustainability in a rural area

Athanasios Ragkos and Vasileios Ambas

ABSTRACT

Irrigation works aim to increase the efficiency of water use and economic benefits for farmers. This study adopts a broader view and investigates their potential to contribute to the achievement of other sustainability objectives. In particular, the paper employs a multi-objective programming (MOP) model, which examines the possibilities of simultaneously achieving four conflicting objectives with the upgrade of an irrigation network in a rural area in Greece. The four objectives are maximization of economic result (economic sustainability) and of employment (social sustainability) as well as the minimization of agrochemical use and irrigation water consumption (environmental sustainability). The compromise is sought through different cropping patterns either by restructuring existing crops (Scenario 1) or by also introducing new crops (Scenario 2). The results show that solutions in Scenario 2 perform much better in all dimensions of sustainability; however, large increases in economic performance and employment come with lower environmental gains. A Cost-Benefit Analysis shows that very few solutions yield positive Net Present Value and the investment could be halted if benefits relating to social and environmental sustainability are disregarded. Results are discussed in conjunction with the proposal of a new governance scheme, which could assume broader roles in supporting sustainable development.

Key words | cost-benefit analysis, crop restructuring, governance, multi-objective programming, public-private partnerships, technical and economic data

Athanasios Ragkos (corresponding author)
Hellenic Agricultural Organization – ELGO-DIMITRA,
Agricultural Economics Research Institute,
Terma Alkmanos,
115 28 Athens,
Greece
E-mail: *ragkos@agreri.gr*

Vasileios Ambas
Department of Agriculture,
University of Western Macedonia,
Terma Kontopoulou,
531 00 Florina,
Greece

HIGHLIGHTS

- Achievement of sustainable development through irrigation works.
- Quantification of social and environmental benefits from an irrigation work.
- Examination of simultaneous achievement of conflicting objectives.
- New insights into governance of irrigation networks for sustainable development through public-private partnerships.

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INTRODUCTION

According to the Sustainability Assessment of Food and Agriculture Systems of the Food and Agriculture Organization (FAO 2014), there are four dimensions in sustainable development. *Economic resilience* deals with issues relating to local economic development and operational profits of businesses. Complementary to this, *social wellbeing* includes equity, labor rights and quality in order to satisfy human needs and aspirations for a better life. *Environmental integrity* examines the management of water resources, biodiversity and other environmental goods and services, within an ecosystem approach across the whole food and agriculture sector. Apart from these three dimensions, good *governance* has also been noted as an integral element of sustainability – although not always examined as a separate dimension – and highlights the need of coordinating efforts and setting effective procedures towards sustainability. These dimensions were reflected in the 17 sustainable development goals proposed by the United Nations in 2015 and adopted by all United Nations Member States (United Nations 2015).

Sustainable development of rural areas constitutes one of the key policy goals in the European Union (EU). The new European Union (EU) Common Agricultural Policy (CAP) objectives for 2021–2027 focus on broader issues of interest to rural areas including fair income, vibrant rural areas and environmental care (https://ec.europa.eu/; European Commission 2020) and seek to implement measures that will – *inter alia* – encourage innovation in rural areas and improve farm infrastructure and amenities for rural dwellers. In this context, public infrastructure – including irrigation works – can serve as a tool for sustainable development (Jägermeyr *et al.* 2017). Irrigation works predominantly aim to increase of water use efficiency, which will also permit the design of more efficient irrigation plans, combined with deeper knowledge of crop needs (Kourgialas *et al.* 2019). Irrigated agriculture is linked to increased farm incomes but irrigation works can also contribute to sustainability through promoting environmental balance, the provision of ecosystem services, employment and social equity, especially in areas where the small percentage of irrigated land causes social conflicts for access to it.

Since irrigation works can serve objectives related to sustainable development, effective governance of irrigation water use and allocation is required to valorize the expected results of an irrigation investment. In Greece, the competent bodies for the management of local irrigation networks are the Local Land Reclamation Organizations (TOEB in Greek). TOEB are independent collective non-profit organizations governed by public law, under the supervision of Regional Authorities (see Dercas 2020) for a detailed presentation of the evolution of the framework). Their specific responsibilities are described in their Statutes and typically include the smooth operation and management of irrigation and land reclamation works, compilation of irrigation programmes, setting up and collection of irrigation fees as well as drafting studies for necessary reparation, improvement and/or expansion works. Despite being collective bodies, TOEB have not generally undertaken broader roles in Greek rural areas, such as proposing strategies for agricultural development, orientation towards innovation and improvement of human resources involved in the farming sector.

The construction of an irrigation work is accompanied by its financial appraisal, which demonstrates its feasibility and the conditions under which it is beneficial and profitable. Research regarding water management and irrigation project appraisal is rich (for instance see Latinopoulos 2005; Tillery & Jones 2007; Panagopoulos *et al.* 2014) and is mainly based on the Cost-Benefit Analysis (CBA), which is the established methodology (Hoehn & Randall 1987; Hanley & Spash 1993). As Tsakiris *et al.* (2017) pointed out, however, CBA cannot always capture indirect socio-economic benefits of irrigation works and dams. Indeed, environmental benefits are sometimes neglected due to market failures, while the potential to achieve broader sustainable development objectives is not reflected in economic performance indicators. In addition, the costs of irrigation works can be exaggerated or not estimated inaccurately (Psychoudakis *et al.* 1995). Therefore, appraisal with purely economic criteria could lead to underestimation of their real contribution in quality of life, environment and job creation.

In order to overcome this shortcoming, the financial appraisal is often supplemented with a socioeconomic and environmental analysis, which incorporates social and environmental issues. Yet, a considerable body of literature focuses on the environmental effects of irrigation water management in terms of water consumption and does not consider impact on the development process in rural areas. Latinopoulos (2008) examined the environmental, social and economic effects of irrigation water pricing on rural areas with multi-objective techniques and found that higher water prices could compromise economic and social sustainability objectives. Another significant part of relevant research analyzes the relationship between irrigation water consumption and economic performance (Latinopoulos & Mylopoulos 2005; Georgiou & Papamichail 2008). In the same context, Michailidis *et al.* (2009) described the process of economic analysis of an irrigation system by incorporating risk analysis and allowing for variability in cost elements using the real options method. Berbel *et al.* (2011) concluded that decision making about water management needs to take into account complex interactions among various factors, which cannot be tackled by an analysis of cost effectiveness alone. In this context, Niu *et al.* (2016) – with a two-stage fuzzy stochastic programming method – and Xu *et al.* (2019) – with an equilibrium model – analysed the importance of equity in irrigation water distribution to achieve sustainability. Capitanio *et al.* (2015) emphasized the importance of irrigation for the sustainable development of Italian agriculture under the sustainability objectives of CAP 2014–2020. General and partial equilibrium models have also been used to analyze the economics of water allocation (Dudu & Chumi 2008).

The purpose of this study is to showcase how an irrigation work can serve to achieve broader objectives related to the sustainability of rural areas. In particular, the paper describes the development of a Multi-Objective Programming (MOP) model that seeks to compromise conflicting objectives regarding the maximization of farm incomes and employment (economic and social sustainability) and the minimization of agrochemical use and water consumption (environmental sustainability). The method has been used before in agricultural economic analysis. Mosleh *et al.* (2017) used MOP and suitability analysis to propose the optimal cropping pattern for a rural area in Iran. Groot *et al.* (2018) combined MOP with other methods to explore multifunctional landscapes is many parts of the world. The study of Xevi & Khan (2005) focused on water use in agriculture in contrast to the achievement of environmental objectives. Galan-Martin *et al.* (2017) applied MOP along with life cycle assessment and water footprint concepts to examine the optimal allocation of irrigated and rainfed wheat production in Spain. Li *et al.* (2018) applied interval MOP in a Chinese irrigation district to examine how water savings can be achieved simultaneously with higher yields and economic performance.

In this paper, the analysis focuses on a Greek community for which technical and economic indicators are derived for main crops and for new crops that could be introduced in the cropping pattern. This way, the paper approaches irrigation works as opportunities for development. In order to emphasize this aspect of irrigation works, the paper also discusses the role of irrigation governance in the coordination of efforts to more towards higher levels of overall sustainability in rural areas.

MATERIALS AND METHODS

Study area

Characteristics

The study area is the Community of Limnochori in the Regional Unit of Florina, Region of Western Macedonia (RWM), Greece (Figure 1) (590–600 m a.s.l.). The population of the Community and of the whole Municipal Unit was 257 and 2.952 persons in 2011, with significant decreasing trends compared to previous decades (ELSTAT 2011). Unemployment constitutes one of the main problems of the whole Region, rating to 22.3% and harshly affecting especially younger people (ELSTAT 2011). RWM was ranked 11th among the 13 Greek Regions in terms of GDP (2,1% of national GDP) but 5th in terms of GDP per capita (14.800 €) (59% of EU average) in 2018 (Eurostat 2020), mainly due to the operation of coal-based electricity plants. Agriculture is the main source of employment and income in the study area, followed by employment in energy production in the electric power plants. However, RWM is actually in the course of a serious transition, as the coal-based energy production will be significantly

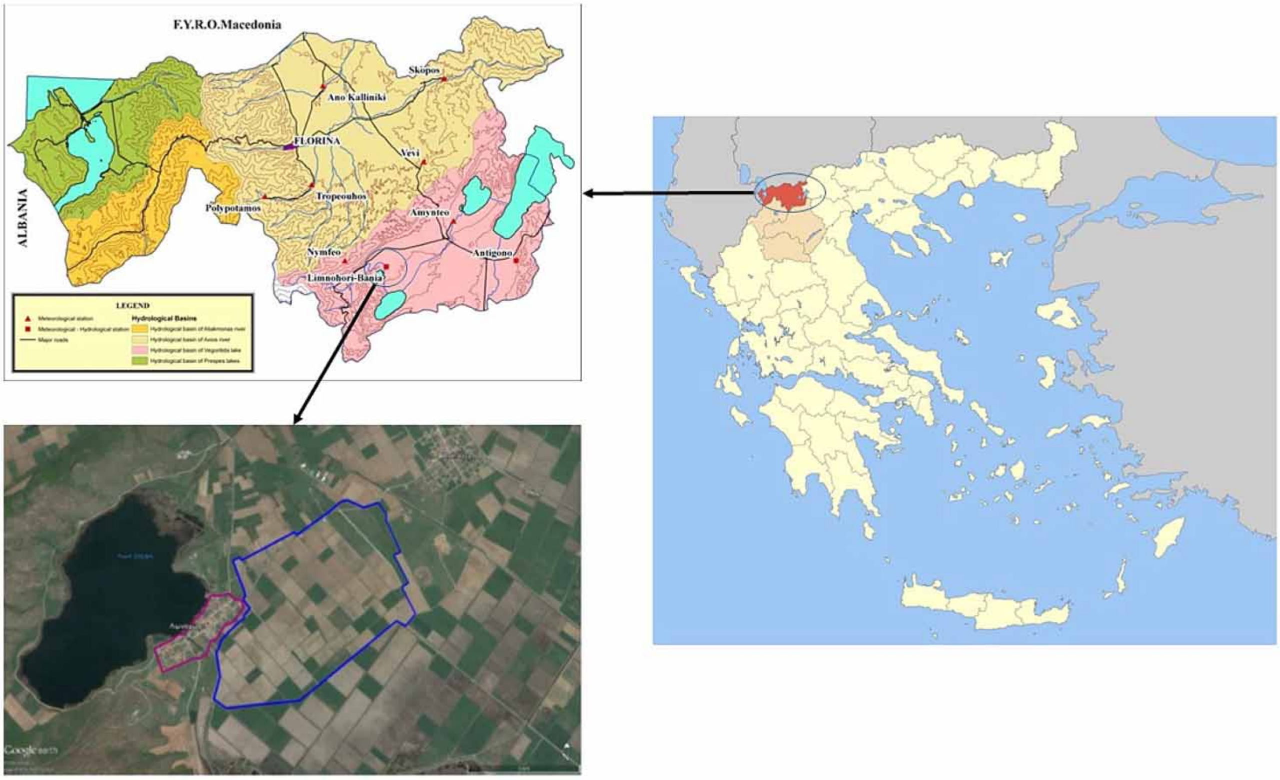

Figure 1 | Map of the study area (Limnochrori, Regional Unit of Florina, Western Macedonia, Greece). ***Note***: The blue and pink polygons denote the irrigated area in the present situation and the additional irrigated area in the future situation respectively. The full colour version of this figure is available in the online version of this paper, at http://dx.doi.org/10.2166/ws.2021.106.

reduced (Karlopoulos & Sidiropoulos 2020). Therefore, interventions to induce income generation and employment in other sectors of the economy is crucial.

Agricultural production in the study area is characterized by the predominance of few arable crops (maize, winter cereal, lucerne, potatoes, peas for livestock) which account for more than 90% of the total cultivated land, while sugar beet production has been significantly reduced in the past few years. The cropping pattern is the result of a long process of adjustment under the influence of climate and soil conditions but also of the Common Agricultural Policy, in the form of income support or of direct subsidies on the volume or acreage of production in previous periods. Through this process, necessary infrastructure has been formed and specific farming practices have prevailed, formulating a fairly intensive production pattern with high requirements in irrigation water, pesticides, fertilizers and other inputs. One of the problems in the farming sector of the study area is disguised unemployment, as the existing cropping pattern has low human labor requirements, with significant seasonal variation and peaks.

Irrigation network in the study area

The existing irrigation network covers 213,5 ha. It uses open canals and is supplied with water from Lake Zazari nearby. It was constructed in 1985 with an annual recoverable water quantity from the lake of 1,190,000 m^3 for a four-month irrigation period (Evangelidis 2017a). Since then, however, its capacity has been reduced, due to evaporation from the open canals and the use of old irrigation methods (mainly sprinklers) resulting in significant water losses. Also, about 30 ha are actually not irrigated due to network damages. Due to this situation, an upgrade and repair of the irrigation network has been planned and designed. Optimization of water use will be achieved through a standard closed pressure fully automated network, with innovative technologies that will ensure proper operation as well as gradual replacement of sprinklers by drip irrigation. This will lead to less water losses and higher water availability for farmers, which will allow expansion of the total irrigated area by 64 ha to a total of 276,7 ha, without increasing the amount of water recovered from the lake annually. Specific works that will be undertaken are described in the relevant technical and economic studies (Evangelidis 2017a, 2017b) and include

- Replacement/reconstruction of the existing hydrant inside lake Zazari with new equipment, in the same spot and with the same capacity of 1,190,000 m^3 per year
- A 78 m water pipeline from the hydrant to the pumping station
- Construction of a pumping station for network supply, in a municipal area 13 m from the shore of the lake
- A 360 m water pipeline from the pumping station to the limit of the irrigated area
- Replacement of existing canals by a pipeline network (approximately 11 km)
- A 3.183 m water pipeline from the pumping station to the limit of the dilatation of the irrigated area
- A pipeline network for the irrigation of additional 64 ha without increasing water recovery from the lake. The total irrigated area after construction will thus be 276,7 ha

Methodological approach

Model development

The analysis in this paper is based on an application of multi-objective programming (MOP), an optimization method that examines the possibilities of simultaneously achieving conflicting objectives. The model in this study is specified to include more objectives reflecting all dimensions of sustainability. The multiobjective problem for p objectives (Z_1,Z_z…Z_p) is formulated as follows (Cohon 1978; Romero & Rehman 1989; Zeleny 2012)

$$\begin{aligned}&\text{maximize}\, Z(x_1, x_2 \ldots x_j)\\&= [Z_1(x_1, x_2 \ldots x_j), Z_2(x_1, x_2 \ldots x_j), \ldots.., Z_p(x_1, x_2 \ldots x_j)]\\&\text{subject to}\ (x_1, x_2 \ldots x_j) \in F_d \qquad (1)\end{aligned}$$

where $x_1 \ldots x_j$ are the different activities through which maximization can be achieved (variables). Among different methods to solve the multi-objective problem, this study applies the ϵ-constraint method (Romero & Rehman 1989), which is expressed as follows

$$\text{maximize}\ Z_h(x_1, x_2 \ldots x_j) \qquad (2)$$

$$\text{subject to}\ (x_1, x_2 \ldots x_j) \in F_d$$

$$Z_\kappa(x_1, x_2 \ldots x_j) \leq L_k$$

where $k = 1, 2, \ldots, h-1, h+1, \ldots, p$

In this model, Z_h is one of the p objectives which is set as the objective function for optimization (minimization or maximization). The remaining p-1 objectives (Z_k) are included as constraints in the model specification. This specification is a linear programming (LP) problem – which is specified in Equation (3)

$$\max(\min) \sum_{j=1}^{M} c_j x_j = Z$$

$$\text{subject to} \sum_{j=1}^{M} a_{i_j} x_j \leq A_i$$

$$\sum_{j=1}^{M} \beta_{ij} x_j \leq B_\iota$$

$$x_j \geq 0 \qquad (3)$$

In the above LP problem, Z stands for the Z_h objective, while c_j is the vector of coefficients of M variables (activities), whose vector is denoted by x_j and stands for the contribution of each activity x_j to the objective function. α_{ij} are the requirements per unit of x_j for constraint A_i, while the set of the Z_k alternatives is expressed as a set of constraints, where β_{ij} are the coefficients of variables x_j and B_i is the available quantity of the specific constraint. This LP problem is specified similarly and solved for each one of the *p* conflicting objectives.

The solution of each one of the LP problems is included in a *pxp* table, the pay-off matrix, where columns represent the Z_p objectives and rows LP solutions. Therefore, the elements of the pay-off matrix are the values of each optimized objective Z_h and the value of Z_k objectives included as constraints in the corresponding model specification. The elements of the diagonal of the pay-off matrix (M_p) indicate an optimal solution to the MOP problem; that is, the infeasible solution where all conflicting objectives are optimized, while the difference between the minimum (m_p) and the maximum (M_p) of each Z_p objective define the range within each objective can range.

Based on the pay-off matrix, the MOP model is transformed to a right-hand-side parametric model (RHS-PP). The mathematical expression of the RHS-PP model is the same as the LP model (Equation (3)); however, the right-hand-side value of a constraint (A_i or B_i) is allowed to vary within an acceptable range, which yields multiple optimal solutions according to the availability of the constraint. In MOP, *p-1* RHS-PP models are specified, where one Z_h objective is the objective function in all specifications, while the remaining Z_k objectives are set as constraints and in each specification one of them is the parametrized (varying) constraint. The available quantity Bi of each Z_k constraint is allowed to vary between m_p and M_p

$$m_p \leq Z_k \leq M_p \tag{4}$$

This guarantees feasibility and non-inferiority for each solution (Ragkos & Psychoudakis 2009). For each specification, this procedure yields a set of alternative optimal solutions according to the availability of the varying constraints, all of which constitute an approximation of the non-inferior set of solutions (Cohon 1978). The final set of solutions reflects different options, each one of which compromises the conflicting objectives at different levels.

In the MOP application in this paper, the possibilities of achieving four conflicting objectives (Z_p) are examined.

- *Z1. Maximization of economic result* (Gross margin = Gross revenue – Variable expenses). This objective reflects higher economic sustainability, linked to higher economic performance of farms. For the calculation of the gross margin, hired labor expenses are not included in variable expenses, as the study does not discern between sources of farm labor (family or hired).
- *Z2. Maximization of employment* (hours of farm labor). This relates to the social sustainability of the sector, as more jobs in the farming sector would render it a more alluring alternative. Considering that young people seem to consider farm employment as an option to overcome high unemployment rates, this objective also reflects opportunities to keep population in the area or even to attract young people to return. Since the increase of employment is a general objective, the model does not discern between hired and family labor.
- *Z3. Minimization of pesticide and fertilizer use (agrochemicals)* (value of inputs per ha). The reduction in the use of agrochemical inputs relates to environmental sustainability. Residues of pesticides pollute water reserves and soil, while the excessive use of nitrogen fertilizers has led to degradation of surface and ground water (Pretty *et al.* 2000). In this study we include the value of pesticides and not physical units (e.g. kg of agrochemicals and fertilizers), because their expression in € provides an option for their simultaneous consideration – as it is difficult to add their quantities. Since farming practices and input prices are stable in the model, changes in the value of pesticides reflect changes in their total quantities used.
- *Z4. Minimization of irrigation water use.* Irrigation water saving constitutes one of the main objectives relating to the environmental sustainability of the production system. As described above, the new irrigation network will permit the irrigation of more hectares by reducing water losses and increasing irrigation efficiency.

It should be noted that the MOP problem presented here assumes that there are no changes in the production practices before and after the construction of the irrigation work. The compromise of the conflicting objectives is, therefore, sought only through changes in the cropping pattern, with crop restructuring which leads to optimization of each objective or to different levels of simultaneous achievement of all objectives.

Using the results of the ϵ-constraint method, the trade-offs between objectives can be calculated (Cohon 1978). Trade-offs represent the shadow price of a parametrized constrained input i.e. the additional amount of the objective function that can be derived by increasing the availability of the constrained input by one unit.

Common constraints in all model specifications include

- *Land constraints.* The irrigated land supported by the irrigation network in the existing situation was 212.7 ha. The new network will allow the irrigation of 64 additional hectares, which are actually cultivated with winter cereal (wheat and barley, arid crops). The model includes constraints regarding the maximum acreage of each crop, taking into account agronomic and market factors
- *Labor constraints,* which simulate the requirements for human labor of all crops
- *Capital constraints,* which refer to the availability of variable capital for purchased inputs

The paper examines two scenarios in order to demonstrate the potential effects of the irrigation work on sustainability.

- *Scenario 1 – Optimization without introducing new crops*. Scenario 1 involves the restructure of the existing crops (maize/silage, lucerne, potatoes, livestock peas) and the expansion of their cultivation in the additional 64 irrigated hectares. The optimal solutions in this scenario show if the irrigation work could have positive effects on the development of the area without significant changes in the cropping pattern
- *Scenario 2 – Crop restructuring (optimization) with the introduction of two new crops with more dynamic potential.* These two crops are
  - Chamomile, which is a non-irrigated crop with high labor requirements and relatively low investment costs. Cultivation is quite extensive, as only small quantities of nitrogen fertilizers are applied (usually no more than 100 kg/ha) and pesticides are not necessary. The acreage of aromatic plants in the broader region had expanded during the last few years, with similar development trends for other activities across the value chain (standardization and processing units, retail sales).
  - Fresh peas, an irrigated crop that requires intensive use of agrochemicals (fertilizers, herbicides and insecticides) but also human and machine labor. One of the main opportunities for this crop is contractual production, already occurring in the area.

The new cropping pattern in this case would require a mid-term development strategy for the area in order to facilitate the transition.

Cost-benefit analysis

Based on the results of MOP, a CBA of the construction of the irrigation work was conducted. For each solution, the Net Present Value (NPV) and the Internal Rate of Return (IRR) were calculated, which are two of the most commonly used indicators for the appraisal of construction works. In this paper, net cash flows were discounted with a 3% rate – which is considered satisfactory for a public investment – and the NPV was calculated over a period of 50 years. The IRR stands for the discount rate, which returns zero NPV and expresses the marginal return on invested capital, which can be compared to bank and loan interest rates.

The annual economic benefits from the investment (irrigation work) were calculated as the difference between the economic output (gross margin) in the optimal existing solution and the future situation. This approach was used because this difference would reflect the difference between the existing and future situation attributable to irrigation only. Indeed, a comparison between future optimal and existing sub-optimal organization would include the difference between actual and optimal organization in the existing situation, which is not related to irrigation but to other factors. Therefore, the optimization of the existing situation provides an alternative to the irrigation work, as is common for CBA assessments. The optimal existing solution was derived by means of an LP model (Formula 3) where land constraints were set close to the existing acreage of each crop and showed how the existing cropping pattern could be rearranged to achieve optimal economic performance. The future benefits (gross margin, Z1) were calculated from the selected optimal solutions of the MOP model.

Data

Data for the LP and MOP models were derived combining surveys and secondary (published) sources. Technical and economic indicators for production inputs (value of fertilizers and pesticides), labor requirements, product yields and market prices were obtained from the Region of Western Macedonia (2009) and were then updated with interviews with farmers and verified by two local experts. Irrigation water requirements were calculated based on Ambas (2010), using a method that considered the needs of all crops, annual rainfall – based on meteorological data from a local station – and evapotranspiration. In more detail, Ambas (2010) calculated evapotranspiration with five different methods and estimated parameters of each method, yielding a total of 26 values of evapotranspiration. The main evaporation method considered was the FAO56 Penman-Monteith method with clear-sky radiation estimated using spectral analysis and solar radiation from raw data. Effective rainfall was calculated by means of the Soil Conservation Service method. The indicators used in the MOP model (c_{ij} and β_{ij}) for the four objectives are presented in Table 1.

Construction costs of the irrigation work were calculated to 3,427,419.35 €, including all surcharges foreseen by Greek law except VAT (technical works were budgeted to 2,441,475.24 €, 439,465.54 € (18%) were general expenses and contractor profit, 432,141.12 € (15) were unforeseen expenses and 114,337.46 € were budget revision). Annual costs raised to a total of 41,7887.24 €/year including maintenance costs (0.25% of construction costs per year), electricity costs and management/operation costs (wages for two persons employed full-time 18,564 €/year) (Evangelidis 2017b).

Table 2 | Optimal cropping pattern under the existing situation

Crops	Acreage (ha)
Maize	77.5
Silage	19.4
Potatoes	13.8
Lucerne	69.2
Peas	0
Cereal	96.8
TOTAL	**276.7**
Objectives	
Gross margin (X1000€)	439.5
Agrochemicals (X1000€)	59.5
Labor (Labor Units[a])	12.5
Water (X1000 m^3)	844.3[b]

[a]1 Labor Unit = 1,720 h.
[b]Water consumption here represents crop requirements and not the total consumption.

RESULTS

Table 2 presents the basic LP solution, where the existing situation (before the construction of the irrigation work) was optimized. Non-irrigated cereals cover 96.8 ha, therefore they are cultivated even in areas that can be irrigated. This is due to the fact that the available water is used for crops with higher gross margin per ha, which are more demanding in irrigation. In addition, the reduced capacity of the existing network leads to losses and inefficient use of the annual

Table 1 | Variable coefficients (c_{ij} and β_{ij}) of the four conflicting objectives considered in the MOP model

	Z1 (max) Gross margin (€/ha/year)	Z2 (max) Labor (h/ha/year)	Z3 (min) Agrochemicals (€/ha/year)	Z4 (min) Irrigation water (m^3/ha/year)
Existing crops				
Maize	1,536	100	280	4,150
Silage	1,664	80	325	4,150
Potatoes	3,572	160	640	5,834
Lucerne	2,822	120	125	5,230
Dry peas (livestock)	344	120	175	3,033
Cereal	450	20	140	0
New crops				
Chamomile	4,800	1,300	50	0
Fresh peas	2,482	450	175	3,576

recoverable water quantity. In irrigated land, maize, silage and lucerne account for more than 90%. Note that water consumption in Table 2 expresses the total requirements of crops and not the actual consumption, which should be considerably higher due to water losses from evaporation and reduced irrigation efficiency in the existing situation.

Table 3 presents cropping patterns and the pay-off matrices for both scenarios. Differences between the highest and the lowest values of the four objectives indicate the possibilities of increasing or decreasing each one of them. Gross margin could be increased from 471.4 thousand € to 572.1 thousand € (21.3%) and employment from 15.5 to 17.7 LU (2.2 more jobs or an increase of 14.2%). Furthermore, a decrease from 79.6 to 63.8 thousand € for the value of agrochemicals (19.8%) and considerable irrigation water savings (from 1,184.4 to 1,067.5 thousand m^3 or by 9.9%) could occur. The acreage of irrigated crops was higher for solutions maximizing gross profit and employment, mainly because potatoes were included with an acreage of 41.5 ha in both optimal cropping patterns. Livestock peas (8%) and winter cereal (13%) were included in the solutions relating to environmental sustainability (minimizing agrochemical and irrigation water use), along with maize (and silage), which occupied half of the total available land. The acreage of lucerne was relatively stable across all four cropping patterns (21–25%).

In Scenario 2, which considers the inclusion of new crops (chamomile and fresh peas) (Table 3), the ranges of the values of the four objectives were not significantly different, as increases of 21.4% and 13.7% can be achieved for gross margin (482.7–639.7 thousand €) and employment (25.6–28.9 LU) respectively and savings of 9.9% and 19.8% could occur for irrigation water (975.6–1,184.4 thousand m^3) and agrochemicals (55.6–78.9 thousand €). Cropping patterns varied across the four solutions, as only the two new crops (camomile and fresh peas) were included in all solutions. Gross margin was maximized mainly with the inclusion of maize, lucerne and potatoes (76.3%) and when dry peas for livestock feeds were excluded. For the maximization of labor, the acreage of maize was increased

Table 3 | Pay-off matrices in the two scenarios – results of multi-objective programming

	Scenario 1. Existing crops				Scenario 2. Existing and new crops			
	Z1 (max) Gross margin	Z2 (max) Labor	Z3 (min) Agrochemicals	Z4 (min) Irrigation water	Z1 (max) Gross margin	Z2 (max) Labor	Z3 (min) Agrochemicals	Z4 (min) Irrigation water
Non-irrigated crops (ha)	**27.7**	**36.0**	**17.1**	**36.0**	**23.9**	**47.1**	**11.9**	**47.1**
Winter cereal	27.7	36.0	17.1	36.0	12.8	36.0	0.8	36.0
Chamomile	–	–	–	–	11.1	11.1	11.1	11.1
Irrigated crops (ha)	**249.1**	**240.8**	**259.6**	**240.8**	**252.9**	**229.6**	**264.8**	**229.7**
Lucerne	69.2	69.2	57.6	69.2	69.2	69.2	46.2	52.6
Maize	110.7	138.4	138.4	110.7	100.5	121.7	138.4	110.7
Dry peas (livestock)	0.0	22.1	22.1	22.1	0.0	22.1	22.1	22.1
Potatoes	41.5	11.1	41.5	11.1	41.5	0.0	41.5	0.0
Silage	27.7	0.0	0.0	27.7	25.1	0.0	0.0	27.7
Peas (fresh)	–	–	–	–	16.6	16.6	16.6	16.6
Pay-off matrices								
Gross margin (X1000€)	**572.1**	*471.4*	538.9	474.7	**639.7**	500.6	593.8	*482.7*
Agrochemicals (X1000€)	*79.6*	**63.8**	79.2	65.2	77.2	**55.6**	*78.9*	59.4
Labor (LU)	16.7	15.9	**17.7**	*15.5*	28.1	26.1	**28.9**	*25.6*
Water (X1000m^3)	1,177.9	1,067.5	*1,184.4*	**1,067.5**	*1,184.4*	993.5	*1,184.4*	**975.6**

even more (138.4 ha – 50% of total land) along with lucerne and potatoes (31.7%). With regards to environmental sustainability, the use of agrochemicals was minimized by increasing the acreage of cereal (57.0%), lucerne (25.0%) and livestock peas (8.0%), while irrigation water consumption was minimized by increasing silage (10.0%) and winter cereal (13.0%) apart from maize (40.0%).

The comparison of the two pay-off matrices illustrates how the inclusion of new dynamic crops in the cropping pattern could have significant impact on all dimensions of sustainability. Indeed, maximum gross margin and employment were higher by 11.8% and 63.6% respectively in Scenario 2, while in the same scenario additional reduction of 12.9% and 8.6% could be achieved in the value of agrochemicals and water consumption.

The results of multi-objective programming yielded 21 optimal solutions in total for both scenarios (10 for S1 and 11 for S2). Table 4 presents ten selected plans among the 21 optimal solutions yielded in both scenarios. Each one of these plans compromises the four objectives and reflects varying levels of economic, social and environmental sustainability. Solutions are ranked according to the level of irrigation water use and each successive solution in each scenario (S1.1-S1.9 and S2.1-S2.11) represents higher gross margin. A key finding is that increases in economic and social sustainability were achieved mainly with the inclusion of potatoes and high acreage of maize and a reduction in winter cereals. On the contrary, potatoes were excluded for livestock peas, maize and/or silage when environmental objectives were achieved to higher degrees. Cropping patterns differed across solutions. As irrigation water use increased, the acreage of winter cereal was reduced, dry livestock peas were excluded, and the cultivation of lucerne was maximized.

Based on the results of the MOP model, for both scenarios, Table 5 presents the trade-offs between objectives Z2–Z4 and gross margin (objective Z1). As expected, trade-offs increase for lower levels of input (agrochemicals, labor, water) use. It is interesting to notice that the shadow price (trade-off) of labor in Scenario 1 is considerably higher compared to Scenario 2, as in Scenario 1 labor use is generally much lower. When it comes to water, the use of less water increases its shadow price significantly, which reflects the importance of this input.

Figure 2 illustrates the various contributions of the irrigation work that can be considered in its appraisal. The

Table 4 | Optimal cropping pattern with the new irrigation network for the developed scenarios

	S2.1	S2.3	S2.5	S1.1	S1.5	S2.8	S1.9	S1.6	S2.9	S2.11
Non-irrigated crops (ha)	**47.1**	**47.1**	**47.1**	**36**	**36**	**47.1**	**36**	**27.7**	**20.2**	**23.9**
Winter cereal	36	36	36	36	36	36	36	27.7	9.1	12.8
Chamomile	11.1	11.1	11.1	–	–	11.1	–	–	11.1	11.1
Irrigated crops (ha)	**229.7**	**229.7**	**229.7**	**240.8**	**240.7**	**229.7**	**240.8**	**249.1**	**256.6**	**252.9**
Lucerne	52.6	11.1	69.2	69.2	38.7	69.2	69.2	69.2	69.2	69.2
Maize	110.7	110.7	138.4	138.4	110.7	81.9	110.7	110.7	138.4	100.5
Dry peas (livestock)	22.1	22.1	0	22.1	22.1	0	0	0	0	0
Potatoes	0	41.5	5.5	11.1	41.5	41.5	33.2	41.5	32.4	41.5
Silage	27.7	27.7	0	0	27.7	20.5	27.7	27.7	0	25.1
Peas (fresh)	16.6	16.6	16.6	–	–	16.6	–	–	16.6	16.6
OBJECTIVES										
Gross margin (X1000€)	483	514	538	471	497	614	546	572	622	640
Agrochemicals (X1000€)	59	81	58	64	81	74	75	80	72	77
Labor (LU)	26	27	26	16	16	27	16	16	29	29
Water (X1000m^3)	976	1,001	1,028	1,068	1,086	1,088	1,129	1,178	1,184	1,184

Note: S1 and S2 stand for Scenario 1 and Scenario 2 respectively and numbers after the dots the sequence number of each solution in each scenario. In this table, solutions are presented according to the volume of water consumption.

Table 5 | Trade-offs between gross margin and use of agrochemicals, labor and irrigation water

Agrochemicals		Labor		Irrigation water	
Value of agrochemicals (thousand €)	Trade-offs (€/€)	Hours of labor (Thousand hours)	Trade-offs (€/hour)	Use of irrigation water (thousand m^3)	Trade-offs (€/m^3)
Scenario 1					
78.2	2.40	28.8	14.66	1,168	0.27
74.0	6.24	28.1	31.34	1,111	1.16
63.8	7.02	26.7	80.75		
Scenario 2					
77.2	2.40	49.1	2.94	1,184	0.27
73.2	6.24	29.6	4.39	1,165	1.09
57.2	9.01	28.8	5.54	1,063	1.25
55.6	12.00	26.7	17.76		

NPV was marginally positive in only two solutions (S2.9 and S2.11), while the IRR was less than 4% – or even negative – in all solutions. This shows that the expected economic performance of the investment was low – especially when new crops were not considered – despite the fact that gross margin was higher than the optimal existing situation in all solutions. This is presented in Figure 3, where also other contributions were taken into account. Indeed, all scenarios entailed higher levels of employment in the area, which was more than double for Scenario 2. Furthermore, in all solutions there was more irrigation water use compared to the existing situation, without, however, increasing the quantity recovered from the lake and also ensuring the irrigation of additional areas. Nevertheless, in only two out of ten solutions (S2.1 and S2.5) was the use of agrochemicals lower than the optimal existing situation and these solutions performed badly in terms of NPV and IRR.

DISCUSSION

The MOP model yielded a set of non-inferior solutions that reflect different levels of achievement of conflicting objectives. The sustainable development pattern based on these objectives is in line with the CAP Specific Objectives for 2021–2027 (https://ec.europa.eu/). Depending on the choice of the specific optimal solution, objectives regarding environmental care, fair income for farmers and competitiveness are met. However, the choice of the best solution is subject to internal and external factors. Internal factors are related to strengths and weaknesses of the farming sector in

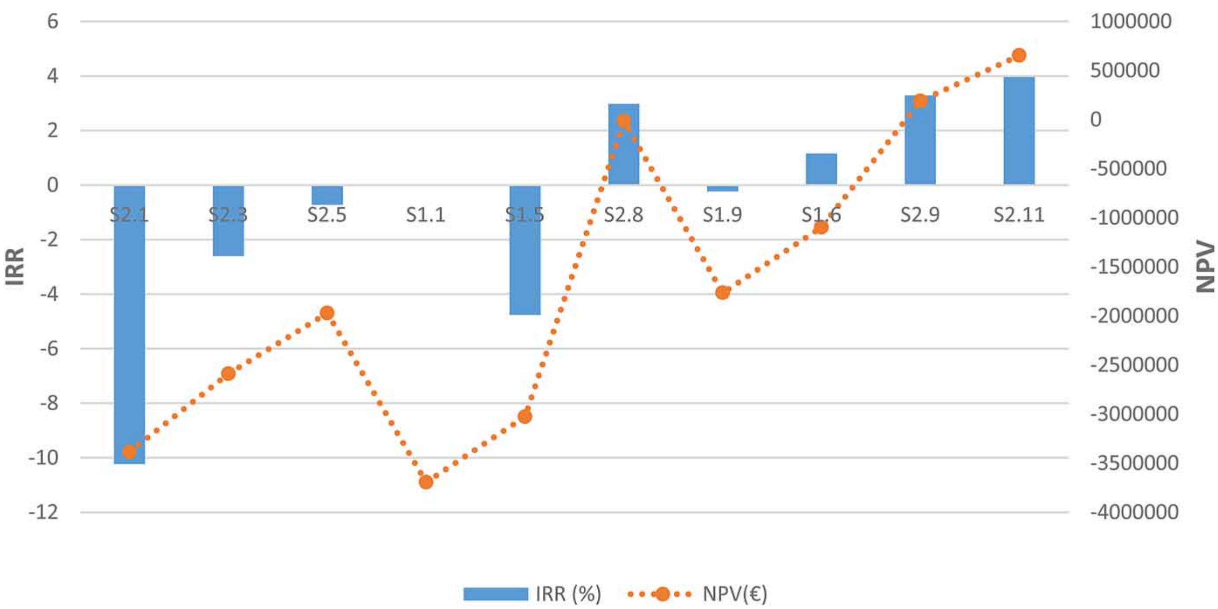

Figure 2 | Cost-benefit analysis indicators in selected MOP solutions. ***Note***: S1 and S2 stand for Scenario 1 and Scenario 2 respectively and numbers after the dots the sequence number of each solution in each scenario. In this figure, solutions are presented according to the volume of water consumption.

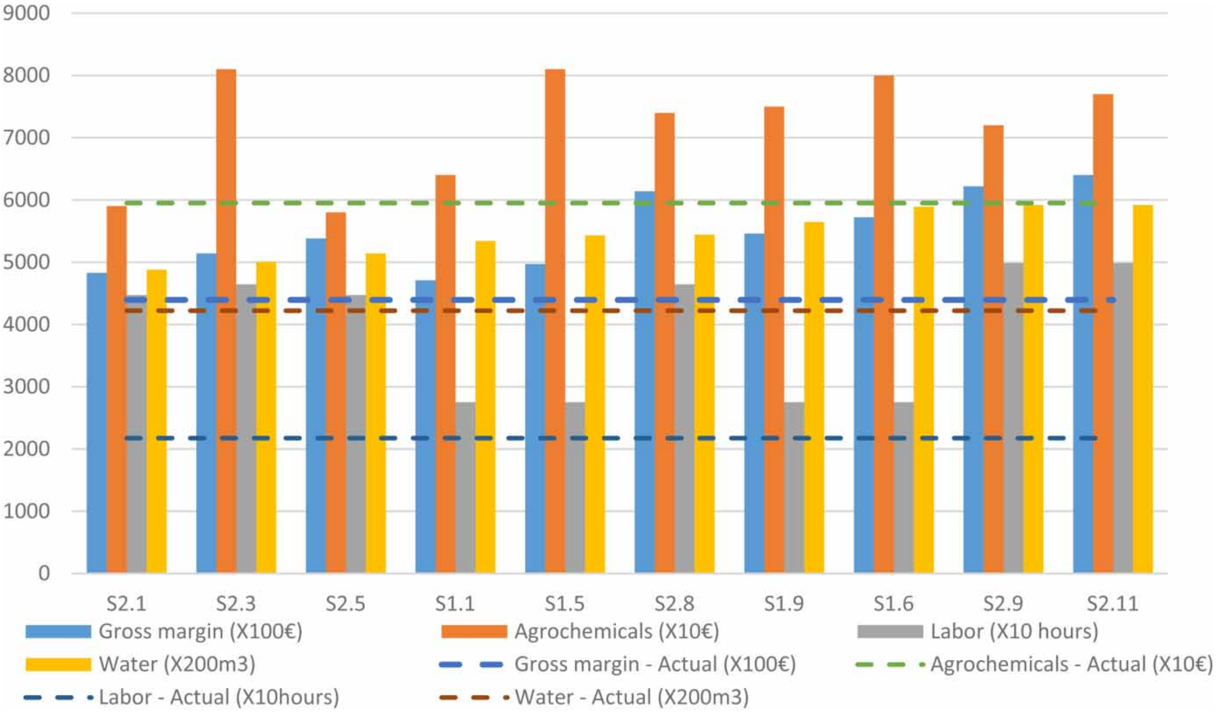

Figure 3 | Achievement of social and environmental sustainability objectives in selected MOP solutions. ***Note***: S1 and S2 stand for Scenario 1 and Scenario 2 respectively and numbers after the dots the sequence number of each solution in each scenario. In this figure, solutions are presented according to the volume of water consumption.

the area and primarily include locals' preferences and aspirations – not only of farmers. For example, reactions could be expected if property issues arize, especially for newly irrigated land. In addition, the sustainable development process should ensure that conditions are met, including access to capital, training and advice. In any case, the views of the affected population should be explored, in order to valorize the potential of the irrigation project to induce a new development process in the area. On the other hand, external factors represent the influence of general policy objectives, the evolution of farm policies and income support schemes for specific crops, the economic environment, other employment opportunities, environmental policies in force and other socio-economic challenges. Therefore, this choice is also contingent upon broader policy objectives.

The increase of the irrigated areas will only have marginal effects on the development process, if it is not accompanied by strategic planning and effective governance. There is a need for a new improved scheme not only to manage water but also to provide guidance to farmers and assist the transition to crop restructuring towards higher levels of sustainability. In this context, this study considers the perspective of redefining the role of TOEB by introducing alternative and more flexible – and potentially more efficient – forms of administration and management of irrigation projects such as public-private partnerships (PPPs) (Warner *et al.* 2008). These are government initiatives for cooperation in which the role of the state entity in the operation and maintenance of irrigation projects is transferred to another body through a management agreement. PPPs could assume the form of financially autonomous government agencies and involve a professional Water Users Association or even private companies (Kleemeier & Lockwood 2012; Lamaddalena & Khadra 2012; Aarnoudse *et al.* 2018). This increases the participation of farmers, who become co-responsible for the management and operation of the project.

PPPs become increasingly popular as they ensure important benefits, mainly because they counterbalance bureaucratic issues and public funding requirements for operation. In particular, PPPs can be cost efficient in determining irrigation fees – as a result of consensus of involved stakeholders – based on objective criteria and acceptable collection mechanisms. In addition, they can act as intermediate actors between government and farmers with increased flexibility and can be more responsive to local needs, as they motivate the active participation of local actors. This could be expected to reduce social conflicts due to competition for access to irrigation water, especially when the participation of farmers is active, substantially influencing the decision-making process. A PPP could also be effective in undertaking advisory and supporting roles for farmers in the process of transition towards more sustainable development, thus supporting crop restructuring to achieve benefits as reported in this paper. This role corresponds to the fourth dimension of sustainability, as PPP could also undertake broader roles in local societies, relating to agricultural development as well as training, advice and communication. Despite these benefits, PPPs in irrigation water management could be proven inefficient under the influence of numerous factors, including cases where farmers' involvement is not active (Gastineau 2006; Zhanq & Tariq 2020).

An important aspect that affects the successful operation of irrigation works is the calculation of irrigation fees. This study shows that the imposition of lower or higher irrigation fees could affect the gross margin of farms and – to some extent – economic sustainability of farm production in the area, which would also affect other dimensions of sustainable development. Therefore, one of the main duties of the collective governance scheme in charge of irrigation management would not only be the effective calculation of irrigation fees but also the option to readjust them dynamically. In Europe, there is accumulated practical and academic experience from a variety of methods and schemes (Berbel *et al.* 2007). In Greece, the efficient calculation of irrigation water fees can play an important role in its efficient use and can also be affected by policies in force (Manos *et al.* 2006).

CONCLUSIONS

This study described the development of a MOP model to examine the extent to which an irrigation work could contribute to sustainable development and induce economic, social and environmental improvements. The results showed that there is significant potential for increases in all dimensions of sustainability. The CBA confirmed that the consideration of only the economic performance in the appraisal could neglect other important benefits that are not directly reflected in financial indicators. The advantage of the MOP approach is that the solutions it provides allow consolidation of many of these benefits without excessive data requirements or analysis.

In order to achieve sustainable results, the study pinpoints the importance of effective governance, which should be based on inclusive participatory approaches of farmers and other affected stakeholders. Thus, the human factor is of paramount importance for the success of such a project, which will ultimately determine the exact conditions for the realization of the project and the exploitation of the advantages that this entails. However, the proposed PPP scheme constitutes an alternative to the existing TOEB schemes and should aim to support their operation and to redefine their objectives, by adding broader roles in their portfolios. PPP could therefore provide them with flexibility and better managerial capacities. A particular function of the PPP governance scheme could also include ongoing monitoring and ex-post evaluation of sustainable development in the area. This would also show the degree of adaptation of farmers to the optimal cropping pattern that would be chosen.

The methodology presented in this study can be easily applied in other settings and even for larger irrigation works and areas, with larger affected populations. However, this approach is subject to two limitations. First, farming practices in the model represent the observed practices in the area, but with this specification, other practices (such as organic production or integrated pest management) are not considered. This option should be taken into account in future research. Second, the expected environmental gains from more efficient water use and less agrochemicals have been found to have non-market values (Ragkos & Theodoridis 2016), which can be included in CBA frameworks through the application of non-market valuation techniques.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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