Journal of Engineering Science and Technology Review 10 (6) (2017) 146 - 153

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Mathematical Programming Model for Procurement Selection in Water Irrigation Systems. A Case Study

Modesto Pérez-Sánchez[1,]*, Manuel Díaz-Madroñero[2], P. Amparo López-Jiménez[1] and Josefa Mula[2]

[1]*Hydraulic and Environmental Engineering Department, Universitat Politècnica de València, Valencia, Spain*
[2]*Research Centre on Production Management and Engineering (CIGIP), Universitat Politècnica de València, Alcoy, (Alicante), Spain*

Received 2 April 2016; Accepted 20 December 2017

Abstract

The development tools to optimize the process and helping management to get margin are used inside of the industrial manufacture. Water networks management are not alien to this need. The optimization of the water resource is currently done in big basins, but it is not a general practice in irrigation networks that operate as water distribution companies to supply the farmers' demand. Nowadays, this management is not optimized and the costs are not minimized. This research introduces a mathematical programming model to optimize the replenishment process in a local irrigation network with the aim to decide what volume is procured (source, quantity and timetable) as well as what volume is stored while minimising the involved total costs. The final objective is to improve the sustainability of the water systems. The use of this tool reduces the water costs in 52.2% as well as enables to define the necessary source and the electrical schedule along the year. This definition optimizes the operating of the water system and enables to reduce the water price from 0.23 €/m^3 (current water management) to 0.11 €/m^3 (proposed model).

Keywords: Water management, irrigation network, water source, sustainability

1. Introduction

The development tools that are used to improve the water management takes on special relevance, particularly, when the area presents a high deficit of the water resource. Currently, this issue is present in many countries as consequence of the increase of the population, the decrease of the water resources and the increase of the energy prices [1]. These constrains are joined to the need to increase the sustainability in the agricultural management. This sustainability includes the feasibility of the farmers and therefore, the improvement of the water resource benefits both natural resources and the profitability of the farmers. In Mediterranean area, these main problems (scarcity of the water and low profit) are endured by the farmers. Both problems are related because the water can reach a significance percentage in the production costs [2]. Worldwide, this cost is variable, and it depends on the geographical location, varying even within the same country or province. In some cases, the irrigation cost can reach until 25% of the production costs [3].

The development of decision support tool to manage the water resource of a basin were reviewed for many researcher by using the linear and non-linear techniques [4], particularly in river-basins scale [5, 6]. The correct management of the river basin causes significance positive sustainable impacts (e.g., water savings, economic, social) when the directive programs are well defined by the water managers [7]. However, if the sustainability parameters want to be improved in the total management of the water resource, this analysis also have to do at small scale. One of these systems, and the most important, is the agriculture, as it consumes 80% of the worldwide used volume [8] when the water use is considered. Hence, several researches were developed in order to establish decision support that manages the irrigation needs of the crops [9], but there are few references to help water managers of irrigation water networks in small scale for implementing strategies tools for making decisions related to select the water volume and origin, schedule to do it, as well as considering the minimum storage in the reservoir.

Mathematical programming is an analytical procedure to determine the optimum allocation of scarce resources. These allocation problems can be presented in very different ways. In this sense, mathematical programming techniques are employed in a large number of problems, such as production planning [10], supplier selection [11], transport problems [12], distribution [13], financial planning [14], forest planning [15], scheduling flights [16], among others. One of the reasons why mathematical programming is a widely used tool is the significant progress made by optimization software due to the increased calculation power of computers and to the fall in hardware costs [17].

Thus, the main contribution of this paper is to introduce a mathematical programming model for addressing the replenishment process in a local irrigation network with the aim to decide what volume is procured (source, quantity and timetable) as well as what volume is stored while minimizing the involved total costs. Moreover this model is validated using data from a real water system.

The rest of the paper is organized as follows: Section 2 provides the problem description and the corresponding statement. Section 3 presents the mathematical formulation of the proposed model. Next, Section 4 introduces an application of the proposed model in the case study. Finally, Section 5 provides conclusions and future research lines.

*E-mail address: mopesan1@upv.es

doi:10.25103/jestr.106.17

2. Problem description

The irrigation modernization carried out in developed countries increased the hydraulic efficiency but it also grew the energy consumption [18]. The irrigation modernization caused the water resources to be mixed in the different reservoirs to be supplied on the network according to farmers' demand. As consequence, the water has different origins and therefore, it has different prices. In some cases, the water managers don't have sufficient volume to supply the demand and they have to use all water resources and all electric tariff to guarantee the consumption. However, there are situations in which, the water manager has the possibility to choose the water used volume of each origin as well as the used electric tariff to be pumped the water whether it is necessary to distribute the demanded flows. The lack of development in irrigation communities causes their water managers don't carry out strategies to adapt the volume and pumped schedule to new situation, in general, and they continue developing the water management that was developed when the energy prices were lower or the water system was distributed by channel flow. Therefore, a sustainable water management have to be focused on getting the necessary water volume to satisfy the demand over time, minimizing the water selling price. To do so, the water managers have to decide the water origin, volume, the need to be stored it in the reservoirs as well as the pumped schedule according to electric tariff (Figure 1). Besides, the previous constraints should develop as a function of the maximum transfer flow. This capacity depends on infrastructures (e.g., pipeline diameter, capacity of the pumped system), the available flows (e.g., well's flow, treated flow in wastewater plant) and/or the water license that establishes the maximum volume consumed by irrigation community of that origin.

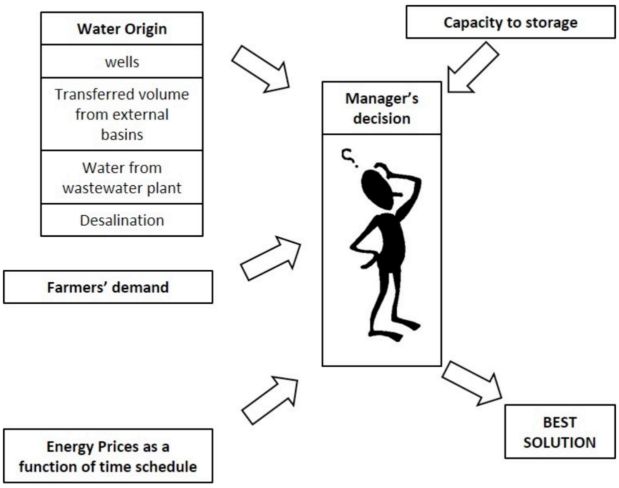

Fig. 1. Inputs to water manager's decision

Therefore, the proposed approach solves the problem to decide the used volume of each origin in the irrigation water distribution network, minimizing the procurement costs, and hence, the selling price of water to farmer as well as minimizing the stored volume in the reservoir. Furthermore, this volume should be minimum to reduce the evaporation losses and leakages in the same.

The problem addressed in this study is focused on optimizing the management of irrigation pressurized water distribution networks. Thus, it can be stated as follows:

- Given:
  - A set of water procurement sources
  - The possible procurement methods for each water source
  - The water demand over the planning horizon
  - The capacities for each source per period and method
  - Initial inventory level at the tank
  - Capacity of the tank for storing water and minimum safety stock
  - Inventory water holding cost and procurement fixed and variable costs from each source and method

- To determine:
  - The volume to procure from each source with each method per period
  - The water inventory level in the tank in each period

- The main goal to meet is:
  - To minimize total costs including procurement costs and inventory costs while meeting customers demand.

- Moreover, the following assumptions have been made:
  - All input data are deterministic and therefore the possible uncertainty inherent to demand and costs variations has not been considered.
  - Hydraulic performance levels of pipelines are not considered and therefore evaporation and distribution losses are not introduced in the model.

3. Model formulation

This section proposes a mathematical programming formulation for the addressed problem. The nomenclature defines the sets of indexes, parameters and decision variables for the proposed model as follows.

Indexes

$i \in I$ Procurement sources
$m \in M$ Procurement methods
$t \in T$ Time periods
$k \in K$ Months in the year

Sets

M_t^K Set of time periods in month k

Parameters

d_t Demand in period t (in m^3)
CM_{it} Maximum procurement level for source i in period t (in m^3)
CMT_i Monthly maximum procurement level for source i (in m^3)
$CH_{i,m}$ Monthly available time for the procurement in source i with method m (in hours)
$IMIN_t$ Satefy stock level of stored water in period t (in m^3)
$IMAX_t$ Maximun level of stored water in period t (in m^3)

cpv_{imt} Procurement variable cost for source i with method m in period t (in euros/m^3)
cpf_{imt} Procurement fixed cost for source i with method m in period t(in euros/m^3)
ci_t Storage cost in period (in euros/m^3)
cf_{im} Procurement fixed cost for source i with method m over the planning horizon (in euros/m^3)

Decision variables
I_t Level of stored water in period t (in m^3)
Q_{imt} Amount of procured water from source i with method m in period t (in m^3)
Y_{imt} 1 if any amount of water is procured from source i with method m in period t (in m^3), 0 otherwise
F_{im} 1 if any procurement from source i with method m is placed over the planning horizon, 0 otherwise

Objective function

$$Min\ z = \sum_t ci_t \cdot I_t + \sum_i \sum_m \sum_t cpv_{imt} \cdot Q_{imt} + \sum_i \sum_m \sum_t cpf_{imt} \cdot Y_{imt} + \sum_i \sum_m cf_{im} \cdot F_{im} \quad (1)$$

Subject to

$$I_t = I_{t-1} + \sum_i \sum_m Q_{imt} - d_t \qquad \forall t \qquad (2)$$

$$I_t \le IMAX_t \qquad \forall t \qquad (3)$$

$$I_t \ge IMIN_t \qquad \forall t \qquad (4)$$

$$\sum_m Q_{imt} \le CM_{it} \quad \forall i \forall t \qquad (5)$$

$$\sum_m Y_{imt} \le 1 \qquad \forall i \forall t \qquad (6)$$

$$Q_{imt} \le CM_{it}\ Y_{imt}\ \forall i \forall m \forall t \qquad (7)$$

$$\sum_m \sum_{t \in M_t^K} Q_{imt} \le CMT_{it} \qquad \forall i \qquad (8)$$

$$\sum_{t \in M_t^K} Y_{imt} \le CH_{im} \qquad \forall i \forall m \qquad (9)$$

$$I_t,\ Q_{imt} \in \mathrm{R} \qquad (10)$$

$$Y_{imt},\ F_{im} \in \{0, 1\} \qquad (11)$$

Equation (1) corresponds to the objective function of the addressed problem, which aims to minimize the total costs related to the procurement of water from the different sources, including fixed and variable costs, and also the inventory holding cost in the supplier tank. Constraint (2) expresses the inventory balance in the supplier tank while Constraints (3) and (4) establish the minimum and maximum possible levels in it, respectively. Constraint (5) limits the amounts to acquire from each source in each time period with respect to its maximum supply capacity. Constraint (6) imposes only one method for each source in each period. The activation of decision variable Y_{imt} when decision variable Q_{imt} is greater than 0 is enabled with Constraint (7). Constraints (8) and (9) correspond to the limitation of the monthly volume for each source and the time limitation for each source and method, respectively. Constraint (9) establishes the real values for decision variables I_t and Q_{imt} while Constraint (11) imposes the binary values for decision variables Y_{imt} and F_{im}.

4. Results and Discussion. Application in a real Spanish irrigation network

4.1. Case study

The present research analyzes a real irrigation network where the proposed model was applied. This water supply is located in a township of Alicante (Spain). The network supplies 260 hectares (Figure 2).

The most extended crop is vineyard, although there is a small area with oil trees. The water is accumulated in a reservoir with a maximum capacity of 550000 m^3. The topography varies between 590 and 380 m above sea level. The reservoir is located sufficiently high (610 m above the sea level) to guarantee the minimum pressure in all irrigation consumption points. The pipelines of the network are built on smelting, with diameters ranging between 550 and 80 mm. The installation has 65 multiuser hydrants, supplying to 110 irrigation points, connected to steel collector in the hydrant by polyethylene pipes.

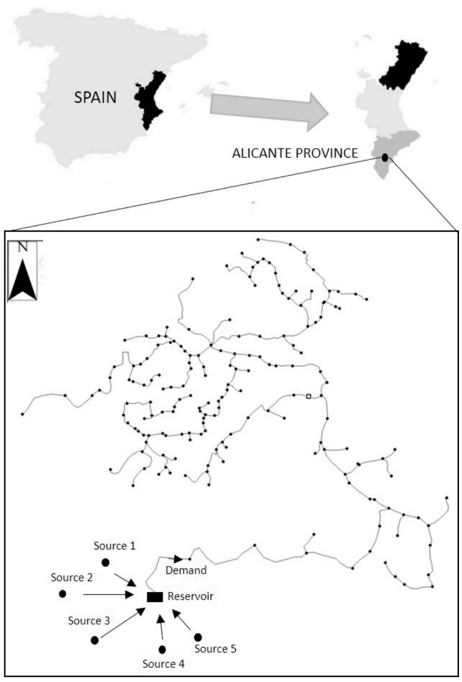

Fig. 2. Case study

When the research was developed, the manager and responsible of the procurement from the different sources used a heuristic procedure based on his experience and personal judgement supported by a spreadsheet. This kind of spreadsheet-based procedures often can lead to suboptimal results and important errors that may involve substantial costs [19, 20].

There were 5 possible sources to get the water resource to supply the farmer's demand. Sources and monthly demand are shown in Table 1. Sources 1 and 2 supplied resource since a external transfer to other basins. Source 3 corresponded to water resource from desalination and it had a high price, particularly 0.60 €/m^3. Sources 4 and 5 were related with water from different wells. To do so, the price was variable and depended on electric schedule that was divided on six periods from P1 (more expensive) to P6 (cheaper). Besides, each period considered the fixed electrical tariff (Table 17 in Appendix 1).

In contrast, the demand was registered by one flowmeter each hour, and the monthly cumulated volume are shown in Table 1. The set of data regarding to the application in this local Spanish supplier are shown in Table 13 to Table 17, in Appendix 1. The data related to demand in each period can be also found at the following link: http://personales.upv.es/ fcodiama/jestr/demand.txt. In this example, the considered time periods are 8760 (annual hours in 2018). Regarding the storage in the reservoir, a cost of 0.0003 euros/m^3 per hour is considered to determine the inventory cost. This cost is not real since it is a value to punish the storage in the management, when it is not necessary. Therefore, the inventory cost represents a mathematical tool to minimize the storage. The variation volume was considered between 44815 m^3 (minimum level to guarantee a stock) and 527407 m^3 (maximum used level). The initial inventory level at the beginning of the planning horizon has been 250000 m^3.

Table 1. Sources of the irrigation network

	Method	Price (€/m^3)	Demand Month	Volume (m^3)
Source 1	Fixed	0.25	January	39708
Source 2	Fixed	0.35	February	37062
Source 3	Fixed	0.60	March	39129
Source 4	Variable	–	April	56581
	P1	0.56	May	64441
	P2	0.50	June	60844
	P3	0.35	July	58777
	P4	0.30	August	58319
	P5	0.20	September	48152
	P6	0.12	October	29227
Source 5	Variable	–	November	20933
	P1	0.70	December	32581
	P2	0.65	Total	545755
	P3	0.49	–	–
	P4	0.42	–	–
	P5	0.35	–	–
	P6	0.25	–	–

The proposed model was implemented by using the modelling language MPL [21] and the corresponding resolutions were carried out with Gurobi solver version 7.0.1 [22] in a computer with a Inter Core i5 1.80 GHZ processor and 4 GB RAM memory. The maximum solution gap and the maximum CPU time were 1% and 300s, respectively.

Table 2 shows the results by the proposed model and those obtained by the current heuristic procedure that were applied in the water system. As confirmed by Table 2, the proposed model outperforms the current heuristic procedure based on the personal judgment and experience of the manager in the irrigation network. The table shows:

- Total water management costs: This cost represents the addiction of the final inventory costs, the procurement variable costs and the procurement fixed costs.
- Final inventory costs: This cost represents the price of the stored water that is inside of the reservoir in the hour equal to 8760 (last time period in the considered planning horizon).
- Procurement variable costs: This cost represents the price of the purchased water and it depends on selected source.
- Procurement fixed costs: This cost represents the fixed price that must be paid by the water manager when the source is pumped (Sources 4 and 5) according to electric tariff and schedule.

In this case, the main improvement is related to final inventory and variable procurement costs because it is a common practice for the water managers of these water systems to have the reservoir in maximum level although this volume is not necessary, and therefore, excessive in the majority of the time.

Table 2. Results obtained by the current procedure and the proposed model

	Current heuristic procedure (€)	Proposed model (€)
Total water management costs	128108.80	61181.31
Final inventory costs	52740.70	11203.75
Procurement variable costs	72168.09	46777.56
Procurement fixed costs	3200.00	3200.00

The proposed model reduces 52.2% the total water management costs when it is compared to current management. The difference of final stored volume between current management and proposed model is 166147.8 m^3. Therefore, it enables the reduction of the final inventory costs significantly.

4.2. Computational Experiments for Different Scenarios

In order to validate the proposed model, several experiments for different scenarios were carried out. Five set of scenarios were considered, and they were related to variations on the demand levels (d_{it}), the variations on sources capacities (CM_{it}, CMT_{it}, CH_{im}), the variations on maximum inventory capacity ($IMAX_i$), the increase of fixed procurement costs (cf_{im}) and the limitation of procurement methods in some sources. The description of the 30 experiments associated to these scenarios are shown from Table 3 to Table 7. The aim of these developed experiments is to know the costs oscillations when the variables (i.e., demand, capacity, source) change. This strategy to analyze the behaviour of the water system can be used in the decision making process of the water manager. This knowledge enables to define the management of future strategies in order to plan the water system. Some strategies can be the closed sources, management of the water storage in reservoir, defining the capacity of reservoir, among others.

Table 3. Experiments description for scenario 1

Experiment code	Description
S1D5	Decrement of 5% in demand levels
S1D10	Decrement of 10% in demand levels
S1D15	Decrement of 15% in

	demand levels
S1D20	Decrement of 20% in demand levels
S1I5	Increment of 5% in demand levels
S1I10	Increment of 10% in demand levels
S1I15	Increment of 15% in demand levels
S1I20	Increment of 20% in demand levels

Table 4. Experiments description for scenario 2

Experiment code	Description
S2D5	Decrement of 5% in procurement capacities
S2D10	Decrement of 10% in procurement capacities
S2D15	Decrement of 15% in procurement capacities
S2D20	Decrement of 20% in procurement capacities
S2I5	Increment of 5% in procurement capacities
S2I10	Increment of 10% in procurement capacities
S2I15	Increment of 15% in procurement capacities
S2I20	Increment of 20% in procurement capacities

Table 5. Experiments description for scenario 3

Experiment code	Description
S3D5	Decrement of 5% in maximum inventory capacity
S3D10	Decrement of 10% in maximum inventory capacity
S3D15	Decrement of 15% in maximum inventory capacity
S3D20	Decrement of 20% in maximum inventory capacity
S3I5	Increment of 5% in maximum inventory capacity
S3I10	Increment of 10% in maximum inventory capacity
S3I15	Increment of 15% in maximum inventory capacity
S3I20	Increment of 20% in maximum inventory capacity

Table 6. Experiments description for scenario 4

Experiment code	Description
S4I5	Increment of 5% in fixed procurement costs
S4I10	Increment of 10% in fixed procurement costs
S4I15	Increment of 15% in fixed procurement costs
S4I20	Increment of 20% in fixed procurement costs

Table 7. Experiments description for scenario 5

Experiment code	Description
S5E7	Elimination of procurement method 7 from sources 6 and 7
S6IE67	Elimination of procurement method 6 and 7 from sources 6 and 7

4.3. Results

Tables from 8 to 12 show the variable costs, fixed, final inventory and total water management costs for each experiment. In all experiments, the total water management costs was lower than the current management. Therefore, the analysis of these experiments in each scenario shows:

- The current water management can be improved reducing the total costs and therefore, increasing the farmers' profit. If the total water management costs is observed, its values were 52.2% lower than current costs. These values shows the management must be modified quickly.
- All scenarios only used the source 4 to supply the demand. If the results are deeply analyzed, the used schedule was P6 and the source was pumped on daily days (only in the night) and the weekend. The rest of periods (from P1 to P5) were not used to satisfy the demand.
- The current management (heuristic procedure) used a stored volume was the maximum (527407 m3), while the maximum stored volume were around 249990 m3
- The demand variations (scenario 1) don't have implications in the stored volume neither the used source. The variations of the cost was 50% at least. Therefore, the system can increase the irrigation area and users.
- The demand variations causes lineal variations in the total water management costs (Figure 3).
-

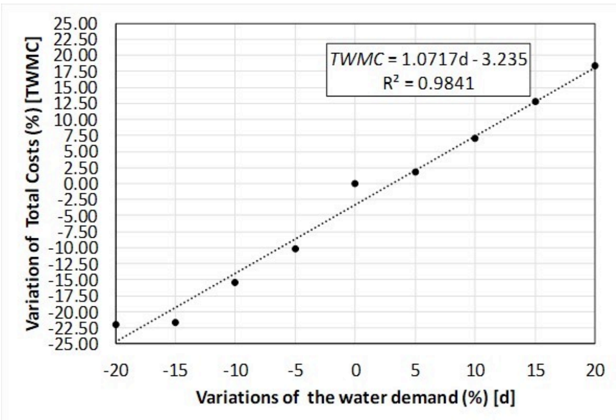

Fig. 3. Variation of the total water management costs as a function of the demand

- When the procurement capacities vary (scenario 2), the water system does not have any oscillation in the stored volume neither in the fixed procurement costs. The maximum variation of the total costs was 4.3%.
- Scenario 3 showed the capacity of the reservoir doesn't have influence in the water system operating, showing the reservoir is inflated.
- The increase of fixed procurement costs (scenario 4) doesn't affect in the selection of the source, minimizing the use of the different periods, particularly, the schedule P6.

Table 8. Results for scenario 1

	Total Water Management Costs (€)	Final Inventory Costs (€)	Procurement variable costs (€)	Procurement fixed costs (€)
S1D5	54966.16	11203.75	40562.41	3200.00
S1D10	51775.01	11203.75	37371.26	3200.00
S1D15	47955.06	11203.75	33551.32	3200.00
S1D20	47730.20	11203.75	33326.57	3200.00
S1I5	62310.85	11203.75	47907.11	3200.00
S1I10	65470.80	11203.75	51067.06	3200.00
S1I15	68961.95	11203.75	54558.20	3200.00
S1I20	72467.50	11203.75	58063.75	3200.00

Table 9. Results for scenario

	Total Water Management Costs (€)	Final Inventory Costs (€)	Procurement variable costs (€)	Procurement fixed costs (€)
S2D5	58591.71	11203.75	44187.96	3200.00
S2D10	58855.71	11203.75	44451.96	3200.00
S2D15	58942.11	11203.75	44538.36	3200.00
S2D20	59909.31	11203.75	45505.56	3200.00
S2I5	58363.71	11203.75	43959.96	3200.00
S2I10	58272.51	11203.75	43868.76	3200.00
S2I15	58442.91	11203.75	44039.16	3200.00
S2I20	61951.71	11203.75	47547.96	3200.00

Table 10. Results for scenario 3

	Total Water Management Costs (€)	Final Inventory Costs (€)	Procurement variable costs (€)	Procurement fixed costs (€)
S3D5	58447.71	11203.75	44043.96	3200.00
S3D10	58474.11	11203.75	44070.36	3200.00
S3D15	58469.31	11203.75	44065.56	3200.00
S3D20	58474.11	11203.75	44070.36	3200.00
S3I5	58464.51	11203.75	44060.76	3200.00
S3I10	58462.11	11203.75	44058.36	3200.00
S3I15	58476.51	11203.75	44072.76	3200.00
S3I20	58452.51	11203.75	44048.76	3200.00

Table 11. Results for scenario 4

	Total Water Management Costs (€)	Final Inventory Costs (€)	Procurement variable costs (€)	Procurement fixed costs (€)
S4I5	58638.91	228752.18	44075.16	3360.00
S4I10	58794.11	11203.75	44070.36	3520.00
S4I20	59138.11	11203.75	44094.36	3840.00
S4I30	59412.51	11203.75	44048.76	4160.00

Table 12. Results for scenario 5

	Total Water Management Costs (€)	Final Inventory Costs (€)	Procurement variable costs (€)	Procurement fixed costs (€)
S5E6	117170.00	11203.75	97666.25	8300.00
S5E67	120902.85	11203.75	105199.10	4500.00

5. Conclusions

The present research develops a mathematical programming tool that can be used to improve the water management in water systems, particularly, in irrigation systems. The analysis of previous researchers showed the need to develop it since the majority of the current systems is not operating under optimized conditions and they apply criterion related to use of the channel flow. Therefore, the use of this tool enables the reduction of costs and therefore, the increase of the margin in the farmers.

Besides, the use of the mathematical programming model allows water managers to differ- entiate the source that are necessary sources, and therefore, the water manager could define the strategies to manage the rest of source. This tool can also be used to define the electric schedule when the sources have to be pumped to reach the reservoir. This discretization is very important since there are some periods (e.g., P1, P2) that have high price to be used. Knowing the timetable previously enable to hire the correct schedule with the electric company and avoiding penalties of them when the water managers use periods that are not contracted.

The mathematical programming tool was successfully applied in a real irrigation network that is currently operating without support tool by the experience of the water manager and using criterion that are not adequate since they are out-dated. The use of this tool reduces the water costs in 52.2% as well as enables to define the necessary source and the electrical schedule along the year. This definition optimizes the operating of the water system and enables to reduce the water price from 0.23 €/m^3 (current water management) to 0.11 €/m^3 (proposed model).

Finally, to validate the mathematical model and knowing the variation of the water system when the variable changes, thirty experiments have been developed on five different scenarios. These experiments show the variability in the total water management cost, sources and sched- ule that should be considered to minimize the water costs. Therefore, the powerful of this tool has been demonstrated as well as its utility in the management of the irrigation water systems, contributing to do more sustainable these systems.

References

1. N.-S. Hsu, W.-C. Cheng, W.-M. Cheng, C.-C. Wei, W. W.-G. Yeh, Optimization and capacity expansion of a water distribution system, Advances in Water Resources 31 (2008) 776–786.
2. P. Rogers, Water is an economic good: How to use prices to promote equity, efficiency, and sustainability, Water Policy 4 (2002) 1–17.
3. L. Romero, M. Pérez-Sánchez, P. López-Jiménez, International Journal of, International Journal of Energy and Environment 8 (2017) 51–62.
4. G. Mendoza, H. Martins, Multi-criteria decision analysis in natural resource management: A critical review of methods and new modelling paradigms, Forest Ecology and Management 230 (2006) 1–22.
5. S. Suárez-Almiñana, M. Pedro-Monzonís, J. Paredes-Arquiola, J. Andreu, A. Solera, Linking Pan-European data to the local scale for decision making for global change and water scarcity within water resources planning and management, Science of the Total Environment 603-604 (2017) 126–139.
6. R. Warren, The role of interactions in a world implementing adaptation and mitigation solutions to climate change., Philosophical transactions. Series A, Mathematical, physical, and engineering sciences 369 (2011) 217–41.

7. F. A. Ward, M. Pulido-Velázquez, Efficiency, equity, and sustainability in a water quantity–quality optimization model in the Rio Grande basin, Ecological Economics 66 (2008) 23–37.
8. M. Pérez-Sánchez, F. Sánchez-Romero, H. Ramos, P. López-Jiménez, Energy Recovery in Existing Water Net- works: Towards Greater Sustainability, Water 9 (2017) 97.
9. S.-F. Kuo, G. P. Merkley, C.-W. Liu, Decision Support for Irrigation Project Planning Using a Genetic Algorithm, Agricultural Water Management 45 (2000) 243–266.
10. M. Diaz-Madroñero, J. Mula, B. Andres, R. Poler, S. Sanchis, Capacitated Lot-Sizing and Scheduling Problem for Second-Tier Suppliers in the Automotive Sector, Springer, Cham, 2018, pp. 121–129.
11. M. Díaz-Madroñero, D. Peidro, P. Vasant, Vendor selection problem by using an interactive fuzzy multi-objective approach with modified S-curve membership functions, Computers & Mathematics with Applications 60 (2010) 1038–1048.
12. M. Díaz-Madroñero, D. Peidro, J. Mula, A fuzzy optimization approach for procurement transport operational planning in an automobile supply chain, Applied Mathematical Modelling 38 (2014) 5705–5725.
13. J. Hegeman, D. Peidro, M. del Mar Alemany, M. Díaz-Madroñero, A Decentralized Production and Distribution Planning Model in an Uncertain Environment, Springer, Berlin, Heidelberg, 2014, pp. 317–353.
14. A. Bilbao-Terol, M. Arenas-Parra, V. Cañal-Fernández, Selection of socially responsible portfolios using goal programming and fuzzy technology 189 (2012) 110–125.
15. C. Alayet, N. Lehoux, L. Lebel, M. Bouchard, Centralized supply chain planning model for multiple forest companies, INFOR: Information Systems and Operational Research 54 (2016) 171–191.
16. M. Bazargan, Flight scheduling through optimizing flight block and ground times: A case study 21 (2015) 299–315.
17. R. Poler, J. Mula, M. Díaz-Madroñero, Linear Programming, in: Operations Research Problems, Springer London, London, 2014, pp. 1–48.
18. J. Corominas, Agua y Energía en el riego en la época de la sostenibilidad, Ingeniería del Agua 17 (2010) 219–233.
19. J. J. Caulkins, E. Morrison, T. Weidemann, Spreadsheet errors and decision making: evidence from field interviews, Journal of Organizational and End User Computing 19 (2007) 1–23.
20. A. C. Dzuranin, R. D. Slater, Business Risks All Identified? If You're Using a Spreadsheet, Think Again, Journal of Corporate Accounting & Finance 25 (2014) 25–30.
21. Maximal Software Incorporation, MPL Modeling System Release 5.0, 2016.
22. Gurobi Optimization Incorporation, Gurobi 7.0.1 (2017).

Annex 1

Table 13. Volume capacity for each source

i	CM_{it} (m^3/month)	CMT_i (m^3/period)
1	40000	120
2	500000	306
3	75000	324
4	75000	360
5	125000	450

Table 14. Time capacity for each available source and method

		CH_{im}											
i	***m***	***k* = 1**	***k* = 2**	***k* = 3**	***k* = 4**	***k* = 5**	***k* = 6**	***k* = 7**	***k* = 8**	***k* = 9**	***k* = 10**	***k* = 11**	***k* = 12**
4	2	132	120	0	0	0	0	286	0	0	0	0	126
4	3	220	200	0	0	0	0	66	0	0	0	0	210
4	4	0	0	126	0	0	126	0	0	120	0	126	0
4	5	0	0	210	0	0	210	0	0	200	0	210	0
4	6	0	0	0	336	336	0	0	0	0	352	0	0
4	7	392	352	408	384	384	384	392	744	400	392	384	456
5	2	132	120	0	0	0	0	286	0	0	0	0	126
5	3	220	200	0	0	0	0	66	0	0	0	0	210
5	4	0	0	126	0	0	126	0	0	120	0	126	0
5	5	0	0	210	0	0	210	0	0	200	0	210	0
5	6	0	0	0	336	336	0	0	0	0	352	0	0
5	7	392	352	408	384	384	384	392	744	400	392	384	456

Table 15. Acquiring method for each hour per month and weekends for source 4

Hour	***k* = 1**	***k* = 2**	***k* = 3**	***k* = 4**	***k* = 5**	***k* = 6**	***k* = 7**	***k* = 8**	***k* = 9**	***k* = 10**	***k* = 11**	***k* = 12**	***Weekend***
h1	7	7	7	7	7	7	7	7	7	7	7	7	7
h2	7	7	7	7	7	7	7	7	7	7	7	7	7
h3	7	7	7	7	7	7	7	7	7	7	7	7	7
h4	7	7	7	7	7	7	7	7	7	7	7	7	7
h5	7	7	7	7	7	7	7	7	7	7	7	7	7
h6	7	7	7	7	7	7	7	7	7	7	7	7	7
h7	7	7	7	7	7	7	7	7	7	7	7	7	7
h8	7	7	7	7	7	7	7	7	7	7	7	7	7
h9	3	3	5	6	6	5	3	7	5	6	5	3	7
h10	3	3	5	6	6	4	3	7	4	6	5	3	7
h11	2	2	5	6	6	4	3	7	4	6	5	2	3
h12	2	2	5	6	6	4	2	7	4	6	5	2	3
h13	2	2	5	6	6	4	2	7	4	6	5	2	2

h14	3	3	5	6	6	4	2	7	4	6	5	3	2
h15	3	3	5	6	6	4	2	7	4	6	5	3	2
h16	3	3	5	6	6	5	2	7	5	6	5	3	2
h17	3	3	4	6	6	5	2	7	5	6	4	3	3
h18	3	3	4	6	6	5	2	7	5	6	4	3	3
h19	2	2	4	6	6	5	2	7	5	6	4	2	3
h20	2	2	4	6	6	5	2	7	5	6	4	2	3
h21	2	2	4	6	6	5	2	7	5	6	4	2	2
h22	3	3	4	6	6	5	2	7	5	6	4	3	2
h23	3	3	5	6	6	5	2	7	5	6	5	3	2
h24	3	3	5	6	6	5	2	7	5	6	5	3	2

Table 16. Acquiring method for each hour per month and weekends for source 5

Hour	***k* = 1**	***k* = 2**	***k* = 3**	***k* = 4**	***k* = 5**	***k* = 6**	***k* = 7**	***k* = 8**	***k* = 9**	***k* = 10**	***k* = 11**	***k* = 12**	***Weekend***
h1	7	7	7	7	7	7	7	7	7	7	7	7	7
h2	7	7	7	7	7	7	7	7	7	7	7	7	7
h3	7	7	7	7	7	7	7	7	7	7	7	7	7
h4	7	7	7	7	7	7	7	7	7	7	7	7	7
h5	7	7	7	7	7	7	7	7	7	7	7	7	7
h6	7	7	7	7	7	7	7	7	7	7	7	7	7
h7	7	7	7	7	7	7	7	7	7	7	7	7	7
h8	7	7	7	7	7	7	7	7	7	7	7	7	7
h9	3	3	5	6	6	5	3	7	5	6	5	3	7
h10	3	3	5	6	6	4	3	7	4	6	5	3	7
h11	2	2	5	6	6	4	3	7	4	6	5	2	3
h12	2	2	5	6	6	4	2	7	4	6	5	2	3
h13	2	2	5	6	6	4	2	7	4	6	5	2	2
h14	3	3	5	6	6	4	2	7	4	6	5	3	2
h15	3	3	5	6	6	4	2	7	4	6	5	3	2
h16	3	3	5	6	6	5	2	7	5	6	5	3	2
h17	3	3	4	6	6	5	2	7	5	6	4	3	3
h18	3	3	4	6	6	5	2	7	5	6	4	3	3
h19	2	2	4	6	6	5	2	7	5	6	4	2	3
h20	2	2	4	6	6	5	2	7	5	6	4	2	3
h21	2	2	4	6	6	5	2	7	5	6	4	2	2
h22	3	3	4	6	6	5	2	7	5	6	4	3	2
h23	3	3	5	6	6	5	2	7	5	6	5	3	2
h24	3	3	5	6	6	5	2	7	5	6	5	3	2

Table 17. Variable and fix procurement costs for each source and method

i	***m***	cpv_{imt} **(euros/m^3)**	cpf_{imt} **(euros/procurement)**	cf_{im} **(euros/year)**
1	1	0.25	5.00	-
2	1	0.35	7.00	-
3	1	0.60	12.00	-
4	2	0.56	11.20	7200
4	3	0.50	10.00	6000
4	4	0.35	7.00	5200
4	5	0.30	6.00	4500
4	6	0.20	4.00	3800
4	7	0.12	2.40	3200
5	2	0.70	14.00	8500
5	3	0.65	13.00	7300
5	4	0.49	9.80	5800
5	5	0.42	8.40	4900
5	6	0.35	7.00	4250
5	7	0.25	5.00	3600