American Journal of Sciences and Engineering Research www.iarjournals.com

American Journal of Sciences and Engineering Research

E-ISSN - 2348 -703X, Volume 4, Issue 4, 2021

Pareto Optimization for Alleviating Water Conflicts Between Urban and Agriculture Sectors Subject to Water Rights

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Abstract: *A quantitative management model, which allows for an assessment of water allocation between agricultural and municipal needs based on water rights and demand, is proposed. The model is based on a pareto optimization procedure that can be shared between the municipal and agriculture sectors. The model refers to the water rights of the sectors, just as one would refer to an investment portfolio. The investing sector receives more utility from the right to larger amounts of water and suffers from uncertainties associated with water supply. The model is based on the work of Markowitz (1952), which constructs a risk-diversified investment portfolio by building an Optimal Pareto (OP) combination for the rights of the two main sectors. Subsequently, a simulation model was run and utilized to evaluate an optimal solution, including a sensitivity analysis. The simulations showed that the likelihood of demonstrating combined rights could serve as a Pareto Optimization as long as the solution increased as follows: (i) the distress of the water economy increased (i.e., the larger the municipal demand, the larger is the proportion of the expected groundwater recharge); (ii) the water capacity of the reservoir decreased, and; (iii) the risk aversion of the two sectors increased.*

Key words: Pareto optimization; Agricultural sector; Municipal sector; Water rights; Water storage.

I. Introduction

The issues of water resources are strongly linked to two competing water sectors: the agriculture sector and the urban sector, and are also related to economic policies, primarily in water-scarce regions [1,2], which highlight the problem of water scarcity subject to availability and attempts to solve the problem by applying the "Modern Portfolio Theory" [3,4]. The "Portfolio" model has been applied to the Murray-Darling Basin region of Australia. Other sectors that must be considered include the industrial sector, animal needs,

 Received-12-07-2021, Accepted- 19-07-2021

green purposes, tourism, and clean energy. Agriculture is typically the largest water consumer in most countries, ranging from approximately 60% to approximately 90% of the total potential production of high-quality water [5,6]. Although the share of agricultural output in national production is gradually decreasing in most countries; however, the related water requirements still play an important role in the economy of most countries. Similar assumptions are mainly applicable to countries that are located in arid and semi-arid regions and areas, which are frequently subject to droughts [7-10].

In most countries, water allocation mainly refers to the legal rights to water supply [11,12]. However, it is also vulnerable to drought hydrological events associated with the existing water potential in the country [13-17]. Water scarcity is due to excessive and uncontrolled water extraction from aquifers, population growth, economic development, and reduced natural recharge, which is caused by climate changes and urbanization processes [18-20] (e.g., expanded paved roads in urban areas). Hence, the national decision-making level faces issues related to the ongoing struggle between the urban and agricultural sectors regarding water distribution patterns, legal rights to distribution, and related economic implications [21-24].

Water allocation across various sectors in each country is usually based on the country's Water Rights (WR) [24, 25, 26]. Water rights are based on the heritage of previous generations and/or historical events [27, 28]. The implementation of the water rights policy is an efficient way to promote water allocation among consumers and consequently its' efficient utilization [2, 29, 30]. Water rights may also be associated with a reduction in agricultural production due to the reduction in irrigated areas. However, adequate decisions, on the other hand, may increase agricultural production depending on the smart and logical use of the virtual water that is "stored" in the banks (e.g., aquifers). In situations of abundant water resources, these rights and the related water allocations for all quotas can be easily achieved [31]. Problems arise when the total amount of water available is insufficient and national authorities must decide how to allocate water subject to the rights.

A decision support model is proposed for Optimal Pareto (OP) allocation of water, which is linked to scarcity and is subject to WR [26, 32-38]. The proposed model provides a logical support tool for national authorities to allocate the limited amount of water available. The novelty of this work stems from the option of allowing decision-making subject to the WR between the two main competing sectors - agriculture (including nature reserves and other "green" purposes) and municipals (including the industry) [39]. To some extent, the developed model can be compared to the hydro-economic models developed by Borrege-Martin et al., (2020) [40] for the Guadalquivir River Basin region (Southern Spain), Colombia [41] and the Yellow River Basin in China [42]. In most countries, industrial water requirements are around 5% of the total potential [43]. The prevailing trend in developed countries is to allocate water to the municipal sector rather than to the agricultural sector. It stems from the fact that the municipal sector puts water in the first place and the agricultural sector puts it in the second one (the residual).

The model developed here within quantifies the initial rights of the two sectors and examines under the existing conditions whether the water economy has reached the OP point, or whether it is necessary to create an updated combination of rights so as to arrive at this equilibrium.

The assumption made here is that water rights can be treated as a Portfolio Investment (PI). Water resources problems can be simulated by PI and then efficiently analyzed via economic tools [44] (Table 1). This combined economic–engineering approach has been mentioned in the past but has received only limited attention [45-46]. The model is based on the diversification of risk [3]. We also used a utility function as demonstrated by Bodie et al. (2002) [47]. The utility function was used to quantify the damage stemming from water supply uncertainty, while estimating uncertainty by variance (σ^2). The problem of water supply uncertainty is a universal issue discussed by Finch (1998) [48] in Britain, Ritchie et al., (2004) [49] in Australia and Meinzen-Dick (2014) [50] in Italy.

Table 1. **Comparative characteristics of water right allocation problems versus investment portfolio**

Parameter	**Investment Portfolio problem ("Markovitz model", 1952)**	**Water rights allocation problem**
Expectancy	Expectancy (percent) of the return on the investment portfolio	Expectancy (percent in absolute water amounts) of water rights of each sector
Standard deviation	Standard deviation in the expectancy of the Investment Portfolio (return given in percent)	Standard deviation in water rights of each sector (absolute water amounts)
Correlation coefficient	Correlation coefficient between returns of two investments	Correlation between water amounts allocated to each sector
The proportion of the asset - α	Proportion of return of the second asset in the portfolio	Proportion of water rights allocated to agriculture

The second section proposes two models: (i) water systems without storage, where all rainwater is consumed by both sectors, and (ii) water systems with storage, where the aquifers are recharged and are also the source of water supply for the two main sectors [51]. The third section of the paper simulates optimal solutions via a combination of rights, including sensitivity analyses for OP solutions, where the main variables are municipal water demand, the level of risk aversion in both sectors and the related storage volumes [52]. It is based on the shadow price analysis, similar to other works [53]. The means of reducing the demand for water agricultural production depends on the technical efficiency improvements and the policy of water-saving application techniques where for example drip irrigation has many advantages over sprinkler irrigation.

II. The Pareto Optimization Model

2.1 General

The goal of the proposed model is to define in quantitative terms the water rights that will improve water allocation policies in at least one of the sectors [36, 54]. Water allocation will be maintained without causing damages in other sectors until OP equilibrium is reached. There is often a tendency for designers in developed countries to adapt in the following order of priority: (i) the first preference for water use is allocated to the municipal sector; (ii) a second preference is given to the industry (in this case, it is part of the municipal sector); (iii) the agriculture sector obtains the third preference, and; (iv) other purposes, such as "green" purposes. To simplify the model, only the two primary sectors are considered, with the municipal sector having the first preference and the agricultural sector having the second (residual) preference. The conclusion is that the agricultural sector receives, annually, the residual water after allocation has been granted to the municipal sector.

As mentioned earlier, the OP model is based on the Markowitz model [3]. The Markowitz model demonstrates the effectiveness of risk diversification when creating an investment portfolio containing selected stocks with a correlation coefficient of less than one. The application of the Markowitz model is conducted through the utility function, as described by Bodie et al. (2002) [47]. Bodie et al. (2002) [47] utilized a fractional concept of a kind of theoretical data, whereas in real life, the problems of water resources consider real-life values.

The proposed model consists of two parts without and with storage (Sections 2.2 and 2.3). The models are based on the following assumptions:

1) The water quality is in agreement with uniform standards (drinking water quality).
2) Both sectors are risk-averse and aim at maximizing the utility of the water rights. This assumption is made despite the existence of multiple options involving risk: indifference or in an affinity manner.
3) The model does not refer to water prices, but only to the quantity of rights allocated to each sector.
4) The preferred water rights are an asset of the municipal sector and the residual water is allocated to the agricultural sector.
5) Water desalination is not considered.
6) There is no change in water demand over time (years).
7) The expected value and variance of groundwater recharge is constant over time.
8) The recharged groundwater is fully utilized by both sectors each year (this assumption will change in the second part of the model when it refers to the existence of water storage).
9) The model ignores the utility stemming from the amount of water that remains in the reservoir at the end of the planned horizon (i.e., this is addressed only in the model that includes storage).

2.2 A Model without Storage

2.2.1 Implementation of the Markowitz Model (1952)

The model begins by describing a method of allocating water in accordance with water rights, and with the municipal sector getting the first preference. The annual (potential) groundwater recharge for the country is indicated by R_t, which is assumed to be a random parameter with a normal distribution, a mean expected value of μ and a variance of σ_μ^2.

Water allocation is expressed in Million Cubic Meters per Year (MCMY):

$$R_t \sim N(\mu, \sigma_\mu^2) \tag{1}$$

It is assumed that the municipal sector requires a fixed amount of water each year, which is given by MUN^D (MCMY). The annual allocation of water to the municipal sector in year t (MUN_t) (given by MCMY) is as follows:

$$MUN_t = MUN^D \quad \text{if} \quad MUN^D \leq R_t \tag{2a}$$

or

$$MUN_t = R_t \quad \text{if} \quad R_t < MUN^D \tag{2b}$$

Similarly, the annual amount of water allocated to agriculture is given by AGR_t (based on MCMY):

$$AGR_t = R_t - MUN^D \quad \text{if} \quad MUN^D \leq R_t \tag{3a}$$

or

$$AGR_t = 0 \quad \text{if} \quad R_t < MUN^D \tag{3b}$$

The water rights for each sector are given by the expected value (mean) and the variance of the water quantity rights. The analysis utilizes a planning horizon of t years. E_{MUN} denotes the expected value for the municipal sector and E_{AGR} denotes the expected value for the agricultural sector. The municipal sector variance is denoted by σ^2_{MUN} and the agricultural sector variance is denoted by σ^2_{AGR} . The assumption made in this work is that a linear combination of water rights will improve the situation in at least one of the sectors without damaging the second sector (OP).

The water rights of the two sectors (municipal and agricultural) are expressed by the expected value and the water variance allocated to each sector. The parameter α (dimensionless, $0 \leq \alpha \leq 1$) is defined to express the proportion of water rights attributes and belongs to the agricultural sector. When one sector has a water right α, the other sector will have (*1*- α) of that water right. For example, when α = 0 for the agricultural sector, the municipal sector possesses exclusive rights, while when α = 1 for the agricultural sector, it implies that all rights are allocated to the agricultural sector. The expectations of the sectors having a linear combination of rights are as follows [using the notations E_{MUNP} and E_{AGRP} such that P (portfolio) indicates the expectations in the case of a combination of rights]:

$$E_{MUNP} = (1-\alpha)\, E_{MUN} + \alpha\, E_{AGR} \tag{4}$$

$$E_{AGRP} = \alpha\, E_{MUN} + (1-\alpha)\, E_{AGR} \tag{5}$$

The parameter ρ_{MA} indicates the correlation coefficient between the quantities allocated to the two sectors in year t. The variances of the sectors are as follows [using the notations σ^2_{MUNP} and σ^2_{AGRP}, where P [in the subscripts of the variance equations (6) and (7)] indicates the variance in the case of a combination of rights]:

$$\sigma^2_{MUNP} = (1-\alpha)^2\, \sigma^2_{MUN} + \alpha^2\, \sigma^2_{AGR} + 2(1-\alpha)\, \alpha\, \rho_{MA}\, \sigma_{AGR}\, \sigma_{MUN} \tag{6}$$

$$\sigma^2_{AGRP} = \alpha^2 \sigma^2_{MUN} + (1-\alpha)^2\, \sigma^2_{AGR} + 2\,(1-\alpha)\, \alpha\, \rho_{MA}\, \sigma_{AGR}\, \sigma_{MUN} \tag{7}$$

2.2.2 Model Demonstration via the Use of Utility Functions

To quantify the benefits of each sector, the utility function according to [47] will be applied to both sectors (for simplicity, it is assumed that the utility functions are similar in both sectors). Actually, the utility function U has three variables: expected value (E), variance (σ^2), and a variable representing the right to receive water (X) (each variable has a positive coefficient). The utility-related function is given by the following equation:

$$U = CX + YE - A\sigma^2 \qquad (8)$$

where U is the utility function stemming from the water rights, E is the expected value of the amount of water, σ^2 is the variance of the water supply, and X represents the right to receive a specific amount of water. When E > 0, water rights are received, thus X = 1, otherwise X = 0. It is similar to the principle of the Beneficial Use Test (BUT), which has been established by the US Courts as one of the main criteria for upholding water rights [55-56]. According to this test, it is possible to negotiate a user's water rights if no beneficial service is used. An additional legal subject along this line is under the heading of "Use it" or "Lose it" factor [13].

It is necessary to confirm that no negative utility of water rights is obtained for the coefficients "Y", "A" and "C" in equation (8) (since such type of utility function may produce negative utility values). "A" is the risk aversion coefficient of water distribution between the two sectors. For any other condition, equation (9) must be satisfied:

$$C > A\sigma^2 - E \qquad (9)$$

The focus in current work will be on improving the situation of these sectors, in relation to their starting point, without reference to a situation where there are no rights at all. According to the signs of the equation, it can be observed that the higher the expectancy, the greater is the utility. On the other hand, the higher the value of the variance, the smaller the utility. Likewise, the utility increases in accordance with the right to receive water. These conditions are given by equations (10) to (12):

$$dU/dE > 0 \qquad (10)$$

$$dU/d\sigma^2 < 0 \qquad (11)$$

$$dU/dX > 0 \quad (12)$$

Since the utility function is identical for both sectors, it can obtain an OP, subject to a constraint on the linear combination of rights and the following set of equations:

$$\text{Max:} \quad U_{MUNP} = E_{MUNP} - A\,\sigma^2_{MUNP} \quad (13)$$

ST

$$E_{MUNP} = (1-\alpha)\,E_{MUN} + \alpha\,E_{AGR} \quad (4)$$

$$\sigma^2_{MUNP} = (1-\alpha)^2\,\sigma^2_{MUN} + \alpha^2\,\sigma^2_{AGR} + 2(1-\alpha)\,\alpha\,\rho_{MA}\,\sigma_{AGR}\,\sigma_{MUN} \quad (6)$$

The purpose of the model is to evaluate the factor α that maximizes the U_{MUNP} variable. The maximum utility of the municipal sector can be obtained by substituting the two constraints, E_{MUNP} and σ^2_{MUNP}, in the objective function to obtain the value of α. It should be noted that since the utility functions of both sectors are identical, both sectors (municipal and agricultural sectors) will share rights in complementary proportions when $\alpha^* > 0.5$ (α^* is the value of the optimal solution). Consequently, the acquired utility will become the utility of the agricultural sector. This implies that when $\alpha^* > 0.5$, then optimal allocation will be obtained at the point $(1-\alpha^*)$.

2.3 A Model with Storage

A model with storage describes and exemplifies a method for distributing water based on water rights, where the municipal sector takes precedence over the agricultural sector. Let us make the assumption that there exists a given fixed water storage volume, RES_{MAX} (see Assumption 8 in section 2.1). It can also be assumed that the municipal demand is given by MUN^D and the agricultural demand is given by AGR^D:

$$AGR^D = \mu - MUN^D \quad (14)$$

Furthermore, $RESB_t$ is assumed to be the water storage volume at the beginning of period t, while $RESE_t$ is water storage volume at the end of period t. The quantity of water in the storage at the beginning of time period t is equal to the quantity of water contained at the end of time period t-1. At time period t = 0, the storage space is empty:

$$RESB_t \equiv RESE_{t-1} \quad (15)$$

The water supply for each period is given by S_t:

$$S_t = RESB_t + R_t \tag{16}$$

Based on these three situations, several conditions can be identified (in a period where $RES_{MAX} < RESE_t$ has a storage volume constraint that is effective, so $RESE_t = RES_{MAX}$):

a) The supply of water is greater than the sum of the demands of the two sectors:

$$S_t \geq MUN^D + AGR^D \tag{17}$$

In this case, the following are given:

$$MUN_t = MUN^D \tag{18}$$

$$AGR_t = AGR^D \tag{19}$$

$$RESE_t = S_t - MUN^D - AGR^D \tag{20}$$

b) The supply is greater than the municipal demand, but it is insufficient for both sectors:

$$S_t \geq MUN^D \quad \text{and} \quad S_t < MUN^D + AGR^D \tag{21}$$

In this case, the following conditions are satisfied:

$$MUN_t = MUN^D \tag{22}$$

$$AGR_t = 0 \tag{23}$$

$$RESE_t = S_t - MUN^D \tag{24}$$

c) The supply is less when the municipal demand is given by:

$$S_t < MUN^D \tag{25}$$

In this case, the following equilibria are given by:

$$MUN_t = S_t \tag{26}$$

$$AGR_t = 0 \tag{27}$$

$$RESE_t = S_t - MUN^D \tag{28}$$

To illustrate the water allocation policy, it will be arbitrarily assumed that μ = 1,600 (MCMY), t = 5 (years), MUN^D = 1,000 (MCMY) and RES_{MAX} = 250 (MCMY). A numerical example based on the above assumptions is given in Table *2*.

Table 2

Numerical example for the water allocation methodology (R-recharge of groundwater; S-storage)

(1) Period t (years)	(2) Municipal Water Demand MUN^D (MCMY)	(3) Agriculture Water Demand AGR^D (MCMY)	(4) Water Storage Volume at the Beginning of Period t $RESB_t$ (MCM)	(5) The annual (potential) Recharge of Groundwater R_t (MCMY)	(6) The annual Supply of Water S_t (MCMY)	(7) The Annual Allocation of Water to the Municipal Sector MUN_t (MCMY)	(8) The Annual Allocation of Water to the Agriculture Sector AGR_t (MCMY)	(9) Water Storage Volume at the End of Period t $RESE_t$ (MCM)
1	1,000	600	0	1,800	1,800	1,000	600	200
2	1,000	600	200	1,400	1,600	1,000	600	0
3	1,000	600	0	1,100	1,100	1,000	100	0
4	1,000	600	0	900	900	900	0	0
5	1,000	600	0	2,000	2,000	1,000	600	250

It can be observed from Table 2 that the storage capacity at the beginning of the second year is 200 MCMY, the recharge is 1,400 MCMY, and the supply is 1,600 MCMY, and is based on the demand of the two sectors (1,000 MCMY and 600 MCMY), there will be no residual storage space left by the end of the year.

III. Results and discussion

3.1 Simulation of the model without Storage

To demonstrate the Pareto Optimization (PO) equilibrium, a one-time simulation model was tested for a planning horizon of 50 years (t = 50 years). The potential groundwater recharge (R - MCMY) was assumed to be normally distributed with a mean value of 1,600 MCMY and a standard deviation of 500 MCMY [$R \sim N(1{,}600, 500^2)$]. In this simulation, the expected value of R is given by ER as 1,637 MCMY with a standard deviation (SD) of 538 (MCMY). To prevent situations of negative utility due to water allocation rights, the coefficient of the general water rights [Equation (8)] was set to C = 30,000 and the expectation coefficient in the utility function was set to Y = 1 (Since for both sectors E > 0, thus X = 1 and therefore the intercept of the function for both sectors is 30,000). The risk aversion coefficient was checked for three scenarios: (i) A = 0.03; (ii) A = 0.04, and; (iii) A = 0.05. Three municipalities were tested for different water demands: (a) MUN^D = 1,000 MCMY; (b) MUN^D = 1,250 MCMY, and; (c) MUN^D = 1,500 MCMY. An increase in MUN^D is associated with greater economic water stress (Table 3).

It was found that the situations of both sectors improved only under conditions of water stress (MUN^D = 1,500 MCMY) and combined rights (α > 0). For an adequate analysis of the differences (Table 3), columns 8 and 9 are compared with columns 11 and 12, respectively: α increases along with a higher risk aversion of the sectors (Table 3: α > 0 for all MUN^D = 1,500 MCMY).

Table 3. **Simulation results of the model without storage [U_{MUN} and U_{AGR} are the utilities before Optimal Pareto equilibrium, where U_{MUNP} and U_{AGRP} are the utilities after Optimal Pareto equilibrium]**[1]

(1) Coeffie. of Risk Aversion of The Sectors	(2) Municipal Water Demand	(3) Expectancy Water Allocation of the Municipal Sector	(4) Expectancy Water Allocation of the Agriculture Sector	(5) SD Water Allocation of the Municipal Sector	(6) SD Water Allocation of the Agriculture Sector	(7) Correl. Coeffie. Between Amounts of Water Allocated to the Sectors	(8) Utility of Municipal Sector Before OP	(9) Utility of Agricul. Sector Before OP	(10) OP Prop. of Water Rights Belonging To the Agriculture Sector	(11) Utility of the Municipal Sector After OP	(12) Utility of the Agricul. Sector After OP
A	MUN^D (MCMY)	E_{MUN} (MCMY)	E_{AGR} (MCMY)	SD_{MUN} (MCMY)	SD_{AGR} (MCMY)	ρ_{MA}	U_{MUN}	U_{AGR}	α*	U_{MUNP}	U_{AGRP}
0.03	1,000	966	671	1,221	478	0.39	30,518	23,818	0	30,518	23,818
0.03	1,250	1,168	469	193	419	0.47	30,057	25,202	0	30,057	25,202
0.03	1,500	1,338	300	276	340	0.52	29,048	26,829	0.11	29,083	27,351
0.04	1,000	966	671	1,221	478	0.39	30,369	21,533	0	30,369	21,533
0.04	1,250	1,168	469	193	419	0.47	29,687	23,446	0	29,687	23,446
0.04	1,500	1,338	300	276	340	0.52	28,285	25,672	0.16	28,377	26,576
0.05	1,000	966	671	1,221	478	0.39	30,220	19,249	0	30,220	19,249
0.05	1,250	1,168	469	193	419	0.47	29,316	21,691	0	29,316	21,691
0.05	1,500	1,338	300	276	340	0.52	27,522	24,515	0.18	27,680	25,773

1) When α* > 0.5 it is written (1- α*) as α

Table 4.

Simulation Results of the Model Including a Maximum Storage Volume of 250 MCMY

(1) Coeffien. of Risk Aversion of the Sectors	(2) Mun. Water Demand	(3) Agr. Water Demand	(4) Expectancy Water Allocation of the Municipal Sector	(5) Expectancy Water Allocation of the Agriculture Sector	(6) SD Water Allocation of the Municipal Sector	(7) SD Water Allocation of the Agricult. Sector	(8) Correl. Coeffien. Between Amounts of Water Allocated to the Sector	(9) Utility of Municip. Sector Before OP	(10) Utility of Agricul. Sector Before OP	(11) OP Prop. of Water Rights Belonging To the Agricultu. Sector	(12) Utility of the Municipal Sector After OP	(13) Utility of the Agricultu. Sector After OP
A	MUN^D (MCMY)	AGR^D (MCMY)	E_{MUN} (MCMY)	E_{AGR} (MCMY)	SD_{MUN} (MCMY)	SD_{AGR} (MCMY)	ρ_{MA}	U_{MUN}	U_{AGR}	α^*	U_{MUNP}	U_{AGRP}
0.03	1,000	600	980	476	76	206	0.62	30,809	29,199	0	30,809	29,199
0.03	1,250	350	1,198	258	142	143	0.67	30,597	29,644	0	30,597	29,644
0.03	1,500	100	1,388	68	224	45	0.75	29,881	30,006	0.44	30,211	30,225
0.04	1,000	600	980	476	76	206	0.62	30,752	29,855	0	30,752	29,855
0.04	1,250	350	1,198	258	142	143	0.67	30,397	29,439	0	30,397	29,439
0.04	1,500	100	1,388	68	224	45	0.75	29,378	29,986	0.3	29,866	30,115
0.05	1,000	600	980	476	76	206	0.62	30,695	28,347	0	30,695	28,347
0.05	1,250	350	1,198	258	142	143	0.67	30,197	29,234	0	30,197	29,234
0.05	1,500	100	1,388	68	224	45	0.75	28,876	29,965	0.21	29,404	30,044

3.2 Simulation of the Model Including Storage

Additional simulation tests included the amount of water stored in the system. The three volumes examined were RES_{MAX} = 250 MCMY, RES_{MAX} = 500 MCMY and RES_{MAX} = 750 MCMY. Tables 4 to 6 present the results for each of the given maximum storage volumes.

Table 5.

Simulation Results of the Model Including a Maximum Storage Volume of 500 MCMY

(1) Coefficient of Risk Aversion of the Sectors	(2) Municipal Water Demand	(3) Agriculture Water Demand	(4) Expectancy Water Allocation of the Municipal Sector	(5) Expectancy Water Allocation of the Agriculture Sector	(6) SD Water Allocation of the Municipal Sector	(7) SD Water Allocation of the Agriculture Sector	(8) Correl. Coefficient Between Amounts of Water Allocated to the Sectors	(9) Utility of Municipal Sector Before OP	(10) Utility of Agricul. Sector Before OP	(11) OP Prop. of Water Rights Belonging To the Agriculture Sector	(12) Utility of the Municipal Sector After OP	(13) Utility of the Agricu. Sector After OP
A	MUN^D (MCM/y)	AGR^D (MCM/y)	E_{MUN} (MCM/y)	E_{AGR} (MCM/y)	SD_{MUN} (MCM/y)	SD_{AGR} (MCM/y)	ρ_{MA}	U_{MUN}	U_{AGR}	α^*	U_{MUNP}	U_{AGRP}
0.03	1,000	600	991	506	35	183	0.74	30,953	29,500	0	30,953	29,500
0.03	1,250	350	1,217	279	102	125	0.71	30,904	29,809	0	30,904	29,809
0.03	1,500	100	1,423	73	177	44	0.72	30,488	30,015	0.14	30,501	30,160
0.04	1,000	600	991	506	35	183	0.74	30,941	29,165	0	30,941	29,165
0.04	1,250	350	1,217	279	102	125	0.71	30,799	29,652	0	30,799	29,652
0.04	1,500	100	1,423	73	177	44	0.72	30,177	29,996	0.4	30,315	30,277
0.05	1,000	600	991	506	35	183	0.74	30,929	28,830	0	30,929	28,830
0.05	1,250	350	1,217	279	102	125	0.71	30,695	29,495	0	30,695	29,495
0.05	1,500	100	1,423	73	177	44	0.72	29,865	29,976	0.45	30,186	30,197

Table 6. **Results of the Model Including a Maximum Storage Volume of 750 MCMY**

(1) Coefficient of Risk Aversion of the Sectors	(2) Mun. Water Demand	(3) Agriculture Water Demand	(4) Expectancy Water Allocation of the Municipal Sector	(5) Expectancy Water Allocation of the Agriculture Sector	(6) SD Water Allocation of the Municipal Sector	(7) SD Water Allocation of the Agriculture Sector	(8) Correl. Coefficient Between Amounts of Water Allocated to the Sectors	(9) Utility of Municipal Sector Before OP	(10) Utility of Agricu. Sector Before OP	(11) OP Prop. of Water Rights Belonging to the Agriculture Sector	(12) Utility of the Municip. Sector After OP	(13) Utility of the Agricu. Sector After OP
A	MUN^D (MCM/y)	AGR^D (MCM/y)	E_{MUN} (MCM/y)	E_{AGR} (MCM/y)	SD_{MUN} (MCM/y)	SD_{AGR} (MCM/y)	ρ_{MA}	U_{MUN}	U_{AGR}	α^*	U_{MUNP}	U_{AGRP}
0.03	1,000	600	995	528	28	162	0.54	30,971	29,746	0	30,971	29,746
0.03	1,250	350	1,229	294	78	116	0.69	31,049	29,888	0	31,049	29,888
0.03	1,500	100	1,444	79	147	40	0.75	30,801	30,030	0	30,801	30,030
0.04	1,000	600	995	528	28	162	0.54	30,963	29,485	0	30,963	29,485
0.04	1,250	350	1,229	294	78	116	0.69	30,989	29,753	0	30,989	29,753
0.04	1,500	100	1,444	79	147	40	0.75	30,586	30,014	0	30,586	30,014
0.05	1,000	600	995	528	28	162	0.54	30,955	29,224	0	30,955	29,224
0.05	1,250	350	1,229	294	78	116	0.69	30,929	29,618	0	30,929	29,618
0.05	1,500	100	1,444	79	147	40	0.75	30,372	29,998	0.24	30,412	30,217

Of the 27 cases presented in Tables 4 to 6, it was possible to identify 7 cases where the combined rights reached an OP equilibrium. Similarly, for the simulated case presented without storage only under stress conditions (MUND = 1,500 MCMY), improved combined rights were reached for both sectors ($\alpha > 0$). For the maximum volume storage of 750 MCMY, only one case was identified in which the Pareto-Optimal equilibrium was not previously reached [last row of Table 6 ($\alpha > 0$)]. This is in contrast to situations with smaller storage volumes (250, 500 MCMY). Under these conditions, three cases for each storage volume can be envisioned.

IV. Conclusions

This work highlights the optimization and decision-making issues that are subject to uncertainties. The model considers employing an operational process that is applicable to the actual information and available technologies and is based on the Optimal-Pareto algorithm. Within the framework of the optimization procedure, a series of criteria such as water rights are considered. The objective of this work is to optimize the allocation of water to the agricultural and urban sectors under stress conditions.

A novel heuristic algorithm that combines the Optimal-Pareto algorithm and niche availability techniques is presented. From the simulation results, it is possible to identify the probability that the combining rights will lead to an OP solution. The OP solution increases subject to the following conditions: (i) the higher the degree to which the economy is in a state of distress (i.e., the greater the municipal demand as a proportion of the expected groundwater recharge); (ii) as the reservoirs become smaller, and; (iii) as the risk aversion of the sectors increases. Therefore, for countries in such circumstances, consideration should be given to combining rights across sectors so as to improve the overall welfare of the water economy.

In future works, additional elements could be added to the model such as the following: (a) changes in municipal and agricultural demand; (b) other methods of division between the two main water sectors; (c) desalinization or importation of water, and; d) changes in the capacity of storage facilities.

Conflicts of Interests

There are no conflicts of interest in reference to the above manuscript.

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Nomenclature

Abbreviations

BUT - Beneficial Use Test

IP -Investment Portfolio

MCM - Million Cubic Meters

MCMY - Million Cubic Meters per year

OP - Optimal Pareto

WR –Water Rights

Notation

A - A coefficient of risk aversion of the sectors.

AGR^D - Agricultural demand, MCMY.

AGR^D - A fixed amount of water that the agricultural sector acquires every year, MCMY.

AGR_t - Annual amount of water allocated to the agricultural sector, MCMY.

C - Fixed positive constant.

E - Expectancy of the amount of water, MCMY.

E_{AGR} - Expected value of the agricultural sector, MCMY.

E_{MUN} - Expected value of the municipal sector (over T years)

E_{MUNP}, E_{AGRP} - Reefers to P [Portfolio] index of the variables indicates expected value under conditions of combined rights for the municipal and agricultural sectors respectively.

ER - Expected value of Recharge in the simulation, MCMY.

MUN^D - A fixed amount of water that the municipal sector acquires every year, MCMY.

MUN_t - Annual water allocation to the municipal sector in the t year, MCMY.

$RESB_t$ (reservoir begin) - Water storage volume at the beginning of period t , MCMY.

$RESE_t$ (reservoir end) - Storage volume at the end of period t, MCMY.

RES_{MAX} - Fixed storage volume, MCMY.

R_t - Annual (potential) recharge of groundwater for the specific country, MCMY.

SD - Standard deviation in the simulation, MCMY.

S_t - Supply of water for each period, MCMY.

t - Time in years

U **-** Utility stemming from water supply according to the WR.

U_{MUNP} – Municipality term stemming from water supply subject to WR.

X - Represents the right to receive water.

Y - Fixed positive constant.

Greek notation

α - The proportion of WR attributed to the agricultural sector.

α* - Value at optimal solution.

σ^2 - Variance of the water supply, MCMY.

σ^2_{AGR} **-** Agricultural sector variance, MCMY.

σ^2_{MUN} **-** Municipal sector variance, MCMY.

σ^2_{μ} **-** Variance of R_t, MCMY.

σ^2_{MUNP} , σ^2_{AGRP} - The variances for the municipal and agricultural sectors respectively, under combined WR conditions, MCMY

ρ_{MA} - Indicates the correlation coefficient between quantities allocated to two sectors.

μ - Expected value of R_t, MCMY.