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RESEARCH PAPER

The Allocation of Groundwater Resources and Managing Conflict between Stakeholders: Evidence from Iran

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Abstract

Scarce water resources often involve decision-makers with conflicting interests. Effective management requires balancing objectives and strategies of multiple stakeholders. The present study analyzes the potential compromise solutions between stakeholders, using a combination of game theory and a positive mathematical programming (PMP) model. The two key players are the government, which minimizes environmental impacts such as groundwater withdrawal, and local farmers, who maximize economic profit. We employ four conflict resolution methods to calculate the players’ payoffs. The results show that creating a transactional relationship between the stakeholders reduces groundwater extraction by 36% and 37%, while the farmers' net income only drops by 8% and 9%, respectively, compared to the baseline scenario.

Keywords: Conflict Resolution, Game Theory, Groundwater Resources, Multi-Objective Optimization, Positive Mathematical Programming.

JEL Classification: C61, C72, Q25, Q34, Q56.

1. Introduction

Over the decades, the world has witnessed rapid population growth and excessive resource consumption, which has led to unsustainable natural resource management practices and poorly implemented policies. These factors contribute to water scarcity in several parts of the world, posing a significant threat to human survival and regional development (Darbandsari et al., 2020; Huang et al., 2021). At the same time, water allocation is becoming a source of conflict, intensifying competition among different sectors reliant on water resources which can often lead to disputes between stakeholders (Naderi, 2024). Disagreements and conflicts are prevalent among stakeholders or beneficiaries of common natural resources (Nazari et al., 2020). These conflicts arise from divergent perspectives on utilizing common resources (Fang et al., 1993; Madani, 2010). For instance, rational interactions concerning a specific issue influence group members and cause conflict when no single member has control over it (Dillon, 1962; Fang et al., 1993). The present study analyzes the potential compromise solutions etween groups of stakeholders, using a combination of game theory (GT) and positive mathematical programming (PMP).

Effective water resource management requires the involvement of multiple stakeholders with conflicting or competitive objectives and strategies (Fang et al., 2002; Zamani et al., 2019a). In the absence of market mechanisms and exclusive property rights that typically govern the exploitation of natural resources, conflicts arise among multiple stakeholders competing for water resources (Wei and Gnauck, 2007). Therefore, developing accurate plans to ensure a reliable water supply and maintain allocation priorities is crucial (Naghdi et al., 2021). Achieving a balance between surface and groundwater extraction and optimizing their use is essential for sustainable resource management. To prevent aquifer depletion, water shortages, and related issues, stakeholders must develop optimal allocation tools for water resource management. Among the various models used in water resource management, game theory is considered one of the most effective. Game theory addresses conflicts with multiple objectives by considering the benefits all stakeholders gain from resource exploitation and their interactions to maximize these benefits (Wang et al., 2003; Raquel et al., 2007; Madani and Hipel, 2011; Nazari et al. 2020). Game theory produces more accurate results than conventional optimization methods because it accounts for the behavior of involved parties. This aspect is often overlooked by conventional approaches when dealing with problems involving multiple decision-makers and criteria (Chhippi-Shrestha et al., 2019; Madani et al., 2015; Bočková et al., 2015; Lee, 2012).

Most studies on conflict resolution focus on its applications in various domains of water management, such as agricultural disputes (Raquel et al., 2007; Oftadeh et al., 2017), reservoir operation problems (Shirangi et al., 2008; Zanjanian et al., 2018; Shapira et al., 2019), river-reservoir systems (Nandalal and Simonovic, 2003; Kittikhoun and Staubli, 2018; Zeng et al., 2019; Mason, 2020), and the conjunctive use of surface and groundwater (Bazargan-Lari et al., 2009; Parsapour-Moghaddam et al., 2015; Rezaei et al., 2017).

Fewer studies explore the management of water resources, leading to the proposal of various quantitative and qualitative methods for water resource allocation (Alizadeh et al., 2017; Madani and Dinar, 2012).

Our research is situated within this emerging body of literature, specifically examining the application of game theory in conflict resolution for water resource management (Li et al., 2023; Di et al., 2021; Naghdi et al., 2021; Darbandsari et al., 2020; Nazari et al., 2020; Chhippi-Shrestha et al., 2019; Zeng et al., 2019; Kicsiny and Varga, 2019; Madani, 2010; Wei et al., 2010; Raquel et al., 2007).

Some of few empirical studies in this line of literature, Chhippi-Shrestha et al. (2019) and Raquel et al. (2007) are the most relevant for our purposes. Chhippi-Shrestha et al. (2019) apply the GT approach to multi-criteria decision analysis for sustainable water reuse in Canada. They find that the weights of sustainability indicators and dimensions affect Pareto optimality and hence the final decision. Raquel et al. (2007) apply game theory to multi-objective conflict for a groundwater problem in Mexico. They find that groundwater extraction decreases when an optimal trade-off is found between conflicting economic and environmental objectives.

Our work extends these findings by integrating conflict resolution methods with a positive mathematical programming model to analyze the potential solutions among groups of stakeholders. Our results go beyond academic discussion to provide actionable insights for policymakers. Understanding how stakeholder groups respond to shared resources is crucial for informing effective decision-making and resource management strategies.

The remainder of the paper is organized as follows. Section 2 explains the structure of the framework, the case study, and the water management problem. Section 3 discusses the results. Finally, Section 4 summarizes the findings and provides conclusions.

2. Methodology

Initially, we define the framework of the game by identifying players and their objectives, and then apply a game theory model to calculate each player's payoffs.

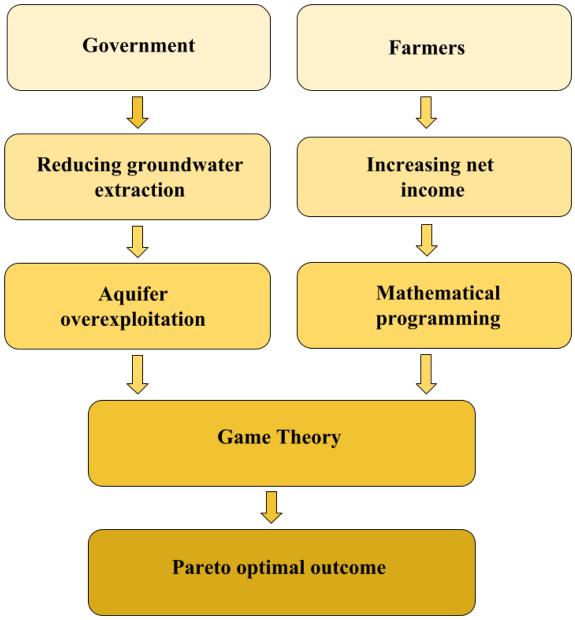

Figure 1. The Diagram of the Empirical Method
Source: Research finding.

2.1 Case Study and Water Management Problem

We evaluate the proposed method in Gorgan, the capital of Golestan Province in northern Iran. The city, which borders the Caspian Sea to the west, serves as a significant case study location. The region is an agricultural area heavily reliant on groundwater for crop irrigation. It encompasses approximately 19,945 wells, with an average extraction of 248 million cubic meters (MCM) per well annually (Iran Water Resources Management Company, 2021). Figure 2 illustrates the geographical location of the case study and its groundwater points.

Groundwater resources in the region are overdrawn, leading to a significant reduction in levels. Increased groundwater pumping has resulted in water-level declines of 4.93 meters during 2010-2020 (Iran Water Resources Management Company, 2021). Water resource management is a complex issue that requires consideration of multiple objectives.

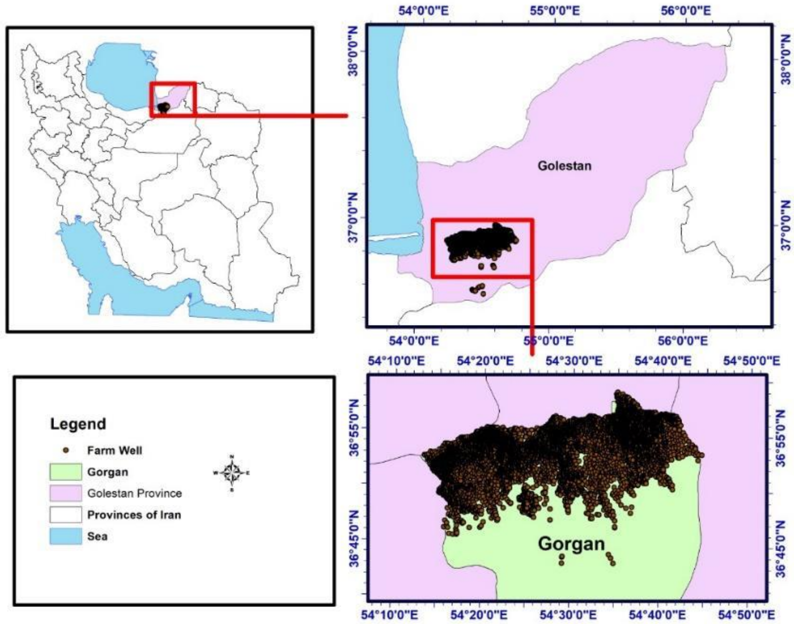

Figure 2. Geographical Location of Gorgan and its Groundwater Points
Source: Research finding.

Given the competitive nature of groundwater resources and the absence of regional research focusing on economic and environmental objectives, this study applies a game theory conflict resolution to achieve these objectives. This study contributes to the existing body of literature by potentially being one of the first to apply PMP and GT optimization-based techniques to manage water resources in the Gorgan region. We utilize data on production costs and prices of agricultural products, alongside additional regional water management information[1].

In modeling the problems outlined above, we consider ten possible groundwater extraction scenarios based on a ten-year historical report on groundwater (Table 1).

Table 1. Different Scenarios of Groundwater Extraction in Gorgan (MCM**)**

Scenarios	1	2	3	4	5	6	7	8	9	10
Groundwater extraction	160	179	195	214	228	264	296	328	358	370

Source: Iran Water Resources Management Company, 2021.

[1]. Production cost and price data are derived from 88 standard questionnaires administered by the Iranian Ministry of Agriculture. Water management data are obtained from the Regional Water Organization of Golestan Province and the Iran Water Resources Management Company.

To assess the economic and environmental impacts of groundwater extraction, we use a PMP-based methodology along with four conflict resolution methods: Non-symmetric Nash solution, non-symmetric Kalai-Smorodinsky, non-symmetric monotonic, and non-symmetric equal loss solutions to determine the optimal extraction level.

2.2 Game Framework

Players form a fundamental component of any game, including beneficiaries, stakeholders, and decision-makers involved in the process (Nazari et al., 2020). The set of players is denoted by N, and the strategic form of the game with n players is as follows:

$$N = \{1,2,\dots,n\} \tag{1}$$

The two key players are the government, which minimizes environmental impacts such as groundwater withdrawal, and local farmers, who maximize economic profit. The government represents the Ministry of Agriculture, while the farmers consist of individuals extracting water for farming activities. Hence, $n = 2$, and $N = total\ farmers + government$. Since the objectives have different value ranges, we transform them into normalized forms while retaining their characteristics. The procedure is as follows.

$$X_{new} = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{2}$$

This normalization scales the data between 0 and 1, referred to as strategic or matrix form. Formally, the model represents the conflict as a pair (S, d), where $S = S_1 \times \dots \times S_n$ denotes the Cartesian product of the players' strategy sets (Nazari et al., 2020). S represents a finite subset of $\mathbb{R}^2$ referring to feasible simultaneous sets of payoffs. The disagreement point $d = (d_1, d_2)$ indicates the worst payoff for players 1 and 2 ($d_1 = d_2 = 0$). This vector, known as the "nadir," provides a reasonable basis for both sides to reach an agreement. f_1 and f_2 denote the coordinate lines, and the Pareto frontier represents a strictly decreasing concave function g defined over the interval $[d_1, f_1^*]$, where $g(f_1^*) = d_2$. Figure 3 illustrates this concept. If vector d represents the status-quo payoff, the set S^+ restricts the feasible payoff set S to the region DAB in Figure 3.

$$S_+ = \{(f_1, f_2) | f \in S, f \geq d\} \tag{3}$$

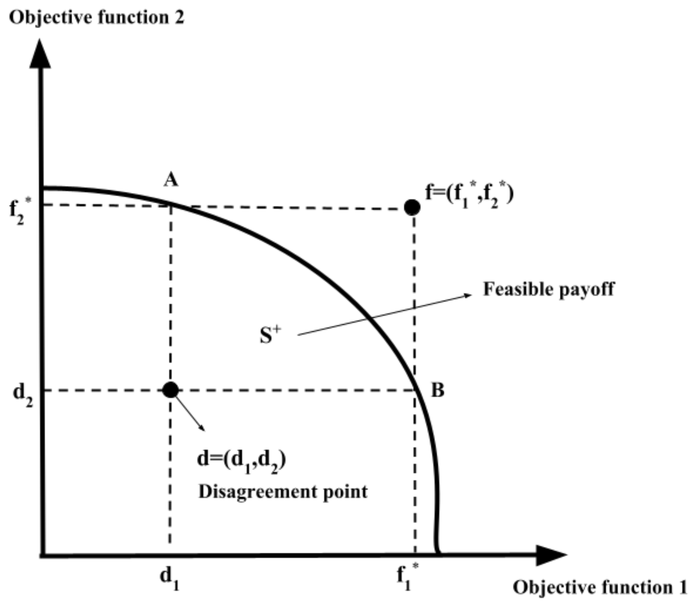

Figure 3. Pareto Frontier of the Two Stakeholders
Source: Research finding.

2.2.1 Conflict Resolution Methods

The Nash solution models bargaining interactions between two players who are uncertain about a feasible payoff. This method identifies a unique point on the Pareto frontier that maximizes the joint payoff, considering the disagreement point for both players, thus preventing an unbounded gain for competitors (Eq. 4). Harsany and Selten (1972), Kalai and Smorodinsky (1975), Chun (1988), and Anbarci (1993) have modified and expanded Nash's original approach.

$$\begin{aligned} &Maximize\ (f_1 - d_1)(f_2 - d_2) \\ &Subject\ to\quad d_1 \le f_1 \le f_1^*, f_2 = g(f_1). \end{aligned} \tag{4}$$

The maximization problems outlined above constitute a two-dimensional optimization framework. At the points where $f_1 = d_1$ and $f_1 = f_1^*$, the objective function equals zero. Incorporating the second constraint into the objective function yields the following formulation:

$$\begin{aligned} &Maximize\quad (f_1 - d_1)(g(f_1) - d_2) \\ &Subject\ to\quad d_1 \le f_1 \le f_1^* \end{aligned} \tag{5}$$

A simple one-dimensional algorithm solves this problem. Furthermore, the first-order condition facilitates the derivation of four conflict resolution methods.

2.2.1.1 Method 1

The non-symmetric Nash solution reformulates Nash's original solution (Nash, 1950), and provides a unique solution to the problem (Harsany and Selten, 1972).

$$\text{Maximize } (f_1 - d_1)^{w_1}(f_2 - d_2)^{w_2} \tag{6}$$

In Equation (5), the vector $w = (w_1, w_2)$ assigns unequal weights to both players, with the sum of the weights equal to 1 ($w_1 + w_2 = 1$). These weights are based on the relative importance of each player's objective. The values for w_1 and w_2 can be adjusted as shown in Figure 4(a) to reflect the importance of each player's goal.

2.2.1.2 Method 2

The Kalai-Smorodinsky (KS) solution offers an alternative to Nash's bargaining solution. We calculate it geometrically by drawing a straight line between the point of disagreement (d_1, d_2) and the ideal point (f_1^*, f_2^*) as shown in Figure 4(b). The KS solution occurs at the intersection of the linear segment and Pareto frontier (Kalai and Smorodinsky, 1975). Hence, we formulate the unique solution within the interval (d_1, f_1^*) as follows:

$$d_2 + \{(f_2^* - d_2)/(f_1^* - d_1)\}(f_1 - d_1) - g(f_1) = 0 \tag{7}$$

Both normalized objectives increase at the same rate along the line connecting the point of disagreement to the ideal point (f_1^*, f_2^*). Different weights apply when the importance of the objectives varies. The higher weight goes to the more important objective, improving it more rapidly. The non-symmetric KS solution results from applying different weights to the KS solution. It also finds an optimal solution at the intersection of the Pareto frontier and straight line (Figure 4(b)).

$$\mathrm{g}(f_1) = (w_2/w_1)f_1 \tag{8}$$

2.2.1.3 Method 3

The area monotonic solution uses the straight line passing through the point of disagreement (d_1, d_2), and the frontier that splits the set S^+ into two half sets (Figure 4(c)). Since the given weights are not equal ($\mathrm{w}_1 \neq w_2$), the non-symmetric conflict modifies accordingly. Based on the non-symmetric area monotonic solution, the ratio of the two areas should equal $\frac{w_1}{w_2}$. Therefore, the root of the non-linear equation below, within the interval (d_1, f_1^*) provides the coordinate solution (Anbarci, 1993).

$$w_2[\int_{d_1}^{x} g(t)dt - {}^{1}\!/_{2}\,(x-d_1)(g(x)+d_2) = w_1[\int_{x}^{f_1^*} g(t)dt - (f_1^* - x)d_2 + {}^{1}\!/_{2}\,(x-d_2)(g(x)-d_2] \tag{9}$$

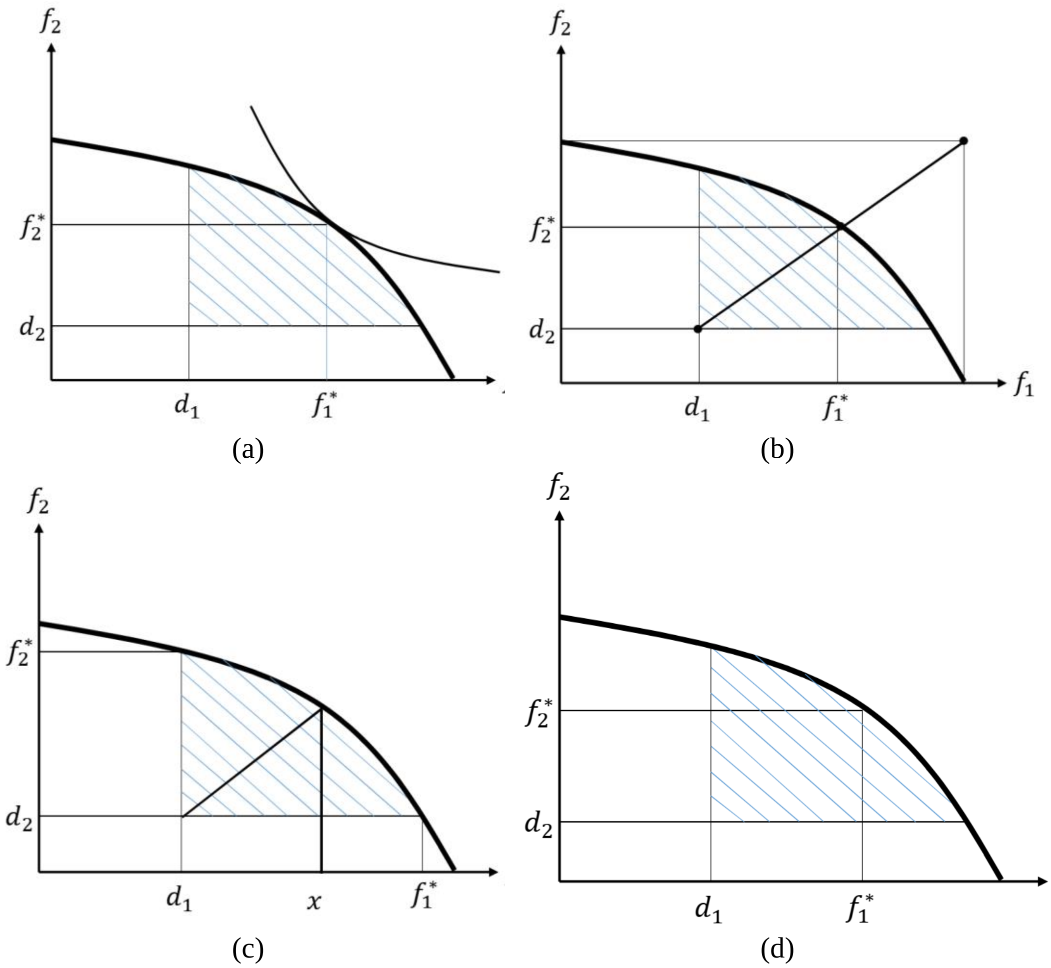

Figure 4. Pareto frontier of the two stakeholders using non-symmetric Nash solution (a), Kalai- Smorodinsky solution (b), Area monotonic solution (c), and the equal loss solution

Source: Research finding.

2.2.1.4 Method 4

The equal loss solution gives equal weights to both objectives, allowing the two parties to reach an agreement simultaneously at the same rate. In contrast, non-symmetric equal loss solution assigns different weights to the objectives. The more important objective experiences a slower rate of loss, and the ratio of the speeds is $\frac{w_1}{w_2}$ (Figure4(d)). Hence, we assign the point $(f_1^* - x)w_1 = (f_2^* - g(x))w_2$ on the Pareto frontier (Chun, 1998).

$$(f_1^* - x)w_1 = (f_2^* - g(x))w_2 \tag{10}$$

2.3 Estimation of Economic Objective

To determine the payoffs of economic objectives, we formulate the PMP. We calibrate the PMP models through a three-step procedure (Kanellopoulos et al., 2010; Cortignani and Severini, 2011; Howitt et al., 2012), as follows:

2.3.1 Step 1. Base Linear Model

In the first stage, we apply a linear programming (LP) optimization model subject to resource constraints. We consider two types of constraints to calculate the players' payoff. The structure of PMP is defined as follows:

$$Max\ Z = \sum_{j=1}^{n} (P_j\, Y_j - C_j)X_j \tag{11}$$

$$\sum_{i=1}^{n} X_j \leq TLand \tag{12}$$

$$A_{min} \leq X_j \leq A_{max} \tag{13}$$

$$\sum_{j=1}^{n} W_j\, X_j \leq T\ Water_m \tag{14}$$

$$X_j = \tilde{X}_j + \varepsilon \tag{15}$$

Equation (11) represents a linear gross margin maximization model where X_j denotes land use for crop j (ha), P_j and Y_j represent the price (IRR per kg) and yield of crop j (kg per ha), respectively. C_j denotes the total cost of crop j (IRR per ha) including pumping, land, irrigation, labor, machinery, and fertilizer costs. n denotes the number of crops considered in the model. Accordingly, Equation (12) represents land constraint where *TLand* is the total available land, fixed 65,688 hectares. Equation (13) ensures that the allocated area for crop j does not exceed the maximum allowable area for that crop and meets or exceeds the minimum area required to fulfill food demand. Equation (14) defines the monthly water usage constraint, ensuring that the water requirement for each crop does not exceed the total amount of water extracted from the wells in a given month. Here, W_j represents the irrigation water requirement (IWR) of crop j, and $TWater_m$ denotes the total groundwater extracted in month m. Finally, we add calibration constraints for the land use of each crop to ensure unique dual shadow prices for each crop activity.

2.3.2 Step 2. Estimation of Yield Parameter with Maximum Entropy

Next, we estimate the parameters of the quadratic PMP yield function for crops using the shadow value derived from the calibration constraint in Equation (16). The quadratic function is as follows:

$$Y_i = \alpha_{ij} NX_{ij} - \beta_{ij} NX_{ij}^2 \tag{16}$$

where α_{ij} and β_{ij} represents the intercept and slope of the non-linear yield function, respectively. NX_{ij} represents the amount of input i used in crop j. Estimating the non-linear parameters, α_{ij} and β_{ij}, using shadow prices represents an ill-posed problem that classical econometric approaches cannot solve (Paris and Howitt, 1998). The Maximum Entropy technique addresses this issue by estimating the parameters of the non-linear yield function (Howitt and Msangi, 2014; Zamani et al., 2019a)

2.3.3 Step 3. Non-Linear Calibrated Model

In the final step, we use the following non-linear quadratic objective function replacing the linear one.

$$Max\ Z = \sum_i \left[\sum_j P_i \left(\alpha_{ij} NX_{ij} - \beta_{ij} NX_{ij}^2 \right) - \sum_i \sum_j C_{ij} NX_{ij} \right] \tag{17}$$

In this step, we calibrate the obtained non-linear model, including Equations (17), (12), (13), and (14), to reproduce the base-year information. Additionally, the quadratic objective form prevents over-specialization of solutions and offers greater flexibility in simulating policy scenarios. (Lee et al., 2019). According to Zamani et al. (2019b), policy scenarios related to limited water extraction require changes to the right-hand side of the water constraints in Equation (3). Thus, we first develop the baseline scenario, which is obtained from the calibrated model based on the land use in the reference year (2020).

3. Results

Table 2 summarizes the results of cropping patterns from the PMP model, with the first row showing groundwater extraction scenarios ranging from 160 to 370 MCM.

It also presents the maximum net income generated by each cropping pattern for every groundwater extraction scenario. Specifically, our findings compare various cropping patterns and groundwater extraction scenarios to the baseline scenario (370 MCM). The results show that reducing groundwater extraction decreases both the area under crops and farmers' net income Specifically, reducing groundwater withdrawal from 370 MCM (10th Scenario) to 160 MCM (1st Scenario) (-57%) causes the total cultivated area to decrease from 65,087 to 29,181 hectares (-55%), while net income drops from 2,410 to 1,740 billion IRR (-28%).

Table 3 presents the payoff matrix for the two players, with the fourth and fifth columns displaying economic and environmental objectives, respectively.

To compute the environmental objective for each scenario, we calculate aquifer overexploitation by dividing groundwater withdrawal by groundwater recharge, using a historical data series of 10 years ($Withdrawal/Recharge$), following the method proposed by Kloezen and Garces-Restrepo (1998). Before applying game theory, we generate the alternatives from 0 to 1, referred to as normalized, for each groundwater extraction scenario. Table 4 shows the normalized payoff matrix for the two players in the economic and environmental categories.

Higher water consumption corresponds to increased net income, while aquifer overexploitation results in negative environmental impacts. Consequently, we apply different weights and scale them within the range of [0, 1]. Figure 5 illustrates the Pareto frontier for the two players, while Tables 5 to 8 present the computational results derived from the four conflict resolution methods under varying weight selections.

Table 2. Net Income and Cropping Pattern for Different Groundwater Extraction Scenarios

Scenarios	1	2	3	4	5	6	7	8	9	10
Groundwater extraction (MCM)	160	179	195	214	228	264	296	328	358	370
Cropping pattern (ha)										
wheat	12337	13575	14618	15855	16767	18940	20828	22717	24487	25025
Soya	5098	5594	6013	6509	6875	7851	8728	9605	10427	10713
Potato	1000	1461	1849	2310	2650	3320	3863	4406	4915	5052
Canola	1212	1406	1570	1765	1909	2346	3753	3160	3541	3768
Bean	989	994	999	1005	1909	1020	1031	1040	1050	1041
Corn	871	1064	1226	1419	1562	1906	2206	2506	2788	2822
Rice	7196	7551	7850	8205	8466	8996	9430	9864	10271	10460
Tomato	377	504	611	738	832	1063	1266	1469	1659	1753
Spring cotton	0	0	0	0	0	484	1038	1592	2112	2299
Summer cotton	13	175	311	437	592	805	970	1135	1289	1326
Barley	88	145	194	252	295	443	584	726	859	828
Total	29181	32469	35241	38495	41857	47174	53697	58220	63398	65087
Net income (Billion IRR)	1740	1850	1930	2020	2080	2210	2290	2360	2400	2410

Source: Research finding.

Table 3. The Payoff Matrix of the Two Stakeholders

Scenarios	**Groundwater extraction (MCM)**	**Land used (hectare)**	**Net income (Billion IRR)**	**Aquifer overexploitation coefficient**
1	160	29181	1740	1
2	179	32469	1850	1.11
3	195	35241	1930	1.21
4	214	38495	2020	1.33
5	228	41857	2080	1.42
6	264	47174	2210	1.65
7	296	53697	2290	1.85
8	328	58220	2360	2.05
9	358	63398	2400	2.23
10	370	65087	2410	2.31

Source: Research finding.

Table 4. Normalized Payoff Matrix of the Two Stakeholders

Scenarios	Groundwater extraction (MCM)	Land used (hectare)	Net income (normalized)	Groundwater extraction (normalized)
1	160	29181	0	1
2	179	32469	0.16	0.91
3	195	35241	0.28	0.83
4	214	38495	0.41	0.73
5	228	41857	0.5	0.66
6	264	47174	0.7	0.48
7	296	53697	0.82	0.32
8	328	58220	0.92	0.16
9	358	63398	0.98	0.02
10	370	65087	1	0

Source: Research finding.

Table 5. Computational Results of Non-Symmetric Nash Solution

Groundwater extraction (MCM)	Net income (Billion IRR)	Environmental returns (f_2)	Economic returns (f_1)	Weight of environmental impacts (w_2)	Weight of economic impacts (w_1)
370	2410	0	1	0	1
332	2380	0.179	0.956	0.025	0.975
323	2370	0.224	0.948	0.05	0.95
315	2360	0.26	0.939	0.075	0.925
309	2360	0.291	0.929	0.1	0.9
303	2350	0.32	0.918	0.125	0.875
297	2340	0.346	0.906	0.15	0.85
292	2330	0.371	0.894	0.175	0.825
287	2330	0.395	0.881	0.2	0.8
282	2320	0.418	0.868	0.225	0.775
277	2310	0.441	0.854	0.25	0.75
273	2300	0.463	0.839	0.275	0.725
268	2290	0.484	0.824	0.3	0.7
264	2280	0.505	0.808	0.325	0.675
259	2270	0.526	0.792	0.35	0.65
255	2250	0.546	0.775	0.375	0.625
251	2240	0.567	0.757	0.4	0.6
247	2230	0.587	0.739	0.425	0.575
242	2220	0.607	0.725	0.45	0.55
238	2210	0.627	0.71	0.475	0.525
234	**2190**	**0.648**	**0.679**	**0.5**	**0.5**
230	2180	0.668	0.657	0.525	0.475
225	2160	0.688	0.635	0.55	0.45

221	2140	0.709	0.611	0.575	0.425
217	2130	0.729	0.587	0.6	0.4
212	2110	0.75	0.561	0.625	0.375
208	2090	0.771	0.535	0.65	0.35
204	2070	0.792	0.507	0.675	0.325
199	2060	0.814	0.478	0.7	0.3
194	2040	0.835	0.448	0.725	0.275
190	2010	0.857	0.416	0.75	0.25
188	1990	0.865	0.383	0.775	0.225
186	1970	0.875	0.348	0.8	0.2
185	1940	0.88	0.312	0.825	0.175
181	1920	0.898	0.274	0.85	0.15
180	1890	0.903	0.234	0.875	0.125
175	1880	0.926	0.216	0.9	0.1
170	1860	0.95	0.192	0.925	0.075
165	1800	0.974	0.091	0.95	0.05
160	1760	0.998	0.044	0.975	0.025
160	1740	1	0	1	0

Source: Research finding.

Table 6. Computational Results of Kalai- Smorodinsky Solution

Groundwater extraction (MCM)	Net income (Billion IRR)	Environmental returns (f_2)	Economic returns (f_1)	Weight of environmental impacts (w_2)	Weight of economic impacts (w_1)
370	2410	0	1	0	1
365	2400	0.025	0.988	0.025	0.975
359	2390	0.052	0.973	0.05	0.95
353	2380	0.081	0.969	0.075	0.925
347	2380	0.111	0.969	0.1	0.9
340	2380	0.142	0.969	0.125	0.875
333	2370	0.176	0.952	0.15	0.85
326	2370	0.209	0.951	0.175	0.825
319	2370	0.242	0.949	0.2	0.8
312	2360	0.275	0.937	0.225	0.775
305	2360	0.309	0.928	0.25	0.75
298	2340	0.343	0.906	0.275	0.725
290	2330	0.378	0.883	0.3	0.7
283	2310	0.413	0.859	0.325	0.675
276	2290	0.449	0.834	0.35	0.65
268	2280	0.485	0.809	0.375	0.625
260	2260	0.521	0.782	0.4	0.6
253	2240	0.557	0.754	0.425	0.575
245	2220	0.593	0.724	0.45	0.55

238	2200	0.628	0.694	0.475	0.525
231	**2180**	**0.663**	**0.663**	**0.5**	**0.5**
224	2160	0.697	0.63	0.525	0.475
217	2140	0.73	0.597	0.55	0.45
210	2110	0.761	0.562	0.575	0.425
204	2090	0.791	0.527	0.6	0.4
198	2060	0.819	0.491	0.625	0.375
192	2040	0.845	0.455	0.65	0.35
188	2020	0.868	0.418	0.675	0.325
183	1990	0.889	0.381	0.7	0.3
179	1970	0.907	0.344	0.725	0.275
176	1940	0.923	0.307	0.75	0.25
173	1920	0.935	0.271	0.775	0.225
171	1890	0.945	0.236	0.8	0.2
170	1870	0.953	0.202	0.825	0.175
169	1850	0.957	0.169	0.85	0.15
168	1830	0.96	0.137	0.875	0.125
168	1810	0.961	0.106	0.9	0.1
165	1790	0.977	0.081	0.925	0.075
164	1770	0.982	0.052	0.95	0.05
161	1750	0.996	0.025	0.975	0.025
160	1740	1	0	1	0

Source: Research finding.

Table 7. Computational Results of Area Monotonic Solution

Groundwater extraction (MCM)	Net income (Billion IRR)	Environmental returns (f_2)	Economic returns (f_1)	Weight of environmental impacts (w_2)	Weight of economic impacts (w_1)
370	2410	0	1	0	1
350	2390	0.096	0.984	0.025	0.975
349	2390	0.101	0.971	0.05	0.95
346	2380	0.113	0.961	0.075	0.925
339	2380	0.148	0.959	0.1	0.9
332	2360	0.182	0.935	0.125	0.875
325	2350	0.214	0.915	0.15	0.85
319	2340	0.244	0.904	0.175	0.825
313	2330	0.273	0.893	0.2	0.8
307	2320	0.3	0.869	0.225	0.775
302	2310	0.326	0.857	0.25	0.75
296	2290	0.35	0.832	0.275	0.725
292	2280	0.373	0.806	0.3	0.7
287	2270	0.395	0.794	0.325	0.675
278	2250	0.436	0.768	0.35	0.65
271	2240	0.473	0.755	0.375	0.625
263	2230	0.508	0.742	0.4	0.6
260	2220	0.524	0.729	0.425	0.575
253	2210	0.555	0.703	0.45	0.55
238	2200	0.626	0.69	0.475	0.525
233	**2200**	**0.652**	**0.687**	**0.5**	**0.5**
240	2180	0.62	0.665	0.525	0.475
245	2170	0.597	0.652	0.55	0.45
242	2160	0.611	0.639	0.575	0.425
234	2150	0.649	0.626	0.6	0.4
231	2140	0.661	0.621	0.625	0.375
226	2130	0.684	0.589	0.65	0.35
219	2100	0.717	0.552	0.675	0.325
215	2110	0.738	0.539	0.7	0.3
213	2070	0.748	0.506	0.725	0.275
211	2060	0.758	0.484	0.75	0.25
206	2050	0.783	0.463	0.775	0.225
198	2020	0.817	0.42	0.8	0.2
192	2000	0.848	0.396	0.825	0.175
191	1980	0.854	0.368	0.85	0.15
182	1930	0.895	0.289	0.875	0.125
174	1910	0.932	0.264	0.9	0.1
168	1850	0.963	0.168	0.925	0.075
165	1820	0.957	0.128	0.95	0.05
163	1760	0.984	0.043	0.975	0.025
160	1740	1	0	1	0

Source: Research finding.

Table 8. Computational Results of Equal Loss Solution

Groundwater extraction (MCM)	Net income (Billion IRR)	Environmental returns (f_2)	Economic returns (f_1)	Weight of environmental impacts (w_2)	Weight of economic impacts (w_1)
370	2410	0	1	0	1
346	2390	0.115	0.983	0.025	0.975
333	2380	0.178	0.956	0.05	0.95
316	2360	0.258	0.939	0.075	0.925
305	2350	0.308	0.923	0.1	0.9
297	2340	0.346	0.906	0.125	0.875
290	2330	0.379	0.89	0.15	0.85
284	2320	0.408	0.874	0.175	0.825
279	2310	0.434	0.858	0.2	0.8
274	2300	0.458	0.842	0.225	0.775
269	2290	0.481	0.827	0.25	0.75
264	2280	0.502	0.811	0.275	0.725
260	2270	0.522	0.795	0.3	0.7
256	2260	0.542	0.779	0.325	0.675
252	2250	0.56	0.763	0.35	0.65
248	2240	0.587	0.747	0.375	0.625
245	2220	0.596	0.73	0.4	0.6
241	2210	0.613	0.714	0.425	0.575
238	2200	0.63	0.697	0.45	0.55
234	2190	0.646	0.68	0.475	0.525
231	**2180**	**0.663**	**0.663**	**0.5**	**0.5**
227	2170	0.679	0.645	0.525	0.475
224	2160	0.695	0.627	0.55	0.45
221	2140	0.711	0.609	0.575	0.425
217	2130	0.727	0.59	0.6	0.4
214	2120	0.742	0.571	0.625	0.375
211	2100	0.758	0.551	0.65	0.35
207	2090	0.774	0.531	0.675	0.325
204	2080	0.79	0.51	0.7	0.3
201	2060	0.806	0.489	0.725	0.275
197	2050	0.822	0.467	0.75	0.25
194	2030	0.838	0.444	0.775	0.225
190	2020	0.855	0.42	0.8	0.2
187	2000	0.871	0.396	0.825	0.175
183	1980	0.888	0.37	0.85	0.15
180	1970	0.906	0.343	0.875	0.125
176	1950	0.924	0.316	0.9	0.1
176	1950	0.924	0.316	0.925	0.075
168	1920	0.96	0.256	0.95	0.05
168	1910	0.96	0.256	0.975	0.025
160	1740	1	0	1	0

Source: Research finding.

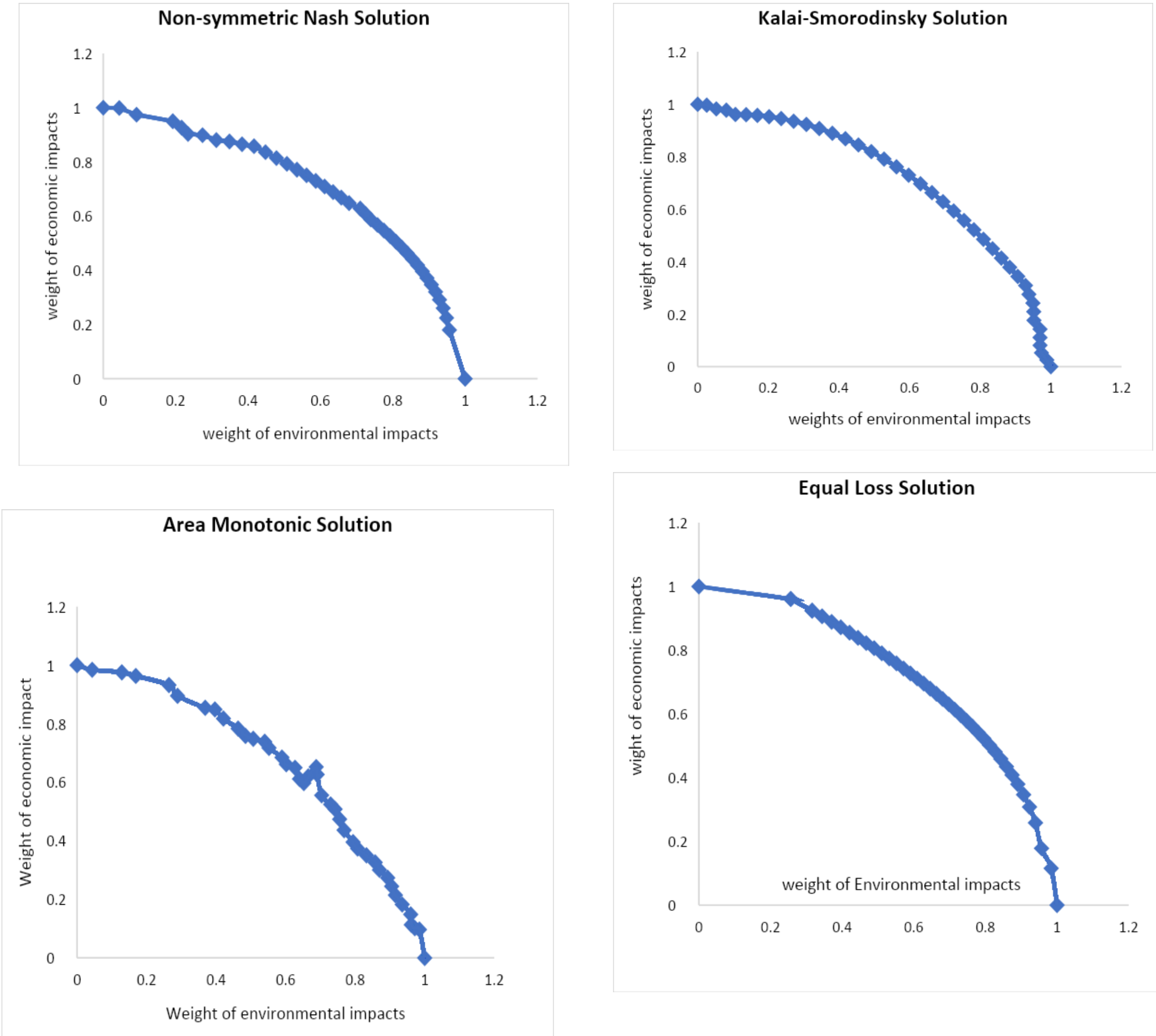

Figure 5. Pareto Frontier of the Two Stakeholders
Source: Research finding.

Table 9. The Optimal Solution of Water Extracted with Equal Weights (Million Cubic Meters)

Weight of environmental impacts	Non-symmetric Nash solution	Kalai-Smorodinsky solution	Area monotonic solution	Equal loss solution
0.5	234	231	233	231

Source: Research finding.

The computational results presented in the tables indicate that as the environmental objective becomes more important in the analysis, less water is allocated to agricultural irrigation optimally. The greater the importance weight given to the economic attributes, the higher the net income, demonstrating this trend across all four methods. When we prioritize economic benefit as the main objective, the optimal groundwater withdrawal reaches its maximum level of 370 million cubic meters. Conversely, when we prioritize the environment as the sole objective, we minimize groundwater extraction. This result aligns with Raquel et al., (2007) who demonstrate that the optimal decision depends on the relative importance weights assigned to conflicting objectives. It also mirrors the findings of Chhipi-Shrestha et al. (2019), who show that the weights of sustainability indicators and dimensions affect Pareto optimality and, consequently, the final decision. According to the Nash and non-symmetric monotonic area solutions, the optimal amounts of extracted water are 234 and 233 million cubic meters, respectively. Meanwhile, the non-symmetric Kalai-Smorodinsky solution and non-symmetric equal loss solution yield an optimal extraction of 231 million cubic meters. Table 9 summarizes the optimal groundwater extraction amounts.

As Table 9 shows, when we assign equal weights to economic and environmental objectives, groundwater extraction decreases by 36% and 37%, while farmers' net income drops by only 8% and 9%. Our study aligns with the findings of Nazari et al. (2020), who demonstrate that creating a compromise solution between the two key players —farmers and the government— leads to a reduction in groundwater withdrawal. Similarly, Raquel et al. (2007) report that groundwater extraction decreases when an optimal trade-off is found between conflicting economic and environmental objectives. Furthermore, our results are consistent with those of Naghdi et al. (2021), Raquel et al. (2007), and Li et al. (2023), who highlight the effective performance of the proposed method in managing the exploitation and allocation of groundwater resources.

4. Conclusion

In the current study, we implement four conflict resolution methodologies coupled with a positive mathematical programming model to consider trade-offs between the involved rational stakeholders. The two key players in this research are the government, which seeks to minimize the negative environmental impacts, including groundwater extraction, and local farmers, who aim to maximize economic profit. We generate ten initial alternatives to explore different groundwater extraction scenarios. According to the results of this study, groundwater extraction decreases by 36% and 37%, while farmers' net income only decreases by 8% and 9%. Nonetheless, the government can compensate for farmers' economic losses by setting a minimum support price. Our findings also reveal a gap between water demand and the supply capacity of water resources. To address water shortages, it is essential to explore alternative (non-conventional) water sources, such as recycled water, brackish water, and rainwater. Additionally, we should consider several general guidelines and potential solutions, including the implementation of advanced technological solutions and practices that enhance water efficiency. Overall, managing water resources is a country-dependent endeavor, which limits its implementation in many nations. To achieve better water resource management, we must address not only physical, economic, environmental, and financial perspectives but also consider social and political goals. Conflicts over water resources may not be as straightforward as they seem; however, the GT approach can simulate and explain the complexities of water-related problems by considering stakeholders' rational behavior, especially in the absence of markets and exclusive ownership rights. This approach offers solutions for different players in both cooperative and non-cooperative conditions, based on various types of information. This flexibility is a significant advantage of GT over conventional optimization techniques. Finally, we acknowledge the limitations of our analysis. This study focuses on two-dimensional games to address water problems. However, future research could explore games with three or more objectives. The approach outlined above can also be applied to various other natural resource problems that inherently involve collective action. We hope that future researchers will extend the implications of this work to other areas.

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