Bottom-up capping (BUC) policy under bargaining techniques for inter-sectoral groundwater trading: a case study from Iran

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ABSTRACT

Cap-and-trade (C&T) policy has led to environmental benefits in some groundwater markets by restricting and economically reallocating water permits. However, top-down approaches for capping permits may face resistance from every affected stakeholder. This paper presents an efficient policy framework to improve the implementation of C&T policies in a real shared aquifer in Iran. To this end, groundwater permits for water-selling farms are capped through a bottom-up capping (BUC) policy. A policy analysis that employs static and dynamic bargaining techniques incorporates farms' utilities. Results reveal that the bargaining techniques propose more acceptable capping strategies than the top-down approach. The BUC policy analysis introduces the proposed strategy by dynamic bargaining as the tradable groundwater permits. The effects of irrigation water sales to the industry sector, evaluated using a cooperative game-based optimization model, show that with the fair reallocation of water trading benefits, the current net benefits of agriculture and industry sectors increase by 55 and 27%, respectively. Furthermore, farms reduce their groundwater withdrawals by 35% compared with the current mode. Therefore, the BUC policy for inter-sectoral groundwater trading under dynamic bargaining can lead to the sustainable use of limited groundwater resources by facilitating the capping strategies and improving the water permits productivity.

Key words: Bargaining, Bottom-up capping (BUC) policy, Fair reallocation, Water trading

HIGHLIGHTS

- Bottom-up capping (BUC) policy under bargaining techniques is presented to facilitate cap-and-trade policies in groundwater markets.
- Policy analysis reveals that proposed capping strategies by the bottom-up approach are more acceptable than the command-and-control approach.
- A cooperative game-based optimization model fairly reallocates water trading benefits among market participants.

INTRODUCTION

Simultaneously with diminishing the role of water supply improvement, the necessity of improving the economic efficiency of water consumption is felt more than ever before (Grafton *et al.*, 2012; Wheeler *et al.*, 2017). A water trading approach that allocates water resources from less productive uses to more productive ones is one way to increase economic efficiency (Shah *et al.*, 2006; Zetland, 2013; Aghaie *et al.*, 2020).

The centralized and decentralized optimization of water trading is the subject of various studies. The centralized optimization goal is to maximize the system's benefits through a top-down decision process (Li *et al.*, 2014; Jansouz *et al.*, 2017; Dou *et al.*, 2019). But decentralized optimization models aim to simulate the behavior of water trading agents (Du *et al.*, 2017; Aghaie *et al.*, 2020). Previous studies have shown the positive economic performance of water trading, where the hydrological balance should also be considered (Wheeler *et al.*, 2014; Safari *et al.*, 2016).

Across the world, groundwater withdrawal is often the outcome of independent decisions made by individuals and organizations without any centralized control over its management (Van der Gun, 2012). This lack of control over groundwater users, who usually have strong economic incentives to withdraw as much water as possible, has led to overexploitation of groundwater resources (Moreaux & Reynaud, 2004; Jafary & Bradley, 2018), with consequences such as groundwater table drawdown, increased salinity, and land subsidence (Goesch *et al.*, 2007). Economic incentives arising from water trading may even exacerbate these adverse effects (Liang, 2013). To mitigate these effects, it has been suggested to implement regulatory policies such as capping groundwater withdrawal permits according to the renewable capacity of aquifers (Richardson *et al.*, 2011; Garrick *et al.*, 2020).

The Murray–Darling Basin (MDB) located in Australia, as a known international example, suffers from a lack of environmental flows. In this basin, to compensate for environmental damages, the capping policy on the extraction of surface and groundwater resources (as the core of the comprehensive water resources management plan) has been considered (Grafton, 2019). Generally, three water governance models including top-down, consensus-based, and bottom-up have been identified in the MDB (Horne & O'Donnell, 2014).

The top-down approach, although it uses the experts' knowledge and the central management model to coordinate state governments and considers the overall benefits of the basin, has not been effective due to disregard for the experiences and values of local communities (Horne & O'Donnell, 2014). Therefore, the consensus-based and bottom-up approaches have also been incorporated in the MDB's environmental protection programs due to the importance of paying attention to the local communities' requirements and creating strong interaction with them.

The consensus-based approach supports collective participation and interaction among local organizations in the MDB to achieve a common output. However, this approach has disadvantages such as the lack of transparency in decisions and risk of producing the best compromise rather than the best outcome (Horne & O'Donnell, 2014). Moreover, in the bottom-up approach, due to the diversity of aims and interests in local communities, the insufficient knowledge of individuals, etc., maintaining the overall benefits of the MDB has been difficult (Smith, 2008; Horne & O'Donnell, 2014). Nevertheless, successful examples can be found in Australia that uses a combination of top-down and bottom-up approaches (Horne & O'Donnell, 2014). Therefore, it is necessary to get the right balance between centralized management and local participation in water resources management projects (Grafton, 2019).

Capping policies on the water resources extractions can be implemented through a bottom-up approach and at the local level, such as restrictions on groundwater extraction in the San Luis Valley of Colorado (Cody *et al.*, 2015), irrigation limitations in the Upper Republican River of Nebraska (Schoengold & Brozovic, 2018), and reductions in the farms' groundwater permits in the Neishabour Plain located in Iran (Ghorbanian *et al.*, 2020).

Nevertheless, water authorities usually cap groundwater permits during a top-down process and inform their owners (Jafary & Bradley, 2018; O'Donnell & Garrick, 2019). Such command-and-control policies, which ignore various stakeholders' utilities, are often challenging to implement and may even face social resistance (Marchiori *et al.*, 2012; Aghaie *et al.*, 2020). Furthermore, there is usually competition among users of a common pool groundwater resource over how much they exploit (Madani & Dinar, 2012).

This paper seeks to answer two questions: (1) how to establish a cap on farms' water permits? (top-down or bottom-up decision-making process?) and (2) what are the benefits of trading water permits after a cap

implementation? To this end, it presents an efficient framework for the analysis of capping and cap-and-trade (C&T) policies in a real case study from Iran.

While capping policy limits farms' groundwater permits, farms using a shared aquifer choose non-cooperative behavior to achieve their utilities (desirable water extraction volume) and, at the same time, respond to the actions of each other. Therefore, this paper models the farms' behavior in choosing capping strategies under the bottom-up approach with bargaining techniques.

Bargaining techniques can help create an arrangement to reach broad agreements among stakeholders on specific policies through negotiation, considering the shared resources' utilities and limitations (Madani, 2010). Thus, these techniques have been used in many water resources management studies to analyze stakeholders' potential behaviors (Carraro & Sgobbi, 2008; Mahjouri & Bizhani-manzar, 2013; Xu *et al.*, 2019).

The proposed bottom-up capping (BUC) policy attempts to achieve broadly accepted policies by setting up a negotiation among farms on the extent of limitation in permits considering the water authority's objectives regarding the aquifer's hydrological balance. The BUC policy employs static and dynamic bargaining techniques to analyze farms' utilities (costs of the imposed capping strategy). These bargaining techniques differ from each other under the status of stakeholders' expected utilities during the negotiation process. The bargaining process continues until farms agree on a set of capping scenarios. The obtained strategies from the BUC policy and the command-and-control approach are compared, and the superior strategy is identified.

Moreover, the proposed policy analysis framework aims to improve the economic efficiency of water use under the C&T policy. The C&T policy allows the exchange of groundwater permits while limiting them according to aquifers' renewable capacity (Thompson *et al.*, 2009; Garrick *et al.*, 2020). Thus, this policy can lead to the sustainable use of limited groundwater resources (Aghaie *et al.*, 2020). The C&T policy considers the superior capping strategy (derived from the capping policy) as the tradable groundwater permits. Then, a cooperative game-based optimization model is developed to evaluate the effects of irrigation water sales on the industry sector.

The optimization model determines the inter-sectoral groundwater exchange volume in such a way as to maximize the net benefit of water buyers and sellers. This model also gives the optimal (the best value among the possible values under the problem's constraints) production amount of different products and the corresponding water consumption volume. Furthermore, the cooperative game model fairly (i.e., considering justice) reallocates the water trading benefits among market participants.

This paper's innovation includes presenting a BUC policy for promoting the implementation of C&T programs by considering stakeholders' utilities. Moreover, this study's advantage is analyzing two different mechanisms, static and dynamic bargaining, for how stakeholders interact in a bargaining process. Finally, the proposed optimization model can consider the water exchange volume by a certain technical method and the production amount of any industrial product as a decision variable.

CASE STUDY

Figure 1 shows the location of the Borkhar aquifer in Iran as a case study. This aquifer has a 1,642.8 (km^2) area and consists of mostly groundwater resources and limited amounts of surface water. This aquifer's average drawdown for 20 years leading up to 2014 has been reported to be 0.62 (m) per year (Zayandab Consulting Engineering Company, 2016).

The study area has suffered from water scarcity. In the aquifer's western regions, the agriculture industry (greenhouse, dairy cattle farm, and broiler chicken farm) and the building industry (stone cutting and brick factory) sectors temporarily purchase the irrigation water. These exchanges are legal and limited, but the exact information regarding their volume is not available (Ahmadi *et al.*, 2019).
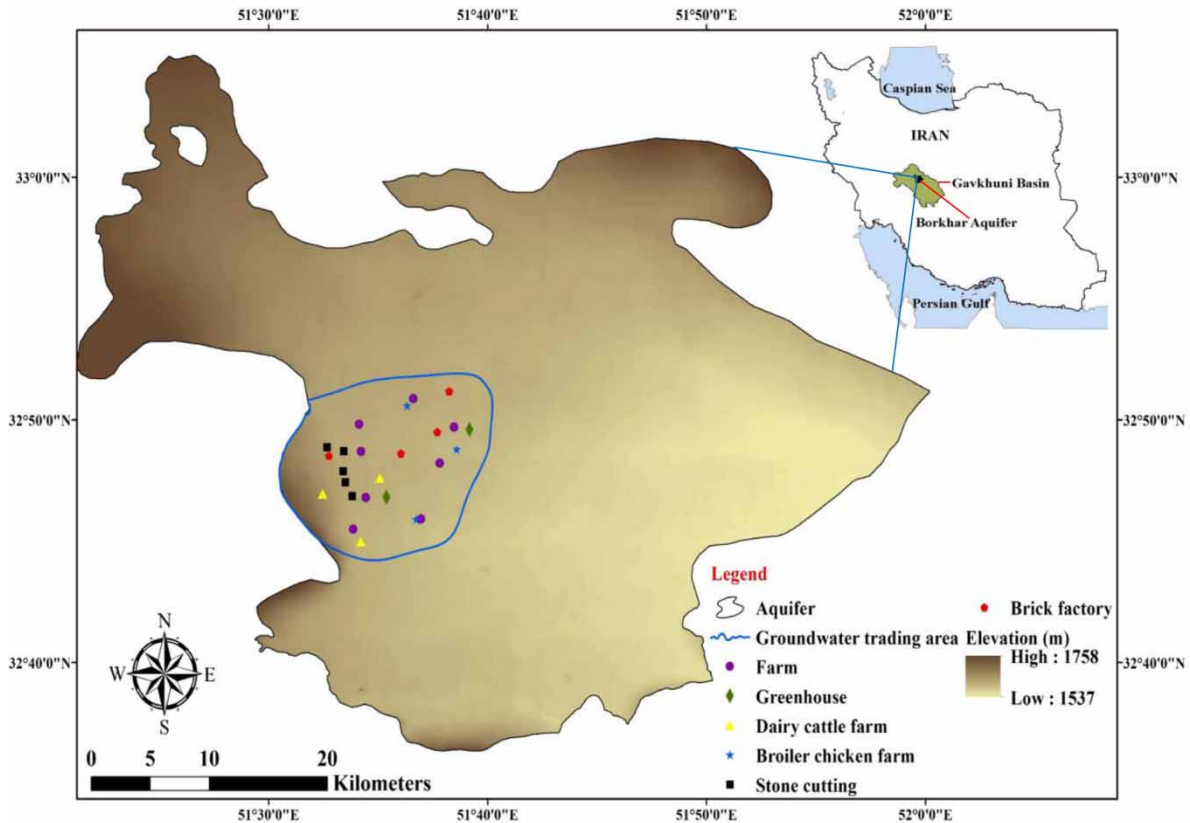
Fig. 1. | Location of the Borkhar aquifer and the groundwater trading units.

The guideline for the implementation of Iran's water markets provides legal and legitimate protection for the unilateral sale of water from the agriculture sector to other sectors with the aim of increasing water use productivity (Ahmadi *et al.*, 2019). Therefore, this paper seeks to evaluate the effects of irrigation water sales on different industrial units at a local scale. Figure 1 depicts the location of 25 water trading units. Furthermore, the data used in the modeling process have been presented in the Supplementary Appendix related to the farming year 2015–2016.

METHODOLOGY

Figure 2 shows the proposed policy analysis framework. First, different strategies for capping groundwater permits become the subject of static and dynamic bargaining among farms. The bargaining process continues until all farms agree on one strategy. The chosen strategy is then entered into the optimization model as the tradable permits in order to determine the optimal pattern of groundwater trading. Finally, a cooperative game model, described in the Supplementary Appendix, fairly redistributes the net benefits of C&T policy.

Bargaining model

The water authority in charge of managing a shared aquifer often controls withdrawal volume by adopting policies that penalize overexploitation (Parsapour-Moghaddami *et al.*, 2015). Under such circumstances, the most
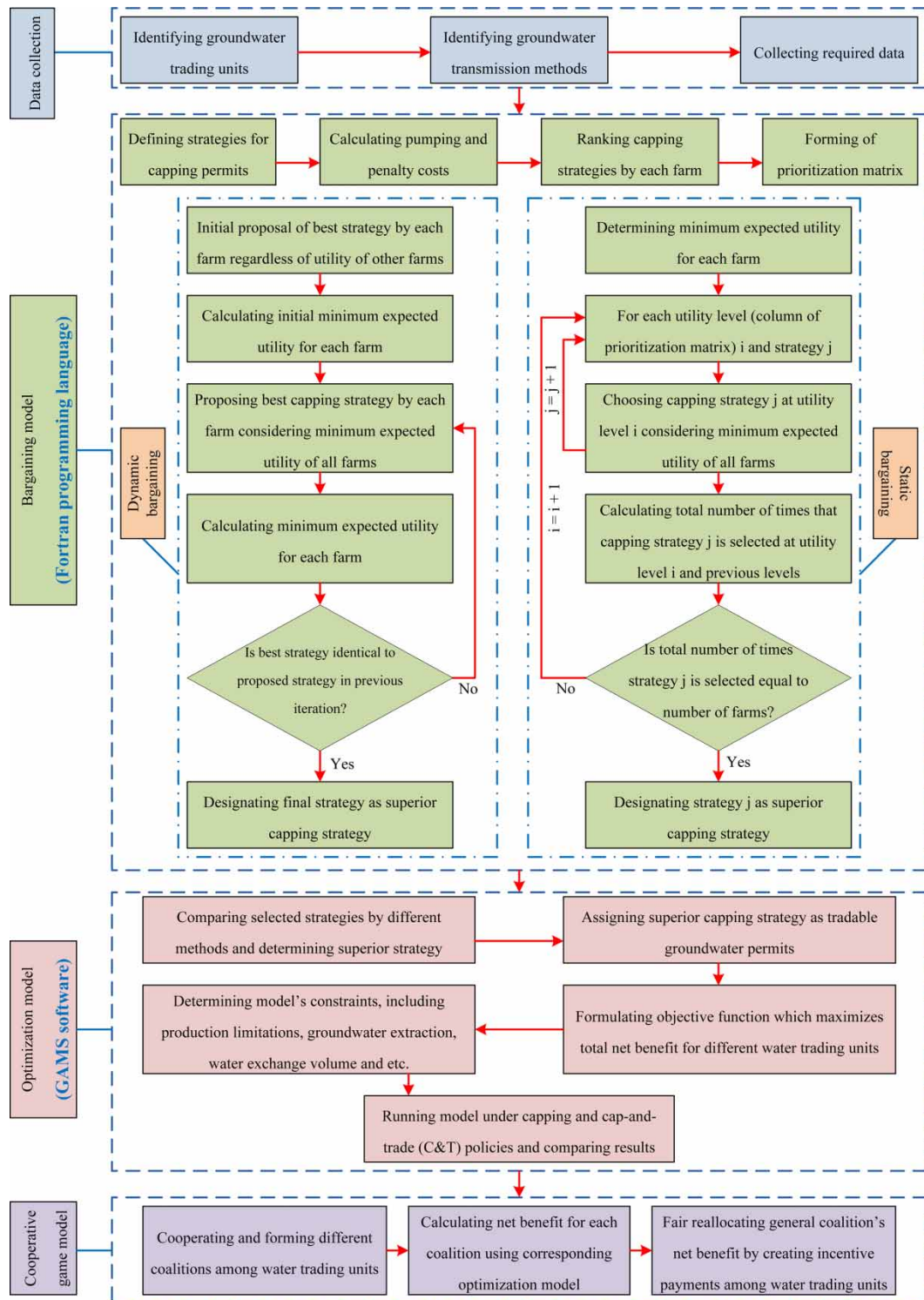
Fig. 2. | Different steps of the proposed policy analysis framework.

favorable strategy of each user will depend on the strategies of other users. Therefore, the problem can be analyzed with the help of bargaining models.

This study introduces the BUC policy for guaranteeing the implementation of a capping policy for groundwater permits. The BUC policy benefits from two different bargaining models developed using the FORTRAN programming language for policy analysis of the capping programs. The bargaining techniques model the negotiation process among water-selling farms on the strategies to cap the groundwater permits. Capping strategies include different combinations of capping scenarios where each farm can choose one scenario.

Farms rank the capping strategies in ascending order of their consequent costs (pumping cost plus penalty cost) from left to right. These ranking results are represented by a prioritization matrix, where the number of rows and columns is equal to the number of farms and strategies, respectively. Equations (1) and (2) calculate the pumping and penalty costs of farm m following the selection of capping strategy s, respectively (Parsapour-Moghaddami et al., 2015),

$$C_{m,s}^{\mathrm{Pu}} = \frac{\mathrm{PW}_{m,s} \times H_s \times t \times \mathrm{EP}}{0.102 \times \eta} \tag{1}$$

$$C_{m,s}^{\mathrm{Pe}} = \frac{\psi \times \Delta H_s^2 \times \mathrm{NB}_m}{\sum\limits_m \mathrm{NB}_m} \tag{2}$$

where C^{Pu} and C^{Pe} show the groundwater pumping and penalty costs (US$). The variables PW, H, and ΔH are the volume of pumped water (m³), average groundwater table (m), and groundwater table variation (m), respectively. NB denotes the net benefits from the sale of crops (US$). The parameters EP, t, η, and ψ also represent the electricity price (equal to 0.075 US$/kWh), pumping time (h), pumping efficiency (equivalent to 0.7), and penalty function coefficient, respectively.

Static bargaining

In this technique (Brams & Kilgour, 2001), after forming the prioritization matrix and before bargaining starts, each farm specifies a minimum limit for its utility. The minimum expected utility for each farm includes choosing a capping strategy with a maximum cost equivalent to the average cost of all the strategies imposed on that farm. Since this minimum utility remains constant during the bargaining process, this technique is called static bargaining.

As shown in Figure 2, the farms start selecting their most favorable strategy (the first column of the prioritization matrix) and fall back to less favorable strategies as the bargaining progresses until reaching an agreement. The most favorable strategy of each farm is the capping strategy with the highest utility for that farm that also meets the minimum expected utility criteria of each other farm. Strategies that cannot meet the minimum utility criteria of all farms are not selected.

Dynamic bargaining

This technique is a modified version of the method proposed by Carraro & Sgobbi (2008). As shown in Figure 2, each farm offers a capping strategy that maximizes its utility (minimizes its costs) regardless of other farms' utilities. Each proposed strategy generates a utility (cost) for the farm that offers it and other farms.

Next, the minimum expected utility of each farm, which is used as a criterion for deciding the acceptability of offers in the next steps, is determined. The minimum expected utility of each farm at each stage of bargaining is equal to the average of the proposed utilities to that farm at the previous step. Since the minimum utility of farms varies during the bargaining process, this approach is called dynamic bargaining.

As shown in Figure 2, at each stage of bargaining, each farm only accepts a capping strategy that gives it a utility higher than its minimum expected utility, obtained from the previous step. Therefore, farms make offers that certainly satisfy this condition. Using a constraint to define the minimum utility that the proposed strategy can generate for bargaining parties causes the offers to converge toward an agreement. Bargaining continues until the convergence condition is satisfied.

Because of the minimum expected utility constraint, at some point, one or more farms may become restricted to unacceptable strategies, or in other words, have no strategy to generate the minimum utility for all farms. Since this bargaining method is designed to reach an agreement among all farms, in that case, bargaining reaches a deadlock.

To address this issue, the bargaining technique is modified. In the revised version, the minimum expected utility constraint is slightly relaxed. In this version, at each stage of bargaining, each farm proposes a capping strategy that, while maximizing its utility, also minimizes the maximum difference between the generated utility and the minimum expected utility of other farms.

Optimization model

The proposed optimization model seeks to find the optimal pattern of inter-sectoral groundwater trading and assess its effects. This model is a mixed-integer programming (MIP) model, which is solved using GAMS software. The formulations of the objective function and constraints are as follows.

Objective function

Equation (3), as the model's objective function, maximizes the total net benefit of all the water buyers and sellers.

$$\text{Max } F = \sum_k \text{NB}_k, \quad k \in \{1, \ldots, M, \ldots, N\} \tag{3}$$

where the NB and F represent the net benefit and value of the objective function (US\$), the subscript k indicates each water trading unit. N and M are also the total number of water trading units and the number of water-selling farms.

Equations (4) and (5) present the net benefit (NB) for each water seller and buyer, respectively. The farm units benefit from the sales of crops and water. But the water buyer units only have the benefits of product sales and have to pay for water purchasing and water transmission.

$$\text{NB}_m = \left[\sum_p \left(\text{SP}_{p,m} - \text{PC}_{p,m} \right) \times Y_{p,m} \times X_{p,m} \right] + \left[(1 - 0.5 \times \omega) \times \text{WP} \times \sum_n \text{SW}_{m,n} \right]$$
$$n \in \{M+1, \ldots, N\}, \ \forall m \in \{1, \ldots, M\} \tag{4}$$

$$\text{NB}_n = \left[\sum_p \left(\text{SP}_{p,n} - \text{PC}_{p,n} \right) \times Y_{p,n} \times X_{p,n} \right] - \left[(1 + 0.5 \times \omega) \times \text{WP} \times \sum_m \text{BW}_{n,m} \right]$$
$$- \left[\sum_m \sum_q \text{TC}_{m,n,k} \times \text{BW}_{n,m,q} \right], \qquad m \in \{1, \ldots, M\}, \ \forall n \in \{M+1, \ldots, N\} \tag{5}$$

The decision variables X, SW, and BW represent the production amount, sold water volume (m³), and bought water volume (m³). For farm (greenhouse) units and livestock (poultry) farms, the variable X is the cultivation

area (ha) and the number of animals, respectively. The number of raised dairy cattle (broiler chicken) is considered as an integer.

The parameters SP, PC, and Y are the sales price, production cost, and yield of each product, respectively. The Supplementary Appendix reports the values of these parameters. Furthermore, WP, TC, and ω show the water sales price, water transmission cost, and transaction cost coefficient, respectively. The water sales price is exogenously determined using water pricing scenarios, as this approach can improve the applicability of the C&T policies.

The water pricing scenarios include a specific percentage increase or decrease relative to the base price of water sales in the study area. Then, the water trading optimization model is run for different water pricing scenarios. The price that gives the best value of the objective function is reported as the water sales price. This price is determined to equal 1 (US\$/m^3).

Technical methods for water transmission are shared aquifer and tanker. The shared aquifer method includes the non-physical transmission of groundwater permits. The cost of this method arises from the monitoring costs of non-physical exchanges and is equivalent to 0.1 (US\$/m^3). The transmission cost for tankers is 0.05 (US\$/m^3/km). Moreover, the value of the transaction cost coefficient is 0.1 (Safari *et al.*, 2016). Half of the transaction cost is paid by the water seller and the other half by the water buyer, where the number of 0.5 indicates this fact in equations.

The subscripts m and n are the water seller and the buyer units, respectively. The subscripts p and q also indicate the product and water transmission method. Similar to the previous equation, M represents the number of farms, and N is the total number of water trading units.

Constraints

Equations (6) and (7) respectively reflect that the groundwater consumption volume for each seller and buyer of water should be less than its available water volume. The available water volume for each farm is the volume of pumped water minus the farm's sold water volume. The sum of the pumped water volume with the bought water volume is equal to the available water volume for each water buyer unit. Moreover, Equation (8) denotes that no water trading unit should engage in groundwater overexploitation.

$$\sum_p \text{WD}_p \times X_{p,m} \leq \text{PW}_m - \text{SW}_m, \quad \forall m \in \{1, \ldots, M\} \tag{6}$$

$$\sum_p \text{WD}_p \times X_{p,n} \leq \text{PW}_n + \text{BW}_n, \quad \forall n \in \{M+1, \ldots, N\} \tag{7}$$

$$\text{PW}_k \leq \text{GP}_k, \quad \forall k \in \{1, \ldots, M, \ldots, N\} \tag{8}$$

where the decision variable PW shows the volume of pumped water (m^3). The parameters WD and GP represent the water demand of the product and the groundwater permit (m^3). Other variables and subscripts are previously defined.

The purchased water volume and the sold water volume are equal in the market, as presented in Equation (9). Equation (10) states that a unit's purchased water volume includes the sum of the purchased volume through different technical methods. Also, Equations (11) and (12) illustrate that a unit can exchange water with several

other units.

$$\sum_n \mathrm{BW}_n = \sum_m \mathrm{SW}_m, \quad m \in \{1, \ldots, M\}, \; n \in \{M+1, \ldots, N\} \tag{9}$$

$$\sum_q \mathrm{BW}_{n,m,q} = \mathrm{BW}_{n,m}, \quad \forall m \in \{1, \ldots, M\}, \; n \in \{M+1, \ldots, N\} \tag{10}$$

$$\sum_n \mathrm{SW}_{m,n} = \mathrm{SW}_m, \quad n \in \{M+1, \ldots, N\}, \; \forall m \in \{1, \ldots, M\} \tag{11}$$

$$\sum_m \mathrm{BW}_{n,m} = \mathrm{BW}_n, \quad m \in \{1, \ldots, M\}, \; \forall n \in \{M+1, \ldots, N\} \tag{12}$$

Similar to previous equations, SW and BW are the sold and the bought water volume (m^3), respectively. The subscripts m and n are the indices for the water seller and the buyer units, respectively. Also, N and M denote the number of all water trading units and the number of farms. Finally, there are lower and upper bounds on the production amount for each product and each water trading unit, as presented in Equations (13) and (14).

$$X_p^{\min} \le X_p \le X_p^{\max} \quad \forall p \tag{13}$$

$$X_k^{\min} \le X_k \le X_k^{\max}, \quad \forall k \in \{1, \ldots, M, \ldots, N\} \tag{14}$$

where X shows the production amount. The subscripts k and p are the water trading units and products.

RESULTS

This section presents the results of the implementation of the proposed policy analysis framework in two parts, including capping groundwater permits and hydro-economic analysis of the proposed policies.

Capping groundwater permits

Based on the guidelines for implementing Articles 27 and 28 of the Law on Fair Water Distribution in Iran (Ahmadi *et al.*, 2019), this paper considers the command-and-control scenario involving a 25% reduction in groundwater permits for water-selling farms.

Moreover, the water authority considers two capping scenarios including a 20 and 30% reduction in permits according to the aquifer's hydrological conditions. Hence, the water-selling farmers have no role in determining this set of capping scenarios, because the scenarios are related to monitoring the quantitative conditions of the aquifer. However, these capping scenarios facilitate more water-selling farms choices so that farms can choose their capping permit scenario based on their utilities during a bargaining process.

There are eight water-selling farms and each of them can choose one of three capping scenarios. Hence, there are a total of 3^8 or 6,561 possible capping strategies. By ranking the capping strategies by farms, the prioritization matrix is formed with a size $8 \times 6,561$. The best capping strategy is selected through the static and dynamic bargaining processes.

Figure 3 shows the groundwater table variations for different values of the penalty function coefficient. As can be seen, imposing penalties of up to 100 (US\$/m^2) makes no change in the groundwater table because these penalties are not high enough to compel the farms to reduce their exploitation. However, farms use the groundwater resource according to their crops' water demand and have no excess withdrawal.
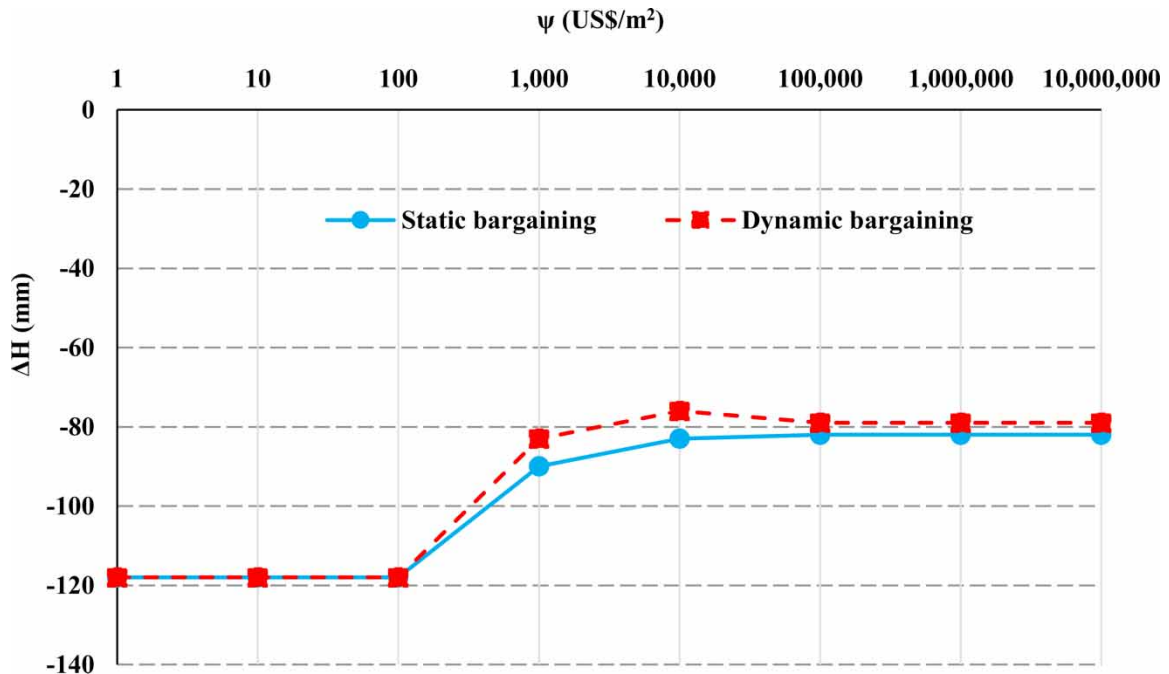
Fig. 3. | Groundwater table variations for different values of the penalty function coefficient.

With further increases in penalties, farms have reduced their withdrawal, which has led to an improvement in groundwater tables. For penalties higher than 100,000 (US$/m^2), all bargaining models show the same change in groundwater table with the increase in the penalty. Indeed, farms agree on the same strategies from this point onward irrespective of the penalty coefficient's rise. Therefore, the optimal value of the penalty function coefficient for use in Equation (2) is 100,000 (US$/m^2).

Table 1 outlines the obtained strategies from different approaches to capping groundwater permits. The dynamic and static bargaining methods propose similar scenarios for the first, third, and fifth farms. For other farms, the dynamic bargaining method results in a greater reduction than the static method. In the command-and-control approach, farms must reduce their permits by 25%.

As shown in Table 1, the dynamic bargaining method provides better economic and hydrological outcomes for the system than other methods. The dynamic bargaining method imposes 7,173 and 6,029 (US$) on the water-selling farms less than the command-and-control approach and the static bargaining method. Furthermore, the dynamic bargaining method improves the groundwater table compared with the other two methods. In the prioritization matrix, most farms have given a better ranking to the scenarios generated by this method.

The results illustrate that the BUC policy generates better outcomes because, unlike the top-down approach, the bargaining techniques do not ignore the farms' utilities. Moreover, the dynamic modeling of interactions among farms in the bargaining process leads to agreements on the capping strategy at a higher utility level in the prioritization matrix. Thus, the policy analysis results suggest that the obtained strategy from dynamic bargaining is superior.

Each homogeneous farm unit implements a different capping scenario than other farms. Therefore, non-compliance is always a risk. Nevertheless, each of the eight homogeneous farm units includes several neighboring sub-farms and all of these sub-farms cap their water permits to the same extent. Thus, this situation does not seem to increase the likelihood of non-compliance risk.

Table 1. | Results of capping groundwater permits.

Method	Outcome	Farm number								Sum
		1	2	3	4	5	6	7	8	
Dynamic Bargaining	Capping scenario	3	3	3	2	1	2	3	2	–
	Penalty cost (US$)	100	87	156	50	37	50	81	56	617
	Pumping cost (US$)	25,461	22,632	40,605	13,997	11,602	13,640	20,719	15,423	164,079
	Total cost (US$)	25,561	22,719	40,761	14,047	11,639	13,690	20,800	15,479	164,696
	Priority rank	255	731	561	824	1,106	1,208	1,173	2,167	–
	ΔH (mm)	-79								
Static Bargaining	Capping scenario	3	2	3	1	1	1	2	1	–
	Penalty cost (US$)	108	94	168	54	40	54	87	61	666
	Pumping cost (US$)	25,463	24,251	40,608	14,931	11,602	14,551	22,200	16,453	170,059
	Total cost (US$)	25,571	24,345	40,776	14,985	11,642	14,605	22,287	16,514	170,725
	Priority rank	257	780	611	882	1,183	1,297	1,184	2,184	–
	ΔH (mm)	-82								
Command-and-Control	Capping scenario	2	2	2	2	2	2	2	2	–
	Penalty cost (US$)	110	96	172	55	41	55	90	62	681
	Pumping cost (US$)	27,283	24,252	43,510	13,998	10,878	13,641	22,201	15,425	171,188
	Total cost (US$)	27,393	24,348	43,682	14,053	10,919	13,696	22,291	15,487	171,869
	Priority rank	238	734	573	829	1,185	1,304	1,279	2,353	–
	ΔH (mm)	-83								

Hydro-economic analysis

Figure 4 represents the sold water volume from farms to various industrial units. The greenhouse and broiler chicken farm units purchase a much lower volume of water than other units. Moreover, the stone cutting units have the peak of the purchased water volume. This difference in water purchase volume among various industrial units is due to differences in their water demands and production restrictions.

The annual volume of sold water is 178,600 (m³), which means farms sell only 1% of their total capped ground-water permits. The building industry units and livestock and poultry farms purchase water as much as possible due to their high productivity. Thus, restrictive policies concerning the industry sector's production amount put the sold irrigation water volume low.

The industrial units choose the water transmission method based on cost criteria. The greenhouse, broiler chicken farm, and stone cutting units receive most of their bought water volume by tankers. Other water buyers choose the shared aquifer method. Overall, results show that 57% of the water sales are done using the shared aquifer method. This method is a non-physical method for groundwater transmission, where the water buyer pumps groundwater from its well equal to the bought water volume.

Figure 4 also depicts the water supply amount for water purchasing units. The water permits under water scarcity conditions do not fully meet the water demands for industrial units. Therefore, these units are forced to purchase water. The livestock and poultry farms and building industries meet 17 and 33% of their water demands through water purchase. However, greenhouses can only provide an insignificant amount (equivalent to 0.1%) of their needs. Therefore, the water trading approach can support part of the industry sector's water demands by reallocating irrigation water without further groundwater exploitation.

Figure 5 visually shows groundwater trading results for individual units. The results indicate that most units participate in the water trading mechanism, and only greenhouse unit 1 does not purchase water. Although
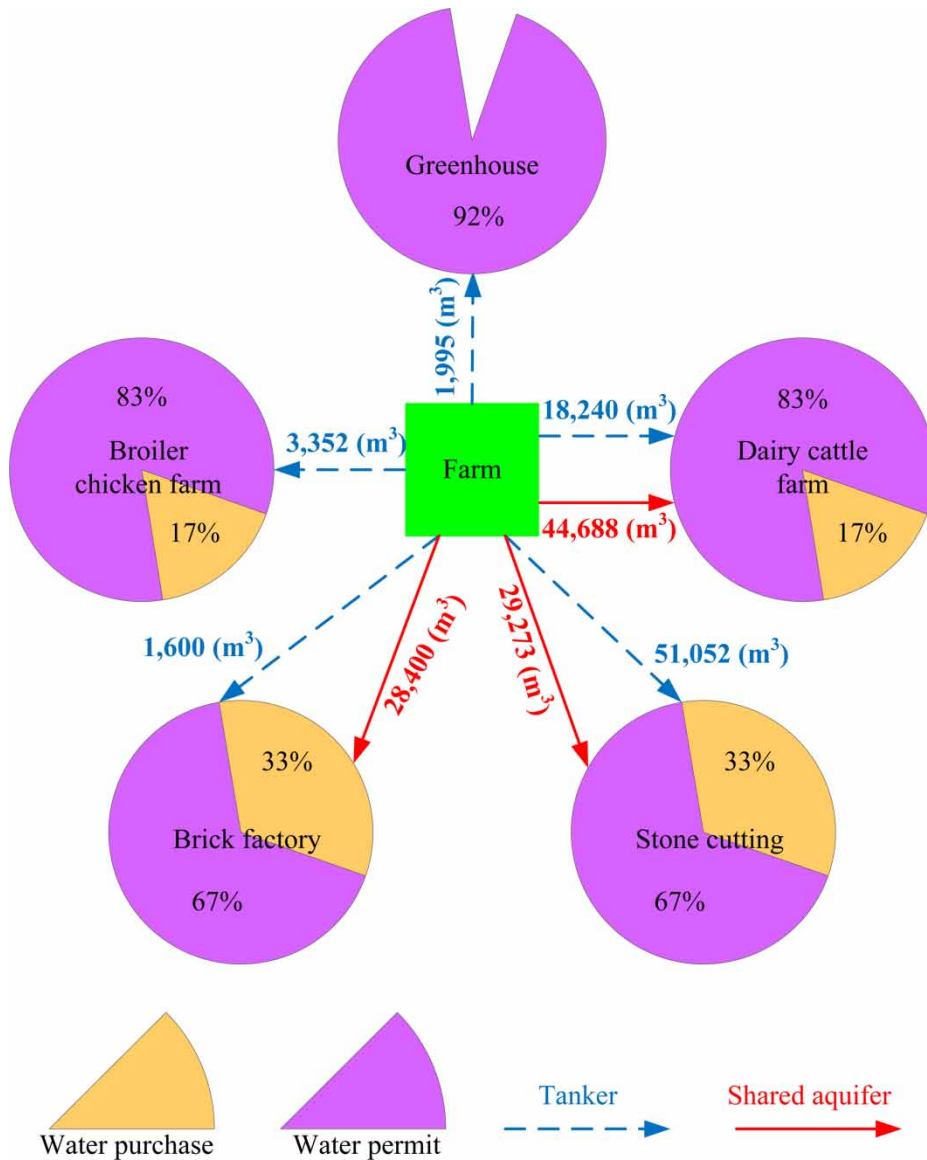
Fig. 4. | The water supply amount for trading units and water exchange volume among them.

the volume of exchanges through the shared aquifer method is higher (Figure 5(b)), more water buyers choose the tanker method due to their short distance from the farms (Figure 5(a)). These buyers only purchase water from a nearby farm unit.

Each water buyer unit often chooses a technical method for water transfer, and only stone cutting unit 3 uses both methods. Moreover, Figure 5(b) illustrates the capped groundwater permits are transmitted from all farms to each buyer, which indicates that the non-physical method has a greater capacity to transfer water in a groundwater trading mechanism.
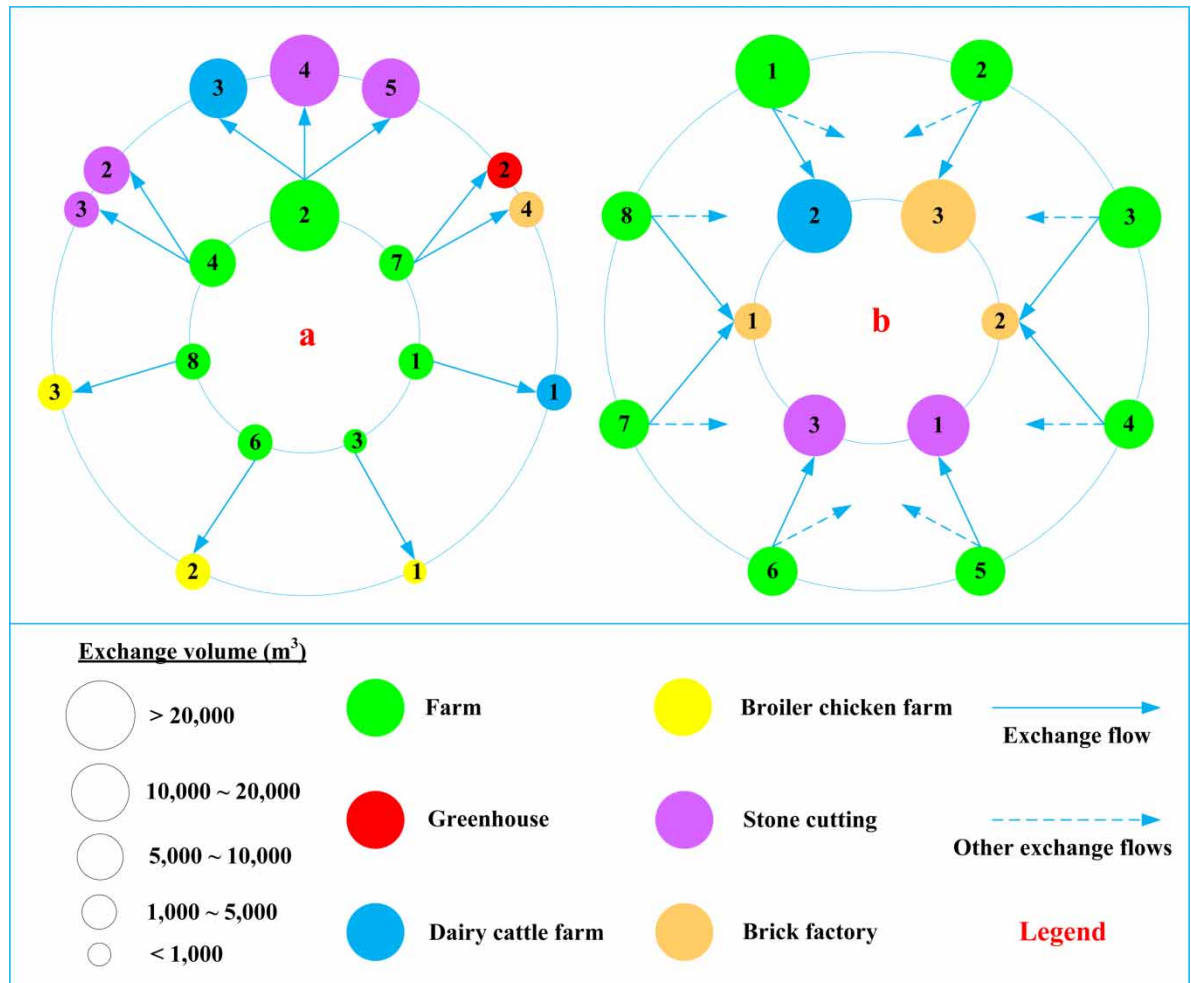
Fig. 5. | Groundwater trading results for individual units: (a) tanker and (b) shared aquifer. (*Note:* The number of each unit is specified inside its corresponding circle. Moreover, in (b), there are several exchanges flows from each seller to all buyer units, which use dashed arrows to simplify the visualization process.)

Figure 6 presents the crop pattern for water-selling farms under capping and C&T policies. Both policies increase the fallow area by reducing the available water volume for farms. However, the C&T policy further increases the fallow area by selling the irrigation water to the industry sector. Furthermore, these policies shift the farms' crop pattern to cultivating profitable crops under production constraints, so that the cultivation area of barley and alfalfa, which have very low productivity, is determined at the lower bound of their production amount.

Table 2 reports the production amount of industrial units. The results illustrate that water purchasing increases the industrial sector's production amount compared to the current mode (capping policy), so that the dairy cattle farm, broiler chicken farm, and building industry units reach their maximum production. Moreover, in greenhouse units, the cultivation area of bell pepper and cucumber increase by 18 and 10%, respectively. In contrast, the cultivation area of tomato with lower productivity decreases by 10% compared to the current mode.
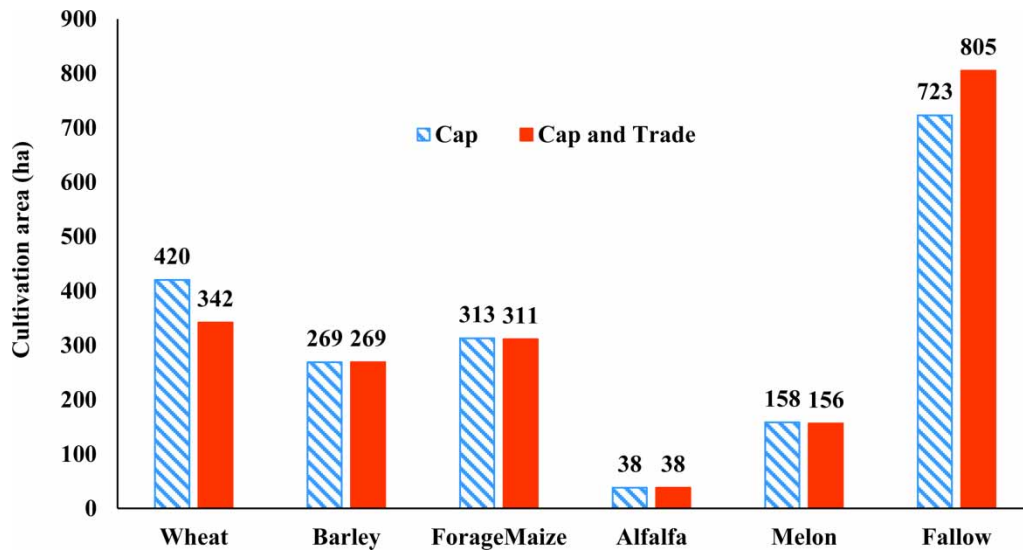
Fig. 6. | Cultivation area for different farm crops.

Table 2. | Production amount for different industrial units.

Water buyer unit	Policy	
	Cap	Cap-and-trade
Dairy cattle farm (number of cattle)	6,900	8,280
Broiler chicken farm (number of chickens)	453,000	543,600
Stone cutting (m²)	1,890,000	2,835,000
Brick factory (t)	150,000	225,000

Table 3 shows the net benefit of water trading units in different modes. With the implementation of the C&T policy, all industrial units receive higher net benefits due to the water purchasing and consequently increase their production. The net benefit of the industry sector increases by 37% compared to the current mode (capping policy). In contrast, by capping the groundwater permits, the farms' production amount, and consequently their net benefit decreases. Nonetheless, the farm units compensate their losses by changing the crop pattern and water sales to the industry sector under C&T policy. These results illustrate the economically positive role of the water trading policy.

The results show that farms benefit less than most industrial units under implementing water trade. While farms have an important role in forming the water transactions as the only water sellers, this issue can negatively affect farms' participation in the market. In this regard, the industrial units can offer more encouragement to farms to participate in the inter-sectoral water trading process by incentive payments. This idea is possible by defining water trading in a cooperative game, where there could be different coalitions among the trading units (see Supplementary Appendix).

According to Table 3, by paying an incentive payment of 882,000 US$ to the agriculture sector, the industry sector increases its net benefit and the agriculture sector compared to their current net benefit (capping

Table 3. | Net benefit for groundwater trading units in different modes (10^3US$).

Mode	Player						
	Farm	Greenhouse	Dairy cattle farm	Broiler chicken farm	Stone cutting	Brick factory	Sum
Cap	1,799	159	2,934	189	5,040	938	11,059
Cap-and-trade	1,906	165	3,438	222	7,455	1,367	14,553
Net benefit reallocation	2,788	164	3,314	213	6,818	1,256	14,553
Side payments	882	−1	−124	−9	−637	−111	0

policy) by 27 and 55%, respectively. If incentive payments are not paid to the farm units, they may even be reluctant to participate in the water market due to receiving less net benefit than the water purchasing industries. As a result, water may not be exchanged, and the net benefit of the industry sector remains at the current mode.

Thus, the significant increase in the net benefit of the agriculture sector (equivalent to 55%) is because, in the inter-sectoral water trading mechanism, farms as the only water sellers play an essential role in increasing the overall net benefit of the system. Therefore, fair reallocation of net benefit from water trading using the cooperative game model can generate more economic incentive for participation in the C&T policy and lead to stable exchanges.

The results indicate that the C&T policy reduces the farms' pumped groundwater volume by 35%. Moreover, given the high productivity of water use in the industry sector, there is no change in this sector's groundwater pumped volume. However, with capping groundwater permits and transmission of irrigation water to the industry sector, the volume of return flows to the aquifer is reduced by 36%. Finally, the hydrological analysis clarifies that groundwater volume in the aquifer is increased by 3%. These results demonstrate the effectiveness of the C&T policy under water scarcity conditions.

CONCLUSION

This paper analyzed the capping and C&T policies on groundwater permits for achieving more favorable economic and hydrological objectives in using a real shared aquifer. The purpose of the capping policy is to improve the aquifer's hydrological conditions. This policy may face opposition from farms when it is implemented with a top-down approach. However, if farms' utilities are considered in developing these policies under a bottom-up approach, the implementation guarantee can be increased.

The water-selling farms have non-cooperative behavior in using a shared aquifer. Therefore, this paper presented the BUC policy to identify the best strategies for capping permits that guarantee a minimum utility level for all farms. The BUC policy creates a negotiation process among farms over capping strategies, which continues until a strategy is agreed upon by all farms.

The results illustrated that the BUC policy generates more acceptable outputs than the command-and-control approach. Furthermore, policy analysis reveals that the dynamic bargaining technique's results were more favorable than those obtained from the static bargaining technique. This finding is due to the dynamic adjustment of minimum acceptable utility during the bargaining process and influencing farms from the previous bargaining stages.

The features of the proposed BUC model are largely consistent with the objectives of an effective governance framework for environmental issues (Horne & O'Donnell, 2014). In this context, (1) the water authority determines the set of capping scenarios according to the aquifer's hydrological conditions (separation of water

users from water use policy-making processes); (2) farms choose their withdrawal volume during a bargaining process (transfer of decision levels to the lowest level); (3) farms participate in the decision-making process and determine their withdrawal volume based on their utilities (respect for the objectives and accountabilities of lower levels or project implementers); and (4) the water authority is aware of the farms' capped permit and withdrawal. However, there is a need to raise awareness among farms about the quantitative conditions of the aquifer and the reasons for the water authority to implement a policy of capping the water permits (looping information flow among different levels of stakeholders).

This paper has tried to increase the implementation guarantee of the capping policy by considering the farms' utilities. Nevertheless, the BUC model, like any other participatory approach, needs legitimacy to be enduring (O'Donnell & Garrick, 2017; O'Donnell et al., 2019). Political science establishes legitimacy in two main ways, including input legitimacy and output legitimacy (Hogl et al., 2012). Input legitimacy focuses on the process and the level of acceptability to people affected by the policy. Moreover, output legitimacy emphasizes the problem solution and outcomes (O'Donnell et al., 2019).

In this regard, the proposed BUC policy tries to guarantee output legitimacy through bargaining techniques, in addition to considering the input legitimacy concept. Indeed, it is necessary to create a shared understanding among all stakeholders, including farms, about the need to implement capping policies (input legitimacy), draw a shared vision for the success of these policies, and make a final decision as a valid decision to be accepted collectively (output legitimacy).

The BUC model seeks to establish horizontal inter-farm relationships (O'Donnell et al., 2019) that improve the input legitimacy. In fact, the interesting element in the BUC policy is the capacity for a more legitimate method of capping water permits, in which water users feel like they have a role in setting the cap and some control over the levels set.

On the other hand, the BUC model considers the output legitimacy by maintaining the macro policies of water conservation (water authority's utilities). Furthermore, the potential legitimacy payoff in using the bargaining techniques is larger than the command-and-control approach because, based on the output legitimacy, bargaining models provide better hydro-economic outcomes. The improvement in output legitimacy for the dynamic bargaining is greatest due to the farms pay attention to the utilities of other farms to reach a consensus while maintaining their utilities.

It should be noted that the use of cultural, social, and executive capacities at the local scale is very effective for building trust and input legitimacy toward aquifer conservation measures and for the farms' participation in these measures (Hogl et al., 2012; O'Donnell et al., 2019; Ghorbanian et al., 2020). Transparency and accountability in decisions and elimination of overlaps are also inevitable components for input legitimacy (Hogl et al., 2012; Grafton, 2019). In this regard, the experience of Neishabour Plain located in Iran in capping the groundwater permits (Ghorbanian et al., 2020) by establishing participatory approaches and strengthening the input legitimacy of regulatory programs can be considered as a successful example.

The policy of selling irrigation water to the industry sector was considered to improve the economic efficiency of using the capped groundwater permits. The C&T policy increases the net benefit of the industry sector by allocating water to more productive uses. Moreover, the sale of irrigation water compensates the farms' losses caused by capping water permits. Nonetheless, despite having an important role in forming the water market, farms benefit less than most industrial units. Therefore, the industry sector facilitates inter-sectoral water trading by paying incentive payments to water-selling farms.

From the proposed policy analysis framework, it can be concluded that adopting a BUC policy under bargaining techniques for inter-sectoral groundwater trading can be an effective and viable solution for managing groundwater resources under water scarcity conditions.

ACKNOWLEDGEMENTS

DATA AVAILABILITY STATEMENT

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

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