An uncertainty-based smart market model for groundwater management

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ABSTRACT

This paper presents a new water market mechanism, which can be used for selecting the best trading policy by incorporating the uncertainties of total annual available water and wholesale price of agricultural products. In this mechanism, water users are asked to submit bid packages via a web-based platform. A bid package represents the real values that a user puts on different quantities of withdrawn groundwater considering its quality. Then, the most reliable water trading policy as well as the price of water are calculated by taking the market endogenous and exogenous uncertainties into account using the regret theory. The results show that by applying the proposed uncertainty-based smart groundwater market mechanisms to the Nough Plain in Iran, the average productivity of water users increases about 18% compared to the status quo condition. Furthermore, based on the outputs of the proposed market model, groundwater is finally distributed to agricultural users almost proportional to their farms area.

Key words: groundwater management, nough plain, regret theory, smart water market, uncertainty

HIGHLIGHTS

• A new seasonal smart groundwater market mechanism is proposed for groundwater management.
• The market time step is determined based on crop growth stages.
• The most reliable water trading policy and price of water are calculated using the regret theory.
• The methodology is evaluated using available data form the Nough Plain in Iran.
• The proposed mechanism increases the average water productivity of users.

INTRODUCTION

The potential ability of water markets to cope with water scarcity has been widely studied in recent years (Hadjigeorgalis 2009; Wei et al. 2011; Kiem 2013; Aghaie et al. 2020). In water markets, both buyer and seller benefit from water trading in a way that for the seller, selling water is more profitable than what he can gain from consuming it. Besides, buying and consuming water for the buyer is more beneficial than selling it. The environment can also get benefit from water markets where regulators reallocate water based on the carrying capacity of shared water resources between users. As a result, water market can make both water users and environment best off (Raffensperger & Milke 2017).

Zeng et al. (2015) addressed water trading modeling for supporting water resources management in arid regions. They showed that water-trading is an effective approach for reallocating limited water resources with the goal of maximizing the total benefit of the system. However, they did not present a mechanism and structure for the market.

It appears from the recent researches that numerous investigations have been conducted to economically and environmentally evaluate the impacts of groundwater markets. However, limited attempts have been made to develop effective mechanisms for operating groundwater markets. For example, in concerning of the side-effects of groundwater market implementation and its prerequisites, Khan & Brown (2019) simulated the behavior of farmers in a groundwater market using a baseline operating model that maximizes the net profit of farmers based on water and land resources constraints. This economic model was used along with a groundwater model to explain the effects of groundwater extraction on the aquifer. They discussed that trading of water entitlements between farmers results in increased economic benefits and, in some cases, reduced environmental violations.

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One of the recent researches introducing a new mechanism to run a smart water market with multipart bids in each auction is a smart water market proposed by Raffensperger & Milke (2017). In this market, an auctioneer requests bids from users, and awards the goods to those who bid highest. It is not a market with fixed prices, like a grocery store is. The smart market provides the trading location, so users need not search for each other. More importantly, a linear program automates the vetting process, so the transaction cost falls considerably. The market can be multi-round. Bidders have the opportunity to see tentative results and can change their bids, subject to rules, before the final round. Allowing multiple rounds helps improve the bidding process. Many bidders do not know their true demand functions and provide poor set of bids. By viewing the results of a test auction, they will have the ability to adjust their bids after seeing whether they would be buyers or sellers and after they evaluate the likely economic impact of that trial bid. The final price of water should be public, and the amount of water that each user takes can be public. The market manager sets prices for water at marginal cost, not the highest bid (Raffensperger & Milke 2017).

In concerning with the groundwater market mechanisms, Raffensperger et al. (2009) presented a deterministic linear program that could be used to operate a smart spot market for groundwater. They presented a case study with notional bids for Marlborough, New Zealand. They claimed that their approach can reduce transaction costs and reduce water users’ risk. Aghaie et al. (2020) designed a deterministic agent-based groundwater market model to analyze the economic and hydrologic impacts of three market mechanisms namely the cap-and-trade scheme, uniform price double-auction and a discriminatory price double-auction in the Rafsanjan Plain in Iran. They also examined the hydrologic and economic effects of water buyback programs. They found that the discriminatory price double-auction is the most hydrologically and economically advantageous mechanism.

Some limited researches have addressed the design of water market mechanisms under uncertainties. To incorporate the endogenous and exogenous uncertainties such as available water and crop price in water markets, a stochastic programming model was adopted by Huang & Loucks (2000). This model allows irrigators to trade their seasonal water extraction entitlements considering precipitation uncertainties. Zeng et al. (2015) proposed a stochastic water trading model for allocating water resources when total available water is uncertain. They analyzed a number of policies for allocating water entitlements and showed that different water entitlements lead to different water shortages, system benefit, and system-failure risk. Du et al. (2017) investigated the effects of uncertain behavioral characteristics of farmers on a hypothetical water market based on a double auction mechanism. Assuming that the probability distribution functions of the mentioned parameters are available, they attempted to analyze the uncertainties of the parameters in their market model.

In the water market, it is crucial for the market manager to determine the total available annual groundwater based on hydro-climatic data and announce it to users for the upcoming year before the auction begins. If the basin-wide available amount of water is not determined with sufficient certainty, a water market model outcome will not be desirable as bids submitted by users might be based on misleading information. Due to the lack of long-term groundwater budget data, it is not possible to accurately estimate the total annual available water. As a result, overestimation or underestimation of the total available water in the market would be inevitable. Therefore, in this paper, the ranges of variations of uncertain variables are taken into account in a new uncertainty-based groundwater market. Also a new structure for bid packages, which considers both the quality and quantity of traded water is proposed.

In the smart water market proposed by Raffensperger et al. (2009), each user offers a bid package for buying and selling water in the groundwater market considering different values for each quantity of water. While in the proposed smart water market, users submit bid packages for different quantities and qualities of groundwater. In other words, in the current groundwater market mechanism, the quality of groundwater of water holders’ affects the final groundwater extraction entitlements (GEEs) and water trading prices. In addition, in the developed methodology, the main existing uncertainties are incorporated using the regret theory. The rest of this paper is organized as follows: First, in the methodology section, a flowchart of the proposed methodology and detailed description of each part of the flowchart is presented. In section 3, the main characteristics of the study area are reported. In the results and discussion section, the main findings of and the proposed uncertainty-based water markets are discussed. Finally, in the last section, concluding remarks and some recommendations for future works are presented.
METHODOLOGY

A flowchart of the proposed smart groundwater market models are illustrated in Figure 1. In following subsections, details of different parts of the flowchart are presented.

Data collection

In this stage, this paper aims at collecting the data needed for smart groundwater market execution such as meteorological data, piezometric data, hydrological data, aquifer bedrock topography and wells discharge data for groundwater modeling during the years of 2006 to 2020 (Iran Water Resources Management Company). Meanwhile, digital data layers of the main characteristics of the study area such as area under cultivation, wells locations, rural districts borders and groundwater quality characteristics are presented for the agents’ identification.

Farmer clustering

According to the findings of Jaghdani & Brümmer (2016), farmers with a higher crop yield per hectare and lower groundwater pH and electrical conductivity (EC) are more likely to purchase water in the Rafsanjan plain’s water market. Likewise, farmers who have lower crop yields and higher groundwater pH and EC are also more likely to sell their water quota. Therefore, in order to find a sub-region for implementing the proposed market mechanism, consideration has been given to crop production per hectare, groundwater pH, and EC criteria.

Adjusting users’ GEEs

A three-dimensional groundwater simulation model is calibrated, verified and hired for exploring different groundwater extraction scenarios and calculating the optimum adjustment coefficient for users’ GEEs to guarantee that the total groundwater extraction is equal or less than the safe yield.

Groundwater is usually a common pool resource and the administrator should regulate all abstractions at the same time. In this paper, the Groundwater Modeling System (GMS) is used for groundwater simulation. The GMS consists of a graphical user interface and some groundwater simulation codes (e.g., MODFLOW, MT3DMS, etc.) (Hemker & van Elburg 1990). Using the groundwater simulation model, the aquifer critical points (i.e., points near environmentally vulnerable areas) in terms of water table drawdown are defined. After generating aquifer response data using the groundwater simulation model, the aquifer response function for the critical points are calibrated and verified. Briefly, an aquifer response function shows how much water withdrawal at each abstraction point effects groundwater table level at each control point. Using this function as an environmental constraint, instead of linking the groundwater simulation model to the market-based optimization model, significantly reduces the computational cost.

Proposing smart groundwater market mechanism

In this market, at first, it is necessary to evaluate the main characteristics of each user (i.e. a coalition of farmers) and estimate its water production function. The smart water market is based on an optimization model to determine water entitlements and prices using a multi-bid auction method. In this market, instead of guessing user’s water values, they are asked to directly bid for water via a web page.

In this paper, a multi-agent optimization model is employed to simulate the proposed smart groundwater market mechanism. Agent-based models (ABMs) have been employed to simulate agents’ actions at macro and micro scales. Several varieties of ABMs have been used for agents’ behavioral modeling such as cellular automata, individual-based models, intelligent agents, and multi-agent models. Cellular automata models (Batty 1997) are identified by defining agents’ processing within a discrete cellular boundary connected to others like automata using neighborhoods of interaction. Individual-based models (Grimm 1999) has been designed to describe the behavior of a single agent. Intelligent agents (Frank et al. 1992) have been generally designed with a level of artificial intelligence to explore the behaviors of general or task-specific intellects. Multi-agent models are generally built with many individual agents, each of which may play a different role or assume a set of distinct tasks in a model of collective behavior. Such models generally assess the interactions between individuals or units such as farmers. Agents in a multi-agent system usually interact with (or within) an environment (Manson & Evans 2007). In this paper, we use a multi-agent model to simulate the behavior of water users based on the proposed groundwater market mechanism.

The proposed multi-agent optimization model determines the water re-allocations and prices while ensuring that the environmental requirements are satisfied (Raffensperger & Milke 2017). This market is operated by a central manager. Water users offer bids as bid packages, and the market manager gathers those bids through a web page to run the smart
Figure 1 | A flowchart of the proposed methodology.
water market and identify potential water exchanging between users. Raffensperger et al. (2009) designed a market for a case when irrigation water is supplied from a joint aquifer. They employed a deterministic optimization model using linear programming without considering the quality of water in pricing and trading of groundwater. They concluded that their approach is able to reduce transaction costs as well as users’ risks and promote the reliability of the aquifer protection.

In the proposed smart water markets, unlike traditional water markets (e.g., Du et al. 2017; Khan & Brown 2019; Razzaq et al. 2019; Aghaie et al. 2020), users do not offer only the price of water; they propose a bid package, which shows price of different quantities and qualities of water (Figure 2). This type of water market can provide prices of water at different locations and times. Therefore, to achieve better bids based on the users’ marginal value of water, an advanced bidding structure has been employed. This structure considers different water quantities and qualities with different prices based on the fact that the very first units of water are more valuable than the next ones (Figure 2). Consequently, the users should offer their bid packages considering this bidding structure. Meanwhile, the water trading prices in this mechanism are determined based on the shadow prices of water extractions by users.

In the proposed market mechanism, users do not to physically buy or sell water. They submit bid packages for different quantities and qualities of water (Figure 2).

In this paper, to simulate the behavior of water users in the process of bidding, a crop production function has been applied to calculate the users’ marginal value of water for specific quantity and quality of water and estimate bid package of each user.

Equations (1)–(9) present the formulation of the proposed smart water market. In this paper, the smart water market mechanism for groundwater trading aim to maximize the value of water considering the environmental constraints. In the smart market model, the objective is to maximize the total value of water. The water price (dual price) is the change in the total value of water if the user total water constraint (Equation (2)) is relaxed by 1 unit. The proposed smart water market is executed based on Equations (1)–(9). The program is written in MATLAB to analyze the results of the proposed market mechanism. Accordingly, the potential groundwater trading partners, groundwater trading prices, GEEsafter trading and final profit for each agent are determined while the effect of the trading on the aquifer is re-evaluated using the groundwater simulation model.

\[
\text{Maximize} \quad \sum_{\text{user } w} \sum_{\text{bids } b} \text{BidPrice}_{b,c,w} \text{bid}_{b,c,w} \\
q_w = \sum_{\text{bid } b} \text{bid}_{b,c,w} \quad \text{for each user } w
\]
Executing the proposed water market for the best values of the uncertain parameters

In this section, the formulation of an uncertainty-based smart water market is proposed to explore a robust solution in water market that is subject to endogenous and exogenous uncertainties using Regret theory. The regret theory is a non-probabilistic method to analyze and evaluate deep uncertainties for a situation in which there is no information regarding probability distribution functions of uncertain parameters. By minimizing the regret criterion of a management scenario, the regret theory aims at finding the best scenario under deep uncertainties. The primary idea behind the regret theory, which was proposed by Bell (1982) and Loomes & Sugden (1982), is that decision-makers often think about decisions that have already been made after the fact. If they have taken other alternatives, will the results be better now? The decision-makers will feel regret inward if the answer is positive. Otherwise, they will feel rejoiced. Consequently, when facing new decision-making problems, decision-makers will generate an expected regret for some expected decision-making scenario based on past experiences and tend to take the strategy which yields the least expected regret. Regret was also described by Linhart & Radner (1989) as the gap between the benefit a decision maker might have made with hindsight and the benefit he actually made. The main concept of the method is similar to the way human beings deal with uncertainties (Poorsepahy-Samian et al. 2012).
Determining the total available water at the beginning of each trading year is a challenging task for the market manager due to existing uncertainties in the precipitation and evapotranspiration. The wholesale price of pistachio (price), which depends on the economic condition is another variable with deep uncertainty. In this manuscript, the ranges of variations of these two uncertain variables are predicted at the beginning of each trading season, and the regret theory is used for selecting the best trading policy considering the regret and total benefit criteria. As shown in Figure 3, to evaluate the regret criterion, all plausible values of total available water and price are considered as different scenarios for inputs of the water market model. The regret value of a trading policy corresponding to scenario $i$, is calculated using the following equation:

$$\text{Regret}_i = \sum_{j=1}^{n} |U_i - U_{ij}|$$

(10)

where, $\text{Regret}_i$ is the regret of trading policy $i$, which has been developed based on scenario $i$; $U_i$ and $U_{ij}$ denote the utility of trading policy $i$ when scenarios $i$ and $j$ occur, respectively. A scenario with lower value of the regret criterion is more favorable.

**Figure 3** | A flowchart of the calculation of the regret criterion.
Case study

Rafsanjan Plain is a sub-basin of Kerman plain which is located in the southeast of Iran, between 54° 52’ to 56° 34’ and 29° 51’ to 30° 51’ longitude and latitude, respectively (Figure 4). It also covers an area of 1,242,100 hectares. Rafsanjan elevation varies between 1,400 and 3,443 m above the sea level. This region has warm summers and cold and dry winters. Rafsanjan aquifer is used for supplying domestic, agricultural, and industrial water uses. The annual precipitation ranges between 60 mm in lowlands to about 120 mm in uplands. Recharge to the aquifer is mainly due to the infiltration of precipitation and irrigation return flow. The average evapotranspiration height in the study area is 3 m/year (Rahnama & Zamzam 2013). Tables 1 and 2 illustrate the components of the general budget and groundwater budget of the Rafsanjan Plain, respectively (IWRMC 2011)

Nough Plain is placed at northwestern of the Rafsanjan Plain (Figure 4). Nough Plain area is about 82,260 hectares, including Ferdousiyeh, Esmail Abad, and Bahraman rural districts. In this region, there are 336 registered drilled wells (Figure 5). Over exploitation of groundwater in their region has resulted in adverse environmental consequences such as pistachio production reduction due to salinity of groundwater and land subsidence.

In Iran, permanent groundwater rights are officially set by Regional Water Board Companies (RWBCs). These companies manage groundwater resources by monitoring groundwater discharges. Farmers in the study area (i.e. the Nough plain in Iran) have historical water entitlements (water rights). These water entitlements, which have been issued by Kerman RWBC, are in the form of water discharge permits in which the pumping rate and the number of hours of water extraction per week have been determined.
### Table 1 | General water budget of the Rafsanjan Plain (annual average, million m³/year)

| Aquifer storage | Surface storage | Total outflow | Transferred water | Groundwater outflow | Evapotranspiration from | Total inflow | Transferred water | Surface flow | Precipitation | Plain | Heights |
|-----------------|-----------------|---------------|-------------------|---------------------|------------------------|---------------|-------------------|--------------|---------------|-------|---------|
| –153.89         | –               | 1,739.95      | –                 | –                   | –                      | 10.07         | 516.54            | 0.04         | 30            | 1,183.3 | 1,586.07 |
|                 |                 |               |                   |                     |                        |               |                   | 30.23        | 32.32         | 482.12 | 1,041.4 |
In the past years, only informal groundwater markets have existed in Iran. Sometimes, different owners of a well informally trade their water entitlements. Recently, Iran’s Supreme Council of Water has allowed the establishment of formal water markets, but currently there is not a legal framework or mechanism for water markets. In the current paper, we try to propose a groundwater market mechanism considering the characteristics of the study area. In the proposed mechanism, at the beginning of each water year, the market manager determines users’ water entitlement exchanges considering the predicted available water and environmental constraints. In this market, groundwater discharges are monitored by both market manager and the RWBC. The environmentally sensitive areas are also defined by the RWBC and Iran’s Department of Environment. Also, the auction interval is annual.

**RESULTS AND DISCUSSION**

The proposed methodology has been applied for designing an uncertainty-based water market for the Nough Plain. In this regard, the proposed hydro-economic model is used to maximize the economic value of water and the three-dimensional

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**Table 2 | Groundwater budget of the Rafsanjan Plain (annual average, million m³/year)**

| Change in groundwater storage | Total discharge | Outflow to other basins | ET from groundwater | Drainage | Draft from groundwater | Total recharge | Recharge from other consumptions | Recharge from field irrigation | Seepage from canals | Recharge from surface flow | Recharge from rainfall | Inflow from other basins |
|-----------------------------|-----------------|-------------------------|---------------------|----------|------------------------|---------------|-------------------------------|-----------------------------|------------------|-------------------------|-----------------------|------------------------|
| -153.89                     | 738.54          | 2.464                   | 0.041               | 0        | 736.03                 | 584.64        | 24.02                         | 231.96                      | 18.14            | 45.5                    | 40.405                | 224.63                 |

**Figure 5 | Location of existing agricultural wells in the study area (i.e., Nough Plain).**
groundwater simulation model (i.e. GMS) is applied to determine the amount of available water and control groundwater table drawdown at control points. In order to determine the participants in the water market, first, the study area has been clustered into a number of sub-regions as the agricultural agents.

The farmers in the study area have been clustered into some homogenous classes based on crop production per hectare, groundwater pH, and groundwater EC criteria (Figure 6). According to the perfect competition principle, the sub-region in the study area with the most variety of classes can be selected as a proper local area for executing the proposed market (Figure 7).

Then, by dividing the selected local market area into nine sub-regions (sub-coalitions), the main features of them are determined using existing data (Table 3). Considering the study area’s crop production per hectare, 135 observed data were used to classify the study area into three classes using the supervised classification: class 1 for high productivity pistachio orchards, class 2 for medium productivity orchards, and class 3 for low productivity orchards. To assess the users’ final classes, the productivity map was overlaid with groundwater pH and EC maps in Arc GIS (Figure 7). Sub-coalitions role as separate agents participating in the GEE trading in the proposed groundwater market model.

![Figure 6](https://example.com/figure6.png)

*Figure 6* | The farmers’ clustering process: (a) Orchards productivity classification, (b) Groundwater pH classification, (c) Groundwater EC classification, (d) Overlying the digital data layers and (e) Final identified area for the local water market implementation.
Afterward, the agents’ bid packages are estimated using the agricultural production function which are inputs of the market model. The production function for pistachio orchard in the study area, is calculated using Equation (11) (Abdollahi Ezat Abadi 2014):

\[
Y = 0.137\frac{W}{C_{0.055}} + 0.05\frac{W^{1.7}}{C_{0.055}} + 0.033\frac{W.S}{C_{0.027}} - 19\frac{W.EC}{C_{1.025}} + 19\frac{W.EC^{2}}{C_{1.025}} + 19\frac{W.C}{C_{1.025}}
\]

where, \(Y\) the denotes Pistachio production (kg/ha.year); \(W\) represents the irrigation water (m\(^3\)/ha.year); and \(EC, S\) and \(C\) are the electrical conductivity of groundwater (\(\mu S/cm\)), soil texture type (Hard = 1, Soft = 0) and pistachio type (Kaleghouchi = 1, Other types = 0), respectively.

In this paper, it is necessary to estimate the total extractable annual water of the aquifer to match the legal GEEs. As a result, the total aquifer entitlement should be scaled to match water users’ GEEs with the total extractable (available) water. The total extractable water should be allocated to each agent by adjusting the wells current GEEs. Towards this end, first, a three-dimensional groundwater model has been modeled to delineate non-uniform groundwater decline resulted from groundwater discharge. The model was created using MODFLOW (Harbaugh 2005) employing the graphical user interface GMS. The model’s boundary conditions have been determined considering the geological condition of the study area.

**Figure 7** | Identification of the sub-coalitions and their associated wells within the proposed local market area.
(Figure 8(a) and 8(b)). The location and water withdrawal from each pumping well are also determined using recorded data (Figure 8(c)). In addition, 96 observation wells with recorded data in the study area are considered in the model (Figure 8(d)). Available monthly groundwater table data are from 2005 to 2020. 75% (120 months) and 25% (40 months) of the data are used for the calibration and verification of the groundwater simulation model, respectively. Figure 9 presents a comparison between the observed and calculated groundwater heads in four randomly chosen piezometers. By comparing the observed hydraulic heads with the simulated ones in the verification process, the mean absolute residual error (MARE), root mean squared error (RMSE) and determination coefficient (DC) have been calculated as 1.86, 0.92 meters and 0.9935, respectively (Figure 9). The results show that there is a good agreement between the observed and calculated values in the calibration and verification stages (Figures 9 and 10).

In Figure 11, the groundwater level of Rafsanjan aquifer is simulated using the groundwater simulation model from 2006 to 2030 under three management scenarios for assessing the effects of reducing groundwater withdrawal by 0, 10 and 30% on the groundwater table drawdown. To estimate the sustainable water extraction from the aquifer in the study area, the coefficient of 1 (status quo), 0.9 (10% users’ abstraction reduction) and 0.7 (30% users’ abstraction reduction) are multiplied to withdrawal wells data of the simulation model from 2020 to 2030, as three groundwater extraction scenarios (Figure 11). As shown in Figure 11, current users’ GEEs (wells extraction rate) should be scaled by 0.7 to match water users’ GEEs with the safe groundwater yield and determine users’ initial GEE (Table 5). To estimate the modified users’ GEEs, the water withdrawal reduction coefficient is applied to the users’ current GEEs at the beginning of the simulation period.

The groundwater simulation model is used to approximate the aquifer response function at specific control points in order to control all groundwater abstractions within the market simultaneously. To achieve this purpose, the groundwater simulation model is used to identify aquifer critical points (i.e., points near environmentally sensitive areas) based on groundwater table drawdown. In Figure 12, point A is considered as a control point due to the considerable accumulated effects of cones of depression. Accordingly, there should be a reliable relationship between abstraction points (wells) and the aquifer status (i.e., groundwater level). The response function in which $H_{CP}$ and $W_{userID}$ indicate groundwater level at

| Well ID | Sub-coalition ID | Area (ha) | Average EC ($\mu S/cm$) | Depth to GW (m) |
|---------|-----------------|-----------|-------------------------|----------------|
| 1,236   | 1               | 175.44    | 5,013                   | 117.5          |
| 334     |                 |           |                         |                |
| 336     | 2               | 95.73     | 4,752                   | 105            |
| 335     | 3               | 204.33    | 4,573                   | 98.3           |
| 337     |                 |           |                         |                |
| 338     |                 |           |                         |                |
| 341     | 4               | 101.2     | 4,533                   | 100            |
| 339     |                 |           |                         |                |
| 351     |                 |           |                         |                |
| 407     | 5               | 268.44    | 4,164                   | 100            |
| 344     |                 |           |                         |                |
| 345     |                 |           |                         |                |
| 346     | 6               | 162.63    | 4,409                   | 102.5          |
| 340     |                 |           |                         |                |
| 386     | 7               | 95.94     | 4,361                   | 105            |
| 347     | 8               | 158.12    | 4,341                   | 105            |
| 348     |                 |           |                         |                |
| 349     | 9               | 108.92    | 4,317                   | 107.5          |
| 385     |                 |           |                         |                |

Table 3 | Main characteristics of the sub-coalitions
control point \((m)\) and the users’ discharge rate \((m^3/day)\) is developed (Equation (11)). The proposed groundwater market model employs the aquifer response function to assess the effects of water withdrawals on the aquifer.

\[
H_{CP} = -0.251W_{334} - 0.078W_{335} - 0.144W_{336} - 0.047W_{337} + 0.307W_{338} + 0.121W_{339} \\
+ 0.131W_{340} + 0.038W_{341} + 0.185W_{343} + 0.500W_{344} - 0.026W_{345} - 0.056W_{346} \\
- 0.146W_{347} - 0.018W_{348} - 0.081W_{349} - 0.304W_{351} - 0.002W_{385} + 0.160W_{386} \\
- 0.096W_{407} + 0.075W_{1236} \quad (R^2 = 0.86, \text{ in the verification stage})
\]

**Stochastic smart water market mechanism**

The proposed multi-agent optimization model estimates water trading price and potential GEE exchanges among users to maximize their final profits. In this regard, one of the main inputs of the smart water market is gathering users’ bid packages that represent the unit value of water among them. These inputs are provided by users using a web page organized by the market manager. Therefore, the transaction cost of water users is very limited (Raffensperger & Milke 2017). In order to run our smart market mechanism for the participants (coalitions of farmers), we need to estimate users’ bidding behavior.

Figure 8 | (a) The three-dimensional groundwater simulation model created using GMS-MODFLOW for the study area, (b) Boundary conditions of the model, (c) Location of pumping wells and (d) Location of observation wells.
In a normal condition, agricultural users are expected to bid based on their marginal benefit from irrigation. In this place, the net benefit diagram of farmers (after adjusting agents’ GEEs) is used to estimate the users’ expected bid packages (Figure 13). Since the bid packages represent the unit price of the water by the user, we differentiate the net benefit equation concerning groundwater extraction at the same intervals to achieve bid package of each agent (Figure 14). The estimated net benefit functions in the range of the agents’ GEEs as well as the bid packages estimated for agent 1 for different quantity and quality of water are presented in Figures 13 and 14, respectively.

In order to incorporate the deep uncertainties of the total annual available water (TAW) and wholesale price of agricultural products (Price) as the exogenous and endogenous uncertain parameters, respectively, some scenarios with similar occurrence probabilities are considered for users to trade (Table 4). Each trading policy is obtained by running the smart water market model for each scenario, considering the different plausible values for TAW and Price based on probable changes in climatic and economic conditions of the study area. The regret theory is utilized to determine the most reliable groundwater pricing and trading strategy. To obtain each trading policy, the smart water market model has been run for each plausible TAW and Price parameters and the regret criterion is calculated for each scenario.

The regret criterion and total benefit of the market local coalition are calculated for each scenario in Table 4 and Figures 15–17. When the comparison is carried on, considering both regret criterion and final benefit of the coalition (Figure 17), the scenario 8 with a relatively lower regret criterion and higher final benefit is selected as the best possible scenario. Based on Table 4, TAW and Price values regarding the scenario 8 are considered as the benchmark for running the
proposed smart market model with the high-reliable values for the uncertain parameters in the next stage. As a result, scenario 8 leads to the most reliable trading policy for the study area in terms of different expected values of TAW and Price. By selecting the most reliable trading policy, if the expected value of the uncertain parameters do not happen, this trading policy will still function properly and the regret of the market manager is minimized.

In the next stage, based on the aforementioned smart water market model (Equations (1)–(8)), the potential trades between agents (sub-coalitions) are presented in Tables 5, and the final profit for each agent are estimated in Figure 18 to satisfy the goals and constraints.

Finally, Table 6 shows the final net benefit earned by each agent and water productivity under different conditions. It is clear that participating in the proposed smart water market have significantly increased the agents' profits comparing to their pre-market conditions based on initial GEE. In both cases, the groundwater extraction is equal to the safe yield. Besides, in the proposed water market, the average users' water productivity in the post-market condition has been increased by 18% compared to the status quo while the environmental constraint is satisfied.

Figure 10 | The observed and simulated groundwater head in the transient condition for the last stress period.

Figure 11 | Temporal variations of mean groundwater table in Rafsanjan Plain for different groundwater extraction scenarios.
After uncertainty-based market mechanism execution and GEE in the water market, the groundwater model is re-run using the new water extraction data of users and the satisfaction of environmental constraints are controlled. Figure 18 shows the annual distribution of allocated and re-allocated groundwater among users based on their farms area. As can be seen in this figure, after applying the proposed market mechanism, the distribution of GEEs becomes more uniform, so that users with large farms area receive more GEEs after joining the groundwater market. The proper distribution of water scarcity risk among farmers is in line with the ‘Law of Fair Water Distribution’ (Parliament of Iran, 1983).

Figure 12 | Location of the environmentally sensitive area in the study area.

Figure 13 | The net benefit function versus annual water consumption for different agents in the study area.
Figure 14 | Bid packages submitted by agent 1 in the proposed groundwater market.

Table 4 | Trading scenarios in terms of TAW and price and their corresponding regret values and total benefits

| Scenario | Price (tomans) | TAW (m³/year) | Regret (tomans) | Final benefit (tomans) |
|----------|----------------|---------------|-----------------|------------------------|
| 1        | 73,000         | 6.80E + 06    | 5.15E + 11      | 8.32E + 10             |
| 2        | 73,000         | 7.82E + 06    | 5.16E + 11      | 9.17E + 10             |
| 3        | 73,000         | 8.84E + 06    | 5.27E + 11      | 9.49E + 10             |
| 4        | 73,000         | 5.78E + 06    | 5.20E + 11      | 7.25E + 10             |
| 5        | 73,000         | 4.76E + 06    | 5.25E + 11      | 6.08E + 10             |
| 6        | 87,600         | 6.80E + 06    | 5.16E + 11      | 9.17E + 10             |
| 7        | 87,600         | 7.82E + 06    | 5.16E + 11      | 7.25E + 10             |
| 8        | 87,600         | 8.84E + 06    | 5.20E + 11      | 7.09E + 10             |
| 9        | 87,600         | 5.78E + 06    | 5.25E + 11      | 6.08E + 10             |
| 10       | 87,600         | 4.76E + 06    | 5.15E + 11      | 8.32E + 10             |
| 11       | 87,600         | 3.78E + 06    | 5.16E + 11      | 9.17E + 10             |
| 12       | 102,200        | 6.80E + 06    | 5.15E + 11      | 8.32E + 10             |
| 13       | 102,200        | 7.82E + 06    | 5.15E + 11      | 9.17E + 10             |
| 14       | 102,200        | 8.84E + 06    | 5.15E + 11      | 10.01E + 11            |
| 15       | 102,200        | 5.78E + 06    | 5.15E + 11      | 6.63E + 10             |
| 16       | 102,200        | 4.76E + 06    | 5.15E + 11      | 7.22E + 10             |
| 17       | 102,200        | 3.78E + 06    | 5.15E + 11      | 8.32E + 10             |
| 18       | 102,200        | 2.78E + 06    | 5.15E + 11      | 9.49E + 10             |
| 19       | 102,200        | 1.78E + 06    | 5.15E + 11      | 10.66E + 10            |
| 20       | 102,200        | 0.78E + 06    | 5.15E + 11      | 11.82E + 10            |
| 21       | 102,200        | 0.78E + 06    | 5.15E + 11      | 12.99E + 10            |
| 22       | 102,200        | 0.78E + 06    | 5.15E + 11      | 14.16E + 10            |
| 23       | 102,200        | 0.78E + 06    | 5.15E + 11      | 15.33E + 10            |
| 24       | 102,200        | 0.78E + 06    | 5.15E + 11      | 16.50E + 10            |
| 25       | 102,200        | 0.78E + 06    | 5.15E + 11      | 17.67E + 10            |
CONCLUSIONS

In this paper, a new uncertainty-based smart water market mechanism was proposed. A numerical groundwater simulation model was used to estimate the safe yield of aquifer and the aquifer response functions. Different plausible values for the total annual available water and wholesale price of agricultural products were considered to propose different trading policies in the study area. To select the best trading policy, the regret theory was applied.

Figure 15 | Final regret of each scenario versus its TAW and Price values.

Figure 16 | The coalition’s final benefit in each scenario versus its TAW and Price values.
In the developed mechanism, agricultural agents propose different prices for different quantities and qualities of groundwater. Therefore, two-dimensional bid packages have been proposed which consider the quantity and quality of water.

By applying the proposed methodology to the Nough aquifer in Iran, it was shown that participating in the uncertainty-based water markets can considerably increase the total benefit of farmers comparing to their benefits when they are using their initial GEEs. Besides, the proposed smart water market can provide more reliable and robust estimations for groundwater price and water trading among users by incorporating the uncertainty of the main inputs.

As water consumption monitoring is a vital prerequisite for an efficient and effective water market, in future studies, and the applicability of using remotely sensed evapotranspiration data should be investigated.

**CONFLICT OF INTEREST**

The authors declare that they have no conflict of interest.
CONTRIBUTIONS

SS: Methodology, Validation, Visualization, Writing – original draft. RK: Conceptualization, Formal analysis, Supervision, Writing – review & editing.

DATA AVAILABILITY STATEMENT

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

REFERENCES

Abdollahi Ezat Abadi, M. 2014 Investigating the Optimal Water-Land, Economical Ratio in Pistachio Areas of Anar and Rafsanjan Technical Report. Ministry of Jehad Agriculture, Pistachio Research Institute, Rafsanjan, Iran.
Aghaie, V., Alizadeh, H. & Afshar, A. 2020 Agent-Based hydro-economic modelling for analysis of groundwater-based irrigation Water market mechanisms. *Agricultural Water Management* **234**, 106140.

Batty, M. 1997 Cellular automata and urban form: a primer. *Journal of the American Planning Association* **63** (2), 266–274.

Bell, D. E. 1982 Regret in decision making under uncertainty. *Operations Research* **30** (5), 961–981.

Du, E., Cai, X., Brozovic, N. & Minsker, B. 2017 Evaluating the impacts of farmers’ behaviors on a hypothetical agricultural water market based on double auction. *Water Resources Research* **53** (5), 4053–4072.

Frank, A. A. U., Campari, I. & Formentini, U. 1992 *Theories and Methods of Spatio-Temporal Reasoning in Geographic Space*. Springer-Verlag, Berlin.

Grimm, V. 1999 Ten years of individual-based modelling in ecology: what have we learned and what could we learn in the future. *Ecological Modelling* **115**, 129–148.

Hadjigeorgalis, E. 2009 A place for water markets: performance and challenges. *Review of Agricultural Economics* **31** (1), 50–67.

Harbaugh, A. W. 2005 MODFLOW-2005, the US Geological Survey Modular Ground-Water Model – the Ground-Water Flow Process. US Geological Survey Techniques and Methods 6-A16. A16.

Hemker, C. J. & van Elburg, H. 1990 *Groundwater Modeling System*. Engineering Computer Graphics Laboratory, Brigham Young University, Utah.

Huang, G. H. & Loucks, D. P. 2000 An inexact two-stage stochastic programming model for water resources management under uncertainty. *Civil Engineering Systems* **17** (2), 95–118.

IWRMC 2011 *Water Resources Balance Sheet in Catchment of Darangir Desert*. Technical Report, Iran Water Resources Management Company, Tehran, Iran.

Jaghdani, T. J. & Brümmer, B. 2016 Determinants of water purchases by pistachio producers in an informal groundwater market: a case study from Iran. *Water Policy* **18** (3), 599–618.

Khan, H. F. & Brown, C. M. 2019 Effect of hydrogeologic and climatic variability on performance of a groundwater market. *Water Resources Research* **55** (5), 4304–4321.

Kiem, A. S. 2013 Drought and water policy in Australia: challenges for the future illustrated by the issues associated with water trading and climate change adaptation in the Murray-Darling Basin. *Global Environmental Change* **23** (6), 1615–1626.

Linhart, P. B. & Radner, R. 1989 Minimax regret strategies for bargaining over several variables. *J Econ Theory* **48**, 152–178.

Loomes, G. & Sugden, R. 1982 Regret theory: an alternative theory of rational choice under uncertainty. *The Economic Journal* **92** (368), 805–824.

Manson, S. M. & Evans, T. 2007 Agent-based modeling of deforestation in southern Yucatan, Mexico, and reforestation in the Midwest United States. *Proceedings of the National Academy of Sciences* **104** (52), 20678–20683.

Poorsepahy-Samian, H., Kerachian, R. & Nikoo, M. R. 2012 Water and pollution discharge permit allocation to agricultural zones: application of game theory and min-max regret analysis. *Water Resources Management* **26** (14), 4241–4257.

Raffensperger, J. F. & Milke, M. W. 2017 *Smart Markets for Water Resources: A Manual for Implementation*, Vol. 12. Springer.

Raffensperger, J. F., Milke, M. W. & Read, E. G. 2009 A deterministic smart market model for groundwater. *Operations Research* **57** (6), 1333–1346.

Rahnama, M. B. & Zamzam, A. 2013 Quantitative and qualitative simulation of groundwater by mathematical models in Rafsanjan aquifer using MODFLOW and MT3DMS. *Arabian Journal of Geosciences* **6** (3), 901–912.

Razzaq, A., Qing, P., Abid, M., Anwar, M. & Javed, I. 2019 Can the informal groundwater markets improve water use efficiency and equity? evidence from a semi-arid region of Pakistan. *Science of The Total Environment* **666**, 849–857.

Zeng, X. T., Li, Y. P., Huang, G. H. & Liu, J. 2015 Modeling water trading under uncertainty for supporting water resources management in an arid region. *Journal of Water Resources Planning and Management* **142** (2), 04015058.

First received 18 August 2021; accepted in revised form 9 November 2021. Available online 19 November 2021.