

Article

Groundwater Extraction in the South Korea's Jeju Island: A Real Options Game Approach under Price Uncertainty

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Abstract: This paper uses a standard non-cooperative sequential game with two homogeneous players to analyze investment options of groundwater development project in South Korea's Jeju island. The model is constructed as an option game taking the uncertainty of water price and the irreversibility of investment into account. The results show that the threshold water price of follower increases with the investment scale of both the leader and the follower while the threshold water price for the leader decreases as the investment scale of the leader increases. This makes the leader choose strategies to maximize the amount of groundwater extraction regardless of the follower's strategy. Based on the results, it is recommended for policymakers to manage sustainable use of groundwater based on the policy measures such as the groundwater extraction quota system.

Keywords: real option game; groundwater extraction; uncertainty; irreversibility; Jeju island

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1. Introduction

Jeju is a volcanic island located in the southwest of South Korea. The island is isolated from the Korean peninsula, but is about a one-hour distance by flight from Seoul (see Figure 1). Designated as a special autonomy province that maintains unique history and culture distinctive from those of the inland of South Korea (hereafter referred to as Korea), Jeju island attracts many tourists worldwide. With the attraction of volcanic mountain views, clement weather, and beaches, the number of visitors, in particular, from China and Japan is growing. The average number of visitors to Jeju is estimated to be approximately 13.6 million annually.

The island with subtropical weather normally records abundant annual rainfall that is about 1.5 times larger than that on the inland. However, because of the lack of perennial rivers, the island is vulnerable to water shortage problems. The water resource on the island is mainly collected mostly beneath the ground due to its unique geological property with permeable basalts into which rain and stream waters easily percolate to accumulate and move slowly in accessible and exploitable aquifers. This results in a lack of perennial streams [1]. As there are limited perennial rivers and streams, groundwater is nearly the sole source of water supply. While Jeju, isolated from the inland, has to meet the water demand by itself, the demand for water is expected to increase due to the increasing population and tourists.

There are vast amounts of literature discussing the economics of water resources for agriculture, livestock, and other uses [2–11]. Since Rubio and Castro [4] and Fisher and Rubio [5] introduced the real options approach to water resources, there has been an ongoing expansion of the application including economic evaluation of irrigation [11–13], water infrastructure investment projects (e.g., dams and hydroelectric power generation [14–19]), and water supply projects [20–25]. Most of the previous studies focus on the economical evaluation of infrastructure investment and water supply project under the assumption of a single player, e.g., supplier, investor, or government.

However, competition among the agents is inevitable given that water resources is limited at least for a given period of time. For example, de Sivla and Hussein [26] focused on the water competition in South America over the La Plata River Basin and Guarani Aquifer System, and examined the conflicts and resolutions from a water politics perspective. Cascão [27] defined the competition for water resources in the Nile River Basin as a hegemonic competition caused by asymmetric power, and proposed non-hegemonic riparians for sustainable and equitable use of water. Lankford and Watson [28] developed the river basic game between Tanzania and Nigeria to resolve the conflicts on water uses in Africa.

Although a large body of the literature was devoted to analyzing water resources, only a few studies were built on a real options game approach. Laukkanen et al. [29] developed a real options game model to analyze the optimal extraction of groundwater among heterogeneous farmers while taking the uncertainty of rainfall into account. The heterogeneous farmers differ in terms of their choice of irrigation technology, which results in different farmer-specific impacts on the aquifer recharge rate. Bhaduri et al. [30–32] use a stochastic Stackelberg differential game to examine sustainable transboundary water sharing, the case of water distribution in the Volta Basin of West Africa between Burkina Faso and Ghana.

In this paper, we build on the real options game model to examine the investor's optimal strategy on groundwater development project, which could provide implications for policymakers to manage sustainable use of groundwater. Specifically, we develop a standard non-cooperative sequential game with two homogeneous players [33] in the context of the groundwater development project in Jeju Island. The model is presented as an option game to invest in water development project, which takes the uncertainty of water price and the irreversibility of investment into account. By combining irreversible investment under uncertainty with non-cooperative sequential game, this paper integrates the two bodies of the literature, i.e., real options and game theory. Real options models have been used to explain uncertainty and irreversibility of investment in a number of contexts, but often times in monopolistic or perfectly competitive framework. On the other hand, games of entry and exit have been studied mostly in a deterministic framework.

The rest of the paper is organized as follows. We present the theoretical model in Section 2. Section 3 provides the numerical analysis in the case of the Jeju Island groundwater development project. Section 4 concludes the paper.



Figure 1. Location of Jeju Island and the study area.

2. Methods

2.1. Model

In this paper, we present a standard non-cooperative sequential game with two homogenous players. The game is presented as an option game where two players sequentially make decisions on groundwater extraction investment under water price uncertainty. The resulting equilibrium is a Markov perfect equilibrium, in which each player's strategy

consists of the current state variables. The Markov perfect equilibrium is derived by assuming that each player exercises a Markov strategy based on the other player's best response, which follows a Markov strategy as well. In Section 3, we use the model to examine a groundwater development project in Jeju Island where water resource management is an important issue because groundwater is nearly the sole source of water supply while the availability of groundwater is limited.

We now introduce the model. Two players are indexed by leader (l) and follower (f). Under the profit maximization, the value function can be written as

$$V_i(p, h) = E \int_0^{\infty} [p(t)q_i(t) - C(L, h(t))q_i(t)]e^{-\rho t} dt \quad (1)$$

where the subscript $i = l$ and f denotes the leader and follower, respectively. In Equation (1), q_i is the amount of groundwater extraction of the corresponding player. $p(t)$ is the price of water. The cost C is a function of L and $h(t)$, where L denotes the surface elevation and $h(t)$ denotes the groundwater level, both are measured in meters. Lastly, ρ is the discount rate and E is the expectation operator.

Water price $p(t)$ evolves exogenously and stochastically according to a geometric Brownian motion (GBM) with drift given by the following expression [12,13,20,21,34]:

$$dp(t) = \mu p(t)dt + \sigma p(t)dz(t) \quad (2)$$

where μ is a drift rate and σ is a volatility rate. dz is the increment of a standard Wiener's process satisfying $E(dz) = 0$ and $E(dz^2) = dt$.

We specify the cost $C(L, h(t))$ as follows:

$$C(L, h) = c_1 + c(h(t)) + c_3 \quad (3)$$

where c_1 denotes charges for utilization of water, which is imposed to players by local government, $c(h(t))$ cost for groundwater extraction depending on groundwater level $h(t)$, and c_3 maintenance cost including costs for meeting water quality requirements and periodic inspections. Let γ denote the marginal cost of groundwater extraction per cubic meter of groundwater from depth of one meter. Thus, $L - h(t)$ represents the depth from which groundwater has to be extracted, and the marginal cost of groundwater extraction per cubic meter can be written as

$$c(h(t)) = \gamma(L - h(t)) \quad (4)$$

Groundwater reservoir ($S(t)$) is assumed to be a single cell [35], which allows us to calculate $S(t)$ as the area of aquifer (m) multiplied by the groundwater level ($h(t)$).

$$S(t) = m \times h(t) \quad (5)$$

where $S(t)$ and $h(t)$ evolves according to

$$dS(t) = d(mh(t)) = (N - q(t))dt \quad (6)$$

$$dh(t) = \frac{N - q(t)}{m} dt = \frac{N - q_l(t) - q_f(t)}{m} dt \quad (7)$$

where N denotes the natural recharge which is calculated as

$$N = \alpha \times m \times r \quad (8)$$

In Equation (8), α and r denote natural recharge rate and total precipitation, respectively. In the simulation, total precipitation is assumed to be fixed at the average precipitation for 30 years.

We now rewrite the value function and constraints as follows.

$$V_i(p, h) = E \int_0^{\infty} [p(t)q_i(t) - c_1q_i(t) - c(h(t))q_i(t) - c_3q_i(t)]e^{-\rho t} dt \quad (9)$$

$$\text{s.t. } dp(t) = \mu p(t)dt + \sigma p(t)dz(t)$$

$$dh(t) = \frac{N - q_l(t) - q_f(t)}{m} dt \quad (10)$$

Using Ito's Lemma and the property that $dt^2 \rightarrow 0$, $dt dz \rightarrow 0$ and $dz^2 \rightarrow dt$, the following Hamilton–Jacobi–Bellman (HJB) equation is obtained [36]:

$$\rho V_l(p, h) = (p - c_1 - \gamma(L - h) - c_3)q_l + \mu p V_{l,p} + \frac{1}{2}\sigma^2 p^2 V_{l,pp} + \frac{N - q_l - q_f}{m} V_{l,h} \quad (11)$$

$$\rho V_f(p, h) = (p - c_1 - \gamma(L - h) - c_3)q_f + \mu p V_{f,p} + \frac{1}{2}\sigma^2 p^2 V_{f,pp} + \frac{N - q_l - q_f}{m} V_{f,h} \quad (12)$$

which are linear and differentiable with respect to q_l and q_f . In this model, the optimal quantity of extraction (q_{opt}) follows the bang-bang solution where if $p < V(p)$, then $q_{opt} = q_{max}$, and if $p > V(p)$, then $q_{opt} = 0$ [34,37]. We can get $V_{l,h} = m(p - c_1 - c(h) - c_3)$ and $V_{f,h} = m(p - c_1 - c(h) - c_3)$ by differentiating Equations (11) and (12) with respect to q_l and q_f , respectively. By substituting these first order conditions into the Equations (11) and (12), the following constrained HJB is obtained:

$$\rho V_l(p) = (p - c_1 - \gamma(L - h) - c_3)(N - q_f) + \mu p V_{l,p} + \frac{1}{2}\sigma^2 p^2 V_{l,pp} \quad (13)$$

$$\rho V_f(p) = (p - c_1 - \gamma(L - h) - c_3)(N - q_l) + \mu p V_{f,p} + \frac{1}{2}\sigma^2 p^2 V_{f,pp} \quad (14)$$

2.2. The Follower's Problem

Since the model is solved backwards, we first solve the optimization problem of the follower. The option value function and the solution for the value function are written as

$$F_f(p) = A_{f,1} p^\beta \quad (15)$$

$$V_f(p) = \frac{(N - q_l^1)p}{\rho - \mu} - \frac{(N - q_l)(c_1 + \gamma(L - h) + c_3)}{\rho} \quad (16)$$

where the superscript 1 denotes after the investment is made. In equation (15), $\beta > 0$ should be satisfied. In Equations (15) and (16), the two unknowns are the threshold water price (p_f^*) and the option constant term ($A_{f,1}$), which are determined by imposing the value matching and smooth pasting conditions. While the value matching condition ($F(p) = V(p) - I_f$) imposes that the net benefit from the investment should exceed the investment cost, the smooth pasting condition ($\partial F(p)/\partial p = \partial V(p)/\partial p$) imposes that the marginal net benefit and the marginal investment cost should be equal at the threshold water price. I_f denotes the initial irreversible investment cost of the follower.

The p_f^* and $A_{f,1}$ are obtained as follows.

$$p_f^* = \frac{\beta}{\beta - 1} \frac{(\rho - \mu) \left[(N - q_l^1)(c_1 + \gamma(L - h) + c_3) + \rho I_f \right]}{\rho} \quad (17)$$

$$A_{f,1} = \frac{N - q_l^1}{\beta(\rho - \mu)} p_f^{1-\beta} \quad (18)$$

Equation (17) shows that an increase in groundwater extraction cost and discount rate increase the threshold water price, which delays the follower's investment. On

the other hand, an increase in groundwater level decreases the threshold water price. $\beta/(\beta-1)$, the option multiplier, represents hysteresis in the real options literature, i.e., the optimal investment threshold under uncertainty should exceed the threshold point without uncertainty.

2.3. The Leader's Problem

The leader's problem is analyzed for the two regimes, i.e., the regime before the follower makes the investment decision and the regime after the follower makes the investment decision.

$$V_l(p) = \begin{cases} \frac{Np}{\rho - \mu} - \frac{N(c_1 + \gamma(L - h) + c_3)}{\rho}, & \text{when } p < p_f \\ \frac{(N - q_l^1)p}{\rho - \mu} - \frac{(N - q_l)(c_1 + \gamma(L - h) + c_3)}{\rho}, & \text{when } p_f \leq p \end{cases} \quad (19)$$

Equation (19) includes an option-like term, which anticipates the negative effects of the follower's investment on the leader's expected payoff. It is not actually the value of the investment option to be exercised by the leader, but the value of the future investment induced by the follower to the leader [33]. $A_{l,1}$ can be obtained as follows.

$$A_{l,1} = \left[\frac{q_f^1 p_f}{\rho - \mu} - \frac{q_f^1 (c_1 + \gamma(L - h) + c_3)}{\rho} \right] p_f^{-\beta_1} \quad (20)$$

Fudenberg and Tirole [38] state that the expected payoff of the two players must be equal at the leader's investment point. For two player preemption games, Fudenberg and Tirole [38] show that there exists a symmetric mixed strategy equilibrium that involves rent equalization, which means that in equilibrium, the expected value of the first mover equals that of the second mover. If it were not the case, one player would have an incentive to deviate and the proposed outcome could not be an equilibrium. In our model, this can be written as follows:

$$\left(A_{l,1} + A_{f,1} \right) p_l^{\beta_1} = \frac{Np_l}{\rho - \mu} - \frac{N(c_1 + \gamma(L - h) + c_3)}{\rho} - I_l \quad (21)$$

Since there is no closed form solution for Equation (21), in the next section, the numerical analysis is used to solve for p_l by using MATLAB. The solution from the Equations (17) and (21) provides the Markov perfect equilibrium.

3. Simulation

3.1. Data

We consider the case of groundwater facility located in the east of Jeju Island (Figure 1). The area of aquifer (m) is 150,682,797 m². Topographic elevation of the facility is 342.6EL. m, with depth of 490 m, and the average groundwater level (h) of 250.75 m in 2015 [39]. The average precipitation (r) of the region is 1,923 mm [40] and the natural recharge rate (α) is 0.431 [41].

The drift rate (μ) and the volatility rate (σ) of the water price (p) that follows the gBm process are estimated using the data obtained from the annual statistics of Jeju Special Self-Governing Province [42]. When we define $y(t) = \log(p(t)) - \log(p(t-1))$ and denote Δ the time interval, it can be shown that $y(t)$ follows the normal distribution, where the mean and variance of $y(t)$ are written as $E(y(t)) = (\mu - \sigma^2/2)/\Delta$ and $Var(y(t)) = \sigma^2\Delta$, where $\mu = \bar{y}/\Delta + s_y^2/2\Delta$ and $\sigma = s_y/\sqrt{\Delta}$ can be obtained from the sample mean (\bar{y}) and the standard deviation (s_y) of $y(t)$ [43]. The price parameters are calculated as $\mu = 0.0436$ and $\sigma = 0.1009$.

Cost parameters are assumed as follows. Charges for utilization of water (c_1) is derived as 0.071 US\$ /m³ [39]. In general, the marginal cost of groundwater extraction, could vary depending on the fuel cost or depth of water [44,45]. However, this paper assumes that the

marginal cost of groundwater extraction (γ) is constant at 0.00038 US\$/m³·m based on [11]. We also assume the constant maintenance cost (c_3) at 0.041 US\$/m³ based on [46]. The maintenance cost should not be constant especially if there exists the saltwater intrusion problem, as the intrusion of saltwater would increase the maintenance cost. However, as [46] discussed, desalination is not a significant issue on Jeju island. Based on [47,48], investment cost for leader (I_l) is calculated as US\$9108,333. Assuming that investment cost for follower is lower than that for leader, we simply multiply I_l by 0.9 to calculate investment cost for follower (I_f). Finally, we take the discount rate $p = 0.054$, which is the average yield of AA- and BBB- grade corporate bonds in 2015 [34].

3.2. Results

Using the parameter values in Table 1, the threshold water price is calculated for three scenarios, the follower's groundwater extraction is set as (i) 80% of q_{max} , (ii) equal to q_{max} , and (iii) 120% of q_{max} . The scenarios allow us to investigate the optimal extraction of the leader (q_l) in response to the possible investment scale of the follower. The scenarios also analyze the threshold water prices corresponding to the investment scale.

Table 2 presents the threshold water price of the leader p^*_l and the follower (p^*_f) for each of the three scenarios. For example, p^*_l and p^*_f are estimated as 0.1239 US\$/m³ and 0.2593 US\$/m³ for scenario 2, respectively. While p^*_f increases with the investment scale of both the leader and the follower, p^*_l decreases as the investment scale of the leader increases. Moreover, for each scenario of the investment scale of the leader, p^*_l is highest when the investment scale of the follower is equal to q_{max} . Table 2 suggests that the leader selects the strategy to increase q_l to lower the p^*_l and raise p^*_f regardless of the follower's strategy. The follower chooses the strategy to decrease q_f to lower p^*_f . Therefore, scenario 3 for the leader and scenario 1 for the follower is the strategic dominance, i.e., $(p^*_l/p^*_f) = (0.6950, 0.2660)$, where the ratio of threshold (p^*_f/p^*_l) is highest with 2.61 as shown in Table 3. The results can be summarized that the leader chooses the strategy to maximize the amount of her groundwater extraction regardless of the follower's strategy.

Table 1. Parameters for simulation.

Category	Parameter	Value	
Groundwater	m	area of aquifer	150,682,797 m ²
	L	topographic elevation	342.6 EL. m
	h	groundwater level	250.75 m
	r	precipitation	1.923 m
	α	natural recharge rate	0.431
	q_{max}	amount of groundwater extraction	122 million m ³
Water Price	μ	drift rate	0.0436
	σ	volatility rate	0.1009
Cost	c_1	charges for utilization	0.071 US\$/m ³
	γ	marginal cost of groundwater extraction	0.00038 US\$/m ³ ·m
	c_3	maintenance cost	0.041 US\$/m ³
Investment	I_l	investment cost of leader	9,108,333 US\$
	I_f	investment cost of follower	7,725,000 US\$
Discount Rate	ρ	discount rate	0.054

We now perform the sensitivity analysis of the investment threshold price over the range of the variables. Figure 2 shows the sensitivity of the threshold water price (p^*_f) with respect to the volatility (σ) and the investment cost of follower (I_f). While an increase in both σ and I_f increases p^*_f , Figure 2 shows that p^*_f is more sensitive to the initial investment cost I_f than the uncertainty σ .

Table 2. Investment threshold price by scenario (unit: US\$/m³).

Factor		Investment Scale of Leader			
		80% of q_{max}	Equal to q_{max}	120% of q_{max}	
Investment Scale of Follower	80% of q_{max}	p_l^*	0.0848	0.0764	0.6950
		p_f^*	0.2427	0.2521	0.2660
	Equal to q_{max}	p_l^*	0.1328	0.1239	0.1158
		p_f^*	0.2475	0.2593	0.2767
	120% of q_{max}	p_l^*	0.1395	0.1248	0.1122
		p_f^*	0.2523	0.2665	0.2873

Table 3. Ratio (p_f^*/p_l^*) of investment threshold price by scenario.

Factor		Investment Scale of Leader		
		80% of q_{max}	Equal to q_{max}	120% of q_{max}
Investment Scale of Follower	80% of q_{max}	0.35	0.30	2.61
	Equal to q_{max}	0.54	0.48	0.42
	120% of q_{max}	0.55	0.47	0.39

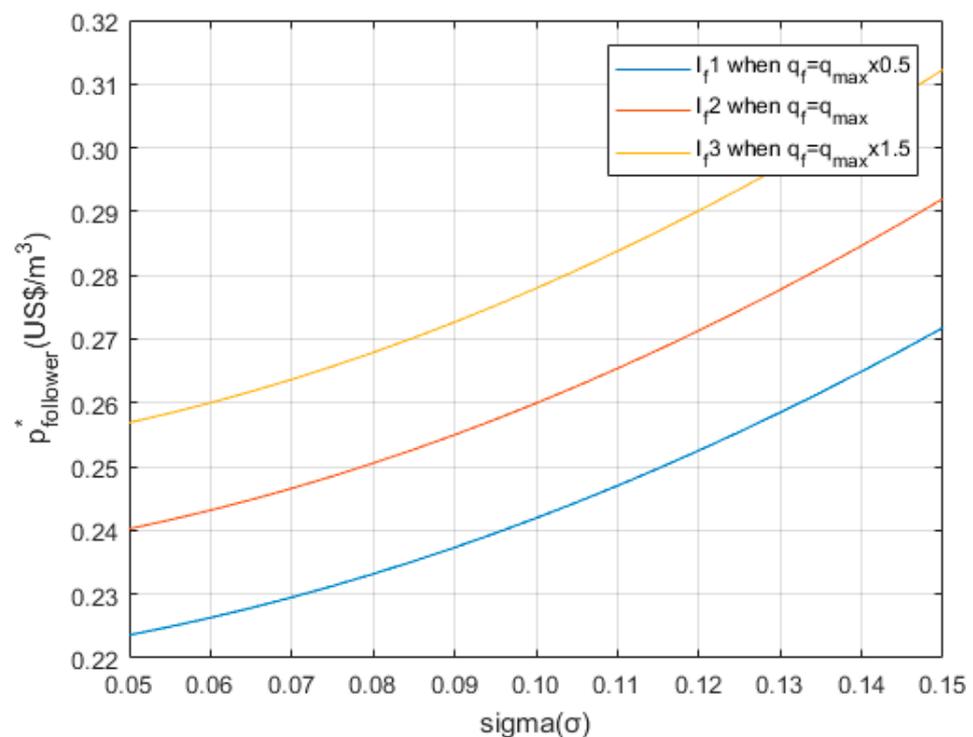
**Figure 2.** Sensitivity analysis of p_f^* with respect to σ and I_f .

Figure 3 shows the effects of the groundwater extraction of the leader (q_l^1) and the follower (q_f) on the threshold water price of the follower (p_f^*). p_f^* increases as q_l^1 and q_f increases, and is more responsive to q_l^1 compared with q_f . It implies that the leader can defer the entry of the follower by increasing q_l^1 and therefore increasing p_f^* , which enables the leader to collect monopolistic profits until the follower enters into the market.

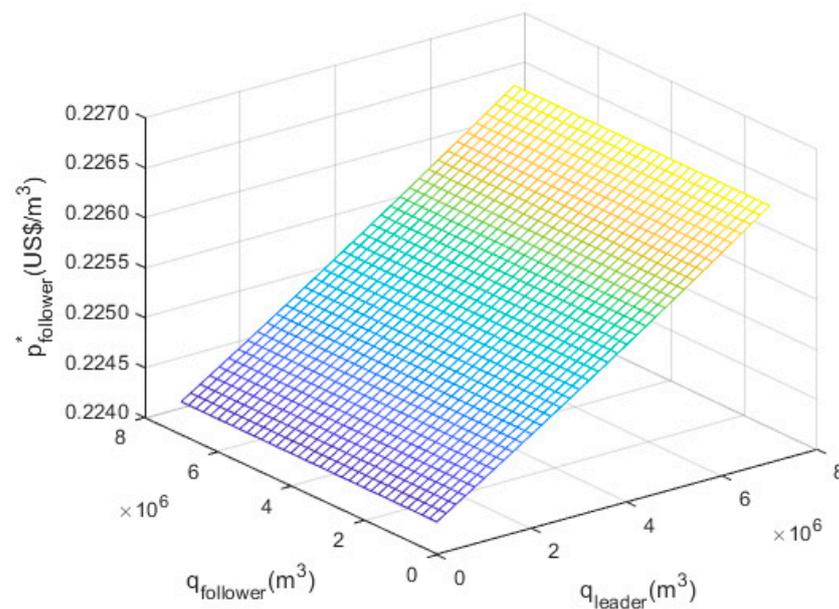


Figure 3. Sensitivity analysis of p_f^* with respect to q_l and q_f .

We now examine dynamics of the extraction cost $c(h(t))$ in Equation (4) and the groundwater level $h(t)$ in Equation (7). We investigate three scenarios where the total groundwater extraction q_{total} is equal to (i) $q_{max} \times 1.5$, (ii) $q_{max} \times 2.0$, and (iii) $q_{max} \times 2.5$.

Figure 4 presents the dynamics of the groundwater extraction cost. As [49] pointed out, late entry of the follower allows the leader to extract the groundwater at a lower cost. Since the leader collects monopolistic profits from preemption, the leader is likely to extract more than the efficient amount. Finally, Figure 5 presents the dynamics of the groundwater level. If the groundwater recharge is greater than the groundwater extraction, the groundwater level will rise, and the positive slope in Figure 5 shows that the recharge is greater than the extraction under all scenarios. On the other hand, it can be shown that the competition between the two players decreases the groundwater level in case of duopoly.

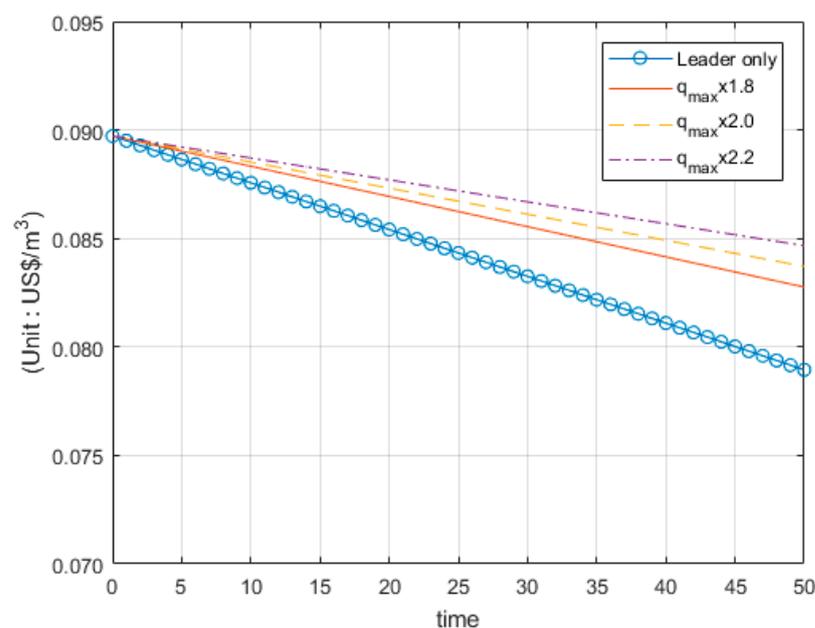


Figure 4. Dynamics of the groundwater extraction cost $c(h(t))$.

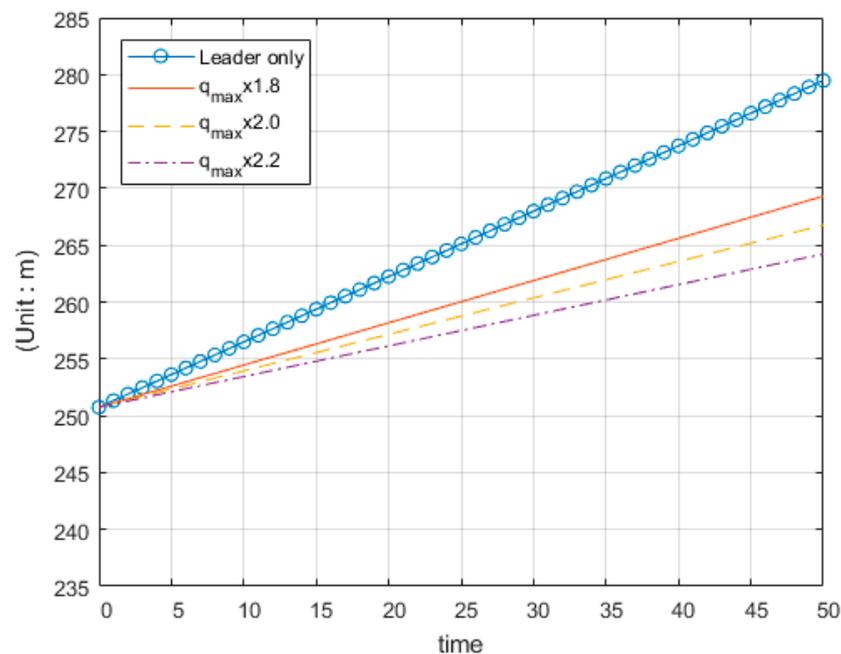


Figure 5. Dynamics of the groundwater level $h(t)$.

4. Conclusions

In this paper, we developed a model of standard non-cooperative sequential game with two homogeneous players to analyze investment decisions on groundwater development project on South Korea's Jeju island. The model was presented as an option game, which allowed us to take the uncertainty of water price and the irreversibility of investment into account.

The results show that the threshold water price of the follower increased with the investment scale of both the leader and the follower while the threshold water price of leader decreased as the investment scale of the leader increased. This made the leader choose the strategy to maximize the amount of her groundwater extraction regardless of the follower's strategy, which allowed the leader to collect monopolistic profits by deferring the entry of the follower. Based on the results, it is recommended for policymakers to manage sustainable use of groundwater based on the policy measures such as the groundwater extraction quota system.

Future research can be extended to several directions. First, our model could be extended to incorporate precipitation uncertainty. Second, it would be interesting to model the conjunctive use of surface water and groundwater. Third, this paper was built on the single-cell aquifer model, which assumed that an aquifer responded uniformly and instantly to groundwater pumping. However, as Brozovic [50] pointed out, our results could be misleading especially if the magnitude of the groundwater pumping externality is large. This should be demonstrated in the future research. Fourth, it is also important to incorporate emerging issues including climate change, ecosystem projection and groundwater quality. Finally, a possible extension could be to develop a model with heterogeneous groundwater developers.

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