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Real Options Analysis of Groundwater Extraction and Management with Water Price Uncertainty†

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ABSTRACT : This paper analyses the investment options of groundwater development project under water price uncertainty. The optimal investment threshold price which trigger the investment are calibrated base on monopolistic real options model. Stochastic dynamic model is set to reflect the uncertainty of water price which follows the GBM (Geometric Brownian Motion) process. Our finding from non-cooperative investment decision model is that uncertainty of water price could deter the groundwater investment by considering the existence of option values. For policy markers, it is easy to manage 'charges for utilization of groundwater' rather than 'performance guarantee ratio' when managing groundwater investment with pricing policy. And it is necessary to make comprehensive and well-designed policies considering the characteristics of regional groundwater reservoir and groundwater developers.

Keywords : Real Option, Groundwater Extraction, Groundwater Management, Water Price Uncertainty

JEL 분류 : C61, D81, Q25, Q58

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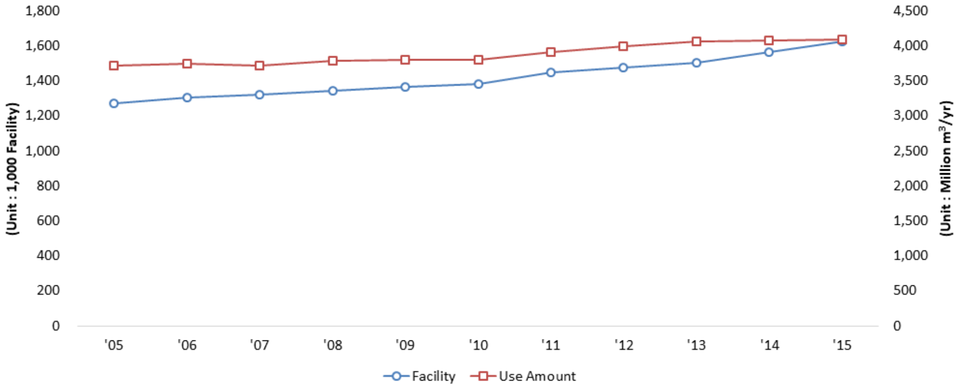
Ⅰ. Introduction

Nowadays, groundwater in many regions is more likely to be extracted in non-sustainable ways. The groundwater level in the aquifer has kept dropping in many parts of the world for the last decades. Unlimited well drilling for the last couple of decades has made the overall extraction rate from the aquifer exceed the recharging rate from rainfalls and other sources. If extraction exceed the natural recharge, groundwater can be regarded as a non-renewable resource (Hartwick and Olewiler, 1986).

As of 2015, 13 of 37 large aquifers around the world are at the risk of exhaustion with the concerned areas being threatened for their utilization of water resources (Richey et al., 2015). In China, two thirds of groundwater and one third of surface water are severely contaminated to allow for no human use. The state of California, U.S.A., which is the eighth largest economy in the world, has suffered a severe drought for four years. Sao Paulo, the largest city of Brazil, suffers water shortage due to droughts and lack of investment (CDP, 2015). In southwestern parts of Australia, the pumping volume of groundwater has increased considerably due to the increasing demand for water available for use and the reduction of recharging volume from the sources of surface water due to climate changes (IPCC, 2010).

In South Korea, there are 1.62 million groundwater facilities nationwide and 4,094 million m^3/yr of groundwater is extracted in 2015. The Compound annual growth rate (CAGR) of facilities and use amount are 2.5% and 1.0%, respectively. As shown in Figure 1, the fluctuations in total usage and number of facilities are not significantly increasing. In the government, the ratio of use amount to development potential is 31.9%, which means that the amount of underground water in Korea is still sufficient (MOLIT and K-water, 2016b).

〈Figure 1〉 Goundwater Facility and Use Amount in Korea



*Source : MOLIT and K-water (2016b)

However, the number of ‘living use facilities’ and ‘agricultural use facilities’ with a large number of facilities and use amount but a low unit usage is continuously increasing (Table 1 and Figure 2). The CAGR of facilities are 1.6% and 4.2%, respectively.

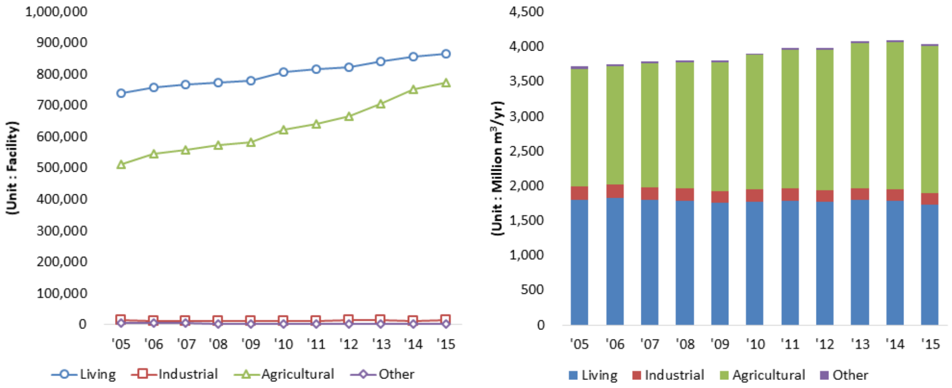
This means that management points to be managed by administrative authorities are increasing. In addition, damage to water pollution due to user’s negligence in management and risk of restoration after use can increase.

〈Table 1〉 Groundwater Use in Korea (2015)

	Facilities (No.)	Use Amount (m^3/yr)	Unit Usage (m^3/yr/facility)
Total	1,626,719 (100%)	4,093,738,197 (100%)	2,517
Living Use	857,544 (53%)	1,786,257,896 (44%)	2,083
Industrial Use	13,485 (1%)	163,991,494 (4%)	12,161
Agricultural Use	752,056 (46%)	2,112,696,161 (52%)	2,809
Other Uses	3,634 (0%)	30,792,646 (1%)	8,473

*Source : MOLIT and K-water (2016b)

〈Figure 2〉 Groundwater Use by Usage during 2005~2015



(a) Groundwater Facility

(b) Groundwater Use Amount

*Source : MOLIT and K-water (2016b)

Researches have continued to examine the economic uses of surface water and groundwater (Burt, 1964; Knapp and Olson, 1995, Tsur, 1997; Winter et al., 1998) and the economic utilization of groundwater for agriculture, livestock, and daily life purposes in developing nations (Mikhail et al., 2010; De Condappa et al., 2011; Evans and Evans, 2012; Douxchamps, 2012; Nasim and Helfand, 2016).

Real Options (RO) is a methodology that allows decision makers to implement strategic investments that reflect future uncertainties. Since Rubio and Castro (1996) and Fisher and Rubio (1997), there has been an ongoing expansion of the application of real options approach to the water resource fields. The main themes include economic evaluation of irrigation facilities (Seo, 2006; Seo et al., 2008; Nasim and Helfand, 2016), economic evaluation of water infrastructure investment projects such as dams and hydroelectric power generation (Mittal, 2003; Michailidis and Mattas, 2007; Wang and Neufville, 2004; Kjaerland F., 2007), and economic evaluation of water supply projects (Clark and Mondello, 2000 & 2002; Gersonius et al., 2013; Yu et al., 2008; Jeong, 2014).

Table 2 shows the major studies applying real options to the water resource sector.

〈Table 2〉 Applications of Water Resource and Real Option

Subject	Source	Underlying Asset	Stochastic Process
Irrigation	Rubio and Castro (1996)	Recharge Rate	GBM
	Fisher and Rubio (1997)	Water Resource Stock	GBM
	Seo (2006)	Cotton Yield	GBM
	Seo et al. (2008)	Cotton Yield	GBM
	Nasim and Helfand (2016)	Water Level	GBM
Infrastructure Investment	Mittal (2003)	Electricity Prices	MBP
	Wang and Neufville (2004)	Electricity Prices	MBP
	Michailidis and Mattas (2007)	Water Value	MBP
	Kjaerland (2007)	Electricity Prices	GBM
	Ryu (2014)	Net Benefit	MBP
Water Supply Investment	Clark and Mondello (2000 & 2002)	Income	GBM
	Gersonius et al. (2013)	Rainfall Intensity	MBP
	Yu et al. (2008)	Operational Cost	GBM
	Jeong (2014)	Water Price	MBP
Real Option Game	Laukkanen, Marita and Koundouri (2006)	Rainfall	GBM
	Bhaduri et al. (2008, 2009, 2011)	Stock of Water	GBM

1. GBM : Geometric Brownian Motion
2. MBP : Multiplicative Binomial Process

Previous studies on real options in the water resources field has focused on river and groundwater as an application. These studies deal mainly with decision-making in a situation where the water price is exogenously determined (Rubio and Castro, 1996; Michailidis and Mattas, 2007), or the water price is endogenously determined by including it in the benefit function or the cost function (Fisher and Rubio, 1997; Mittal, 2003; Wang and Neufville, 2004).

Some studies only deal with the water price uncertainty because the water price is exogenously determined by the exclusive provider (government or local government) in consideration of the inflation (Clark and Mondello, 2000; 2002; Yu et al., 2008; Jeong, 2014). And in some studies, groundwater is considered as a common resource that does not pay for the price and does not consider the price in the model (Seo, 2006; Seo et al., 2008; Nasim and Helfand, 2016).

However, since groundwater is also a limited resource and costs for purification after use are also required, policy makers should take measures to effectively manage groundwater. Therefore, we developed groundwater development investment decision model for groundwater developers, and suggested policy makers to manage groundwater use as pricing policy. This study applied real option approach as a tool for decision making of groundwater investment project under water price uncertainty.

The rest of paper is organized as follows: Section 2 presents an groundwater investment option model. Section 3 performs numerical simulations to explore empirical implications of the model using the data. Lastly, Section 4 provides conclusion.

Ⅱ. Model

We assume a project to develop new groundwater source with confirmed reservoir of S and use it as a water source by extracting it to the surface. The groundwater aquifer is assumed a single cell (Gisser and Sanchez, 1980), and the groundwater level (h) fluctuates continuously according to the groundwater extraction by the developer (decreasing h) and the natural recharge by the precipitation (increasing h).

In this paper, I follows the objective function of Rubio and Castro (1996) and included the depth-dependent groundwater extraction cost, $c(h(t))$, of following literature (Laukkanen and Koundouri, 2006; Nasim and Helfand, 2016; Lee, 2018).

The decision problem for a groundwater developer can be set as follows. In the Eq. (1), the benefit function is $p(t)q(t)$ and the cost function is $c_1q(t)+c(h(t))q(t)+c_3q(t)$. In the Eq. (3) and Eq. (4), each component of the cost function will be described.

$$V(p,h)=E\int_0^{\infty}[p(t)q(t)-c_1q(t)-c(h(t))q(t)-c_3q(t)]e^{-\rho t}dt \tag{1}$$

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

$$dh(t)=\frac{N-q(t)}{m}dt$$

where ρ is the discount rate and E is the expectation operator.

Uncertainty is represented by assuming the water price parameter (p) follows the GBM (Geometric Brownian Motion) (Clark and Mondello, 2000 & 2002, Seo, 2006; Seo et al., 2008)

$$dp(t)=\mu p(t)dt+\sigma p(t)dz \tag{2}$$

where μ is the drift rate of p, σ is the volatility of p and dz is the increment of Wiener's process.

The reason why the water price is used as a variable of groundwater price in this model is as follows. First, if the firm does not develop groundwater, the firm must use tap water instead of groundwater, so the water price becomes reference price. Second, because there is no real groundwater price, only the water price is available to replace the groundwater price.

The costs of groundwater use (C) are composed of three parts which are 'charges for utilization of groundwater (c_1)', 'groundwater extraction cost ($c(h(t))$)' and 'maintenance cost (c_3)'.

$$C(L,h)=c_1+c(h(t))+c_3 \tag{3}$$

The c_1 is 'charges for utilization of groundwater' which is imposed to groundwater developer by local governments for proper development, use, conservation and management of groundwater. And the c_3 is ‘maintenance cost’ which include the cost of meeting water quality requirements through water purification and the cost of ensuring the qualification of use through periodic water quality inspections.

The $c(h(t))$ is a variable dependent on groundwater level. The γ means ‘marginal cost of groundwater extraction’ per unit of lift in won (₩) per cubic meter per meter. It shows the marginal cost of extracting a cubic meter of groundwater from a depth of 1 meter. L means the surface elevation in meters and $h(t)$ means the groundwater level in meters. The difference between the surface elevation and the groundwater level $(L-h(t))$ is the depth from which groundwater has to be extracted. The function $\gamma(L-h(t))$ therefore shows the marginal cost of extraction of a cubic meters.

$$c(h(t)) = \gamma(L-h(t)) \tag{4}$$

The aquifer is assumed to be a single cell, as assumed in the previous study (Gisser and Sanchez, 1980), based on the groundwater level (h) and the area of the aquifer (m). Based on these assumptions, the groundwater reservoir $(S(t))$ in time can be expressed as the product of the area of the aquifer (m) and the groundwater level $(h(t))$.

$$S(t) = m \times h(t) \tag{5}$$

The change in groundwater reservoir at a given point (t) is determined by natural recharge (N) and amount of groundwater extraction $(q(t))$. Here, the natural recharge amount is the product of the natural recharge rate (α), area of the aquifer (m) and the total precipitation (r). The total rainfall is assumed to be fixed at 30 years long term average precipitation (r_{30yr}).

$$dS(t) = d(mh(t)) = (N-q(t))dt \tag{6}$$

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

$$N = \alpha \times m \times r \tag{8}$$

where α is the natural recharge rate(%), m is the area of aquifer (m^2) and r is the total precipitation(m/yr).

The optimization of each period is based on Bellman's Dynamic Programming. By using Ito's lemma's properties ($dt^2 \rightarrow 0$, $dtdz \rightarrow 0$ and $dz^2 \rightarrow dt$), Eq. (1) can be rewritten as follow.[1]

$$\begin{aligned} dV &= V_p dp + V_h dh + \frac{1}{2}[V_{pp} dp^2 + 2V_{ph} dpdh + V_{hh} dh^2] \\ &= V_p(\mu pdt + \sigma pdz) + \frac{1}{2} V_{pp} \sigma^2 p^2 dt + V_h \left(\frac{N-q}{m}\right) dt \end{aligned} \tag{9}$$

Applying the differential operator $\frac{1}{dt}E$ to Eq. (9) and considering that $E(dz) = 0$, Eq. (9) can be rewritten as follow.

$$\frac{1}{dt} E(dV) = \mu p V_p + \frac{1}{2} \sigma^2 p^2 V_{pp} + \left(\frac{N-q}{m}\right) V_h \tag{10}$$

By using Bellman Equation, the following Hamiltonian-Jacobi-Bellman (HJB) equation is obtained.

$$\rho V(p,h) = (pq - c_1 q - c(h)q - c_3) + \mu p V_p + \frac{1}{2} \sigma^2 p^2 V_{pp} + \frac{N-q}{m} V_h \tag{11}$$

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[1] In order to simplify the discussion, the notation t for time is omitted.

After substituting the extraction cost function, $c(h) = \gamma(L - h)$, into the Eq. (11), the following final HJB equation is obtained.

$$\rho V(p,h) = (pq - c_1 q - \gamma(L-h)q - c_3) + \mu p V_p + \frac{1}{2}\sigma^2 p^2 V_{pp} + \frac{N-q}{m} V_h \tag{12}$$

HJB equation is differentiable and linear with respect to $q(t)$, the optimal level of extraction (q_{opt}) follows the bang-bang solution. Under these conditions, the optimal level of extraction (q_{opt}) has the same value as the maximum level of extraction ($q_{\max}$), $q_{opt} = q_{\max}$ (Park, 2004). That is, if $p < V(p)$, then $q = q_{\max}$, and if $p > V(p)$, then $q = 0$.

$$q = \begin{cases} q_{\max} & \text{if}\, p < V(p) \\ 0 & \text{if}\, p > V(p) \end{cases} \tag{13}$$

The first order condition (FOC) for the optimal level of extraction is obtained by differentiating Eq. (12) with respect to $q_{\max}$. The FOC for optimal level of groundwater extraction that specifies an investment rule is Eq. (14).

$$V_h = m(p - c_1 - \gamma(L-h) - c_3) \tag{14}$$

By substituting Eq. (14) into the Eq. (12), the following Constrained HJB is obtained:

$$\rho V(p) = N(p - c_1 - \gamma(L-h) - c_3) + \mu p V_p + \frac{1}{2}\sigma^2 p^2 V_{pp} \tag{15}$$

Since the Eq. (15) is the second-order linear equation in p, applying a standard approach as in Dixit and Pindyck (1994) yields the following solution for the non-homogeneous part of the Eq. (16).

$$V(p) = \frac{Np}{\rho - \mu} - \frac{N(c_1 + \gamma(L - h))}{\rho} \tag{16}$$

The homogeneous part of the Eq. (16) can be solved as follow.

$$V(p) = B_1 p^{\beta_1} \tag{17}$$

Here, the parameter β_1 is positive root of characteristic equation $\mu\beta + \frac{1}{2}\sigma^2\beta(\beta - 1) - \rho = 0$ and the characteristic roots are as follows.

$$\beta_1 = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{(\frac{1}{2} - \frac{\mu}{\sigma^2})^2 + \frac{2\rho}{\sigma^2}} > 1 \tag{18}$$

The solution of HJB equation is composed of the homogeneous solution and non-homogeneous solution. In sum, the project value function $V(p)$ can be derived as follows.

$$V(p) = \frac{Np}{\rho - \mu} - \frac{N(c_1 + \gamma(L - h) + c_3)}{\rho} \tag{19}$$

We now consider the optimal value of the option to invest, $F(p,h)$. In this case, the option value function uses the following Hamiltonian-Jacobi-Bellman (HJB) equation obtained with Ito's Lemma, with the assumption that the profit at the base point does not occur, $\pi(t) = 0$. The option value function $F(p)$ can be derived as follows.

$$F(p) = A_1 p^{\beta_1} \tag{20}$$

The next step is to find the optimal investment threshold price (p^*), which can be derived based on the value-matching condition and the smooth-pasting condition. The value-matching condition means that the value gains attributed to the investment should be equal to the cost of the initial investment. And the smooth pasting-condition means that the marginal changes in the option value ($F(p)$) at the p^* must be equal to that for the marginal changes of the project value ($V(p)$) (Park and Park, 2014).

Value-matching condition

$$V(p) - F(p) = I$$

$$\left[\frac{Np}{\rho - \mu} - \frac{N(c_1 + \gamma(L-h) + c_3)}{\rho}\right] - \left[A_1 p^{\beta_1}\right] = I \tag{21}$$

Smooth-pasting condition

$$V_p(p) - F_p(p) = 0$$

$$\frac{N}{\rho - \mu} - \beta_1 A_1 p^{\beta_1 - 1} = 0 \tag{22}$$

Using Eq. (21) and Eq. (22), the following optimal investment threshold price (p^*) and option constant (A_1) can be obtained.

$$p^* = \frac{\beta_1}{\beta_1 - 1} \frac{(\rho - \mu)[N(c_1 + \gamma(L-h) + c_3) + \rho I]}{\rho N} \tag{23}$$

$$A_1 = \frac{N}{\beta_1(\rho - \mu)}(p^*)^{1-\beta_1} \tag{24}$$

According to Eq. (23), the p^* depends on the exogenous variables such as investment cost (I), groundwater extraction cost factors (c_1, γ, c_3), natural recharge (N), groundwater level (h) and interest rate (ρ).

As investment cost, groundwater extraction cost and interest rates increase, the investment threshold price increases and investment is delayed. And if the groundwater level increases, the investment threshold price decreases and investment is faster.

In addition, the investment threshold price in the absence of uncertainty (p_{npv}^{*}) can be obtained from Eq. (19). In other words, we can derive the p_{npv}^{*} based on $V(p_{npv}) - I = 0$ as follows.

$$p_{npv}^{*} = \frac{(\rho - \mu)[N(c_1 + \gamma(L - h) + c_3) + \rho I]}{\rho N} \tag{25}$$

In conclusion, it can be seen that the 'investment threshold price in the presence of uncertainty (p^{*})' is obtained by multiplying the hysteresis ($\beta_1/(\beta_1 - 1) > 1$) and the 'investment threshold price in the absence of uncertainty (p_{npv}^{*})'. In conclusion, the investment threshold price under uncertainty (p^{*}) is always higher than Marshallian NPV trigger ($p_{npv}^{*} < p^{*}$).

$$p^{*} = \frac{\beta_1}{\beta_1 - 1} \times p_{npv}^{*} \tag{26}$$

III. Empirical Analysis

Based on the groundwater development investment decision model, we use empirical data to analyze how the groundwater development investment is made from the real options perspective.

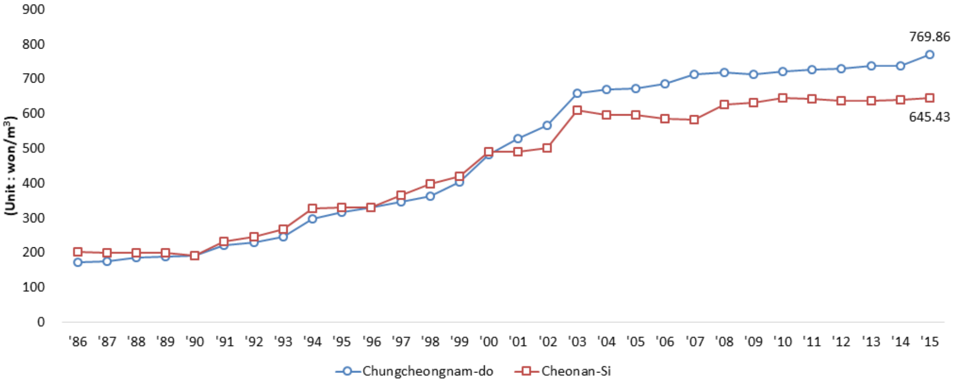
For the simulation of this study, we will focus on Seonggeup-eup, Cheonan-si, Chungcheongnam-do. Cheonan-si has 28,894 groundwater facilities in 2015, and CAGR (4.6%) of facilities is higher than the national average CAGR (3.2%). Also, it is easy to obtain data because there is a national observatory, and it is an area where the ground has all characteristics of rocky layer and alluvial layer.

1. Parameters and Unit of Variables

The price (p) parameters required for the analysis are based on the assumption that tap water is replaced with groundwater. The price data used in this study is obtained from Cheonan-Si's 『Annual Statistics』 which is selected as the subject of empirical study.

Until 2000s, water price had continuously increased. However, since 2006, the water price has shown a steady pattern with CAGR of only 1% (Figure 3). In 2015, the average water price of Cheonan-Si is 645.43won/m^3 (p_{2015}) and average water price of Chungcheongnam-do is 769.86won/m^3, which is higher than the average water price of Cheonan-Si by about 86won/m^3.

〈Figure 3〉 Water Price during 1986~2015



*Source : Cheonan-Si (1986~2016)

We estimates the drift rate (μ) and volatility (σ) of the water price (p_t) following GBM process from the water price data. When we define $y_t = \log(p_t/p_{t-1})$ and set the time interval to Δ, so y_t follows the normal distribution because the price follows GBM.

Since the mean and variance of y_t following the normal distribution are $E(y_t) = (\mu - \sigma^2/2)\Delta$ and $Var(y_t) = \sigma^2\Delta$, we can obtain $\mu = \overline{y}/\Delta + s_y^2/2\Delta$ and $\sigma = s_y/\sqrt{\Delta}$ from the sample mean ($\overline{y}$) and standard deviation (s_y) of y_t. $\Delta = 1$ for estimating the annual drift rate (μ) and volatility (σ) using yearly data, and $\Delta = 1/12$ using monthly data (Park, 2017).

In this paper, parameters are estimated based on the water price of the last 20 years. Table 3 shows the parameters of water price during 1996~2015.

〈Table 3〉 Water Price Parameter during 1996~2015

Parameter	Value
$\overline{y}$ (average of y_t)	0.04
Δ	1
Drift Rate (μ)	0.0370
Volatility (σ)	0.0613

Next, there are cost variables. Costs are composed of three parts. First, charges for utilization of groundwater (c_1) is set at 50% of the 'charges for utilization of water' in accordance with the 「Groundwater Act」. Since the charges for utilization of water at the time of '11~'16 is 170won/m^3 (Han River Water Management Committee, 2016), the c_1 is set at 85won/m^3. Second, marginal cost of extraction of groundwater (γ) is dependent on the extraction depth from groundwater level to surface. It can be calculated by the basic extraction capacity from the relationship between the extracted groundwater quantity and the height of water head (MOLTMA, 2015). The result obtained from this study is 0.45won/m^3·m. Third, maintenance cost (c_3) include the cost of meeting water quality requirements through water purification and the cost of ensuring the qualification of use through periodic water quality inspections. By adapting Kim and Kim (2016), we apply the maintenance cost as 48.79won/m^3.

The investment cost (I) is the sum of the installation cost (I_1) and the performance guarantee (I_2). The installation cost is obtained by Jeju Special Self-Governing Province (2012). And the performance guarantee is the amount deposited in accordance with Article 14 of the 「Groundwater Act」 and Article 17 of the 「Enforcement Decree of the Groundwater Act」 in order to guarantee the implementation of restoration after closure of groundwater well. We set I_2 at 10% (performance guarantee ratio, PGR) of the installation cost of the extraction well when the installation cost of the extraction well exceeded 20 million won (Cheonan-Si, 2016)[2].

Discount rate (ρ) is 5.04% which is the average yields of AA- and BBB- grade corporate bonds through the Economic Statistics System (ECOS)[3] in 2015.

The amount of precipitation (r) is 1,227mm (1.227m) in the mean precipitation of the 2010s. The natural recharge rate (α) is set as 14.61% (KMA, 2011) and the area of aquifer (m) is set as 31,400,000m^2 which is the area of Seonggeo-eup where the target observatory is located. Topographic Elevation is the height calculated from 0m sea level. The topographic elevation of the Seonggeo observatory is 50.33EL.m. Since the groundwater level (h) is measured as the height from the bottom of the observatory, the topographic elevation is converted by setting the depth of the bottom of the observatory to 0m. The converted topographic elevation (L) is 30.66m.

The amount of groundwater usage in this paper assumes the ‘maximum amount of groundwater usage ($q_{\max}$)’, not the current usage (q_{2015}). As suggested in Chungcheongnam-do (2013), the $q_{\max}$ is set at 4,102,000m^3/yr.

Table 4 shows the parameters and values for the empirical analysis.

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[2] The performance guarantee is the money that the groundwater developer can get back if firm restores it at the end of use. However, the groundwater developer also considered the performance guarantee as the investment cost because the performance guarantee have to be invested in the name of restoration cost.

[3] The Bank of Korea, Economic Statistics System (ECOS), Website https://ecos.bok.or.kr/

〈Table 4〉 Parameter values for simulations

Variable		Meaning	Value	Unit
Price	p	Water Price	-	won/m^3
	μ	drift rate	0.0370	-
	σ	volatility	0.0613	-
Costs	c_1	Charges for Utilization of Groundwater	85	won/m^3
	γ	Marginal Cost of Extraction of Groundwater	0.45	won/m^3·m
	c_3	Maintenance Cost	48.79	won/m^3
Investment	I	Total Investment Costs ($I = I_1 + I_2$)	620,278,558	won
Discount Rate	ρ	Discount Rate	5.04	%
Precipitation	r	Precipitation	1,227	m/yr
Groundwater	α	Natural Recharge Rate	14.61	%
	m	Area of Aquifer	31,400,000	m^2
	h	Groundwater Level	26.47	m
	L	Converted Topographic Elevation	30.66	m
	S	Groundwater Reservoir ($S = mh$)	831,158,000	m^3
	N	Natural Recharge ($N = \alpha mr$)	5,628,912	m^3/yr
Extraction	$q_{\max}$	Amount of Groundwater Extraction	4,102,000	m^3/yr

2. Optimal Investment Threshold Price

Table 5 shows the optimal investment threshold price (p^*). According to this, the p^* is 177.00won/m^3. As the water price is 645.43won/m^3 in 2015, it is effective to substitute industrial use water through groundwater investment even if uncertainty is considered.

〈Table 5〉 Optimal Investment Threshold Price (Unit : won/m^3)

Factor	p^*_{npv}	p^*
Discount Rate (ρ)	5.04 %	
Threshold Price	44.82	177.00
Option Multiplier	-	3.9490
β	-	1.3391
Option Constant (A)	-	86,939,703

remark) drift rate (μ) = 0.0370, volatility (σ) = 0.0613

3. Sensitivity Analysis

By using the main variables and parameter, the sensitivity of the investment threshold price is analyzed according to the change of the variables.

Figure 4 shows that the effects of changes in the discount rate (ρ) on the investment threshold price (p^*). p^* is increasing in response to the increasing of discount rate (ρ).

Corollary 1. *The relationship of discount rate (ρ) and investment threshold price is*

$$\frac{\partial p^*}{\partial \rho} = \frac{\beta_1}{\beta_1 - 1} \frac{\mu N(c_1 + \gamma(L - h) + c_3) + \rho^2 I}{\rho^2 N} > 0 \tag{27}$$

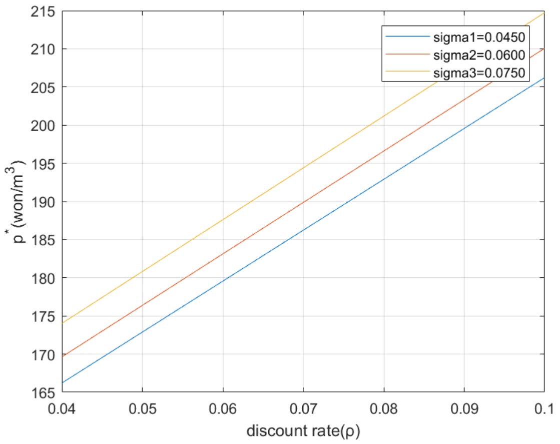
where $\mu > 0$

Figure 5 shows that the effects of changes in the groundwater level (h) on the investment threshold price (p^*). p^* is decreasing in response to the increasing of groundwater level. The result is intuitive because a high groundwater level means the sufficient amount of groundwater reservoir. Another important variable is the volatility of water price. The increase of volatility (σ) can result in an increase of the optimal water price (p^*). The greater volatility increases the p^*, because the firm must have a price well above the break-even water price to be certain that the project.

Corollary 2. *The relationship of groundwater level (h) and investment threshold price is*

$$\frac{\partial p^*}{\partial h} = -\frac{\beta_1}{\beta_1 - 1} \frac{(\rho - \mu)\gamma}{\rho} < 0 \tag{28}$$

〈Figure 4〉 Sensitivity analysis of p^*, with respect to ρ



〈Figure 5〉 Sensitivity analysis of p^*, with respect to h

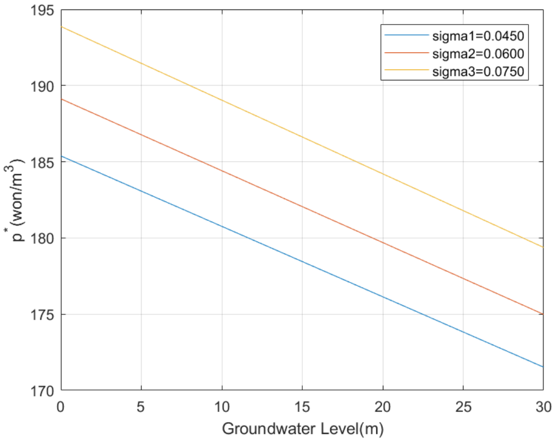


Figure 6 and Figure 7 shows that the effects of changes in the natural recharge rate (α) and precipitation (r) on the investment threshold price (p^*), s, respectively. p^* is decreasing in response to the increasing of natural recharge rate (α) and precipitation (r).

Eq. (29) and Eq. (30) can be derived by partially differentiating α and r, respectively, after substituting $N = \alpha m r$ in Eq. (23).

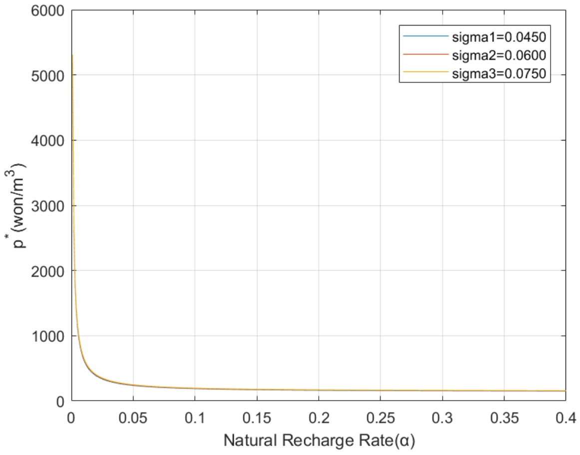
Corollary 3. *The relationship of natural recharge rate* (α) *and investment threshold price is*

$$\frac{\partial p^*}{\partial \alpha} = -\frac{\beta_1}{\beta_1 - 1}\frac{\rho I}{\rho \alpha^2 m r} < 0 \tag{29}$$

Corollary 4. *The relationship of precipitation* (r) *and investment threshold price is*

$$\frac{\partial p^*}{\partial r} = -\frac{\beta_1}{\beta_1 - 1}\frac{\rho(\rho - \mu) I}{\rho \alpha m r^2} < 0 \tag{30}$$

〈Figure 6〉 Sensitivity analysis of p^*, with respect to α



〈Figure 7〉 Sensitivity analysis of p^{*}, with respect to r

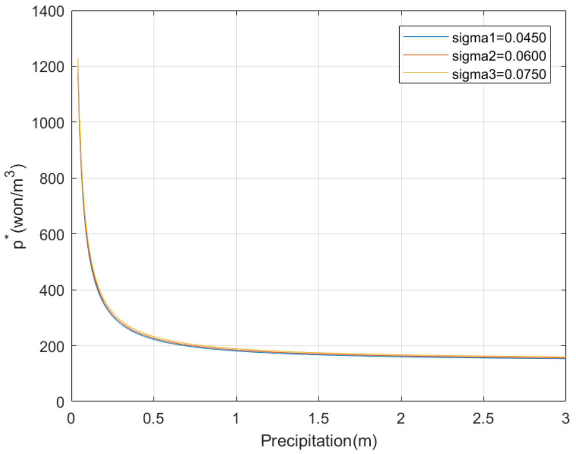
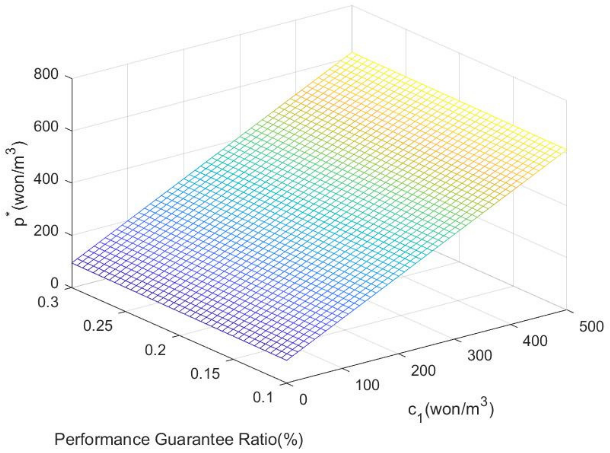


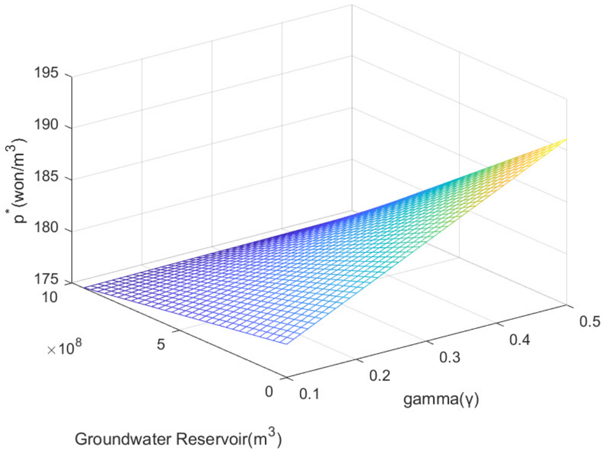
Figure 8 shows that the effects of changes in the charges for utilization of groundwater (c_1) and performance guarantee ratio (PGR) on the investment threshold price (p^{*}). p^{*} is increasing in response to the increasing of PGR and c_1. However, the PGR has little effect on the change of threshold water price. This result implies that the c_1 is the factor that affects groundwater development decision. In conclusion, it is effective for policy makers to manage c_1 rather than PGR when managing groundwater investment with pricing policy.

Figure 9 shows that the effects of changes in the groundwater reservoir (S) and marginal cost of groundwater extraction (γ) on the investment threshold price (p^{*}). p^{*} is increasing in response to the decreasing of S and the increasing of γ. This result implies that the S of target area is the factor that affects groundwater development decision and the groundwater developer's γ is also an important factor.

〈Figure 8〉 Sensitivity analysis of p^* with respect to c_1 and PGR



〈Figure 9〉 Sensitivity analysis of p^* with respect to S and γ



IV. Conclusions and Suggestions

In this paper, we derive the optimal investment threshold price using monopolistic real options approach based on the assumption that firm considers investment in new groundwater development projects under uncertainty of water price.

The optimal investment threshold price under monopoly (p^*) is 177.00won/m^3. The p^* is lower than water price of 2015 which is 645.43won/m^3. It can be concluded that, even if uncertainty of water price is considered, firms will immediately invest in groundwater development project now. In addition, the optimal investment threshold price in the absence of uncertainty (p^*_{npv}) is 44.82won/m^3, which is lower than the presence of uncertainty. A comparison of these results yields $p^*_{npv} < p^* \ll p^*_{2015}$.

In sum, the following policies will be necessary for sustainable groundwater extraction. First, it is necessary to increase the groundwater development and use charge. In the situation where optimal investment threshold price is low, there are incentives to develop groundwater even if the groundwater development and use charge is increasing. Therefore, it is necessary to manage groundwater development incentives by increasing 'charges for utilization of groundwater (c_1)' or 'performance guarantee ratio (PGR)'. It is effective for policy makers to manage c_1 rather than PGR when managing groundwater investment with pricing policy. To make the threshold water price (p^*) equal to the current water price (p_{2015}), we need to raise c_1 to 710won/m^3 (Figure 8).

Second, it is necessary to introduce a system that can differentiate the c_1 by usage. The current groundwater use charge imposes on private use of groundwater by not imposing on the use of public use such as emergency or military facilities, schools and social welfare facilities. And it does not impose on groundwater use for living use (less than 100m^3/day) and agricultural use. As shown in Figure 8, if groundwater use charge is 0 ($c_1 = 0$), p^* is dropping to about 90won/m^3, which means that entry barriers for many small-scale developers to extracting drinking use and agricultural use are much lower than for large-scale developers. Although many of these small-scale facilities do not pay groundwater use charge, they account for 96% of groundwater facilities (Table 1). Based on these funds, we will be able to invest in groundwater management administrative enhancement and groundwater pollution improvement projects.

Third, it is necessary to introduce a system that can differentiate the c_1 by region. The cost of groundwater resources which is the basis for the charges for utilization of groundwater differs according to local groundwater availability and usage status. For example, the ratio of use amount to development potential varies from 10.4% to 87.6% by region (MOLIT and K-water, 2016a). And when the groundwater reservoir (S) is decreasing, the p^* is increasing (Figure 8). The risk of groundwater depletion may arise in areas with high ratio of use amount to development potential. Since the government impose c_1 to manage groundwater extraction, it is reasonable that the levy will also be differentiated according to the regional situation. The imposition structure needs to be elaborately improved so that the levy can reflect the difference.

This paper analyses the investment options of groundwater development project under water price uncertainty. However, the following limitations exist in this paper and there remains a range of subjects to be studied.

First, it is necessary to develop a model by considering precipitation uncertainty. LeCam (1961), Todorovic and Vujica (1969), Alexandersson (1985) and Moon and Cha (2004) analyze that the precipitation follows stochastic process. But, in this paper, we assume that the precipitation is constant as climatological normal (r_{30yr}). In the future, it is also necessary to consider that precipitation or natural recharge is uncertain.

Second, it is necessary to develop a model which dealt with conjunctive use of groundwater and surface water. Research on the economic use of surface water and groundwater has been continued (Burt, 1964; Knapp and Olson, 1995, Tsur, 1997; Winter et al., 1998), but there are few studies that have been conducted using real options approach in Korea.

Third, the studies with heterogeneous agents would be necessary. In this study, we assumed a monopoly firm in groundwater development. However, in reality, it is not just one firm that use groundwater. There are many heterogeneous agents who have different marginal cost of groundwater extraction (Laukkanen, Marita and Koundouri, 2006). In the future, it will be necessary to develop a model considering various groundwater developers and marginal cost of groundwater extraction.

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