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Are Groundwater Monitoring Networks Economical? Cost-Benefit Analysis on the Long-Term Groundwater Supply Project of South Korea

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Abstract: Analyses of the relative economic efficiencies of surface-water and groundwater are important for policy-makers in many water-stressed countries. Groundwater is becoming an increasingly attractive and viable option as a supplementary water source, but its economic background must be understood before implementation. Employing the basic frameworks of the British and US Geological Surveys, we examined the economic viability of groundwater monitoring networks in South Korea, based on an analytic hierarchy process (AHP), pairwise comparison, and cost–benefit analysis. The total cost including installation, maintenance and servicing over the next 50 years is estimated to be US$ 0.79 billion, while the benefits are valued at US$ 2.31 billion. The monitoring network should provide benefits worth 292% of the costs, with the monitoring project thus clearly being economically viable. A sensitivity analysis indicates that the monitoring project is still economical, even if the network installation schedule is delayed slightly. As this study combines both economic and scientific perspectives, it might provide a concrete economic background for implementing groundwater utilization projects elsewhere.

Keywords: groundwater; monitoring network; cost–benefit analysis; AHP; pairwise comparison

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1. Introduction

Water is becoming one of the most pressing societal and geopolitical issues for sustainable development in some Asian regions. It is projected that more than 40% of the world's population will be living in seriously water-stressed areas by 2035, with the availability of ecosystems to provide fresh water becoming increasingly compromised [1]. United Nations University [1] warned that only 60% of water demand will be met by existing resources in the South and Southeast Asian regions by 2030. The World Bank [2] reported that unless government action is taken soon, water scarcity could cost some regions up to 6% of their GDP, spur migration and spark conflict, especially for East Asia and Central Africa.

The effectiveness of water management varies among countries, and rapid development of groundwater resources would be needed in most countries for them to become a viable water source. Groundwater is part of an overall hydrologic system including surface water, and is important in supplying water for irrigation, manufacturing and for other uses. While underground sources provide 80–90% of available water in the US and Europe, they supply only 11% of the total in Korea [1].

With increasing storage and distribution costs of surface-water, groundwater is becoming an increasingly attractive substitute for surface water [3], but the establishment of a national groundwater monitoring system to gauge the level, temperature, pH, and quality of groundwater is expensive.

Since continuous monitoring of any changes in groundwater is a basic role of government, to ensure improvement in groundwater management for water supply as Korea shifts from a largely surface-water based economy to an increasingly groundwater based one, its economic feasibility has become more important. Many approaches based on economic perspectives have been applied to ground and surface water in the US, Spain, UK and other countries [4–7]. The control of underground aquifers, the intensive use of groundwater resources, and the potential changes in both groundwater quality and quantity command the attention of both scientific specialists and policy makers, with economic issues associated with establishing facilities for groundwater supply being important. The economic assessment of groundwater supplies therefore requires a multidisciplinary approach covering costs, water supply policy, water quantity and quality, and applications.

The economic analysis of groundwater based on data provided by monitoring networks should consider not only the efficient use and management of resources, but also the consequential improvements in the ability to cope with related adverse issues such as droughts, and their accompanying risks to the environment, property and life.

South Korea currently has relatively few groundwater monitoring networks compared with major European countries, although there is a national plan to increase monitoring over the next 30 years [8]. However, a systematic analysis of the long-term value of such networks has not yet been undertaken in South Korea, with no economic research into the value of national projects related to groundwater supply. One of the main objectives of this study is to investigate the economic feasibility of groundwater monitoring networks which require the lion's share of the national budget in completing the long-term groundwater supply project; that is, the economic value of the information acquired from the networks is analysed with respect to its cost-benefit relationship, and the adequacy of the evaluation is reassessed through a sensitivity analysis.

1.1. Groundwater Monitoring Networks: Current Facts and Plans

South Korea has been constructing monitoring wells since 1995 to observe the level and quality of groundwater. All six types of groundwater monitoring networks are currently operated with their own objectives: the National Groundwater Monitoring Network (NGMN); the Subsidiary Groundwater Monitoring Network (SGMN); the Groundwater Quality Monitoring Network (GQM including GQMN (Basic Groundwater Quality Monitoring Network) and GPMN (Groundwater Pollution Monitoring Network)); the Local Groundwater Quality Monitoring Network (LQMN); the Groundwater Monitoring Network in Farming Areas (GMFA); and the Seawater Intrusion Monitoring Network (SIMN) [8–10].

The NGMN, GQMN, and GPMN are managed by the central government, and the others are operated by local governments or agencies. They are installed in representative sites according to field characteristics such as land type, topography, hydrogeological measures, background water quality, pollution source, and underground water disturbances. These monitoring networks essentially measure either groundwater levels or groundwater quality. The Groundwater Management Plan has each type of monitoring network scheduled to be installed at the same densities as developed countries by the year 2030 [8] (Figure 1). Therefore, the plan targets 0.10 wells per km^2 for SGMN, 0.33 wells per km^2 for GPMN, 0.01 wells per km^2 for GMFA, and 0.034 wells per km^2 for LQMN.

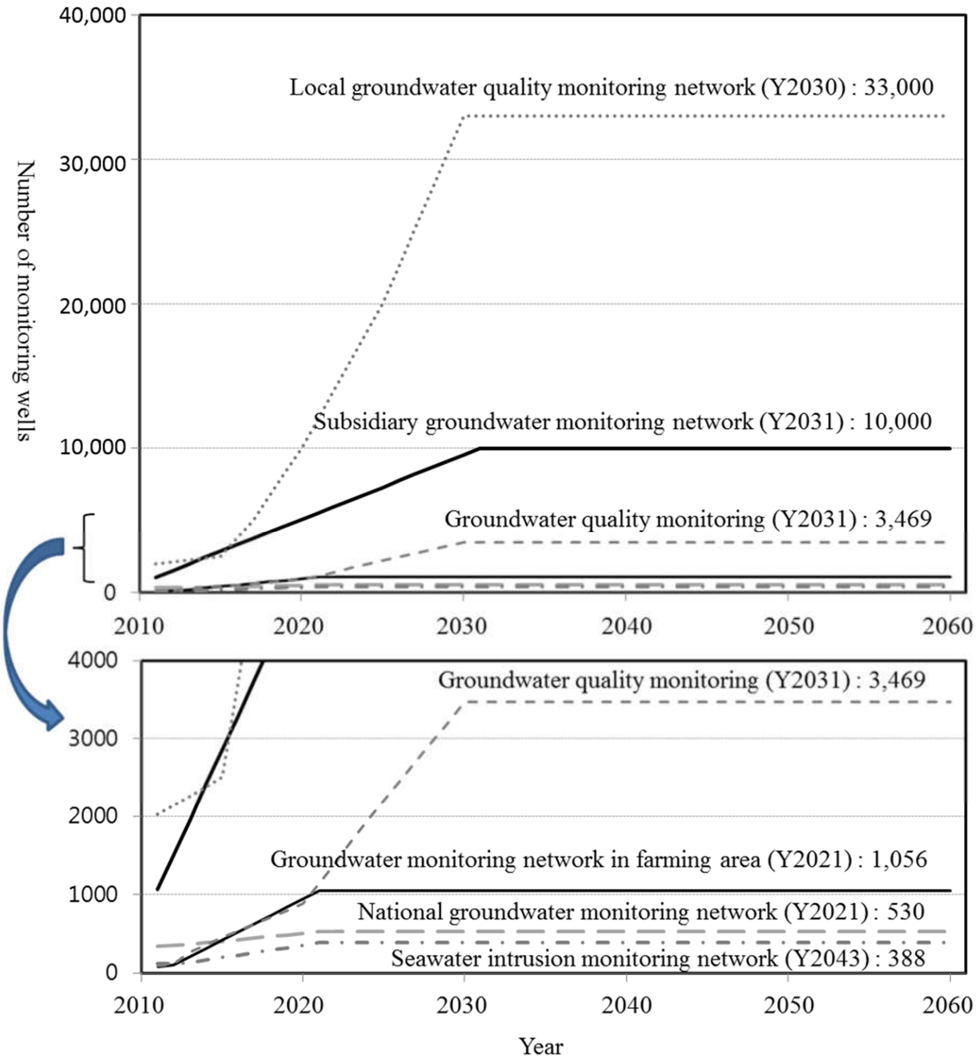


Figure 1. Current groundwater monitoring networks and future plans in South Korea. Source: Ministry of Land, Infrastructure and Transport [8]. Note: (1) The sum of the GQMN and the GPMN is displayed as the GQM. (2) This figure is drawn by the authors.

As a primary network, the purpose of the NGMN was to measure long-term trends in groundwater levels [11]. Its installation began in 1995 and the government plans to increase the number of wells to 530 by 2021 [8]. The GQMN, another primary network, was established to measure background groundwater quality in non-polluted areas. The established background level can be used as a target level when improving polluted groundwater. The Ministry of Environment plans to expand this to 435 sites by 2020 and to 1305 sites by 2030. Electrical conductivity, pH, and temperature are measured automatically, and water samples and analysis are taken twice a year. The GPMN, as a secondary monitoring system, was designed to detect and monitor groundwater contamination in areas likely to be contaminated, such as industrial complexes, closed mines, sanitary landfills, and golf courses. The Ministry of Environment plans to install 2164 of these monitoring wells by 2030. The GQM includes both the GQMN and the GPMN.

The number of these networks was not enough to detect local drawdowns of groundwater levels or contamination due to the complex geology in South Korea and therefore other networks (SGMN, LQMN, GMFA, and SIMN) were additionally proposed [11]. The SGMN was established to measure groundwater levels in the areas not covered by the NGMN, which was proposed to have 10,000 sites by 2031. The LQMN, which is managed by local governments, will be installed at 33,000 sites by 2030; its aim is to measure local groundwater quality. The GMFA will contain 1056 sites by 2021, and automatic measurement systems will be introduced to observe groundwater conditions related to crop production in rural cultivation areas. The SIMN measures seawater intrusions in coastal or island areas, and will contain 388 sites by 2043 [8].

1.2. Literature Review

Whereas the installation and management costs of the networks are fairly straightforward to assess, the benefits of the groundwater monitoring network are difficult to quantify because they include non-use value as well as use value and there is no complete assessment procedure for groundwater monitoring benefits. This means that an indirect approach, such as the analytic hierarchy process with a pairwise comparison, for the estimation of its benefits, can be a more effective tool than a direct estimation. In this study, geological information is used as a relative factor to compare with groundwater information acquired from the monitoring networks because the economic effects of geological information are well defined in many countries.

Studies by the British Geological Survey (BGS) showed two evaluation approaches for measuring the benefits of geological information: an anecdotal approach and a formal assessment as summarized below (Table 1).

Table 1. Previous studies measuring the value of geological information [12,13].

Main Method	Study (Institution)	Case	Empirical Result
Anecdotal and Formal Cost-benefit (Cost-effectiveness) Approach	Ellison and Calow (1996) (BGS) [12]	Evaluates the impacts of information gained through geological mapping projects in the UK.	The annual national baseline value of mapping of the UK is £18.9 million. (B/C = 5.906)
	Bernknopf et al. (1996a) (USGS) [14]	Details the rigorous development of an economic model for valuing geologic map information.	The expected net benefit for the 1:100,000-scale Loudoun County geologic map ranges from $1.28 million to $3.50 million.
	Bernknopf et al. (1996b) [15]	Estimates the economic value of applying geologic map information to siting a waste disposal facility in Loudoun County.	The total benefit of the improved geologic map is approximately $1.5 million. The expected net benefit from use of the 1:100,000 scale map is $0.34 million.
	Reedman et al. (2002) (BGS) [13]	Contains an evaluation and quantification of the net benefits of different levels of detail and improvements in interpretive models contained on geologic maps.	Various results by Bolivia, Indonesia, Peru, Zimbabwe, and Nigeria.
	Halsing et al. (2004) (USGS) [16]	Assesses the costs and benefits of the national map and to estimate its net present benefit to society.	The national map has a net present value of benefits of $2.05 billion with a standard deviation of $490 million over 30 years.
	Kim et al. (2006) [17]	Applies the BGS model (1996) to estimate costs and benefits of the Korean geologic mapping program.	The total benefits ranges from 973 billion Won to 1330 billion Won. The costs were 82 billion Won for 40 years.
Analytical Hierarchy Process (Expert-based)	Booz Allen Hamilton (2005) [18]	Measures the value of geospatial interoperability standards in accessing NASA's scientific information.	Opening geospatial standards had a risk-adjusted ROI of 119.0% which can be interpreted as for every $1 spent, $1.10 is saved.
	Tsangaratos and Koumantakis (2013) [19]	Illustrates the value of geological data and information used to produce landslide susceptibility maps in Greece.	Calculates weight of coefficient of each factor representing the estimation of landslide susceptibility.
Willingness-To-Pay	Bhagwat and Berg (1991) (Illinois State Geological Survey) [20]	Estimate the benefits and costs of geologic mapping conducted in 1980 in Illinois from interviewing with 36 individuals.	According to the most conservative projection, B/C ratio is 0.5 to 1.1.
	US Environmental Protection Agency (1995) [21]	Shows an empirical technique estimating changes in economic value associated with changes in groundwater services.	n.a.
	Bhagwat and Ipe (2000) (Illinois State Geological Survey) [22]	Estimates the value of the geological quadrangle maps (1:24,000-scale) in Kentucky.	The average willingness to pay (WTP) was reported to be $342 per map. The value of the map was at least 25 to 38 times higher than the cost of the mapping program.

Table 1. *Cont.*

Main Method	Study (Institution)	Case	Empirical Result
Expected Utility Theorem	Bouma et al. (2009) [23]	Analyses the added value of an extended satellite monitoring system for the management of eutrophication, potentially harmful algal blooms and suspended sediment and turbidity in the North Sea.	The value of information is estimated to be €74,000 per week and the costs of the new system are only €50,000 per week.
	Castelein et al. (2010) [24]	Defines the geo-information sector and estimate its economic value in terms of turnover, employment, activities and the market in Netherlands.	The total economic value of the Dutch geo-information sector was estimated at €1.4 billion which takes a share of 0.23% in the Dutch economy.

The anecdotal approach has been employed by the BGS to evaluate the impacts of new geological information. This approach was based on the compilation of national, baseline information on policy, guidance, best practice, and government research recommending the use of the information in various sectors such as minerals, waste management, environmental assessment, regional planning, water management, construction industry, education and research, tourism and recreation, agriculture, and forestry [12,16].

As a formal approach, cost-benefit analysis is a simple method comparing the estimated costs and benefits of two or more alternatives. Both the BGS and the United States Geological Survey (USGS), in employing a cost-benefit analysis in their models, defined that the net benefits of each option can be represented as the "expected loss avoided" that arises from using the geological information, minus the costs of producing and disseminating the information [13,14,16,19]. The benefit assessment can be analyzed by comparing the economic impacts of decisions based on the already existing information. In the case of geological information, the potential value may come from: (a) direct savings in terms of avoided costs from contaminations or erosion; (b) reduced potential for liability; (c) lower costs for groundwater protection; (d) safer infrastructure; and (e) improved mineral exploration efficiency [19].

Additionally, an analytical hierarchy process (AHP) with pairwise comparison, through the interviewing of some researchers, senior-level government staff and private individuals, has been widely used to measure the value of geological and geospatial data [18,23].

Martinez-Paz et al. [25] also estimates the environmental and resource costs of groundwater by means of the Contingent Valuation Method and the Production Function Approach in the case of the Gavilán Aquifer. Face-to-face interviews were carried out to calculate use and non-use values, including open-ended questions about the WTP for protecting and preserving an aquifer located in Spain.

2. Research Methods

2.1. Research Process

Among the above four major methods of measuring the value of geological information, we chose to employ a formal cost-benefit analysis and AHP, since water supply projects have been managed not by private market but by public authorities as a public good in South Korea. The AHP is therefore an appropriate method in estimating both direct and indirect benefits of public services such as the water supply. The economic evaluation of groundwater monitoring networks is conducted by the following procedures in this study (Figure 2). First, the costs of each type of groundwater monitoring network, including the costs of construction, maintenance, replacement and water quality tests, are calculated with the existing data recorded by the management agencies or the government (see Appendix A). In the next step, the AHP method with a pairwise comparison, which is between surface water, groundwater, and geologic information, is used to estimate the relative value of the groundwater networks. In this step, the benefits of geologic information are estimated by applying the BGS model. In step 3, we examine the economic validity of the groundwater monitoring networks by comparing their benefits and costs. To ensure the validity of the economic analysis in step 4, as the sensitivity analysis, we reiterate the same analytic procedures and check how the cost-benefit (BC) ratio changes as the number of installed wells changes.

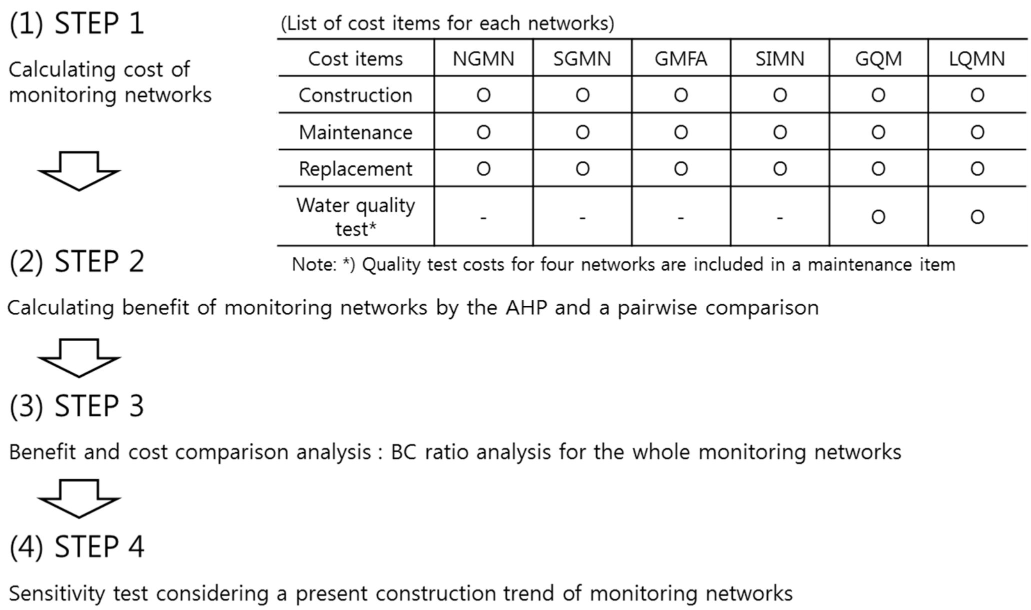


Figure 2. Research procedure of cost-benefit analysis for groundwater monitoring networks.

2.2. Cost–Benefit Analysis

Since a water-related system does not aim to generate profits but has the social goal of providing a public service, the cost–benefit ratio method is more appropriate for groundwater monitoring network evaluation than other methods, as shown in some studies of the BGS and the USGS. In the cost-benefit ratio method, the ratio is calculated using the following formula [26]:

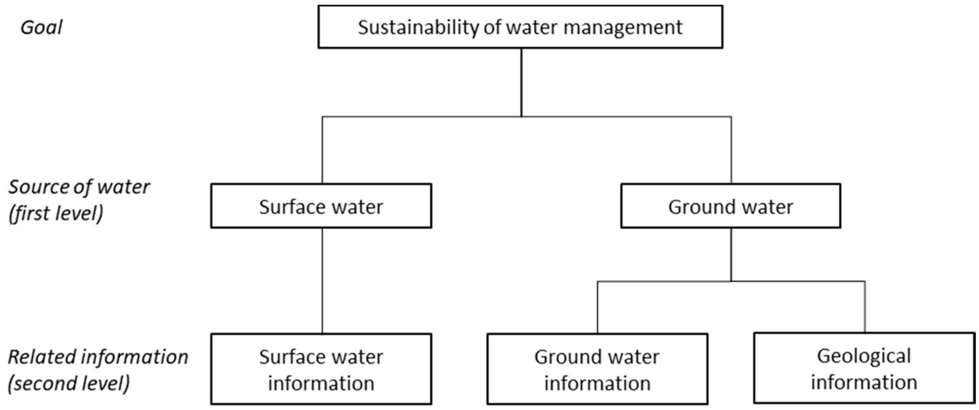
$$\frac{B}{C} = \sum_{t=1}^{n} \frac{B_t}{(1+r)^t} \Big/ \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} \quad (1)$$

where B is present value of benefits, C is present value of costs, r is discount rate, and t is time. The ratio indicates how great the benefits will be per unit of costs for the project, which makes it useful in deciding whether the project should be undertaken under the condition of budget constraints or not.

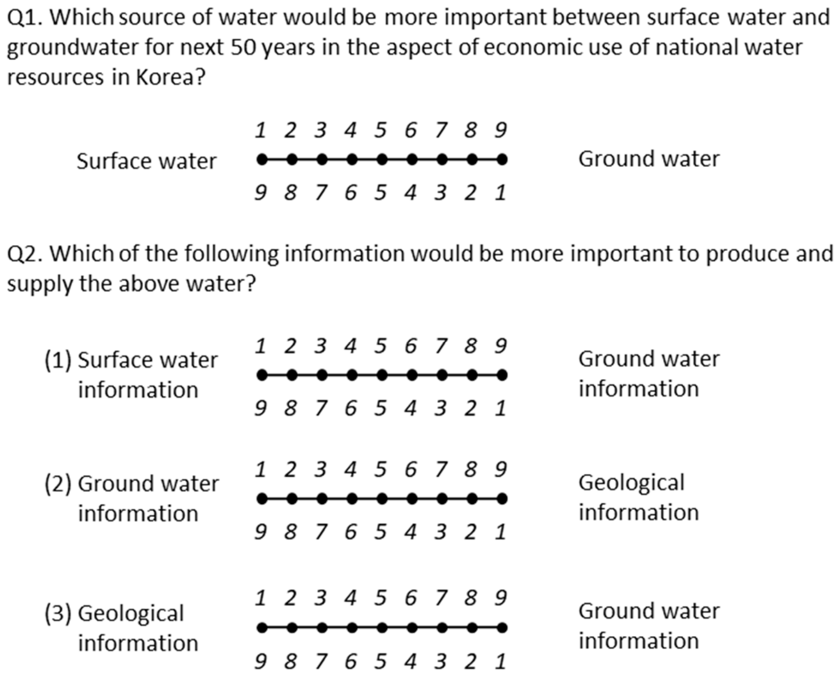
This analysis is conducted under some limited assumptions according to the governmental institute's guidelines [27]. The first assumption regards the planning horizon. This study sets the time frame for the scope of this project as a period of 50 years from the construction of the monitoring wells; therefore, the period of 2011–2060 is considered here as the period generating benefits. The next condition concerns the social discount rate of the costs and benefits. Discount rates have usually been set at between 5.0% and 6.5% in South Korea. The Korea Development Institute (KDI) has usually argued for a relatively low interest rate for water resource projects that could bring long-term costs and benefits. Therefore, two discount rates of 5.0% for the initial 30 years and 6.5% for the next 20 years are used in this research model on the grounds of the KDI's guidelines which has to be applied to the evaluation of all government projects. This discount rate, as stipulated by the KDI, may not be optimal, considering Martinez-Paz et al. [28] findings following a survey of experts that discount rate for the first 30 years should in the range of 3.47%, and 2.84% for the period between 30 and 50 years. However, the 5%/6.5% rates in South Korea are required based on the KDI's analysis of the current and future trend of the Korean economy.

2.3. Analytic Hierarchy Process and Pairwise Comparison

Saaty's AHP is based on the assumption that when faced with a complex decision, the natural human reaction is to cluster the criteria according to their common characteristics. It involves building a hierarchy of criteria and then making comparisons between each possible pair in each cluster [27,29–32]. A pairwise comparison method between the various criteria (surface water, groundwater, and geologic information) is used to assign weights to the different criteria by using a questionnaire (Figure 3).

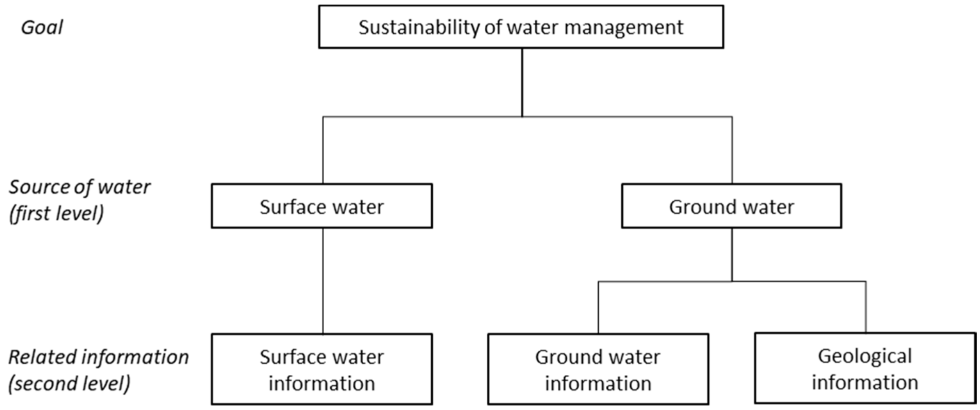


(**a**) The hierarchical value tree

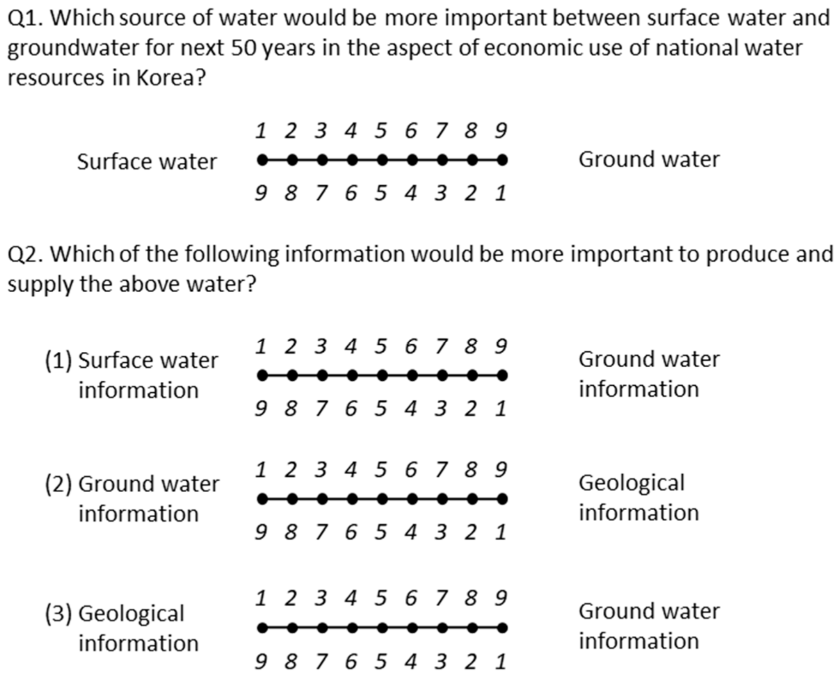


(**b**) AHP questionnaire

Figure 3. *Cont.*



(**c**) The hierarchical value tree



(**d**) AHP questionnaire

Figure 3. The hierarchical value tree and questionnaire for the AHP analysis.

Table 2. An example of a pairwise comparison process for the secondary three criteria [30].

Evaluation Criteria	A Criteria	B Criteria	C Criteria	Geometric Mean	Weights
A criteria	1	a_{12}	a_{13}	$\sqrt[3]{(1 \times a_{12} \times a_{13})} = \mathrm{GM}_1$	$\mathrm{GM}_1/\mathrm{SumGM}$
B criteria	$\frac{1}{a_{12}}$	1	a_{23}	$\sqrt[3]{\left(\frac{1}{a_{12}} \times 1 \times a_{23}\right)} = \mathrm{GM}_2$	$\mathrm{GM}_2/\mathrm{SumGM}$
C criteria	$\frac{1}{a_{13}}$	$\frac{1}{a_{23}}$	1	$\sqrt[3]{\left(\frac{1}{a_{12}} \times \frac{1}{a_{23}} \times 1\right)} = \mathrm{GM}_3$	$\mathrm{GM}_3/\mathrm{SumGM}$
Total				$\mathrm{GM}_1 + \mathrm{GM}_2 + \mathrm{GM}_3 = \mathrm{SumGM}$	

In order to compute the weights for the different criteria, the AHP starts creating a pairwise comparison matrix (Table 2) [30]. The geometric mean is an appropriate measure for combining individual judgments to obtain the group judgment for each pairwise comparison. The matrix is a $m \times m$ matrix, where m is the number of evaluation criteria considered. The entries a_{jk} and a_{kj}, which is a reciprocal of a_{jk}, satisfy the following constraint:

$$a_{jk} \cdot a_{kj} = 1 \quad (2)$$

here, the entry a_{jk} is the importance of the jth criterion relative to the kth criterion [30,33].

Assuming that each F_{jk} is independent, the score of each criterion obtained from the experts can be added together. Here, F_{jk} is the kth secondary criterion constituting the jth primary evaluation criterion. The total score is produced by adding these F_{jk} values and the mean of the total score (MF_{jk}) can also be calculated from the total score. A pairwise comparison matrix for the secondary criteria with their relative values of importance can be produced. With the relative importance between the two criteria, geometric mean and weights were calculated (Table 2).

As described above, we use the relative values of importance to derive the benefit of groundwater monitoring networks.

To test a reliability of the AHP model with pairwise comparison, consistency index $\left\{CI = \frac{(\lambda_{max} - n)}{(n-1)}\right\}$ and consistency ratio (CR) are calculated. Consistency ratio indicates how far the pairwise judgements deviate from a purely random matrix of pairwise comparisons, and is defined as:

$$CR = \frac{CI}{RI} \quad (3)$$

where RI is called random index [30].

Two water sources, surface water and groundwater, are conceptually different from geologic information, and it is not easy to compare them to it because their policy fields, economic aspects, and expected effects are different. Therefore, multiple and diverse discussion on their concepts and effects based on some indicators explaining their characteristics is required to derive the relative importance between them. For a better discussion and understanding, the detailed indicators corresponding to the meanings of the information are derived from previous research and summarized systematically [4,12,26,34]. Subsequently, such research results were provided to the respondents of the questionnaire (Table 3). Consequently, a relative value of importance between the geological, groundwater, and surface water information is assessed by reviewing the provided indicators and comparing those values with the well-defined benefits of geologic information. In previous research, the benefits of information in surface water, groundwater, and geology consist of some selective indicators, as summarized in (Table 3).

Table 3. Some selective indicators used for comparing the benefits of information in surface water, groundwater and geology [4,12,21,26,32].

Indicators	Surface Water	Groundwater	Geology **
Policy aspect	• Governmental (long term) plan and future requirements • Water supply (Domestic, Industrial, Agricultural) * • Flood/drought control * • Restoration of natural resources * • Ecological diversity	• Governmental (long term) plan and future requirements • Water supply (Domestic, Industrial, Agricultural) * • Drought control * • Restoration of natural resources * • Ecological diversity	• Mineral waste management • Environmental assessment • Protection of seaside and water sources • Protection of water quality and water supply • Natural resources management
Economic aspect	• Electricity production * • Cost (Production, Water treatment, Supply, Management) * • Transportation (Canal) *	• Geothermal source • Cost (Production, Water treatment, Supply, Management) *	• Mineral production • Development of local region • Construction economy (Road, railway, port, building, etc.)
User aspect	• Agricultural/industrial productivity • User accessibility • Recreational benefit * • Land use *	• Agricultural/industrial productivity • User accessibility • Land use * • Water welfare	• Real estate and insurance • Health • Education and Research • Recreation/Tourism • Agriculture/Forest

Table 3. *Cont.*

Indicators	Surface Water	Groundwater	Geology **
Others	• Economic benefit * • Future value • Emergency use	• Economic benefit * • Future value • Emergency use	

Note: (1) Asterisks (*) denote items of water benefit proposed by the KDI (2008) [26] and ** denotes items of geology benefit proposed by the BGS; (2) Some of the above indicators are also discussed in Marcouiller and Coggins (1999) [34], Ellison and Calow (1996) [12], and Environment Agency (2007) [4].

3. Cost and Benefit of Groundwater Monitoring Networks

3.1. Cost

The costs of the groundwater monitoring network are determined according to the facility design, maintenance strategy, repair, and reinstallation (Table 4). The design of a groundwater monitoring well depends on the purpose of each monitoring system. For example, the SIMN should have an electric conductivity sensor to detect sea-water intrusion, and the GQMN and the NGMN should have an automatic monitoring system for groundwater quality and quantity measurements. Construction and installation costs of the monitoring networks include a well drilling and remote terminal system and power battery. Maintenance costs include the replacement of old wells and all devices. Service costs include labor charges for replacement and maintenance, and travel expenses for collecting water samples (Table 4).

According to the Groundwater Promotion Act, the owner should report the end of groundwater use to the local government when both closing and drilling a well. By using the national statistics of this data on groundwater wells (www.gims.go.kr), 217,993 pumping wells, which were drilled during the period from 1970 to 1989, are analyzed to calculate their average life cycle (Figure 4). The average life cycle is calculated to be 29.7 years for their periods in service, where the equation is "service period = year of construction − year of removal + 1". Considering the structural similarity of monitoring and pumping wells, the life cycle of groundwater monitoring wells are also considered to be 29.7 years, with the exception of a sensor and telemetering device with a shorter life cycle (Table 4). By using the above installation data and maintenance plan, the costs for each monitoring network for the period 2011–2060 are finally calculated with the total costs amounting to USD 793.6 million. The cost details by type of network are listed below (Table 5).

Table 4. Unit costs of construction and management for groundwater monitoring networks.

Type of Network	Items and Unit Costs (unit: USD/single well)	Remarks
NGMN	• Construction/drilling: 39,965 • Equipment installation: 11,182 • Service: 5386 • RTU replacement: 3516 • Battery replacement: 111	• Service includes labor, travel cost, water analysis fee, reporting, etc. • RTU: Remote terminal unit for data collection and transmission (11% of wells are replaced every year)
SGMN	• Reuse of existing well(Manual installation): 30 • Well installation: 14,567 • RTU installation: 100 • Service(manual): 713 • Service(automatic): 2825 • Equipment replacement: 65	• Reuse means the existing well is used as a monitoring well • Well installation means new well drilling • Service (manual) includes sampling, reporting and water level measuring • Service (automatic) means automatic measurements of water level and quality sensors as well as sampling and reporting

Table 4. *Cont.*

Type of Network	Items and Unit Costs (unit: USD/single well)	Remarks
GMFA	• Construction/drilling: 40,030 • Equipment installation: 767 • Service: 4612 • Replacement (Device and Battery): 4744	• Service includes management, sampling, manual measurements of level, reporting, etc. • Equipment includes water level sensor, logger and telemetering
SIMN	• Construction/drilling: 42,031 • Equipment installation: 10,465 • Service: 674 • Replacement (Device and Battery): 3633	• Equipment includes water level and quality sensors as well as telemetering • Service includes sampling, water analysis, reporting, and level measurement
GQM	• GQMN construction/drilling: 78,761 • GPMN construction: 2902 • GQMN labor and travel: 383 • GPMN labor and travel: 43 • Equipment replacement(GQMN): 338 • Water sample(Fee): 1104 • Water sample(Labor): 58	• GQMN uses a new well and GPMN uses an existing well • Labor and travel costs are needed for sampling, level measurement, etc. GQMN labor cost is high due to equipment inspection
LQMN	• Reuse of existing well: 172 • Service(labor and travel): 128 • Equipment replacement: 296 • Water sample(Fee): 128 • Water sample(Labor): 51	• Equipment replacement includes well protection apparatus, guide plate, etc.

Note: 1US$ = 1100 Korean Won.

Table 5. Present values of total costs for each type of groundwater monitoring network for 50 years (Appendix A).

Type		Construction, Installation, & Well Replacement	Maintenance & Service	Device Replacement	Water Sample Test *	Total
NGMN		7,528,404	70,758,976	3,908,395	-	82,195,775
SGMN	Manual	386,490	61,253,235	17,619	-	246,177,391
	Automatic	80,570,577	103,922,130	27,340	-	
GMFA		37,086,424	126,068,647	8,140,240	-	171,295,311
SIMN		10,449,325	48,662,609	2,716,363	-	61,828,297
GQM	Quality (GQMN)	63,072,618	6,109,509	595,225	33,989,889	108,164,812
	Pollution (GPMN)	3,427,972	969,599			
LQMN		52,744,882	15,300,180	3,906,735	51,989,311	123,941,108
Total						793,602,694

Notes: (1) Maintenance and service costs include fees for water sample tests for NGMN (National Groundwater Monitoring Network), SGMN (Subsidiary Groundwater Monitoring Network), GMFA (Groundwater Monitoring Network in Farming Areas), and SIMN (Seawater Intrusion Monitoring Network); (2) According to KDI (2008) [26], two discount rates of 5.0% for the initial 30 years and 6.5% for the next 20 years are used to calculate net present values.

3.2. Benefits

Each groundwater monitoring network has its own objective function, and therefore, the benefits can be different from each other. However, some of their functions, such as the measurement of groundwater level and basic quality observations, overlap for each network. For example, the NGMN and the SIMN have a similar purpose regarding water level observation, but the SIMN is more beneficial in protecting against seawater intrusion along the coastal line. Additionally, because the benefits of the monitoring networks include both use value and passive value, it is not easy to quantify as mentioned in the above section. Therefore, it is almost impossible to calculate the value of each monitoring network separately, and in this study the benefits are assessed for the whole network based on the network's conceptual average benefits by being compared with the geological information.

When applying the AHP for the benefit estimation, a series of intensive discussions with groundwater and geology specialists in South Korea were conducted by reviewing some indicators for comparison in order to determine the primary and secondary criteria. A hierarchical value tree using the primary and secondary criteria for an assessment of groundwater value was finally proposed

To evaluate the value of groundwater information, a questionnaire survey was made to estimate the relative value of groundwater information compared with surface water and geological information as the second criteria, and also the relative importance of groundwater and surface water as the first criteria considering the proposed indicators. A total of 55 questionnaires were collected from hydrogeologists, surface water specialists and geologists. Interview participants were provided with the monetary value of geological mapping as estimated by Kim et al. [17]. Through several brainstorming sessions, all specialist participants were asked to respond to the relative economic value of groundwater information compared with geological mapping which is estimated to be USD 964.8 million. Therefore, they knew that if one answered "1" for geological information and "2" for groundwater information in the Likert scales, it meant that the monetary value of groundwater information was 2 times greater than that of geological information for the person.

The survey results show that the value of surface water information is 2.37 times more important than geological information, and groundwater information is 2.39 times greater than that of geological information (Table 6). The consistency index is 0.005 and random index is 0.58. The calculated consistency ratio is nearly zero, i.e., 0.009. Because Saaty's rule of thumb is to allow up to 10% inconsistency within the random matrix, this level of consistency is satisfactory.

Table 6. Relative values of groundwater information estimated by the AHP with pairwise comparison.

Item	Surface Water Information/Groundwater Information	Surface Water Information/Geological Information	Groundwater Information/Geological Information
Value	0.72	2.37	2.39

Note: Consistency index: 0.005, Random index: 0.58, Consistency ratio: 0.009.

Applying the BGS model, Kim et al. [10] calculates the value of geological information (1:50,000 scale maps) [12]. In total, seven sectors are considered in estimating the benefits of geological information: mineral products, waste facility construction, environmental impact, groundwater relations, regional development, coastal management, and social infrastructure (Table 7). The total annual benefits of Korean geological information are estimated as USD 56.6 million. Consequently, the total benefits of geological information for 50 years are calculated by multiplying and discounting the annual benefit based on the KDI guidelines such as the discount rate. Finally, the benefits for geological information in South Korea are estimated as USD 964.8 million.

The relative value of groundwater information provided by the monitoring networks, which means ultimately the benefit of the networks, can be estimated by multiplying the value of geological information by the relative importance value, 2.39, of groundwater information (Table 6). Therefore, the benefit of the monitoring networks can be estimated to be about USD 2314.7 million.

Table 7. Estimation of total annual benefits of geological information in South Korea [12,16].

Benefit Sector	BGS's Benefit Items and Key Statistics (USD)	BGS's Contribution Rate	Annual Benefit (USD)	Percentage of Annual Benefit
Mineral Product & Management	- Aggregate production of mineral, sand & gravel (3161 M) × 0.1% - Mineral operators: 3161 M × 0.05%	0.15%	4,741,818	8.4
Waste Facility Construction	- Average costs of facility construction (0.91 M) × Nationwide sites (36 sites/year)	5%	1,636,364	2.9
Environmental Impact Assessment	- Average costs of Environmental Impact Assessment ($107,272 per site) × 250 sites/year	5%	1,340,909	2.3
Groundwater Development & Management	- Average costs of groundwater pumping wells ($9090 per well) × 30,000 wells/year	5%	13,636,364	24.0
Regional Development	- Saving costs of time for staff ($863/local government) × 199 local governments	£1500 per local government	171,818	0.3
Coastal Management	- National expenditure for coastal defense plan & project (207 M, 68 sites)	0.05%	103,636	0.2
Social Infrastructure	- National SOC investment (14,000 M/year)	0.25%	35,000,000	62.0
	Total Annual Benefit		56,630,909	100.0

Based on interviews with geotechnical specialists, Ellison and Calow [12] argued that geological mapping information is worth at least 25% of the value of the site investigation, and considerably more where modern maps and databases are available to enable better decision making and risk assessment to be made. According to Kim et al. [17], the annual average costs for geological site investigation take 1% of the total expenditure of national SOC investment in Korea. We understand that Kim et al. [17] calculated the benefits by multiplying 25% × 1% × SOC investment, hence the 0.25% National SOC expenditure rate for social infrastructure.

4. Results and Sensitivity Test

As mentioned above, the cost of the groundwater monitoring network over the next 50 years is estimated to be USD 793.6 million in present value terms. Meanwhile, the present value of benefit obtained by the AHP analysis has a value of USD 2314.7 million. The BC ratio of the groundwater monitoring network is therefore 2.91, and thus the monitoring network's benefits will greatly exceed the costs over the next 50 years. This high ratio means that the expansion of the existing groundwater monitoring networks is a highly economical solution of great value to an essential issue.

The original trends of the estimated costs and benefits of groundwater monitoring networks, which are calculated through the above process, are plotted in Figure 4.

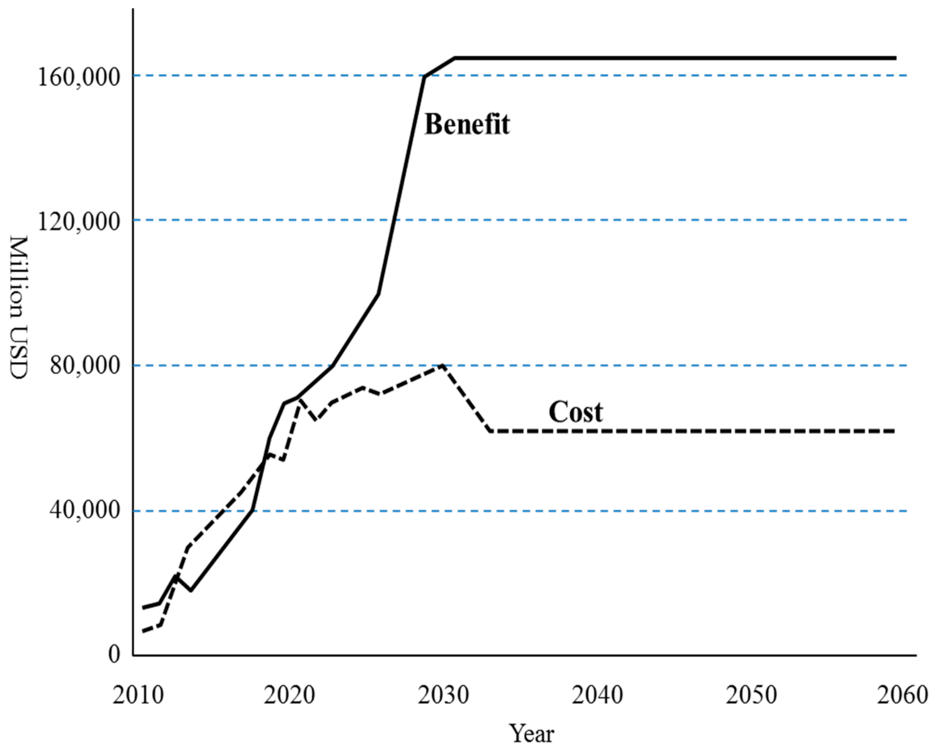


Figure 4. Long-term comparison of benefits and costs of the groundwater monitoring networks.

The trends indicate that the benefits and the costs will increase by almost the same ratio until 2020, but the gap between benefits and costs grows annually after 2020 and until 2030, when the new constructions are fully installed as scheduled.

Future costs and benefits, on which the net present value is based, are predicted values with uncertainty. Therefore a sensitivity test is required to confirm the result and it is important to test the values under both 'optimistic' and 'pessimistic' scenario conditions. If the output values are shown to be very sensitive to changes in a given input value, the model should be checked for the appropriateness and impact of the given variable. The government schedule for the number of monitoring wells is a key point for the cost calculation and therefore additional BC analysis is performed again under the condition of a changed schedule, which means a delay of network installation, in calculating the BC ratio for a sensitivity test.

We run simple OLS (Ordinary Least Square) regressions to project the number of monitoring wells for the target year 2060, based on the previous installation trends, from the late 1990s to 2012, of six different networks (Figure 5). As a result of these regressions, by 2060 we estimate the number of wells by type as following: NGMN 530; SGMN 3977; LQMN 3149; SIMN 388; GMFA 347; and GQM 231. However, in cases of the NGMN and the SIMN, the original target numbers, 530 and 388, will be accomplished in 2018 and 2038 (Appendix B).

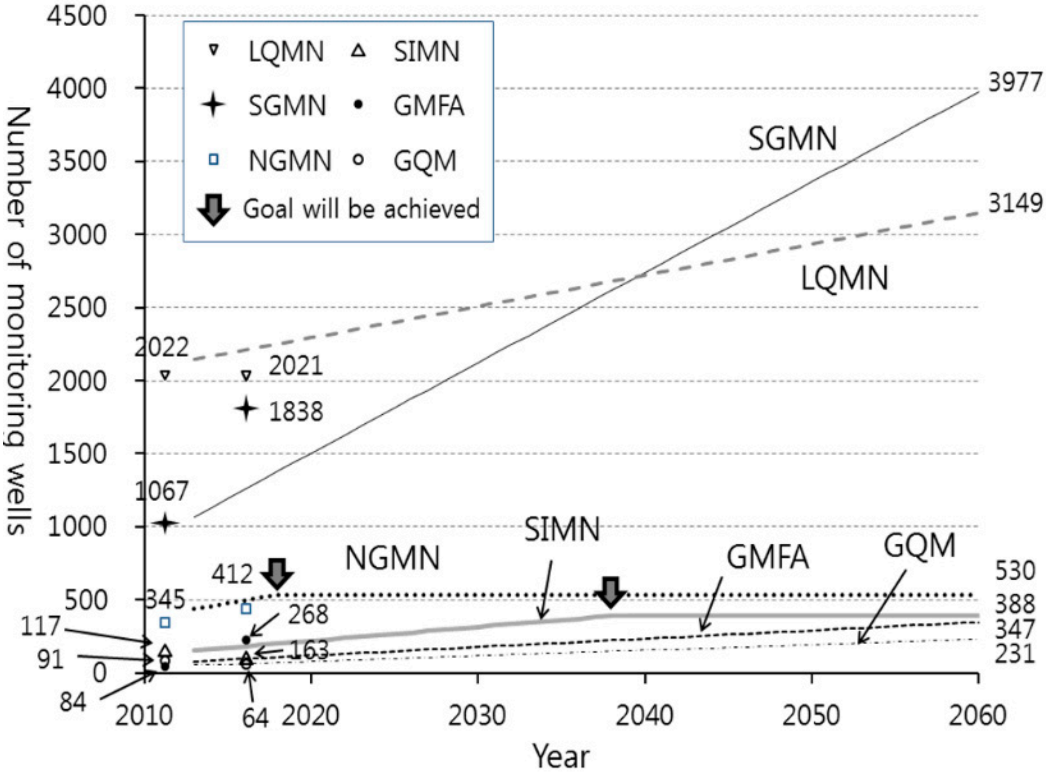


Figure 5. Forecasting groundwater monitoring networks considering recent trends. Note: Symbols denote numbers of groundwater monitoring wells in 2011 and 2016.

Considering these trends, the costs of the networks are recalculated with the same process, becoming about USD 265.6 million, or 33.4% of the total costs. On the other hand, this total number of monitoring wells, 8622, reaches only 17.8% of the planned number of 48,443. Following the previous trends of the above 6 types of wells as shown in Figure 5, we found that the reduction rates of both cost and numbers of wells are not proportionate because lower cost wells such as LQMN and SGMN take over 88% of the total number of wells. This is why the rate of cost reduction is much smaller than that of the number of wells reduced.

On the other hand, the benefits, in proportion to the number of wells, should be reduced to 17.8%, or USD 412.0 million, of the original total benefits. This indicates that the BC ratio is drastically reduced from 2.91 to 1.55 (= USD 412.0 million over USD 265.6) and it means the ratio, which will have decreased by about 47%, is relatively less sensitive than the reduced percentage of the number of monitoring wells (82%). Although the BC ratio is reduced, it is noteworthy that the benefits still outweigh the costs and the value of groundwater monitoring exists still. This result shows that new installations should continue to be made even if the number of monitoring wells remains below the planned target (Table 8).

Table 8. Results and sensitivity test.

Scenarios	Benefit (1000 USD)	Cost (1000 USD)	B/C Ratio
Groundwater project	2,314,782	793,602	2917
Past trend	412,031	265,642	1551

In 2016, the numbers of monitoring networks become 412, 1838, 268, 64, 2021, and 163 for the NGMN, the SGMN, the GMFA, the GQM, the LQMN, and the SIMN, respectively (Figure 5). In the cases of the NGMN, the LQMN, and the SIMN, the actual installation does not meet the target number but the other networks have been installed over the predicted number as of 2016. The recent trend is roughly similar to the past trend from the late 1990s to 2012 and so it is still economical. Even though the recent trend of monitoring well installation may change according to the budget or national policy, it is shown that the continuous installation is important and valuable.

5. Conclusions and Discussion

Especially in water-stressed countries, water authorities have been struggling to design policies that address emerging physical, economic and environmental stress on groundwater resources. In order to contribute to policy discussion, we suggest some basic indicators and a framework, based on the BGS' and the USGS's models of groundwater, for measuring the costs and benefits of groundwater information. For our model, we have assumed, on the basis of Kim et al. [17], who based their calculations on Ellison and Calow [12], that benefits are equal to 25% of National SOC expenditure, which they claim to be on the conservative side and may in truth be more where more detailed and up-to-date maps and databases are used. However, our research goal was to introduce a viable model with which to estimate and analyze the costs involved in building and maintaining the monitoring networks and the various benefit streams expected from them. As shown above, the review of previous research shows significant economic benefits attached to the generation of this type of geological and groundwater information. It is, however, difficult to compare results across studies since they differ in scope and make assumptions regarding which sectors to cover. As much research has verified that benefit-cost ratio of geological information were much greater than one, this analysis of groundwater monitoring networks in South Korea also shows that the benefits are greater than the costs, and demonstrates the economic feasibility of the planned network project in the national groundwater master plan as promoted by the government. Groundwater information, which plays a key role in addressing the challenges of sustainable water supply, contributes to improved decision making processes.

One of the limitations of our research is that we apply the indirect method of estimation by calculating the relative value of groundwater monitoring networks through questionnaire. It is difficult to express the benefit of groundwater information, which is a public good, in monetary terms, because of the limited availability of the necessary information since its market price does not exist. Even more, the benefit assessment is complex due to different spatial and temporal scales on which many of the benefits of the groundwater information operate. This is the main reason why the benefit of each monitoring network cannot be measured separately.

The second limitation of our research is that our valuation of groundwater information, which considers a scope of 50 years, might be recalculated due to the currently unknown effects of climate change in the future, which has been linked to changes in the large-scale hydrological cycle in the long run. We expect that the most significant abnormal weather phenomenon due to climate change is the change of water circulation. Previous studies indicated that greenhouse gases accelerate global warming, resulting in an increase of moisture in the air which strengthens the water circulation process. The long-term change in the rainy season in the Korean peninsula has been studied in many aspects. According to Ryoo [35], comparing precipitation from the 1960s to that of the past 30 years during the rainy season, the number of precipitation days has decreased from 62 percent in the 1960s to 56 percent in the past 30 years. With higher than average temperatures and warmer air that can hold, a pattern might emerge of lengthy dry spells interspersed with brief but heavy precipitation and possible flooding in Korea. Indeed, Ryoo [35] concluded that sudden precipitation causing a greater likelihood of flooding is expected in the future, which would cause instability in surface water supply. Thus groundwater represents a reasonable reliable source of water under such an eventuality. Therefore, because much of the impact of climate change will be felt through changing patterns of water availability [36], groundwater resources are an essential source of water, especially for water-stressed and highly surface-water dependent countries like Korea in the future. In this respect, further research incorporating the factor of climate change in the long-time would be valuable to establish the water management capability on a sustainable basis.

Lastly, we did not discuss the environmental costs of groundwater as Martinez-Paz et al. [25] studied. They concluded that the environmental and resource costs as a result of depletion and degradation of groundwater were 0.454 €/m^3 including the price of the services provided by the groundwater of an aquifer in Spain. As Korea currently uses about 3500 million tons of groundwater as of 2018, the costs would be 1589 million € according to Martinez-Paz's study, which is approximately the same as the benefit we estimated above. However, their costs include the opportunity cost for recreation which may not occur in many groundwater pumping well sites in Korea because 57.2% of pumping wells are being used by households.

The government generally requires an economic validation of a new project. In particular, it is very difficult to explain or quantitatively calculate the importance of a new groundwater project because it is associated with many unknown variables such as hydraulic uncertainties and environmental forecasts such as climate change. This study represents a simple solution with an economic approach for the groundwater monitoring system providing groundwater information, which is a BC analysis and AHP with a pairwise comparison, which will be useful to decision-makers within water authorities not only in Korea but in water-stressed countries throughout the world.

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Appendix A

Table A1. Cost detail of the NGMN (unit: USD).

Year	NGMN	Construction		Installation	Service	Replacement			GDP Deflator *	Discount Rate *
		Plan	Cost			Number of RTU	RTU	Battery		
2011	345	10	399,650	111,818	1,858,274	44	154,736	4886	101.8	
2012	355	10	382,609	111,818	1,637,538	40	145,920	4608	105.6	
2013	365	10	390,846	111,818	1,657,199	52	194,007	6127	108.0	
2014	386	21	895,369	254,610	2,215,742	85	322,744	10,192	110.4	
2015	406	21	914,834	260,145	2,466,026	66	255,723	8075	112.8	
2016	427	21	934,298	265,680	2,730,069	58	229,327	7242	115.2	
2017	448	21	953,763	271,215	3,007,910	41	165,041	5212	117.6	
2018	468	21	973,227	276,750	3,299,584	43	176,700	5580	120.0	
2019	489	21	992,692	282,285	3,605,124	62	260,573	8229	122.4	
2020	509	21	1,012,157	287,820	3,947,797	65	278,616	8798	124.8	
2021	530	21	1,031,621	293,355	4,283,300	61	266,397	8413	127.2	
2022	530				4,283,300	52	232,809	7352	129.6	
2023	530				4,283,300	85	385,890	12,186	132.0	
2024	530				4,283,300	66	304,691	9622	134.4	
2025	530				4,283,300	58	272,325	8600	136.8	6.5%
2026	530				4,283,300	41	195,355	6169	139.2	
2027	530				4,283,300	43	208,506	6584	141.6	
2028	530				4,283,300	62	306,556	9681	144.0	
2029	530				4,283,300	65	326,838	10,321	146.4	
2030	530				4,283,300	61	311,635	9841	148.8	
2031	530				4,283,300	52	271,610	8577	151.2	
2032	530				4,283,300	85	449,328	14,189	153.7	
2033	530				4,283,300	66	353,886	11,175	156.1	
2034	530				4,283,300	58	315,523	9964	158.5	
2035	530				4,283,300	41	225,809	7131	160.9	
2036	530				4,283,300	43	240,459	7593	163.3	
2037	530				4,283,300	62	352,753	11,140	165.7	
2038	530				4,283,300	65	375,283	11,851	168.1	
2039	530				4,283,300	61	357,081	11,276	170.5	
2040	530				4,283,300	52	310,591	9808	172.9	

Table A1. *Cont.*

Year	NGMN	Construction		Installation	Service	Replacement			GDP Deflator *	Discount Rate *
		Plan	Cost			Number of RTU	RTU	Battery		
2041	530				4,283,300	85	512,474	16,183	175.3	5.0%
2042	530				4,283,300	66	402,854	12,722	177.7	
2043	530				4,283,300	58	358,522	11,322	180.1	
2044	530				4,283,300	41	256,122	8088	182.5	
2045	530				4,283,300	43	272,265	8598	184.9	
2046	530				4,283,300	62	398,736	12,592	187.3	
2047	530				4,283,300	65	423,505	13,374	189.7	
2048	530				4,283,300	61	402,319	12,705	192.1	
2049	530				4,283,300	37	248,606	7851	194.5	
2050	530				4,283,300	48	323,945	10,230	196.9	
2051	530				4,283,300	21	142,001	4484	199.3	
2052	530				4,283,300	21	143,711	4538	201.7	
2053	530				4,283,300	21	145,493	4595	204.2	
2054	530				4,283,300	28	197,162	6226	206.6	
2055	530				4,283,300	29	206,673	6527	209.0	
2056	530				4,283,300	31	223,652	7063	211.4	
2057	530				4,283,300	31	226,191	7143	213.8	
2058	530				4,283,300	10	74,687	2359	216.2	
2059	530				4,283,300	21	155,753	4919	218.6	
2060	530				4,283,300	21	157,463	4973	221.0	

Note: (1) All of the above future values are converted into present ones by applying GDP deflators and discount rates of each year, (2) The future costs of service are estimated by a simple regression analysis based on data from 1995 through 2013, (3) Exchange rate: 1US$ = 1100 Korean Won.Source: (1) Ministry of Land, Infrastructure and Transport [8], (2) National Information Center (www.gims.go.kr).

Table A2. Cost detail of the SGMN (unit: USD).

Year	SGMN		Construction & Installation			Service		Replacement	GDP	Discount Rate
	Nation Total	Plan	Manual	Automatic	RTU	Manual	Automatic			
2011	1067	0	-	-	-	513,752	871,631	2283	101.8	6.5%
2012	3079	447	31,941	6,613,380	45,326	756,016	1,282,655	2368	105.6	
2013	5092	447	32,667	6,763,684	46,356	1,001,354	1,698,896	2422	108.0	
2014	7106	447	33,393	6,913,989	47,386	1,256,833	2,132,340	2476	110.4	
2015	9121	447	34,119	7,064,293	48,416	1,522,452	2,582,989	2529	112.8	
2016	11137	447	34,845	7,214,597	49,446	1,798,211	3,050,842	2583	115.2	
2017	13154	447	35,571	7,364,901	50,476	2,084,111	3,535,899	2637	117.6	
2018	15172	447	36,297	7,515,205	51,506	2,380,151	4,038,160	2691	120.0	
2019	17191	447	37,023	7,665,509	52,537	2,686,331	4,557,624	2745	122.4	
2020	19211	447	37,749	7,815,813	53,567	3,002,651	5,094,293	2799	124.8	
2021	21232	447	38,475	7,966,117	54,597	3,329,112	5,648,166	2852	127.2	
2022	23254	447	39,201	8,116,421	55,627	3,665,713	6,219,242	2906	129.6	
2023	25277	447	39,927	8,266,725	56,657	4,012,454	6,807,523	2960	132.0	
2024	27301	447	40,653	8,417,029	57,687	4,369,336	7,413,008	3014	134.4	
2025	29326	447	41,379	8,567,334	58,717	4,736,358	8,035,696	3068	136.8	
2026	31352	447	42,104	8,717,638	59,748	5,113,520	8,675,589	3121	139.2	
2027	33379	447	42,830	8,867,942	60,778	5,500,822	9,332,685	3175	141.6	
2028	35407	447	43,556	9,018,246	61,808	5,898,265	10,006,986	3229	144.0	
2029	37436	447	44,282	9,168,550	62,838	6,305,848	10,698,491	3283	146.4	
2030	39466	447	45,008	9,318,854	63,868	6723571	1,1407,199	3337	148.8	
2031	41497	447	45,734	9,469,158	64,898	7,151,435	12,133,112	3391	151.2	
2032						7,269,679	12,333,725	3447	153.7	
2033						7,383,194	12,526,314	3500	156.1	
2034						7,496,709	12,718,903	3554	158.5	
2035						7,610,224	12,911,493	3608	160.9	
2036						7,723,739	13,104,082	3662	163.3	
2037						7,837,254	13,296,671	3716	165.7	
2038						7,950,768	13,489,260	3770	168.1	
2039						8,064,283	13,681,849	3823	170.5	
2040						8,177,798	13,874,438	3877	172.9	

Table A2. *Cont.*

Year	SGMN		Construction & Installation			Service		Replacement	GDP	Discount Rate
	Nation Total	Plan	Manual	Automatic	RTU	Manual	Automatic			
2041						8,291,313	14,067,027	3931	175.3	5.0%
2042						8,404,828	14,259,616	3985	177.7	
2043						8,518,343	14,452,205	4039	180.1	
2044						8,631,857	14,644,794	4092	182.5	
2045						8,745,372	14,837,383	4146	184.9	
2046						8,858,887	15,029,972	4200	187.3	
2047						8,972,402	15,222,561	4254	189.7	
2048						9,085,917	15,415,150	4308	192.1	
2049						9,199,432	15,607,740	4362	194.5	
2050						9,312,946	15,800,329	4415	196.9	
2051						9,426,461	15,992,918	4469	199.3	
2052						9,539,976	16,185,507	4523	201.7	
2053						9,658,221	16,386,120	4579	204.2	
2054						9,771,736	16,578,709	4633	206.6	
2055						9,885,250	16,771,299	4687	209.0	
2056						9,998,765	16,963,888	4740	211.4	
2057						10,112,280	17,156,477	4794	213.8	
2058						10,225,795	17,349,066	4848	216.2	
2059						10,339,310	17,541,655	4902	218.6	
2060						10,452,825	17,734,244	4956	221.0	

Notes: (1) All of the above future values are converted into present ones by applying GDP deflators and discount rates of each year, (2) The future costs of service are estimated by a simple regression analysis based on data from 1995 through 2013, (3) Exchange rate: 1US$=1100 Korean Won.Source: Ministry of Land, Infrastructure and Transport [8]. Source: (1) Ministry of Land, Infrastructure and Transport [8], (2) National Information Center (www.gims.go.kr).

Table A3. Cost detail of the GMFA (unit: USD).

Year	GMFA	Construction		Installation	Service	Replacement		GDP Deflator	Discount Rate
		Plan	Cost			Device	Battery		
2011	84	13	520,392	9,967	387,474	59,784	1888	101.8	6.5%
2012	107	23	955,061	10,339	485,809	83,904	2650	105.6	
2013	212	105	4,469,768	10,574	1,219,556	418,795	13,225	108	
2014	318	105	4,569,096	10,809	1,927,294	450,984	14,242	110.4	
2015	423	105	4,668,425	11,044	2,703,688	452,995	14,305	112.8	
2016	528	105	4,767,753	11,279	3,548,998	458,653	14,484	115.2	
2017	633	105	4,867,081	11,514	4,463,469	480,396	15,170	117.6	
2018	739	105	4,966,409	11,749	5,447,333	490,200	15,480	120.0	
2019	844	105	5,065,737	11,984	6,539,296	516,917	16,324	122.4	
2020	949	105	5,165,066	12,219	7,669,532	552,921	17,461	124.8	
2021	1056	107	5,351,925	12,454	8,534,273	963,424	30,424	127.2	
2022	1056				8,534,273	529,416	16,718	129.6	
2023	1056				8,534,273	530,100	16,740	132.0	
2024	1056				8,534,273	535,095	16,898	134.4	
2025	1056				8,534,273	558,828	17,647	136.8	
2026	1056				8,534,273	568,632	17,957	139.2	
2027	1056				8,534,273	598,003	18,884	141.6	
2028	1056				8,534,273	637,985	20,147	144.0	
2029	1056				8,534,273	1,108,847	35,016	146.4	
2030	1056				8,534,273	607,848	19,195	148.8	
2031	1056				8,534,273	607,205	19,175	151.2	
2032	1056				8,534,273	611,936	19,324	153.7	
2033	1056				8,534,273	637,669	20,137	156.1	
2034	1056				8,534,273	647,473	20,447	158.5	
2035	1056				8,534,273	679,510	21,458	160.9	
2036	1056				8,534,273	723,493	22,847	163.3	
2037	1056				8,534,273	1,255,027	39,632	165.7	
2038	1056				8,534,273	686,689	21,685	168.1	
2039	1056				8,534,273	684,713	21,623	170.5	
2040	1056				8,534,273	688,378	21,738	172.9	

Table A3. *Cont.*

Year	GMFA	Construction		Installation	Service	Replacement		GDP Deflator	Discount Rate
		Plan	Cost			Device	Battery		
2041	1056				8,534,273	716,101	22,614	175.3	
2042	1056				8,534,273	725,905	22,923	177.7	
2043	1056				8,534,273	760,595	24,019	180.1	
2044	1056				8,534,273	808,558	25,533	182.5	
2045	1056				8,534,273	1,400,449	44,225	184.9	
2046	1056				8,534,273	765,121	24,162	187.3	
2047	1056				8,534,273	761,818	24,057	189.7	
2048	1056				8,534,273	764,820	24,152	192.1	
2049	1056				8,534,273	794,533	25,091	194.5	
2050	1056				8,534,273	790,733	24,971	196.9	5.0%
2051	1056				8,534,273	814,141	25,710	199.3	
2052	1056				8,534,273	893,623	28,220	201.7	
2053	1056				8,534,273	1,497,250	47,282	204.2	
2054	1056				8,534,273	751,179	23,721	206.6	
2055	1056				8,534,273	759,905	23,997	209.0	
2056	1056				8,534,273	768,631	24,273	211.4	
2057	1056				8,534,273	777,357	24,548	213.8	
2058	1056				8,534,273	786,084	24,824	216.2	
2059	1056				8,534,273	794,810	25,099	218.6	
2060	1056				8,534,273	803,536	25,375	221.0	

Note: (1) All of the above future values are converted into present ones by applying GDP deflators and discount rates of each year, (2) The future costs of service are estimated by a simple regression analysis based on data from 1995 through 2013, (3) Exchange rate: 1US$=1100 Korean Won, *). Source: (1) Ministry of Land, Infrastructure and Transport [8], (2) National Information Center (www.gims.go.kr).

Table A4. Cost detail of the SIMN (unit: USD).

Year	SIMN	Construction		Installation	Service	Replacement		GDP Deflator	Discount Rate
		Plan	Cost			Device	Battery		
2011	117	8	336,253	83,724	78,890	58,114	1835	101.8	
2012	127	10	415,244	103,392	608,905	66,120	2088	105.6	
2013	136	9	382,213	95,168	843,950	63,892	2018	108.0	
2014	168	32	1,367,473	340,489	1,122,504	151,123	4772	110.4	
2015	199	32	1,397,201	347,891	1,435,606	161,714	5107	112.8	
2016	231	32	1,426,928	355,293	1,784,823	191,122	6035	115.2	
2017	262	32	1,456,656	362,694	2,171,731	195,104	6161	117.6	
2018	294	32	1,486,384	370,096	2,597,902	199,085	6287	120.0	
2019	325	32	1,516,111	377,498	3,083,060	203,067	6413	122.4	
2020	357	32	1,545,839	384,900	3,595,645	207,049	6538	124.8	
2021	388	32	1,575,567	392,302	3,988,609	218,061	6886	127.2	
2022	388				4,063,866	76,670	2421	129.6	
2023	388				4,139,123	180,690	5706	132.0	
2024	388				4,214,379	192,681	6085	134.4	
2025	388				4,289,636	226,957	7167	136.8	6.5%
2026	388				4,364,893	230,939	7293	139.2	
2027	388				4,440,150	234,921	7419	141.6	
2028	388				4,515,406	238,903	7544	144.0	
2029	388				4,590,663	242,884	7670	146.4	
2030	388				4,665,920	255,091	8055	148.8	
2031	388				4,741,177	89,449	2825	151.2	
2032	388				4,819,569	210,394	6644	153.7	
2033	388				4,894,826	223,791	7067	156.1	
2034	388				4,970,083	262,959	8304	158.5	
2035	388				5,045,340	266,940	8430	160.9	
2036	388				5,120,596	270,922	8555	163.3	
2037	388				5,195,853	274,904	8681	165.7	
2038	388				5,271,110	278,886	8807	168.1	
2039	388				5,346,367	292,291	9230	170.5	
2040	388				5,421,623	102,286	3230	172.9	

Table A4. *Cont.*

Year	SIMN	Construction		Installation	Service	Replacement		GDP Deflator	Discount Rate
		Plan	Cost			Device	Battery		
2041	388				5,496,880	239,962	7578	175.3	
2042	388				5,572,137	254,757	8045	177.7	
2043	388				5,647,394	298,794	9436	180.1	
2044	388				5,722,651	302,776	9561	182.5	
2045	388				5,797,907	306,758	9687	184.9	
2046	388				5,873,164	310,739	9813	187.3	
2047	388				5,948,421	314,721	9939	189.7	
2048	388				6,023,678	329,321	10400	192.1	
2049	388				6,098,934	115,064	3634	194.5	
2050	388				6,174,191	269,529	8511	196.9	5.0%
2051	388				6,249,448	285,724	9023	199.3	
2052	388				6,324,705	278,016	8779	201.7	
2053	388				6,403,097	281,462	8888	204.2	
2054	388				6,478,354	284,770	8993	206.6	
2055	388				6,553,611	288,078	9097	209.0	
2056	388				6,628,868	291,386	9202	211.4	
2057	388				6,704,124	306,511	9679	213.8	
2058	388				6,779,381	67,219	2123	216.2	
2059	388				6,854,638	237,877	7512	218.6	
2060	388				6,929,895	240,488	7594	221.0	

Note: (1) All of the above future values are converted into present ones by applying GDP deflators and discount rates of each year, (2) The future costs of service are estimated by a simple regression analysis based on data from 1995 through 2013, (3) Exchange rate: 1US$ = 1100 Korean Won, *). Source: (1) Ministry of Land, Infrastructure and Transport [8], (2) National Information Center (www.gims.go.kr).

Table A5. Cost detail of the GQM (unit: USD).

Year	GQM			Construction		Service				Replacement	Water Sample		GDP Deflator	Discount Rate
	TOTAL	GQMN	GPMN	GQMN	GPMN	GQMN Labor	GQMN Travel	GPMN Labor	GPMN Travel		Fee	Labor		
2011	91	58	33	4,568,141	95,794	7872	14,348	498	907	2165	100,539	5328	101.8	
2012	111	72	39	5,882,476	117,437	10,137	18,476	610	1112	2788	128,860	6,741	105.6	
2013	273	139	134	11,581,125	412,364	19,958	36,374	2142	3905	5488	272,267	16,926	108.0	
2014	363	205	158	17,527,106	497,554	30,205	55,049	2585	4711	8306	399,081	23,064	110.4	
2015	454	272	182	23,737,872	585,406	40,908	74,556	3041	5543	11,249	531,427	29,453	112.8	
2016	540	305	235	27,148,520	773,278	46,786	85,269	4017	7322	12,866	618,421	35,777	115.2	
2017	626	337	289	30,680,234	968,459	52,872	96,361	5031	9170	14,539	708,568	42,339	117.6	
2018	712	370	342	34,333,014	1,170,949	59,167	107,834	6083	11,087	16,270	801,869	49,138	120.0	
2019	798	402	396	38,106,860	1,380,748	65,670	119,687	7173	13,074	18,059	898,323	56,175	122.4	
2020	884	435	449	42,001,772	1,597,856	72,383	131,920	8,301	15,130	19,904	997,932	63,449	124.8	
2021	1149	566	584	55,662,190	2,117,522	95,924	174,825	11,001	20,050	26,378	1,322,492	84,085	127.2	
2022	1415	696	719	69,807,614	2,655,638	120,301	219,253	13,797	25,145	33,081	1,658,576	105,453	129.6	
2023	1680	827	853	84,438,046	3,212,205	145,514	265,204	16,688	30,415	40,015	2,006,183	127,554	132.0	
2024	1946	957	988	99,553,485	3,787,222	171,563	312,679	19,676	35,860	47,178	2,365,313	150,387	134.4	
2025	2211	1088	1123	115,153,931	4,380,690	198,448	361,677	22,759	41,479	54,571	2,735,967	173,953	136.8	6.5%
2026	2463	1131	1331	121,848,218	5,283,957	209,984	382,703	27,452	50,032	57,743	2,961,519	197,147	139.2	
2027	2714	1175	1539	128,703,680	6,215,720	221,798	404,235	32,293	58,854	60,992	3,193,193	221,036	141.6	
2028	2966	1218	1748	135,720,316	7,175,980	233,890	426,273	37,281	67,947	64,317	3,430,989	245,619	144.0	
2029	3217	1262	1956	142,898,125	8,164,737	246,260	448,817	42,418	77,309	67,719	3,674,908	270,897	146.4	
2030	3469	1305	2164	150,237,109	9,181,992	258,907	471,867	47,703	86,941	71,196	3,924,950	296,869	148.8	
2031	3469	1305	2164			263,083	479,478	48,473	88,343	72,345	3,988,255	301,657	151.2	
2032	3469	1305	2164			267,433	487,406	49,274	89,804	73,541	4,054,199	306,645	153.7	
2033	3469	1305	2164			271,609	495,017	50,044	91,206	74,689	4,117,504	311,433	156.1	
2034	3469	1305	2164			275,785	502,627	50,813	92,608	75,838	4,180,810	316,222	158.5	
2035	3469	1305	2164			279,961	510,238	51,582	94,011	76,986	4,244,116	321,010	160.9	
2036	3469	1305	2164			284,137	517,849	52,352	95,413	78,134	4,307,421	325,798	163.3	
2037	3469	1305	2164			288,313	525,460	53,121	96,815	79,283	4,370,727	330,586	165.7	
2038	3469	1305	2164			292,489	533,070	53,891	98,217	80,431	4,434,033	335,374	168.1	
2039	3469	1305	2164			296,665	540,681	54,660	99,620	81,579	4,497,338	340,163	170.5	
2040	3469	1305	2164			300,841	548,292	55,429	101,022	82,728	4,560,644	344,951	172.9	

Table A5. *Cont.*

Year	GQM			Construction		Service				Replacement	Water Sample		GDP Deflator	Discount Rate
	TOTAL	GQMN	GPMN	GQMN	GPMN	GQMN Labor	GQMN Travel	GPMN Labor	GPMN Travel		Fee	Labor		
2041	3469	1305	2164			305,016	555,903	56,199	102,424	83,876	4,623,950	349,739	175.3	
2042	3469	1305	2164			309,192	563,513	56,968	103,827	85,024	4,687,255	354,527	177.7	
2043	3469	1305	2164			313,368	571,124	57,738	105,229	86,173	4,750,561	359,315	180.1	
2044	3469	1305	2164			317,544	578,735	58,507	106,631	87,321	4,813,866	364,104	182.5	
2045	3469	1305	2164			321,720	586,346	59,276	108,033	88,469	4,877,172	368,892	184.9	
2046	3469	1305	2164			325,896	593,956	60,046	109,436	89,618	4,940,478	373,680	187.3	
2047	3469	1305	2164			330,072	601,567	60,815	110,838	90,766	5,003,783	378,468	189.7	
2048	3469	1305	2164			334,248	609,178	61,585	112,240	91,914	5,067,089	383,256	192.1	
2049	3469	1305	2164			338,424	616,789	62,354	113,642	93,063	5,130,395	388,045	194.5	
2050	3469	1305	2164			342,600	624,399	63,124	115,045	94,211	5,193,700	392,833	196.9	5.0%
2051	3469	1305	2164			346,776	632,010	63,893	116,447	95,359	5,257,006	397,621	199.3	
2052	3469	1305	2164			350,952	639,621	64,662	117,849	96,508	5,320,312	402,409	201.7	
2053	3469	1305	2164			355,302	647,549	65,464	119,310	97,704	5,386,255	407,397	204.2	
2054	3469	1305	2164			359,477	655,160	66,233	120,712	98,852	5,449,561	412,185	206.6	
2055	3469	1305	2164			363,653	662,770	67,003	122,115	100,000	5,512,866	416,973	209.0	
2056	3469	1305	2164			367,829	670,381	67,772	123,517	101,149	5,576,172	421,762	211.4	
2057	3469	1305	2164			372,005	677,992	68,541	124,919	102,297	5,639,478	426,550	213.8	
2058	3469	1305	2164			376,181	685,603	69,311	126,321	103,445	5,702,783	431,338	216.2	
2059	3469	1305	2164			380,357	693,213	70,080	127,724	104,594	5,766,089	436,126	218.6	
2060	3469	1305	2164			384,533	700,824	70,850	129,126	105,742	5,829,394	440,915	221.0	

Notes: (1) All of the above future values are converted into present ones by applying GDP deflators and discount rates of each year, (2) The future costs of service are estimated by a simple regression analysis based on data from 1995 through 2013, (3) Exchange rate: 1US$ = 1100 Korean Won, *) Source: Ministry of Land, Infrastructure and Transport [8]. Source: (1) Ministry of Land, Infrastructure and Transport [8], (2) National Information Center (www.gims.go.kr).

Table A6. Cost detail of the LQMN (unit: USD).

Year	LQMN		Construction	Service		Replacement	Water Sample		GDP Deflator	Discount Rate
	Nation Total	Plan	Cost	Labor	Travel		Fee	Labor		
2011	2022		346,890	91,483	166,730	65,932	257,861	103,812	101.8	
2012	2142	120	359,839	100,506	183,175	72,435	283,295	114,052	105.6	
2013	2261	120	368,017	108,526	197,792	78,215	305,901	123,153	108.0	
2014	2381	120	376,196	116,801	212,874	84,179	329,226	132,543	110.4	
2015	2500	120	4,020,646	125,331	228,420	90,327	353,269	142,223	112.8	
2016	3750	1250	4,106,191	191,997	349,920	138,373	541,178	217,873	115.2	
2017	5000	1250	5,588,983	261,329	476,280	188,340	736,604	296,549	117.6	
2018	6667	1667	5,703,044	355,549	648,000	256,245	1,002,182	403,468	120.0	
2019	8333	1667	5,817,105	453,325	826,200	326,713	1,277,782	514,422	122.4	
2020	10,000	1667	7,117,398	554,657	1,010,880	399,743	1,563,404	629,410	124.8	
2021	12,000	2000	7,254,272	678,388	1,236,384	488,916	1,912,163	769,817	127.2	
2022	14,000	2000	7,391,145	806,385	1,469,664	581,165	2,272,948	915,066	129.6	
2023	16,000	2000	7,528,018	938,650	1,710,720	676,488	2,645,760	1,065,156	132.0	
2024	18,000	2000	7,664,891	1,075,180	1,959,552	774,886	3,030,598	1,220,088	134.4	
2025	20,000	2000	10,142,293	1,215,978	2,216,160	876,359	3,427,462	1,379,861	136.8	6.5%
2026	22,600	2600	10,320,228	1,398,161	2,548,195	1,007,659	3,940,980	1,586,598	139.2	
2027	25,200	2600	10,498,163	1,585,891	2,890,339	1,142,957	4,470,132	1,799,630	141.6	
2028	27,800	2600	10,676,098	1,779,168	3,242,592	1,282,252	5,014,918	2,018,955	144.0	
2029	30,400	2600	10,854,033	1,977,991	3,604,954	1,425,545	5,575,338	2,244,574	146.4	
2030	33,000	2600	11,031,968	2,182,360	3,977,424	1,572,834	6,151,392	2,476,488	148.8	
2031	33,000			2,217,560	4,041,576	1,598,203	6,250,608	2,516,431	151.2	
2032	33,000			2,254,226	4,108,401	1,624,628	6,353,958	2,558,039	153.7	
2033	33,000			2,289,425	4,172,553	1,649,996	6,453,174	2,597,982	156.1	
2034	33,000			2,324,624	4,236,705	1,675,365	6,552,390	2,637,926	158.5	
2035	33,000			2,359,824	4,300,857	1,700,733	6,651,606	2,677,869	160.9	
2036	33,000			2,395,023	4,365,009	1,726,101	6,750,822	2,717,812	163.3	
2037	33,000			2,430,222	4,429,161	1,751,469	6,850,038	2,757,756	165.7	
2038	33,000			2,465,422	4,493,313	1,776,838	6,949,254	2,797,699	168.1	
2039	33,000			2,500,621	4,557,465	1,802,206	7,048,470	2,837,642	170.5	
2040	33,000			2,535,821	4,621,617	1,827,574	7,147,686	2,877,586	172.9	

Table A6. *Cont.*

Year	LQMN		Construction	Service		Replacement	Water Sample		GDP Deflator	Discount Rate
	Nation Total	Plan	Cost	Labor	Travel		Fee	Labor		
2041	33,000			2,571,020	4,685,769	1,852,943	7,246,902	2,917,529	175.3	5.0%
2042	33,000			2,606,219	4,749,921	1,878,311	7,346,118	2,957,472	177.7	
2043	33,000			2,641,419	4,814,073	1,903,679	7,445,334	2,997,416	180.1	
2044	33,000			2,676,618	4,878,225	1,929,048	7,544,550	3,037,359	182.5	
2045	33,000			2,711,817	4,942,377	1,954,416	7,643,766	3,077,303	184.9	
2046	33,000			2,747,017	5,006,529	1,979,784	7,742,982	3,117,246	187.3	
2047	33,000			2,782,216	5,070,681	2,005,152	7,842,198	3,157,189	189.7	
2048	33,000			2,817,415	5,134,833	2,030,521	7,941,414	3,197,133	192.1	
2049	33,000			2,852,615	5,198,985	2,055,889	8,040,630	3,237,076	194.5	
2050	33,000			2,887,814	5,263,137	2,081,257	8,139,846	3,277,019	196.9	
2051	33,000			2,923,014	5,327,289	2,106,626	8,239,062	3,316,963	199.3	
2052	33,000			2,958,213	5,391,441	2,131,994	8,338,278	3,356,906	201.7	
2053	33,000			2,994,879	5,458,266	2,158,419	8,441,628	3,398,514	204.2	
2054	33,000			3,030,078	5,522,418	2,183,788	8,540,844	3,438,457	206.6	
2055	33,000			3,065,278	5,586,570	2,209,156	8,640,060	3,478,400	209.0	
2056	33,000			3,100,477	5,650,722	2,234,524	8,739,276	3,518,344	211.4	
2057	33,000			3,135,676	5,714,874	2,259,892	8,838,492	3,558,287	213.8	
2058	33,000			3,170,876	5,779,026	2,285,261	8,937,708	3,598,230	216.2	
2059	33,000			3,206,075	5,843,178	2,310,629	9,036,924	3,638,174	218.6	
2060	33,000			3,241,274	5,907,330	2,335,997	9,136,140	3,678,117	221.0	

Notes: (1) All of the above future values are converted into present ones by applying GDP deflators and discount rates of each year, (2) The future costs of service are estimated by a simple regression analysis based on data from 1995 through 2013, (3) Exchange rate: 1US$ = 1100 Korean Won, *). Source: (1) Ministry of Land, Infrastructure and Transport [8], (2) National Information Center (www.gims.go.kr).

Appendix B

Table A7. Projection of groundwater monitoring wells by type.

Year	NGMN	SGMN	GMFN	QMN	LQMN	SIMN
2010	335	1067	71	58	2022	136
2011	348	1067	84	91	2022	134
2012	414	1008	107	48	2123	143
2013	435	1069	79	52	2144	153
2014	455	1131	85	55	2166	162
2015	476	1193	91	59	2187	172
2016	496	1255	97	63	2209	181
2017	517	1317	102	67	2230	191
2018	530	1379	108	71	2251	200
2019	530	1441	114	74	2273	210
2020	530	1503	119	78	2294	219
2021	530	1564	125	82	2315	229
2022	530	1626	131	86	2337	238
2023	530	1688	136	90	2358	248
2024	530	1750	142	94	2380	257
2025	530	1812	148	97	2401	267
2026	530	1874	153	101	2422	276
2027	530	1936	159	105	2444	286
2028	530	1997	165	109	2465	295
2029	530	2059	170	113	2486	305
2030	530	2121	176	116	2508	314
2031	530	2183	182	120	2529	324
2032	530	2245	187	124	2550	333
2033	530	2307	193	128	2572	343
2034	530	2369	199	132	2593	352
2035	530	2431	205	135	2615	362
2036	530	2492	210	139	2636	371
2037	530	2554	216	143	2657	381
2038	530	2616	222	147	2679	388
2039	530	2678	227	151	2700	388
2040	530	2740	233	155	2721	388
2041	530	2802	239	158	2743	388
2042	530	2864	244	162	2764	388
2043	530	2925	250	166	2786	388

Table A7. *Cont.*

Year	NGMN	SGMN	GMFN	QMN	LQMN	SIMN
2044	530	2987	256	170	2807	388
2045	530	3049	261	174	2828	388
2046	530	3111	267	177	2850	388
2047	530	3173	273	181	2871	388
2048	530	3235	278	185	2892	388
2049	530	3297	284	189	2914	388
2050	530	3359	290	193	2935	388
2051	530	3420	295	196	2957	388
2052	530	3482	301	200	2978	388
2053	530	3544	307	204	2999	388
2054	530	3606	313	208	3021	388
2055	530	3668	318	212	3042	388
2056	530	3730	324	216	3063	388
2057	530	3792	330	219	3085	388
2058	530	3853	335	223	3106	388
2059	530	3915	341	227	3127	388
2060	530	3977	347	231	3149	388

Notes: The number of wells is estimated by a simple regression analysis based on data from 1995 through 2013. Source: (1) Ministry of Land, Infrastructure and Transport [8], (2) National Information Center (www.gims.go.kr).

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