
Allocating local groundwater monitoring stations for South Korea using an analytic hierarchy process

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Abstract A national groundwater-monitoring network consisting of 320 stations has been operated by the Ministry of Construction and Transportation and the Korea Water Resources Corporation since 1995. The network was established as a result of the Groundwater Act of Korea, and a supplementary local groundwater monitoring network containing 10,000 stations will be established throughout the country by the year 2011. A method of allocating stations and organizing the local monitoring network has been developed, based on the analytic hierarchy process (AHP), using pairwise comparison. Several evaluation criteria were selected for determining the required number of the monitoring stations at specific local districts. Weights of the selected criteria were assigned by the pairwise comparison, reflecting hydrogeological conditions and supported by pertinent questions to 93 groundwater experts. To evaluate appropriateness of this method, an example city, Jeonju, was selected where groundwater levels were monitored; seven stations were determined as to be required for the supplementary groundwater-monitoring network. The study demonstrated

the usefulness of the AHP. The concepts of the development and the structure of the AHP model can be applied to site or well selections within a particular district.

Résumé Un réseau national de surveillance des eaux souterraines comprenant 320 stations a été mis en place en Corée par le Ministère de la Construction et du Transport et la Corporation des Ressources en Eau de Corée depuis 1995. L'implémentation du réseau est le résultat du Décret Eaux Souterraines de Corée, et un réseau local supplémentaire de 10,000 stations sera installé sur tout le pays d'ici 2011. Une méthode de placement des stations et d'organisation du réseau local de surveillance a été développée sur base d'un processus de hiérarchie analytique (AHP en anglais) utilisant la comparaison par paire. Plusieurs critères d'évaluation ont été sélectionnés pour déterminer le nombre requis de stations de surveillance par districts locaux et spécifiques. Les poids des critères sélectionnés ont été déterminés par la comparaison par paire, reflétant les conditions hydrogéologiques et supportés par des questions pertinentes adressées à 93 experts en eau souterraine. Pour évaluer si cette méthode est appropriée ou non, l'exemple d'une ville où les niveaux des eaux souterraines sont surveillés, Jeonju, a été sélectionné; il a été déterminé que sept stations seraient nécessaires pour le réseau de surveillance supplémentaire. L'étude a démontré l'utilité de l'AHP. Les concepts du développement et de la structure du modèle AHP peuvent être appliqués pour la sélection de sites ou de puits à l'intérieur d'un district particulier.

Resumen El Ministerio de Construcción y transportes y la Corporación de Recursos hídricos de Corea han mantenido desde 1995 una red de control de aguas subterráneas nacional consistente en 320 puntos de agua. La red se estableció como resultado de la Ley de Aguas subterráneas de Corea y sobre el año 2011 se establecerá una red suplementaria local con 10,000 puntos de agua. El método para localizar los puntos de agua y organizar la red de control local se ha basado en los Procesos Analíticos Jerarquizados (AHP) usando comparaciones por pares. Se seleccionaron varios criterios de evaluación para determinar el número de puntos de agua monitorizados necesarios en distritos locales específicos. Los pesos de los criterios seleccionados se asignaron mediante comparaciones por pares, reflejando condiciones hidrogeológicas y sop-

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rtados por preguntas pertinentes a 93 expertos en aguas subterráneas. Para evaluar lo apropiado de este método se seleccionó una ciudad de ejemplo, Jeonju, en la que los niveles de agua subterránea fueron monitorizados; se determinó que se necesitaban siete puntos de agua para la red de control suplementaria. El estudio demostró la utilidad de AHP. Los conceptos del desarrollo y la estructura del modelo AHP puede ser aplicado para situar o seleccionar pozos dentro de un distrito particular.

Keywords Groundwater monitoring · Analytic hierarchy process · Kriging · Contamination · Pairwise comparison

Introduction

Groundwater levels and quality are regularly monitored at groundwater-monitoring stations throughout South Korea. Results of the groundwater monitoring are used to evaluate the spatial and temporal changes in the hydrology, and monitoring of climate and other hydrologic factors are used to sustain the quantity and quality of the groundwater resources in South Korea (Bender et al. 2001). The Ministry of Construction and Transportation (MOCT) and the Korea Water Resources Corporation (KOWACO) have organized and managed the national groundwater-monitoring network since 1995 (Lee et al. 2005).

The Korean national groundwater-monitoring network consists of 320 monitoring stations. Both a shallow monitoring well installed in alluvial deposits and a deep monitoring well installed in the bedrock aquifer are present at most monitoring stations. An integrated multi-sensor installed in each monitoring well automatically measures groundwater level, water temperature, and electrical conductivity four times per day. The hydrologic data are automatically transmitted to a host computer in the KOWACO through a modem or a wireless connection. In addition, a full suite of groundwater chemical analyses reflecting hydrochemical conditions are completed two times every year in all the national groundwater-monitoring wells (Lee et al. 2006).

Many countries have water-management and water-policy problems. These problems include multiple decision criteria related to water supply, water quality, and groundwater monitoring (Bella et al. 1996; Makowski et al. 1996; Ballesterio et al. 2002). Management of

Table 2 Prerequisites for the secondary evaluation criteria

Prerequisites	Explanation
Representative	Items that can show overall or general conditions of groundwater wells
Objectivity	Items that can exclude the subjectivity of the assessors
Convenience for data collection	Items that can be collected with equal quality
Simplicity	Items where the pre-treatment process or data manipulation is simple
Independency	Items that can avoid overlapping with other items

groundwater resources has been more poorly organized when compared to surface-water resources with respect to quantity and quality in South Korea. Although various authorities including MOCT, KOWACO, the Ministry of Environment (MOE), the Korea Agricultural & Rural Infrastructure Corporation (KARICO), and other governmental institutions have been performing groundwater resources management, a better designed and unified management plan is required.

The national groundwater-monitoring network may not fully represent the hydrologic conditions at a local basis. The geology of the country varies greatly by regions (Won et al. 2006). Consequently, the central government decided to implement a supplementary local groundwater-monitoring network reflecting hydrologic conditions of specific districts. The local monitoring network will provide essential information of local groundwater conditions along with the national groundwater-monitoring network. The objective of the local groundwater-monitoring network is to assist in maintaining groundwater resources by preventing groundwater declines resulting from overpumping and monitoring changes in groundwater quality on a local basis. The local network will contain 10,000 monitoring stations throughout the country. The monitoring network will be composed primarily of existing groundwater wells and a small numbers of newly installed wells. These 10,000 stations would not be equally distributed in 165 districts (cities and counties) throughout the country because each district has different groundwater use patterns, hydrogeology characteristics, amount of water use, and environmental and societal conditions. Therefore, a method for allocating the monitoring stations to specific administrative districts considering hydrogeologic, environmental, and societal factors for a specific district is needed.

In this study, a method for allocating supplementary local groundwater-monitoring stations in each administrative district was used. To establish the method reflecting the local hydrogeologic and environmental characteristics, a limited number of evaluation criteria were selected and organized into levels. Because relative importance of the evaluation criteria influencing the required number of monitoring stations would be different with each criterion, the analytic hierarchy process (AHP; Saaty 1992) was used. In the AHP, the pairwise comparison was conducted with the evaluation criteria for the purpose of determining the relative importance. The method used in this study

Table 1 Primary evaluation criteria and assigned objectives

Primary evaluation criteria	Assigned objectives
Degree of development and amount of groundwater use	To prevent groundwater overpumpage To secure the water resources
Necessity of monitoring whether groundwater is contaminated or not and the contamination is progressing	To understand situation of contamination To divide into contaminated zones and uncontaminated zones
Degree of dependency on groundwater for households	To guarantee water resources in the area not supplied by water service

Table 3 Secondary evaluation criteria and assigned objectives

Secondary criteria	Explanation	Assigned objectives
Number of groundwater wells	Number of the permitted and reported facilities including other groundwater facilities	To show the degree of groundwater development and use
Density of groundwater wells	Dividing the number of the permitted and reported facilities, including other groundwater facilities by area	To assign more weight in the urban areas than in mountainous (non-urban) areas
Amount of groundwater use	Total amount of groundwater used per year	To compensate for the increased use at 1 well that is, i.e., permitted as opposed to 10 other wells that are not
Number of wells used for drinking-water supply	Number of wells used for drinking-water supply except those wells considered incongruous	To classify uncontaminated areas
Number of contamination sources	Number of potential contamination sources from an annual statistics report	To assign more weight in areas that have the possibility of contamination
Number of contaminated wells	Number of the contaminated groundwater wells	To monitor groundwater contamination and the contamination process
Number of households using only groundwater	Rate of households not supplied by water service according to an annual statistics report	To guarantee water resources in areas not supplied by water service
Amount of groundwater used for drinking	Amount of groundwater used for drinking-water supply	To guarantee drinking-water resources

was applied to allocate monitoring wells to districts (every city and county) in South Korea. The city of Jeonju was selected as an example to demonstrate that the suggested number of the monitoring stations is appropriate and reasonable for maintaining the groundwater network. The same concept and method was applied to each “dong (an administrative unit)” belonging to Jeonju. For this study, the groundwater levels at the area of interest were estimated by kriging from the seven stations selected using the method. Differences between the estimated and the measured water levels were evaluated.

Because management of groundwater resources contains a unique set of features such as site-specific hydrogeologic and socio-environmental conditions not found in other AHP application areas (e.g., business, marketing, transportation), this study utilizes management and decision analysis for groundwater resources. The ultimate goal of this study is to allocate the required number of groundwater stations for the supplementary local groundwater-monitoring network throughout the country using the AHP.

Methodology

The AHP has been effective in structuring many types of complex multi-criterion problems (Jaber and Mohsen 2001) and has been successfully applied to many complex planning, resource allocation, and priority setting problems in business, energy, transportation, water policy, site selection, and suitability analysis (Banai-Kashani 1989; Bantayan and Bishop 1998; Ballesterio et al. 2002). Design of water resources systems is generally complex in nature as the design involves a large number of criteria that are tangible and intangible, as well as qualitative and quantitative (Raju and Pillai 1999). Decision-making involves preferential selection among competing alternatives. Often, such alternatives are difficult because of the complexity of the decision context. More applications of the AHP in natural resources and environmental sciences are appearing (Jandric and Srdjevic 2000; Hartman and Goltz 2002; Luria and Aspinall 2003) and a spatial decision support system for natural resource planning and management was

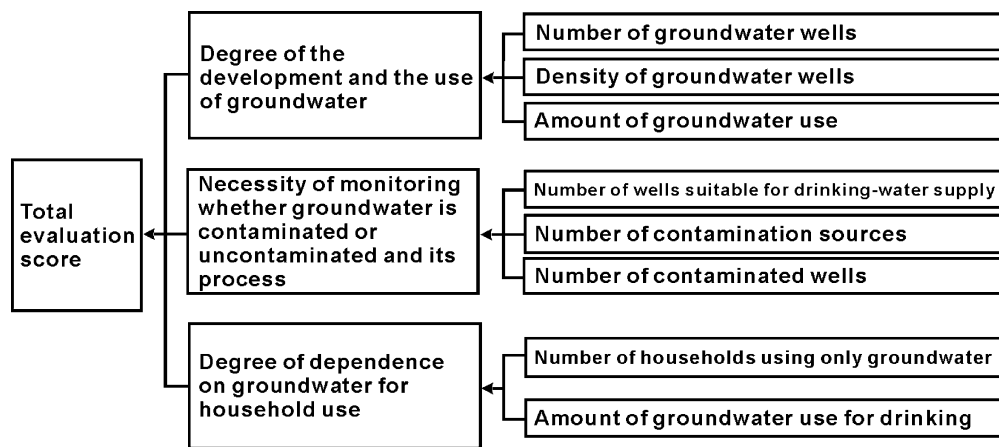
**Fig. 1** The evaluation structure of the primary and secondary criteria

Table 4 An example of a pairwise comparison process

Evaluation criteria	A	B	C	Geometric mean	Weights
A	1	V_{12}	V_{13}	$\sqrt[3]{(V_{13} \times V_{23} \times 1)} = GM_1$	$GM_1/SumGM$
B	$1/V_{12}$	1	V_{23}	$\sqrt[3]{(1/V_{12} \times 1 \times V_{23})} = GM_2$	$GM_2/SumGM$
C	$1/V_{13}$	$1/V_{23}$	1	$\sqrt[3]{(1/V_{12} \times 1/V_{23} \times 1)} = GM_3$	$GM_3/SumGM$
Sum				$GM_1 + GM_2 + GM_3 = SumGM$	

developed that uses a multiple attribute decision-making model (Marttunen and Hämäläinen 1995; Prato and Hajkowicz 1999; Ríos Insua et al. 2000).

The AHP is based on three main features (Forman 1990; Luria and Aspinall 2003):

1. A hierarchy that orders the evaluation criteria in structure
2. A comparison technique for determining the relative importance of each criterion
3. A judgment scale for the pairwise comparison phase determining the relative importance of each criterion

The process structures a problem from an overall objective to various primary criteria, secondary criteria (sub-criteria), and so on down to the lowest level (Saaty 2000). The objective or the overall goal of the decision is represented at the top level of the hierarchy. The primary and the secondary criteria contributing to the decision are represented at the lower levels. Finally, the decision alternatives or evaluation items are at the last level of the hierarchy. Once these hierarchies of relevant factors or criteria have been established, a pairwise comparison matrix of each criterion within each level is constructed (Jaber and Mohsen 2001). Each criterion can be weighted against other criterion within the same level. Each level is related to the levels above and below it and the entire scheme is tied together mathematically (Saaty 1983). The method applied in this study is based on the AHP. The AHP generally includes several evaluating criteria. Each criterion was structured into three levels in this study: the goal to be achieved, the primary criteria, and the secondary criteria.

Primary evaluation criteria

Proper evaluating criteria contributing to the decision consist of primary and secondary criterion. These criteria were identified from an extensive literature review (MOCT and KOWACO 2002; MAF and KARICO 2003) and from responses to a questionnaire sent to groundwater experts during the study period. The primary criteria usually are represented by the main goal (Luria and Aspinall 2003). Therefore, the criteria were carefully selected considering the purposes of the supplementary local groundwater-monitoring network, where water-level and quality changes are regularly monitored to protect groundwater resources from overpumpage and potential contamination. Primary evaluation criteria selected in this study were (1) the degree of the groundwater development and amount of the groundwater use, (2) the administrative necessity for

monitoring whether groundwater contamination is present or not present, and (3) the degree of dependency on groundwater for household use (Table 1).

The change of groundwater levels may occur due to increasing groundwater use. Increasing groundwater use may cause unregulated groundwater pumping that lowers groundwater levels. Basically, the administrative district, where there is substantial groundwater use, defines the need for groundwater-monitoring stations. Groundwater is very important as a secondary source in South Korea. Therefore, it is necessary to define and delineate the extent of groundwater contamination and to divide the area of interest into contaminated and clean zones. Also, an area where groundwater is used for drinking should be designated as the groundwater conservation area according to the Groundwater Act. These areas require much intensive monitoring for protection from contamination.

Water service is not available for all South Korean residents. Residents without water service may secure their household water from groundwater or surface-water sources. In this study, groundwater is considered to be a unique water source for household uses in areas where water service is not available. In areas without water service, where residents drink groundwater, the number of monitoring stations should be increased.

Secondary evaluation criteria

There are various kinds of secondary evaluation criteria reflecting the hydrogeologic, environmental, and societal conditions for certain districts. Many reports issued from MOCT, KOWACO, MOE, and KARICO were collected and reviewed to find items applicable to the secondary evaluation criteria and, consequently, 31 items were selected. It appeared not to be feasible to use all the 31 items as the secondary criteria in the evaluation. Even though the literature survey reveals that there are a large number of secondary criteria affecting the evaluation, empirical evidence indicates that not every criterion improves the usefulness and applicability of the AHP

Table 5 Fundamental judgment scale for pairwise comparisons (adapted from Hafeez et al. 2002)

Relative importance between two criteria	Intensity of relative importance
Equal importance or indifference	1
Weak importance	3
Strong importance	5
Demonstrated importance	7
Absolute importance	9
Intermediate values	2, 4, 6, 8

Table 6 List of symbols F_{ij}

Symbol	Explanation
F_i	The i th primary evaluation criterion
F_1	Degree of groundwater development and groundwater use
F_2	Necessity of monitoring whether groundwater is contaminated or uncontaminated and the progress of any contamination
F_3	Degree of dependency on groundwater for household use
F_{ij}	The j th secondary evaluation criterion constituting the i th primary evaluation criterion
F_{11}	Number of groundwater wells
F_{12}	Density of groundwater wells
F_{13}	Amount of groundwater use
F_{21}	Number of wells suitable for drinking-water supply
F_{22}	Number of contamination sources
F_{23}	Number of contaminated wells
F_{31}	Number of households using only groundwater
F_{32}	Amount of groundwater use for drinking-water supply
FW_i	Weight of the i th primary criterion
FW_{ij}	Weight of the j th secondary criterion of the i th primary criterion
SF_{ij}	Total score of the j th secondary criterion of the i th primary criterion
MF_{ij}	Mean value of SF_{ij}
IV_{ij}	Relative importance between F_i and F_j
IV_{ik}	Relative importance between F_{ij} and F_{ik}
X_{ij}^k	Property of F_{ij} at the estimation district k city or county
x_{ij}^k	Standard value of F_{ij} at the estimation district (k ; city or county)
TS_k	Total evaluation score at the evaluation district (k ; city or county)

model (Atthirawang and MacCarthy 2001). In order to improve the usefulness and applicability, prerequisites extracting proper secondary criteria from the collection of 31 items were used (Table 2). Based on the prerequisites, eight items were selected as the secondary evaluation criteria: (1) number of groundwater wells, (2) density of groundwater wells, (3) amount of groundwater use, (4) number of wells suitable for drinking-water supply, (5) number of contamination sources, (6) number of wells with contaminated water, (7) number of households using only groundwater as their water source, and (8) amount of groundwater use for drinking-water supply.

The secondary evaluation criteria for each objective are explained in Table 3. After detailed examination of the primary and the secondary evaluation criteria, the secondary criteria were grouped into one of the categories of the primary evaluation criteria that are closely related. Thus, the evaluation structure was organized as shown in Fig. 1.

Determination of the weights of evaluation criteria

Because the relative importance of the evaluation criteria determining the optimal number of the monitoring stations is different with each criterion, the AHP was used. The AHP was developed to solve a specific kind of problems that involves the relative importance of evaluation criteria. This solution is achieved by evaluating a set of the relevant criteria and sub-evaluation criteria through a series of pairwise comparisons (Jandric and Srdjevic 2000; Srdjevic et al. 2000). There are many different methods of pairwise comparison. The distribution method is one of the most commonly used. This method allows the decision maker to derive geometric means as weights (Luria and Aspinall 2003). An example pairwise comparison process is presented in Table 4. The geometric mean is an appropriate measure for combining individual judgments to obtain the group judgment for each pairwise comparison. In order to conduct the pairwise comparison, the relative importance associated with the comparative judgments should be numerically determined according to the relative importance between two evaluation criteria (Table 5).

The relative importance of the criteria in this study was decided by consulting many experienced experts in groundwater hydrology to enhance the reliability of the subjective judgments. Several relevant questions in a questionnaire were asked of 93 university professors and researchers of groundwater science from various institutes who attended the 2002 Fall Meeting of the Korea Society of Soil and Groundwater Environment. Prior to dissemination of the questionnaire, the background and objectives of the supplementary local groundwater-monitoring network were explained to the experts. For the primary evaluating criteria, the questions, "Between two criteria, which is the more important one?" and "How much more important?" were asked with respect to the three already selected primary criteria. Because experts are not readily able to express absolute judgment, the judgment was derived from the index of the judgment scale in Table 5. In addition, for the secondary evaluation criteria, the question, "What is the score of the criterion according to relative importance?" was also asked with respect to the eight already selected secondary criteria. In this way, the analyst of the questionnaire did not need to have an overview of all the criteria and adjust all the judgments at the end of the method. Responses to the questions were used to decide the relative importance of the criteria.

Table 7 Weights of F_i and F_{ij} through SF_{ij} and MF_{ij}

F_i	Weights (FW_i)	F_{ij}	No. of experts answering questionnaire	Total score (SF_{ij})	Mean of total score (MF_{ij})	Weights (FW_{ij})
F_1	0.38	F_{11}	92	785	8.53	0.46
		F_{12}	92	752	8.17	0.36
		F_{13}	92	657	7.14	0.18
F_2	0.34	F_{21}	93	674	7.25	0.16
		F_{22}	93	771	8.29	0.30
		F_{23}	93	862	9.27	0.54
F_3	0.28	F_{31}	93	779	8.38	0.66
		F_{32}	93	692	7.44	0.34

Table 8 Calculation of weights for each secondary criterion

F_{ij}	F_{11}	F_{12}	F_{13}	Geometric mean	Weights
F_{11}	1	1.36	2.39	1.48	0.46
F_{12}	1/1.36	1	2.03	1.14	0.36
F_{13}	1/2.39	1/2.03	1	0.59	0.18
Sum				3.21	1.00
F_{ij}	F_{21}	F_{22}	F_{23}	Geometric mean	Weights
F_{21}	1	1/2.04	1/3.02	0.56	0.16
F_{22}	2.04	1	1/1.98	1.01	0.30
F_{23}	3.02	1.98	1	1.81	0.54
Sum				3.38	1.00
F_{ij}	F_{31}	F_{32}	—	Geometric mean	Weights
F_{31}	1	1.94	—	1.39	0.66
F_{32}	1/1.94	1	—	0.72	0.34
Sum				2.11	1.00

Establishing the evaluation method

Weights of the secondary evaluation criteria

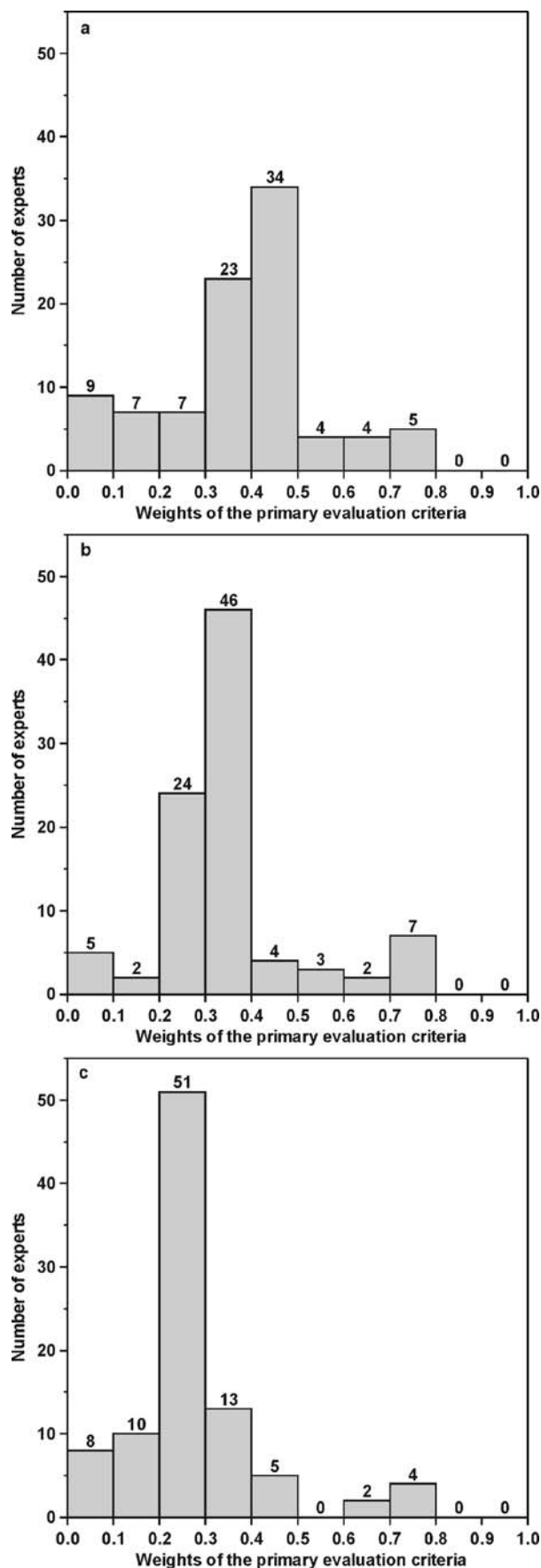
As previously described, a question, “How much F_{ij} (the j th secondary criterion of the i th primary criterion) is important?” was asked of 93 experts (see Table 6 for the abbreviations and symbols used in this section). One expert inadvertently omitted the answer for F_{ij} with 10 full marks (Table 7). Assuming that each F_{ij} is independent, the score of each criterion obtained from the 92 experts can be added. The SF_{ij} (total score of the j th secondary criterion of the i th primary criterion) is presented in Table 7. In addition, the MF_{ij} (mean of the total score) can be calculated from SF_{ij} . Prior to the pairwise comparison, IV_{jk}^i (relative importance between F_{ij} and F_{ik}) should be calculated as follows: between F_{ij} and F_{ik} , if $MF_{ij} - MF_{ik} > 0$, then $IV_{jk}^i = MF_{ij} - MF_{ik} + 1$. F_{ij} is more important than F_{ik} as much as IV_{jk}^i , and if $MF_{ij} - MF_{ik} < 0$, then $IV_{jk}^i = 1 / (MF_{ij} - MF_{ik} + 1)$. Therefore, F_{ij} is less important than F_{ik} , as much as $1 / (MF_{ij} - MF_{ik} + 1)$, where $i, j, k = 1, 2, 3$, respectively.

Based on the above discussion, the pairwise-comparison matrix for these secondary criteria with their relative importance can be constructed. Then, FW_{ij} (weight of the j th secondary criterion of the i th primary criterion) can be calculated as shown in Table 8. The results of FW_{ij} are also presented in Table 7. It can be seen that the “number of groundwater wells (F_{11})” is the most important criterion because it has the highest weights (0.46) among the three secondary criteria. These criteria consist of “the number of groundwater wells (F_{11})”, “density of groundwater wells (F_{12})”, and the “amount of groundwater use (F_{13})” grouped into “degree of the development and use of the groundwater (F_1)”. The “number of contaminated wells (F_{23})” and “number of households using only groundwater (F_{31})” ranked first in each primary criterion (F_2, F_3).

Weights of primary evaluation criteria

As previously described, two questions, “Which do you feel is more important between the two criteria (factors)?”

Fig. 2 Distribution of the primary criteria weights from 93 groundwater experts. **a** Distribution of FW_1 (weights of F_1), **b** distribution of FW_2 (weights of F_2), and **c** distribution of FW_3 (weights of F_3)



and “To what degree?” were asked of the 93 groundwater experts. Their answers can be applied directly to determine the relative importance (IV_{ij}) between F_i and F_j . Unlike the secondary evaluation criteria, the weights of the primary criteria can be calculated without the calculation of IV_{ij} from every answer obtained from the questionnaire. Distribution of the 93 weights of the primary criteria obtained is shown in Fig. 2. The distributed weights in the figure were taken as an average to obtain a single weight of the primary criteria (FW_i ; Table 7). Consequently, the F_1 will have the most effect (weight 0.38) on the optimal number of monitoring wells, whereas the F_3 will have the least effect (weight 0.28).

Evaluating consistency of judgment

Central to the AHP is the method of pairwise comparisons and the consistency index (CI) and consistency ratio (CR) are a means in the AHP of measuring consistency of judgment (Golden and Wang 1989; Donnegan and Dodd 1991; Robins 1997). Consistency ratios were calculated to measure appropriateness of the relative weights for the secondary evaluation factors used in this study. As a general rule, a CR of 0.10 or less is considered acceptable. The CI and CR are calculated using weighted sum vector ($= \sum (IV_{jk}^i \cdot FW_{ij})$) and consistency vector ($= \text{weighted sum vector} / FW_{ij}$). Table 9 shows consistency evaluation results of the relative weights. The consistency ratios of 0.002 and 0.008 for the F_1 and F_2 , respectively, indicated that the levels of consistency were acceptable. In addition, for F_3 , the levels of consistency were also considered acceptable based on only two secondary evaluation factors.

Allocating the number of the monitoring stations

To allocate the number of the monitoring stations for the 165 districts (counties or cities) throughout South Korea, the total evaluation score for each district should be calculated. The number of the monitoring stations in the district is in proportion to the total evaluation score for each district. Multi-criterion evaluation was used to combine a set of criteria to form the total evaluation score. Criteria were combined in weighted linear combination by applying

a weight to each one. With a weighted linear combination, and a summation of the results to yield, the total evaluation score was determined (Eastman et al. 1995).

The standardized values (x_{ij}^k) from the property of secondary criterion (X_{ij}^k) are multiplied by the weights (FW_{ij}) of the criterion, and then are added in one level. The added values are multiplied by weights of their primary criterion in the level above. Consequently, the total score is the summation in each primary criterion determined by using the weighted summation. The total score of the evaluation district k (TS_k) can be calculated as follows:

$$TS_k = \sum_i^{N_1} \left[FW_i \cdot \sum_j^{N_{1j}} (FW_{ij} \cdot x_{ij}^k) \right] \quad (1)$$

where

- FW_i Weight of the i th primary criterion
- FW_{ij} Weight of the j th secondary criterion for the i th primary criterion
- x_{ij}^k standard value of F_{ij} (the j th secondary criterion for the i th primary criterion) or F_i (the i th primary criterion) at the evaluation district k
- N_1 Number of primary evaluation criteria (=1, 2, 3),
- N_{1j} Number of the j th secondary evaluation criterion F_{ij} for F_i , $i, j=1, 2, 3$ (if $i=3$, then $j=1, 2$), $k=1, 2, 3, \dots, 165$.

The standard value (x_{ij}^k) of the j th secondary evaluation criterion F_{ij} for the i th primary evaluation criterion F_i at the evaluation district k is standardized using the property (X_{ij}^k) of the j th secondary evaluation criterion F_{ij} for the i th primary criterion F_i . To standardize X_{ij}^k , the mean ($\bar{X}_{ij}^k$) and standard deviation (σ) of are taken with respect to all the 165 districts. The standard value (X_{ij}^k) can be calculated as follows:

$$x_{ij}^k = \frac{X_{ij}^k}{\sigma}, \quad (2)$$

$$\text{where } \sigma = \sqrt{\frac{\sum (X_{ij}^k - \bar{X}_{ij}^k)^2}{N}}$$

N number of the evaluation districts (=165).

Table 9 Consistency ratios for the evaluation factors

Factor	Weight	Weighted vector				Weighted sum vector	Consistency vector	λ^a	CI ^b	CR ^c
F_{11}	0.46	0.460	0.490	0.430	1.380	3.000	3.003	0.001	0.002	
F_{12}	0.36	0.338	0.360	0.365	1.064	2.955				
F_{13}	0.18	0.192	0.177	0.180	0.550	3.054				
F_{21}	0.16	0.160	0.147	0.179	0.486	3.037	3.010	0.005	0.008	
F_{22}	0.30	0.326	0.300	0.273	0.899	2.997				
F_{23}	0.54	0.483	0.594	0.540	1.617	2.995				
F_{31}	0.66	0.660	0.660	–	1.320	1.999	2.000	0.000	0.000	
F_{32}	0.34	0.340	0.340	–	0.680	2.001				

^a Mean of consistency vector

^b Consistency index ($CI = \lambda - n/n - 1$, n = number of evaluation factors)

^c Consistency ratio ($CR = CI/RI$, RI = random index, 0.58 when matrix size is 3)

Table 10 The results from the properties of F_{ij} at each city or county/district

No. District (k)		X_{11} (each)	X_{12} (each/km ²)	X_{13} (m ³ /yr)	X_{21} (each)	X_{22} (each)	X_{23} (each)	X_{31} (%)	X_{32} (m ³ /yr)	Total score (TS _k)	Calculated number of stations
1	Seoul	14,957	41.22	37,403,019	4	6,954	322	0.0	71	2.954210	239
2	Incheon	4,309	5.20	25,306,979	0	2,518	192	3.8	1,713,934	1.227970	99
3	Gapyeong	446	0.58	11,291,486	9	96	0	40.2	4,371,950	0.472261	38
4	Goyang	4,238	16.61	17,456,316	0	643	3	4.8	0	0.471043	38
5	Gwacheon	196	5.47	143,865	0	31	0	3.0	0	0.094272	8
6	Gwangmeong	1,642	47.35	2,562,059	0	153	0	1.0	0	0.613546	50
7	Gwangju	5,545	12.93	11,934,171	0	309	0	28.9	0	0.576781	47
8	Guri	153	12.23	724,518	1	128	23	1.3	0	0.240619	19
9	Gunpo	646	18.29	1,127,720	0	222	0	0.5	172,000	0.268381	22
10	Kimpo	1,064	3.85	2,688,254	0	324	0	36.5	0	0.397278	32
11	Namyangju	56	0.12	26,280	0	348	0	20.5	0	0.209499	17
12	Dongducheon	2,057	22.05	8,584,374	0	154	1	9.0	116,800	0.412382	33
13	Bucheon	1,903	45.21	17,641,822	0	899	1	0.3	0	0.729455	59
14	Seongnam	507	4.09	3,723,901	0	430	0	0.3	1,600	0.134552	11
15	Suwon	989	9.31	10,696,436	0	834	0	1.5	12,000	0.287719	23
16	Siheung	2,529	19.85	9,441,379	0	198	9	6.6	0	0.410927	33
17	Ansan	860	6.91	5,647,511	0	320	25	1.4	0	0.241035	20
18	Anseong	2,890	5.30	20,823,662	3	301	1	44.6	1,292,000	0.583182	47
19	Anyang	568	43.37	8,320,896	0	408	3	0.5	0	0.590510	48
20	Yangju	2,666	8.71	8,089,275	0	467	0	39.4	0	0.546976	44
21	Yangpyeong	12,819	14.68	47,904,917	0	99	5	70.9	298,111	1.140727	92
22	Yeoju	8,200	13.76	32,618,923	0	186	1	58.8	291,456	0.896209	73
23	Yeoncheon	601	0.87	5,245,600	0	145	0	13.5	0	0.155424	13
24	Osan	1,305	30.89	2,119,199	0	133	4	6.2	0	0.465112	38
25	Yongin	1,288	2.35	9,625,305	0	713	4	20.0	51,100	0.346746	28
26	Uijeongbu	1,838	34.86	9,984,545	0	98	0	7.0	25,200	0.523298	42
27	Uiwang	1,466	22.94	5,438,500	0	273	0	5.8	0	0.391545	32
28	Icheon	2,608	5.70	26,654,014	1	221	4	45.6	430,050	0.564387	46
29	Paju	9,114	13.38	22,676,179	0	426	0	39.3	0	0.789246	64

30	Pyeongtaek	4,935	11.06	23,273,103	7	523	0	20.4	1,029,307	0.562277	45
31	Pocheon	641	0.78	12,838,705	0	639	0	55.8	0	0.555076	45
32	Hanam	2,547	28.52	10,917,785	0	102	25	16.5	26,650	0.615616	50
33	Hwaseong	8,527	12.43	42,197,907	22	551	0	63.8	21,240	1.029257	83
34	Gangneung	6,013	5.86	17,099,608	2	299	0	13.3	341,020	0.411658	33
35	Goseong	1,349	2.06	6,438,926	6	67	0	16.2	650,000	0.226828	18
36	Donghae	580	3.60	4,502,922	0	154	2	4.6	1,212,000	0.156508	13
37	Samcheok	2,167	2.05	3,644,105	0	116	0	22.3	0	0.271068	22
38	Sokcho	335	3.33	383,910	0	113	38	2.0	0	0.189141	15
39	Yanggu	2,716	3.88	2,422,068	0	39	0	41.6	3,650	0.436319	35
40	Yangyang	870	1.40	7,034,041	0	56	0	35.0	0	0.315948	26
41	Yeongwol	329	0.29	1,660,790	0	51	0	35.2	37,800	0.283840	23
42	Wonju	6,266	7.46	33,771,651	23	335	58	17.9	497,050	0.707362	57
43	Injae	1,971	1.23	774,168	2	71	4	28.4	180	0.306478	25
44	Jeongseon	402	0.35	4,079,831	1	92	0	24.8	37,230	0.220754	18
45	Cheolwon	1,044	1.16	9,458,180	0	64	2	29.9	1,108,135	0.318158	26
46	Chuncheon	6,337	5.69	1,612,674	0	269	0	14.1	0	0.389573	32
47	Taeback	526	1.77	301,896	0	108	0	2.0	0	0.066817	5
48	Peongchang	388	0.27	1,095,289	1	70	0	42.3	35,249	0.341947	28
49	Hongcheon	4,144	2.31	7,402,979	0	106	0	40.6	0	0.467359	38
50	Hwacheon	1,509	1.69	5,151,775	0	42	0	54.6	94,900	0.480095	39
51	Hoengseong	5,523	5.57	6,728,093	0	71	0	59.7	130,170	0.680898	55
52	Daegu	4,460	5.83	45,923,644	0	2,016	75	1.0	191,600	0.788836	64
53	Daejeon	21,553	42.67	39,848,329	179	1,347	81	6.1	715,339	1.986313	161
54	Gongju	17,411	17.42	40,689,346	0	34	0	52.0	0	1.114068	90
55	Geumsan	10,428	18.17	21,828,106	0	24	0	60.0	1,089,525	0.992440	80
56	Nonsan	25,738	42.18	29,239,376	12	291	2	46.0	280,946	1.649876	133
57	Dangjin	15,626	24.05	15,980,884	252	114	3	100.0	4,030,399	2.068033	167

58	Boryeong	6,544	11.58	18,706,958	3	250	0	49.0	610,850	0.757977	61
59	Buyeo	21,183	34.21	27,843,009	0	139	0	57.0	476,987	1.464553	118
60	Seosan	22,409	30.52	37,643,386	4	153	1	53.0	784,181	1.459584	118
61	Seocheon	13,874	39.86	23,578,093	13	117	0	63.0	1,256,895	1.405196	114
62	Asan	4,944	9.64	41,823,719	43	343	2	50.0	3,150,109	0.888163	72
63	Yeongi	9,303	25.77	48,370,061	0	178	0	52.0	492,905	1.031103	83
64	Yeasan	10,773	21.42	23,097,080	0	144	1	61.0	48,545	1.046886	85
65	Cheonan	15,353	24.97	42,209,647	119	443	19	25.0	1,132,980	1.329098	108
66	Cheongyang	6,952	14.71	12,693,746	7	78	4	21.0	768,415	0.586578	47
67	Taeon	9,873	20.60	30,938,118	10	50	2	50.0	65,000	0.948153	77
68	Hongseong	20,935	36.93	6,744,090	0	93	11	58.0	185,635	1.488292	120
69	Goesan	10,775	12.90	22,926,681	13	75	0	72.8	1,388,101	1.083453	88
70	Danyang	1,597	2.18	1,701,672	10	53	0	37.3	259,230	0.381505	31
71	Boeun	10,906	18.86	18,021,518	21	92	0	65.3	563,486	1.090599	88
72	Yeongdong	6,946	8.31	10,137,461	13	103	1	39.1	2,230,095	0.689218	56
73	Okcheon	10,945	20.69	17,026,815	0	144	22	42.9	2,078,574	1.013945	82
74	Eumseong	12,720	24.45	33,127,134	11	415	0	54.9	2,158,550	1.216266	98
75	Jecheon	10,181	12.01	20,211,650	3	194	30	25.9	1,389,995	0.792168	64
76	Jincheon	9,228	23.11	26,684,520	45	223	5	52.3	4,825,309	1.194753	97
77	Cheongwon	24,353	20.12	35,955,950	25	307	0	60.5	1,479,168	1.530207	124
78	Cheongju	10,678	76.22	14,853,981	0	527	25	5.2	370,221	1.376366	111
79	Chungju	15,219	15.57	50,283,367	8	288	21	25.8	1,832,279	1.016818	82
80	Gyeongsan	1,789	4.43	32,274,776	0	445	0	14.8	0	0.316805	26
81	Gyeongju	1,498	1.24	36,411,425	14	435	0	32.8	36,607,653	1.358491	110
82	Goryeong	2,181	5.79	26,861,784	3	150	24	60.4	2,771,730	0.772368	62
83	Gumi	1,766	3.05	10,973,302	0	542	11	10.0	401,400	0.297451	24
84	Gunwi	2,074	3.43	31,128,482	0	48	0	57.8	0	0.567760	46
85	Gimcheon	11,324	16.46	15,509,684	0	188	16	37.7	0	0.873996	71
86	Mungyeong	5,512	6.07	6,425,591	0	122	7	20.7	16,410	0.422619	34
87	Bonghwa	4,208	3.52	5,076,216	0	35	0	65.5	4,037,271	0.754795	61
88	Sangju	5,813	4.65	12,768,473	0	101	6	46.3	2,322,875	0.663629	54
89	Soengju	4,699	7.63	36,718,305	0	131	0	77.6	466,690	0.866182	70

90	Andong	6,604	4.36	14,014,594	0	200	0	29.2	0	0.497274	40
91	Yeongdeok	483	0.69	5,872,924	1	129	2	19.8	1,995,859	0.252817	20
92	Yeongyang	481	0.68	3,527,404	0	24	0	58.2	1,623,607	0.500488	40
93	Yeongju	3,800	5.71	6,001,214	1	154	0	25.3	46,545	0.391979	32
94	Yeongcheon	1,766	1.92	23,113,021	7	266	0	39.0	893,750	0.464363	38
95	Yecheon	6,301	9.54	4,970,005	0	65	0	60.9	120,450	0.752963	61
96	Ulleung	9	0.12	9,800	0	8	0	23.3	0	0.175317	14
97	Ulsan	1,586	1.61	28,206,432	0	119	0	43.7	10,950	0.437383	35
98	Uiseong	2,425	2.07	15,399,297	12	98	13	56.1	419,240	0.610670	49
99	Cheongdo	347	1.63	17,558,266	16	51	0	69.1	43,800	0.600036	49
100	Cheongsong	1,090	1.31	3,221,650	0	33	1	62.5	0	0.519443	42
101	Chilgok	3,772	8.37	35,523,492	1	264	0	34.7	3,406,423	0.626727	51
102	Pohang	1,046	1.16	22,825,194	0	700	72	13.7	6,249,964	0.644628	52
103	Busan	8,324	12.91	56,445,446	5	2,911	670	1.9	932,355	2.874294	233
104	Ulsan	2,769	2.97	19,858,281	10	877	55	13.6	146,000	0.553838	45
105	Gwangju	7,540	15.04	21,701,556	10	1,040	70	5.0	300,000	0.834098	67
106	Gangjin	6,484	13.13	14,831,972	0	48	0	63.0	62,655	0.821369	66
107	Goheung	13,357	17.38	56,639,820	8	140	0	66.0	3,244,731	1.241920	100
108	Gokseong	9,820	17.98	16,418,432	7	89	0	67.0	37,636	1.020018	83
109	Gwangyang	2,055	4.71	23,720,733	0	135	1	19.0	1,724,260	0.345969	28
110	Gurye	2,252	5.12	9,980,946	2	36	0	54.0	64,378	0.542874	44
111	Naju	12,099	20.13	12,354,926	1	190	0	56.0	586,226	1.039797	84
112	Damyang	10,710	23.66	15,614,612	4	114	0	71.0	49,056	1.135833	92
113	Mokpo	610	15.58	3,089,882	0	300	0	1.0	0	0.250695	20
114	Muan	7,566	17.54	19,505,501	0	162	0	74.0	72,220	1.006223	81
115	Boseong	10,733	16.72	23,126,964	3	86	0	64.0	54,750	1.009010	82
116	Suncheon	12,738	14.16	30,635,267	6	334	4	19.0	0	0.767019	62
117	Sinan	1,845	2.82	8,332,310	2	27	1	64.0	745,007	0.596293	48

118	Yeosu	6,643	13.60	18,360,798	1	360	0	20.0	247,670	0.572757	46
119	Yeongkwang	12,759	26.98	70,882,130	0	90	0	58.0	0	1.185393	96
120	Yeongam	8,314	16.13	18,266,543	0	91	0	71.0	171,258	0.978901	79
121	Wando	4,519	11.54	14,155,056	2	32	0	70.0	445,110	0.810592	66
122	Jangseong	12,563	24.30	14,594,143	0	67	0	76.0	2,592	1.214187	98
123	Jangheung	5,894	9.77	20,247,735	0	62	0	70.0	882,885	0.847923	69
124	Jindo	1,275	3.09	1,407,009	31	50	0	66.0	347,605	0.637580	52
125	Hampyeong	10,549	26.97	27,921,741	7	64	0	68.0	444,102	1.168603	95
126	Haenam	17,521	19.05	51,595,707	1	90	0	69.0	35,040	1.291009	104
127	Hwasun	4,626	6.13	26,881,108	0	66	0	60.0	2,912,205	0.756983	61
128	Gochang	23,749	26.99	28,931,975	13	60	0	64.1	149,020	1.513052	122
129	Gunsan	3,055	8.13	5,141,117	0	296	3	17.1	223,326	0.370198	30
130	Gimjae	16,397	30.04	41,753,874	0	204	0	46.1	281,090	1.224612	99
131	Namwon	17,607	21.78	32,894,368	3	120	0	47.9	263,778	1.160484	94
132	Muju	1,154	1.84	4,425,794	0	39	0	51.6	0	0.445905	36
133	Buan	9,723	19.96	7,940,841	3	110	0	54.7	619,297	0.949165	77
134	Sunchang	10,543	21.67	5,546,266	0	109	0	76.1	49,640	1.126179	91
135	Wanju	7,165	8.73	13,946,517	0	115	0	71.2	91,828	0.861765	70
136	Iksan	36,347	32.31	15,415,401	4	635	0	20.7	23,503	1.658371	134
137	Imsil	3,776	7.40	6,665,228	9	57	3	74.1	332,828	0.788093	64
138	Jangsu	3,466	6.69	3,407,874	2	42	3	75.5	156,500	0.757458	61
139	Jeonju	3,728	18.30	8,158,558	1	650	0	7.5	94,300	0.481699	39
140	Jeongeup	17,241	23.65	39,110,959	9	180	0	34.0	239,635	1.096507	89
141	Jinan	2,496	4.57	3,722,163	0	43	1	68.5	2,007,213	0.692726	56
142	Geojae	3,368	8.49	7,454,408	0	189	0	22.1	24,000	0.392217	32
143	Geochang	2,559	3.25	12,813,907	0	89	0	44.9	616,546	0.484696	39
144	Goseong	1,173	2.29	10,132,884	0	106	0	55.9	0	0.500619	41
145	Gimhae	7,144	15.77	45,474,879	1	598	197	19.5	10,010,425	1.488289	120
146	Namhae	3,935	11.31	10,489,522	0	81	0	65.8	0	0.748974	61
147	Masan	1,721	5.58	34,022,840	1	510	3	8.2	352,620	0.310721	25
148	Milyang	927	1.17	15,202,774	0	141	0	52.4	87,000	0.468775	38
149	Sacheon	1,532	4.05	16,919,715	0	286	0	20.2	323,550	0.310640	25

150	Sancheong	2,422	3.07	34,652,327	1	53	0	73.1	262,500	0.700027	57
151	Yongsan	1,418	3.02	5,709,663	6	363	36	29.6	136,490	0.475072	38
152	Uiryeong	1,404	3.14	15,626,815	2	49	0	69.9	1,208,180	0.651858	53
153	Jinju	4,817	7.34	53,347,816	16	295	2	12.5	4,929,082	0.579041	47
154	Jinhae	1,168	12.22	10,666,960	43	152	0	6.5	0	0.338598	27
155	Changnyeong	1,452	2.76	3,306,750	0	120	0	60.2	267,090	0.546544	44
156	Changwon	8,236	29.01	45,365,124	0	58	112	14.6	0	1.048040	85
157	Tongyeong	2,629	11.20	10,186,061	0	167	0	20.3	1,956,996	0.437078	35
158	Hadong	3,435	5.29	11,241,873	11	57	0	66.0	121,802	0.690331	56
159	Haman	1,401	3.52	4,362,694	11	162	0	48.3	0	0.488152	39
160	Hamyang	3,931	5.51	65,578,766	5	67	0	59.1	24,167,398	1.313930	106
161	Hapcheon	1,823	1.94	19,586,022	0	79	0	72.0	2,373,560	0.700391	57
162	South Jeju	2,280	3.71	736,095,535	71	87	0	0.1	10,198,800	1.367250	111
163	North Jeju	863	1.20	179,694,561	86	118	0	0.1	11,907,900	0.732858	59
164	Seogwipo	1,072	4.27	41,155,510	28	95	0	0.1	0	0.196067	16
165	Jeju	867	3.49	30,860,690	65	438	0	0.0	7,931,400	0.495071	40

Application results of the method

The supplementary local groundwater-monitoring stations are under consideration and a total of 10,000 monitoring stations will be established throughout the country by 2011. Not all the 10,000 monitoring stations will be newly installed. For most stations, existing wells will be used. Only if the monitoring well is not available at the proper location for the station, a new well will be installed. The

method described above was applied to allocate the required number of the monitoring stations for each district.

Prior to applying the method, the data listed in Table 3 were obtained from the relevant reports of each district. The properties of the evaluation criteria (number of groundwater wells, density of groundwater wells, amount of groundwater use, number of contamination sources, number of contaminated wells, number or proportion of households not serviced by a water supply, and amount of groundwater used for drinking) were evaluated and summarized for data manipulation. Because the data should have the same quality and integrity for each district, the data were obtained from the same sources and for the same time period. The evaluation criterion F_{31} was used to determine the number of households dependent only on groundwater for water supply, although it was not possible to investigate all the households. Therefore, the proportion of households not serviced by

Table 11 Mean and standard deviation of the each evaluation property

Evaluation property	Mean ($\bar{X}_{ij}^k$)	Standard deviation (σ)
Number of groundwater wells (each)	5,997.97	6,266.88
Density of groundwater well (each/km ²)	12.50	12.15
Amount of groundwater use (m ³ /year)	23,968,174.66	59,113,679.76
Number of wells used for drinking-water supply (each)	8.60	27.84
Number of contamination sources (each)	301.36	647.09
Number of contaminated wells (each)	14.21	62.72
Proportion of household not serviced by water supply (%)	37.54	24.98
Amount of groundwater use for drinking-water supply (m ³ /year)	1,237,611.04	3,780,037.30

Table 12 Full process of the calculation for Seoul, South Korea

F_i	F_{ij}	X_{ij}^k	x_{ij}^k	$FW_{ij} \cdot x_{ij}^k$	$\sum_{j=1}^{N_{ij}} (FW_{ij} \cdot x_{ij}^k)$	$FW_i \cdot \sum_{j=1}^{N_{ij}} (FW_{ij} \cdot x_{ij}^k)$	TS_k
F_1	F_{11}	14,957	2.389	1.099	2.434	0.925	2.954
	F_{12}	41.22	3.393	1.222			
	F_{13}	37,403,019	0.633	0.114			
F_2	F_{21}	4	0.144	0.023	5.968	2.029	
	F_{22}	6,954	10.747	3.224			
	F_{23}	322	5.134	2.772			
F_3	F_{31}	0.0	0.000	0	0.0	0.0	
	F_{32}	71	0.000	0			

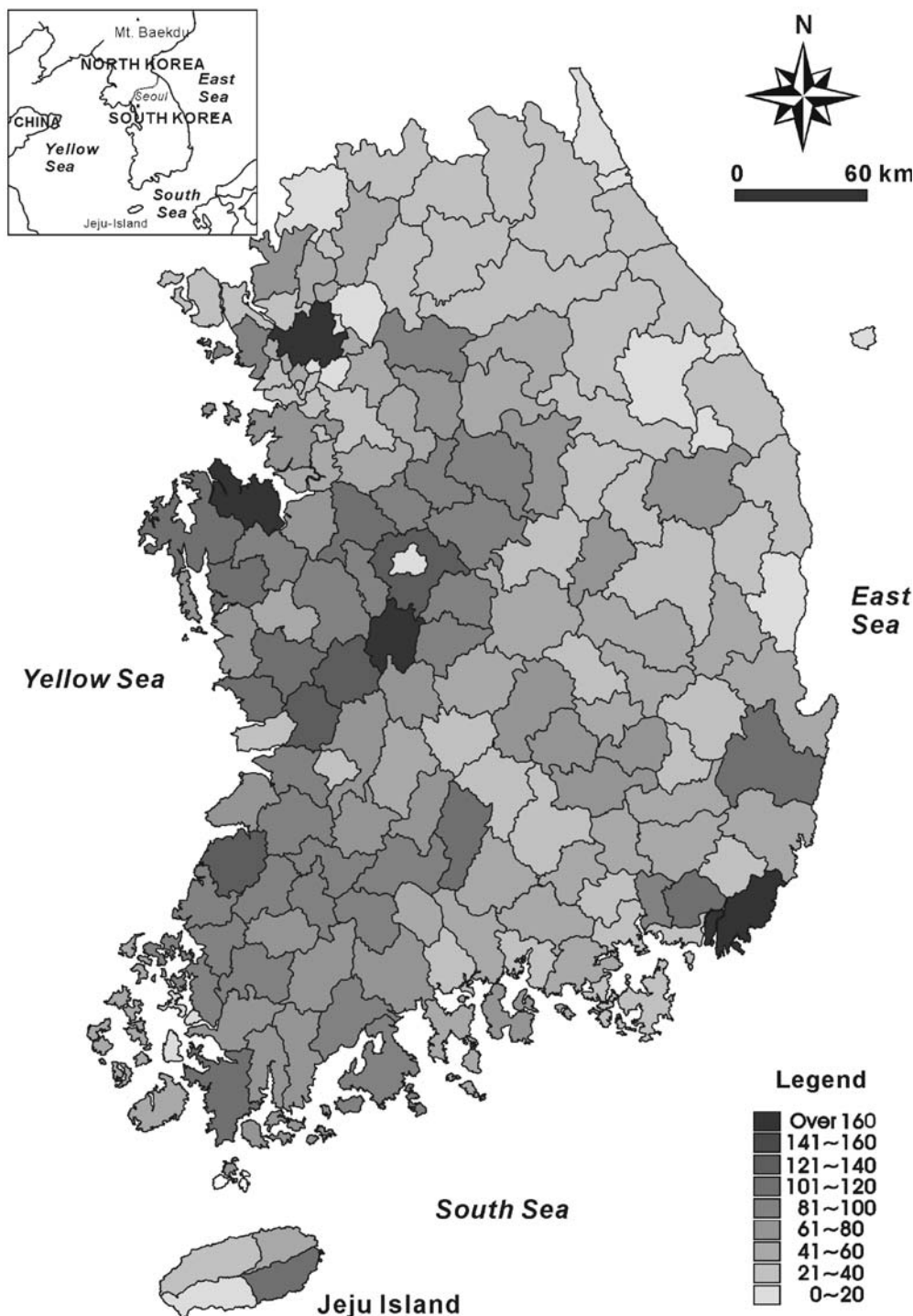


Fig. 3 Geographical distribution of the determined optimal number of the local groundwater-monitoring stations throughout South Korea

water supply was used instead of F_{31} in this study. The collected data for the evaluation are summarized in Table 10.

Standardization of the property

Because evaluation criteria have different dimensions, the method used in this study was established based on the

comparison between each evaluation criterion and the sum of the total evaluation score times the weighting value. For example, a district was assumed to contain 2,400 groundwater wells, a well density of 0.2 each/km², and a total groundwater use of 1,000,000 m³. The values, 2,400 wells, 0.2 each/km², and 1,000,000 m³ neither can be compared nor can be made a sum. If the three values, 2,400 wells, 0.2 each/km², and 1,000,000 m³, can be

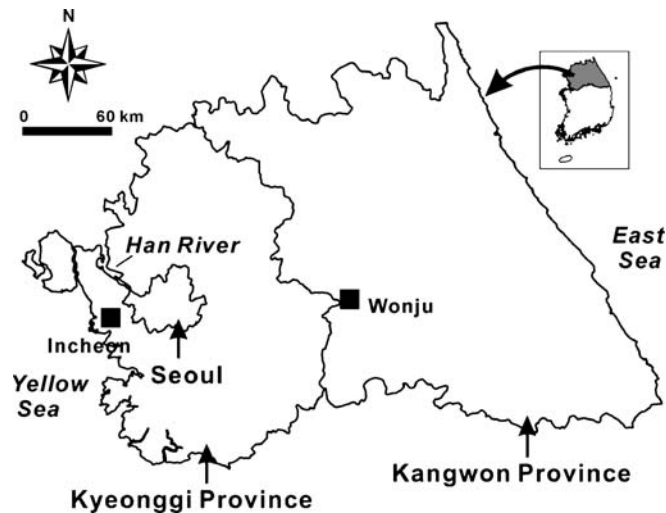


Fig. 4 Locations of Seoul, Kyeonggi, and Kangwon provinces in South Korea

computed as a sum, the amount of groundwater use will have much greatest effect due to its largest magnitude. This results in masking the influences of the other factors. Therefore, the standardization process, equalizing the influence of the properties, makes it possible to compare and sum the properties (Lee et al. 2001). The property (X_{ij}^k) can be converted to the standard value (x_{ij}^k) using Eq. 2. Mean and standard deviation of each evaluation property are presented in Table 11.

Total evaluation score (TS_k)

The optimal number of monitoring stations is calculated in proportion to the total evaluation score (TS_k) for each district. Equation 1 determines the total evaluation score. The standard value () obtained from Eq. 2 was multiplied by each weight (FW_{ij}) and the value was summed up for

the same i th primary evaluation criterion category and then multiplied again by the weight (FW_i) again. Finally, through the summation, the total evaluation score was calculated. Example of a calculation procedure for the capital of South Korea (Seoul) is presented in Table 12.

Number of the monitoring stations

The number of the groundwater-monitoring stations calculated from the total evaluation scores is also shown in Table 10. For geographical representation, a nine-interval classification between the minimum and maximum values is used in Fig. 3; for example, assigning the nine ranges in an increasing order to 0~20, 21~40, 41~60, 61~80, 81~100, 101~120, 121~140, 141~160, and over 161 stations, respectively. In Fig. 3, it can be seen that a

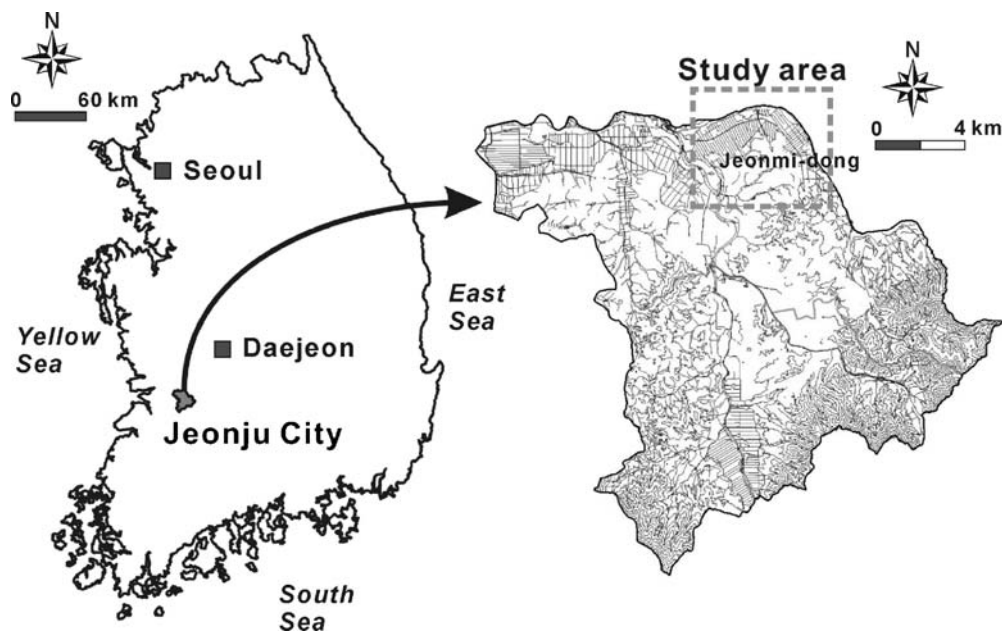


Fig. 5 Map of South Korea showing the location of the study area in the city of Jeonju

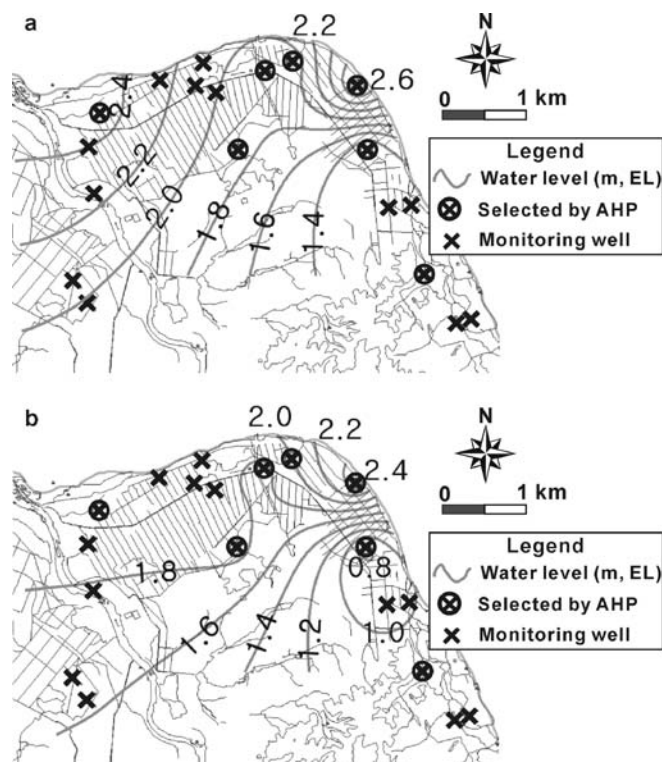


Fig. 6 The inferred groundwater elevation (EL), in meters above sea level, determined by kriging. **a** May 2000, and **b** October 2000

large number of monitoring stations is concentrated in the western part of the country.

Seoul has a large population (over 10.5 million in 2000; see Table 10; Lee et al. 2005). There also are many satellite cities around Seoul that are mainly located in the western part of the country. Although the area of the Kyeonggi province is smaller than other provinces in the country (Fig. 4), many industrial complexes have been built there and a large number of wells have been installed; therefore, Kyeonggi province contains many more groundwater-monitoring stations than other provinces (see Fig. 3). The number of wells being installed in the province is still gradually increasing because of the amount of groundwater pumpage. The Kangwon province is the largest in size (see Fig. 4), but the required number of the monitoring station is the lowest of all the provinces (see Fig. 3). This is because most of the Kangwon province comprises the mountainous areas and the population is much smaller than other provinces, which means that the amount of groundwater use is small compared to other provinces. Therefore, the Kangwon province requires fewer groundwater-monitoring stations than other provinces. This result

reasonably reflects the actual hydrogeologic and societal conditions in the provinces.

Validation of the method

The city of Jeonju was chosen to evaluate the validity of this method and groundwater levels were monitored in the city. The required number of local groundwater-monitoring stations at Jeonju (No. 139 in Table 10) is 39. These 39 stations are distributed throughout the entire city. Therefore, the same approach and methodology previously applied to entire districts (cities and counties) was also applied to each “dong (an administrative unit)” in the city. The dong is an administrative unit one-step lower than a city. There are 40 dongs in the city. According to the results of the method application, the studied area in the city of Jeonju requires seven stations for the supplementary groundwater-monitoring network (Fig. 5). Groundwater levels in the study area were measured at a total of 19 existing groundwater wells including the seven wells designated as the supplementary local groundwater-monitoring stations in May and October of 2000.

Table 13 Results of comparison between inferred groundwater levels and measured groundwater levels

Statistics	May 2000 residual	October 2000 residual	Residual of groundwater-level change from May to October
Minimum	-1.09	-1.23	-0.09
Maximum	1.21	1.16	0.22
Mean	0.04	0.05	0.04
Standard deviation	0.62	0.63	0.09

The groundwater levels and their distribution in the study area were delineated by a kriging method using water-level data collected at the seven stations selected through the AHP method and the residuals between the inferred and the measured groundwater levels were calculated. The distribution of inferred groundwater levels is shown in Fig. 6. In the figure, $\otimes$ means that the monitoring stations were selected as the supplementary local groundwater-monitoring wells and 'x' means the wells where water levels were measured for this verification. The mean of residuals between inferred groundwater levels determined by kriging and measured water levels was low.

Furthermore, the mean and standard deviation of residuals between temporal changes in inferred groundwater levels and actual groundwater levels at the 19 monitoring wells from May to October was much lower (Table 13). Therefore, it is concluded that the seven local groundwater-monitoring stations reasonably and economically represent the water-level distribution and its temporal variation for the demonstration district (dong) without losing significant overall hydrologic information.

Summary and conclusions

Construction of a supplementary local groundwater-monitoring network consisting of 10,000 stations throughout South Korea is under way to supplement the national groundwater-monitoring network. This report presented a method for allocating the local groundwater-monitoring network using an analytic hierarchy process (AHP). An important goal of this study is to provide assistance to policy makers, planners, and decision makers to determine the optimal location or to allocate the monitoring stations for their city or county.

Based on an extensive literature review and questionnaires distributed to 93 groundwater experts, the primary and secondary evaluation criteria were selected to reflect each district's hydrogeologic and relevant societal conditions. The primary evaluation criteria were represented by the main goal of the supplementary groundwater-monitoring network. The monitoring network was explained in detail by the secondary evaluation criteria that were placed on a third level. In addition, weights of the criteria were assigned by pairwise comparison and pertinent questions to the experts.

The required number of the groundwater-monitoring stations was calculated in proportion to the total evaluation score. Consistency ratios for the evaluation criteria indicated that the levels of consistency were acceptable. To verify that the suggested number of monitoring stations calculated from this study is reasonable, the city of Jeonju was selected as an example for analysis. For the demonstration area in Jeonju, the mean of residuals between inferred water levels using seven local groundwater-monitoring stations determined by the developed method with AHP and measured water levels was low and its temporal change was much lower. Therefore, the proposed seven stations for

the local monitoring network appeared reasonable. The developed method appears to be a valid aid for allocating the supplementary local groundwater-monitoring stations in each administrative district in South Korea.

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