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Integrated Consideration of Quality and Quantity to Determine Regional Groundwater Monitoring Site in South Korea

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Abstract As the purpose of the regional groundwater monitoring station is to observe both quality and the levels of groundwater in South Korea, it is most efficient and economical to establish the monitoring station at a site able to observe these two items simultaneously. A weighting and ranking method using GIS technology was used for the development of a site selection model. This model uses a land-use type of target area with regard to quality and a lineament length density with regard to quantity. It was shown that this weighting and ranking method is appropriate and convenient for selecting a monitoring site because it proposes the relative importance and priority of groundwater monitoring for each site. Additionally, if this method is used together with the other method like an analytical hierarchy process (AHP) method, the optimal and specific monitoring site can be easily selected and the additional field investigation can be reduced.

Keywords Groundwater monitoring · Weighting and ranking · GIS · Land use · Lineament · Analytical hierarchy process

1 Introduction

A groundwater monitoring network is essential to examine the impacts of climate changes and human activities on groundwater quantity and quality. This network can also be used for observing the impacts on the environment from groundwater resources development. Therefore, an optimally designed monitoring network can ensure the effective acquisition of groundwater quantity and quality data for various purposes.

Five kinds of monitoring stations have been established in Korea: "National Groundwater Monitoring Station (NGMS)" under the MOCT (Ministry of

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Construction and Transportation), "Groundwater Quality Monitoring Station (GQMS)" under the MOE (Ministry of Environment), "Subsidiary Groundwater Monitoring Station (SGMS)" under the local governments, "Seawater Intrusion Monitoring Station (SIMS)" under the MAF (Ministry of Agriculture and Forest) and Drinking Water Monitoring Station (DWMS) under the MOE (Table 1).

Three hundred twenty NGMSs have been constructed throughout the whole area since 1995 and their locations were selected with regard to the hydrogeologic units, topography, and other observations. However, these monitoring wells are not sufficient to observe groundwater quality and quantity conditions because the Korean peninsula is mostly composed of mountainous areas and complex geologic structures and it produces uneven hydraulic features in a geologic body. Therefore, the plan for an additional subsidiary groundwater monitoring station was established, which can be managed by local government officials, to construct 10,000 monitoring wells by 2011 (Kim 2005; Lee et al. 2007).

This subsidiary monitoring station is required to monitor groundwater quality and quantity simultaneously while considering financial efficiency because of the high costs of constructing and managing the monitoring wells. The purpose of this study is to propose a pragmatic and simple method which can satisfy the simultaneous monitoring objectives for subsidiary monitoring stations, and to select optimal monitoring sites for the construction of regional groundwater monitoring wells using GIS tools and a weighting and ranking method.

2 Previous Studies

A number of approaches to the design of groundwater monitoring networks have been developed (Sophocleous et al. 1982; Andricevic and Foufoula-Georgiou 1991; Gibbons 1991; Loaiciga et al. 1992; Hudak et al. 1993). Existing approaches can be classified into four categories—qualitative, simulation, variance-based and optimization. The most widely used method is a qualitative one with which the monitoring network is designed by calculations and judgments by the investigator without using mathematical methods. The second one uses some hydraulic coefficients for a simulation and is able to determine the detection capability of a monitoring network (Meyer et al. 1989). The variance reduction approach is a method to minimize the variance of estimation error of pollution concentration at some sampling sites (Ben-Jemaa et al. 1995; Lee and Ellis 1996; Storck et al. 1997).

Most of these methods require some detailed data such as aquifer flow features, hydraulic coefficients, pollution sources, water levels, water use, and contaminant transport mechanism. However, it is not easy to collect these data for a regional area without any precise investigation and sometimes the estimated values are used for a simulation or a model. In this study, a model for monitoring site selection focuses on the simultaneous consideration of quality and water levels, as reviewing the results of previous studies on groundwater quality and quantity.

Many past researches have revealed that land use type is an important factor for groundwater quality distribution and changes in most regions. Some research activities (Waller 1983; Van Duijvenbooden et al. 1985; Gilliom et al. 1995; de Olivares 1998; Vecchia 2003) have been aimed at determining quality monitoring plans using an assessment of the relationship between land-use patterns and the

Table 1 Classification of groundwater monitoring stations in Korea

Category	Based on	Function	Operation	Number of wells
NGMS (National Groundwater Monitoring Station)	Article 17 of Groundwater Act	Primary network	MOCT and KWATER	320
GQMS (Groundwater Quality Monitoring Station)	Article 18 of Groundwater Act	Secondary network	MOE and local government	2,021
SGMS (Subsidiary Groundwater Monitoring Station)	Article 17 of Groundwater Act	Secondary network	Local government	10,000
SIMS (Seawater Intrusion Monitoring Station)	Rural Area Consolidation Act	Secondary network	MAF	192
DWMS (Drinking Water Monitoring Station)	Drinking Water Management Act	Secondary network	MOE, KIGAM and private drinking water company	77

The number of SGMS is a target number by the year 2011

MOCT Ministry of Construction and Transportation, *KWATER* Korea Water Resources Corporation, *MOE* Ministry of Environment, *MAF* Ministry of Agriculture and Forest, *KIGAM* Korea Institute of Geoscience and Mineral Resources resulting groundwater quality. Van Duijvenbooden et al. (1985) indicated that monitoring well locations should be selected while considering soil types and land use at each location.

Additionally, many other researches for correlativity between land use and groundwater quality have been done. Sloto (1987), Blickwedel and Wood (1988), Pope et al. (2002) and Robinson (2002) indicated that the quality of shallow groundwater was highly related with land use and residential condition. The USGS and US EPA reported that heavily farmed regions are generally provide a source of nutrients and dissolved solids into the groundwater. High nitrate values are sometimes associated with agricultural land use. Undisturbed forest land may provide a more steady and uncontaminated groundwater quality. A dense residential area may generate contaminants by runoff from paved areas. An unsewered area with many homes on septic systems may affect the groundwater quality by adding nitrates and chloride (Risser and Siwiec 1996; EPA 1990, 1994). The USGS (1999) considered nitrate values over 2.0 mg/L and orthophosphate concentration over 0.02 mg/L as having been effected by human activities. From these results, land use type which may be originated from social development or agricultural activity can be generally considered as an important factor to achieve the object of groundwater quality monitoring.

Groundwater well development is generally popular in the area of high groundwater productivity and it has also been revealed that the productivity is related with a lineament distribution, especially in fractured crystalline basement area. Of course, the construction of groundwater well and its production can also be affected by some other parameters such as socio-economical factors, drilling technology, topography, sediments and geology. Groundwater well development in Korea is also common in the agricultural areas because of water demand, and wells are generally located in plains, valleys or near river regions which have been formed by sedimentation, faults, joints or other tectonic activities. Additionally, high productive site of groundwater can be a main target of monitoring because this pumping site can have a possibility of affecting the surrounding hydraulics of aquifer and causing a drawdown of water levels.

Many studies analyzing hard rock aquifer yields and geologic structure have been carried out over the past decades (Siddiqui and Parizak 1971; Daniel 1989; Briz-Kishore 1993; Knopman and Hollyday 1993; Gustafsson 1994; Mabee et al. 1994; Sidle and Lee 1995; Sander et al. 1996, 1997; Park et al. 2000; Neves and Morales 2007; Sander 2007). Daniel (1989) found that the wells in valleys or draws had average yields three times those of wells on hills and ridges. Briz-Kishore (1993) also showed that well productivity was mainly influenced by the characteristics of the shallow fracture zones. The study by Mabee et al. (1994) examined 35 bedrock wells and found that aquifer transmissivity, normalized by well depth, was positively related to well proximity to fracture-correlated lineaments. Sidle and Lee (1995) observed that hydraulic conductivity is related to the orientation of geologic structures. Park et al. (2000) revealed that the lineaments originated from fractures are related with well yields using a numerical model of a dual-permeability FEM model. Neves and Morales (2007) studied that more productive wells are concentrated mainly along the regional geologic structures and the most productive wells are located in areas with brittle structures by transtensional stress. Sander (2007) reviewed much lineament research and concluded that, although the easy access to a decision platform for well siting based on lineament, GIS and various peripheral tools is a great improvement, it also presents a risk because some groundwater exploration programs suffer from low success rates due to political and economical barriers which are beyond the control of the lineament analysts.

Lineaments produced the highly weathered area in South Korea. Lots of farm land and residential facilities have been located in and around this area. And many groundwater wells have been constructed in this area and most of them have a fully or partly screened PVC casing to get more water from upper sediment and bedrock layers simultaneously. Therefore, groundwater in a well is usually a mixture of shallow and deep groundwater and the productivity of a well is also affected partly or mostly by the upper sediments which are the weathered zone produced by lineament, fault and other geologic activities. In this study, lineament is considered as an important factor for groundwater productivity of a well in terms of not only a bedrock aquifer but also shallow aquifer.

3 General Groundwater and Geology

The characteristics of groundwater recharge and infiltration depend on the transmissivity and storativity of the aquifer. In Korea, two types of aquifers exist, the shallow aquifer and deep aquifer. The shallow aquifer exists within unconsolidated sediments while the deep aquifer is a bedrock aquifer. The area of unconsolidated sediments is about 27,390 km^2 and is about 28% of the total area of Korea. They are distributed along main rivers. The average thickness of the unconsolidated layer is 2∼30 m and the productivity of wells in this aquifer ranges from about 30 to 800 m^3/day. This aquifer type has been the source of agricultural water supply for many rural regions since 1950. The other main aquifer, the deep aquifer, exists along faults, joints, and boundaries of rocks that are included in the old consolidated rocks and were formed by tectonic activities (MOCT 2002).

The amount of annual groundwater recharge estimated is 16.3 billion cubic meter which is about 12% of annual precipitation. In this recharge, the practical amount of groundwater is estimated to be 10.9 billion m^3. Currently, the annual groundwater exploitation is only 3.7 billion cubic meter and this amount is 11% of water resources usage and 94% of total usage is for domestic and agricultural purposes (MOCT 2002).

The overall geographical relief of Korea is higher in the eastern mountainous area and lower in the western area. The groundwater recharge, therefore, is more active in the eastern whereas the groundwater discharge is predominant in the western area. The principal aquifer media types in Korea can be grouped into several such as unconsolidated or semi-consolidated clastic sediments, porous or fractured volcanic rock, fractured igneous or metamorphic rock, carbonate rock, and consolidated sedimentary rock. In general, the depth to groundwater from the surface has good correlation with geographic relief and the mean depth to water table has range of 5 to 10 m below the surface.

4 Factors for a Model Construction

4.1 Groundwater Quality and Land Use

To reveal the relationship between land use and groundwater quality, NGMSs and GQMSs' monitored data and their land use types were used. One hundred sixty-three deep monitoring wells from among all the NGMSs and 781 monitoring wells from among all the GQMSs were selected for a quality description and a trend analysis (Fig. 1). Generally, the depth of water sampling for the NGMSs is about 30 to 60 m below the surface and for the GQMSs it is about several tens of meters. At all monitoring wells, water quality sampling and analysis was conducted twice a year,

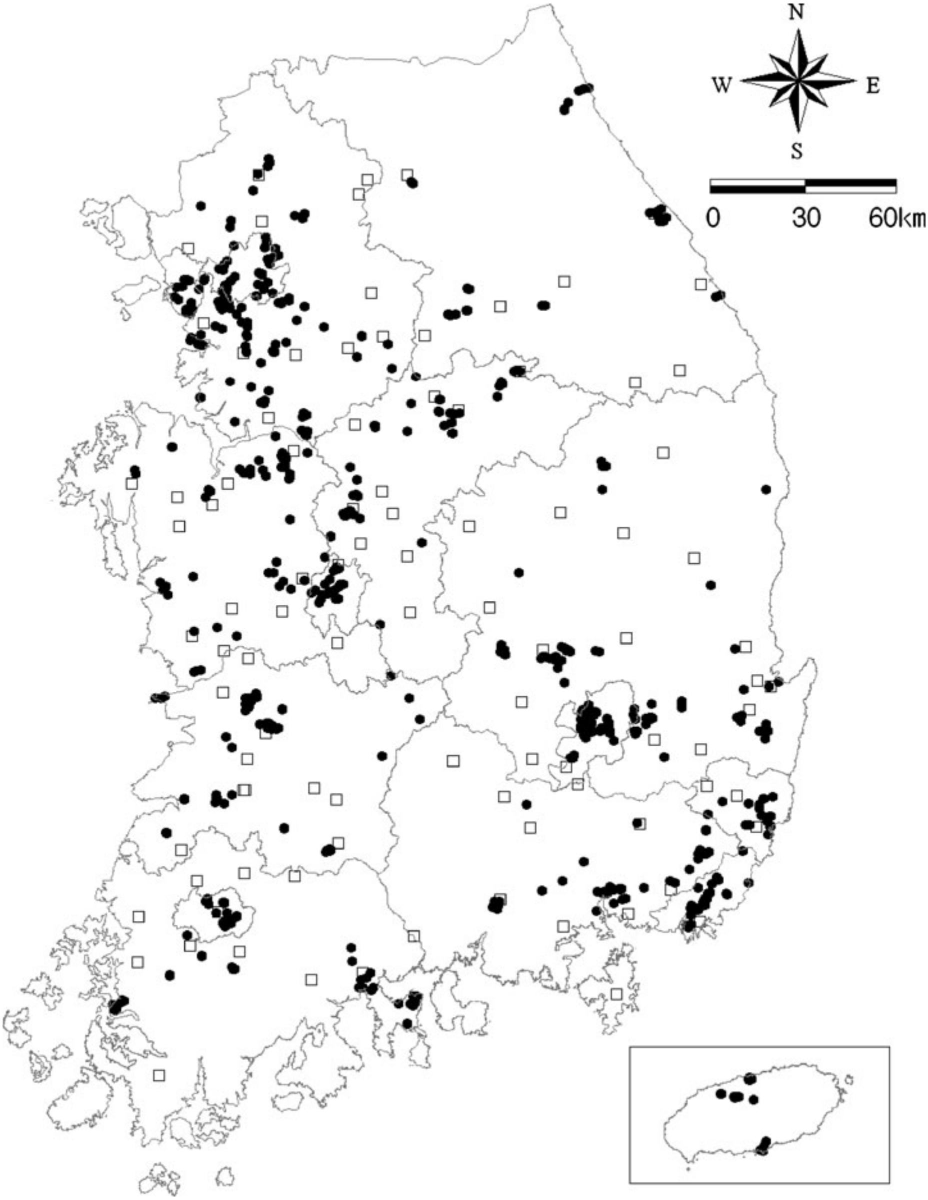


Fig. 1 Location of groundwater monitoring wells (*box*, 163 NGMSs; *circle*, 781 GQMSs) used for an analysis of the relationship between land use and groundwater quality

in spring and fall. After pumping for one or two hours to remove the inside water, water samples were collected with no-bacterium bottles, and then transported to a laboratory immediately.

The land use of monitoring sites was classified into 13 types by the MOE (2002). Groundwater quality test was conducted periodically for 15 items for the NGMSs, pH, COD, Cl, Coliform group, NO_3N, CN, Cd, As, Pb, Hg, Organic phosphorous, Phenol, Cr^{6+}, TCE and PCE. 17 water quality items for the GQMSs were analyzed periodically which are Cd, Hg, Pb, Cr^{6+}, As, CN, PCB, Organic phosphorous, TCE, PCE, Phenol, pH, Electric conductivity, COD, NO_3N, ABS and Cl.

Some of the quality components were not considered in this study because their concentrations were under the quality detection limits, or most of them were not detected in groundwater samples in Korea. Therefore, we need not consider them as a criterion for assessing the local groundwater monitoring sites at a regional scale. In this study only four variables with continuous data and detectable values, Cl, COD, EC and NO_3N, were used. About 11,000 groundwater quality data from 1995 to 2001 were used for statistics for quality and trend analysis. The amounts of sampling data were about 7 to 12 sets at each well.

To statistically examine the difference of quality concentrations for 13 land use types, an Analysis of Variance (ANOVA) was used. With the ANOVA, the null hypothesis is:

$$H_o : \mu_1 = \mu_2 = ... = \mu_k \tag{1}$$

where μ_i is the mean of group i. As a result of the ANOVA using the log-transformed four variables based on a normal distribution hypothesis, the p values for the mean values of log-EC, log-COD, log-NO_3N, log-Cl were below a significant level of 0.05. This explained that there were some gradual differences for the mean values of the four quality variables according to the land use types in Korea (Table 2). In this study, the mean values for each land use type are used for a first input parameter to construct a model to determine the monitoring well location.

On the other hand, considering the purpose of groundwater quality monitoring, the groundwater monitoring well should also be used for the prediction of quality condition of the future using the past trend. To find which area shows an upward trend in groundwater quality, Sen's method was used for each monitoring site (Gibbons 1994). Table 2 summarizes the result of the trend analysis for Cl, COD, EC, and NO_3N according to the land use types.

As seen in Table 2, agricultural regions (B and C) show high mean concentration for NO_3N for last 7 years and also there is no distinct increase during this period. This means that NO_3N concentration was already high in early 1990s and the consumption of nitrogenous fertilizer has not increased since that time (Fig. 2). Therefore, NO_3N is important from a viewpoint of its mean value of concentration but does not become important for its trend. On the other hand, golf courses and nearby regions (S) have a relatively low mean concentration and high trend on NO_3N, which means that there has been a continuous consumption of fertilizer in this area. In the river and nearby region with a possibility of pollution (F), general waster dumping region (I) and specific waster dumping region (J), the pollutants can produce high concentration of Cl but distinct upward trends of concentration do not happen because of the high construction technology of treatment facility after early 1990s. Similarly, the urban residential region (T) shows a relatively high concentration of Cl because of the

Table 2 Normalized weighting values for each land use type using the ranking method

a) Mean of the quality concentration																
Land use	Mean value of wells				Straight rank				Weight				Normalized weight			
	Cl	COD	EC	NO_3N	Cl	COD	EC	NO_3N	Cl	COD	EC	NO_3N	Cl	COD	EC	NO_3N
B	44.62	1.78	177.48	6.71	7	3	1	2	7	11	13	12	0.077	0.120	0.143	0.132
C	51.96	2.20	166.71	4.75	5	2	5	9	9	12	9	5	0.099	0.130	0.099	0.055
F	76.83	1.41	131.42	3.27	2	7	8	12	12	7	6	2	0.132	0.076	0.066	0.022
G	20.23	0.80	85.72	3.06	12	12	12	13	2	2	2	1	0.022	0.022	0.022	0.011
I	88.87	1.33	174.31	6.00	1	8	4	4	13	6	10	10	0.143	0.065	0.110	0.110
J	59.30	1.43	176.97	6.49	3	6	2	3	11	8	12	11	0.121	0.087	0.132	0.121
K	26.27	1.33	118.15	5.57	10	8	9	6	4	6	5	8	0.044	0.065	0.055	0.088
N	18.67	1.69	105.72	4.56	13	4	10	10	1	10	4	4	0.011	0.109	0.044	0.044
O	40.31	1.27	175.74	5.17	8	10	3	8	6	4	11	6	0.066	0.043	0.121	0.066
P	35.70	1.17	137.01	5.71	9	11	7	5	5	3	7	9	0.055	0.033	0.077	0.099
S	24.34	2.28	103.88	4.15	11	1	11	11	3	13	3	3	0.033	0.141	0.033	0.033
T	58.79	1.67	161.11	5.38	4	5	6	7	10	9	8	7	0.110	0.098	0.088	0.077
U	46.62	0.79	77.51	35.08	6	13	13	1	8	1	1	13	0.088	0.011	0.011	0.143
Sum									91	92	91	91				

Table 2 (continued)

b) Trend of the quality concentration

Land use	Percentage of trend in wells				Straight rank				Weight				Normalized weight			
	Cl	COD	EC	NO_3N	Cl	COD	EC	NO_3N	Cl	COD	EC	NO_3N	Cl	COD	EC	NO_3N
B	4.2	2.8	0.0	0.0	10	12	9	12	4	2	5	2	0.043	0.022	0.050	0.022
C	19.8	6.2	2.7	9.7	3	6	8	5	11	8	6	9	0.117	0.087	0.059	0.098
F	10.2	11.6	5.6	13.3	5	4	3	3	9	10	11	11	0.096	0.109	0.109	0.120
G	3.3	2.9	0.0	2.9	13	10	9	11	1	4	5	3	0.011	0.043	0.050	0.033
I	4.8	15.4	4.8	3.8	9	2	4	9	5	12	10	5	0.053	0.130	0.099	0.054
J	8.3	16.7	0.0	0.0	6	1	9	12	8	13	5	2	0.085	0.141	0.050	0.022
K	5.6	3.7	16.7	3.7	8	9	1	10	6	5	13	4	0.064	0.054	0.129	0.043
N	29.8	2.0	0.0	14.0	1	13	9	2	13	1	5	12	0.138	0.011	0.050	0.130
O	12.5	7.0	6.4	7.0	4	5	2	6	10	9	12	8	0.106	0.098	0.119	0.087
P	5.8	4.4	2.9	10.0	7	8	6	4	7	6	8	10	0.074	0.065	0.079	0.109
S	21.8	5.1	2.8	17.3	2	7	7	1	12	7	7	13	0.128	0.076	0.069	0.141
T	4.2	13.3	4.2	6.7	10	3	5	7	4	11	9	7	0.043	0.120	0.089	0.076
U	4.2	2.9	0.0	5.7	10	10	9	8	4	4	5	6	0.043	0.043	0.050	0.065
Sum									94	92	101	92				

B Agricultural region and agricultural water using region, *C* farm production complex, *F* river and nearby region with a possibility of pollution, *G* industrial complex, *I* general waste dumping region, *J* specific waste dumping region, *K* metallic mine region, *N* Human waste treatment facility and nearby region, *O* public health investigation region, *P* recreation parks, *S* golf course and nearby region, *T* urban residential region, *U* storage tank and nearby region

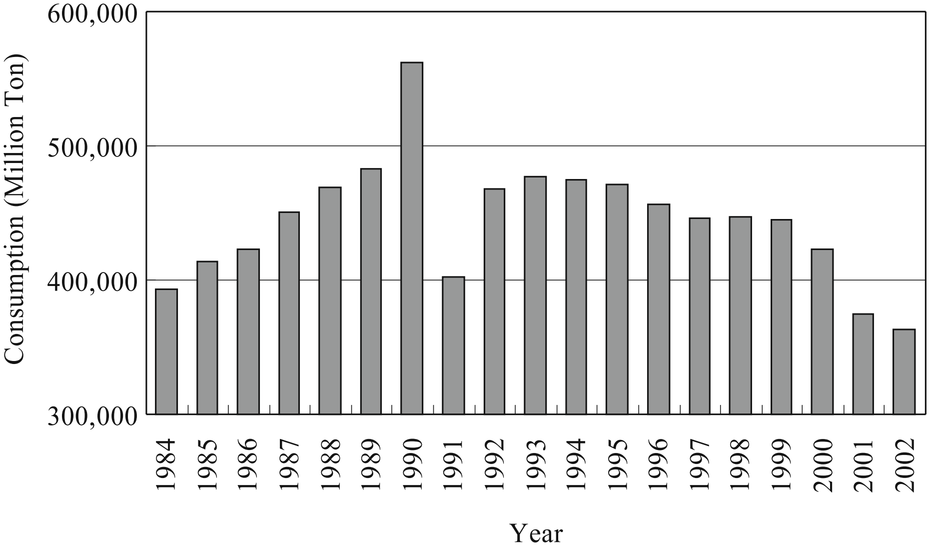


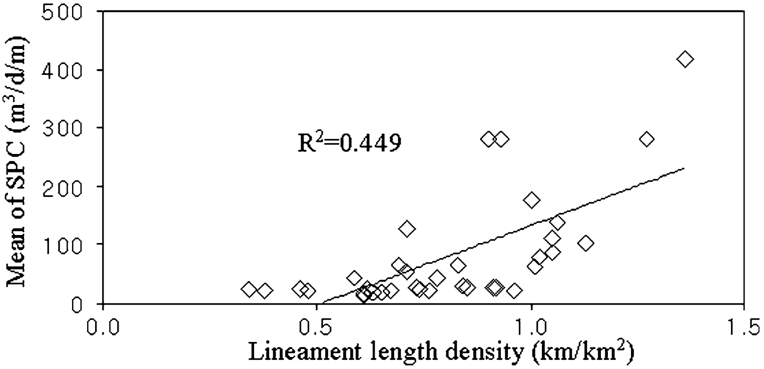
Fig. 2 The trend of nitrogenous fertilizer consumption in Korea (from http://www.kosis.kr)

economical development and urbanization in Korea since 1970s, but the percentage of upward trend during from 1990s to early 2000s is so small because of the extended sewer system, septic tank and other factors in urban areas. Even though the mean concentration and trend for all quality items on land use types can not be explained based on a scientific origin and social environment because of the complexity of cause and effect and data limitation, 13 land use types need to be considered as a main factor based on the previous researches.

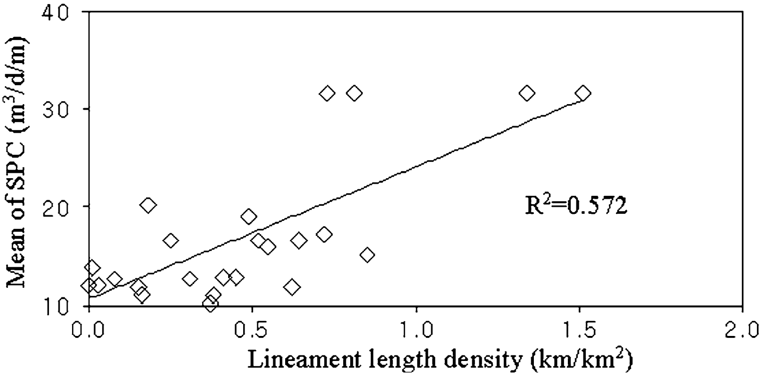
4.2 Groundwater Quantity and Lineament

As described above, well yield is usually related with a lineament formed by fracture. Kim (2005) has studied the relationship between lineament and groundwater productivity in Korea. For two regions, Pohang and Cheonan, the correlation analysis between well yield and three lineament factors, distance to lineament, distance to lineament cross-point, and lineament length density, has been done. The areas are 1,129 km^2 for Pohang and 636 km^2 for Cheonan. In the Pohang region, many kinds of rocks such as sandstone, siltstone, volcanic sediments and shale are distributed from the Cretaceous to Quaternary. Gneissic rocks and intrusive igneous rocks are distributed in the Cheonan region. Many deep well data, which include the location, depth, pumping capacity, geology, and hydraulic coefficients, were collected from the Basic Groundwater Survey based on the Article 5 of the Groundwater Act (MOCT and KOWACO 2003a, b). One hundred fourteen and 184 deep wells for Pohang and Cheonan regions were collected and the average depths were 207.4 and 145.2 m, respectively. The average specific capacities (= Volumetric flow/drawdown = Q/s) were 31.5 m^3/day/m for Pohang and 6.9 m^3/day/m for Cheonan.

The distance to the nearest lineament and the distance to the cross-point were roughly related with specific capacity, and it was also slightly affected by well depth



(a) Pohang district (Mean of SPC > 10m^3/d/m)



(b) Cheonan district (Mean of SPC > 10m^3/d/m)

Fig. 3 Relationship between specific capacity and lineament length density for the Pohang and Cheonan districts, South Korea (Kim 2005)

and rock type. However, two linear regression models between lineament length density and specific capacity were established at 0.05 significance level for Pohang and Cheonan districts and Pearson correlation coefficients were 0.670 and 0.756, respectively (Fig. 3). This means that the former is proportional to the latter and it can be an important factor in determining the site of high specific capacity.

This means that the lineament length density is more simple and useful in explaining groundwater productivity than the other lineament factors. Consequently, lineament length density can be used as a parameter of a model to determine the monitoring well location in this study.

5 Model Development

Considering the object of water quality monitoring, the monitoring site generally satisfies the following criteria:

Firstly, regional groundwater monitoring wells need to be located at the sites which show a high concentration of quality items, and where they can observe the possibility of water quality exceeding the limits. Secondly, the monitoring site should include the points with the possibilities of upward or downward trends in quality. The preliminary recognition of a trend plays a very important role in groundwater quality management.

Despite the limitations of the weighting and ranking method (Jia et al. 1997), in consideration of simplicity and convenience in monitoring site selection and the restricted and insufficient information available for the calculation of real weighting values, the weighting and ranking method was selected for this study. To normalize the ranking values, the rank sum weight method was used in this study, and its equation is:

$$w_j = \frac{n - r_j + 1}{\sum (n - r_j + 1)} \tag{2}$$

where, w_j is a normalized weight for each jth criterion of quality, and r_j is the rank position for each criterion (Malczewski 1999).

From average concentrations and trend percentages of four quality items for 13 land use types, the normalized weights can be calculated (see Table 2). Because it was not easy to define the relative importance between the mean and the trend, the equal importance for two characteristics (mean and trend) was endowed in this study. The total evaluation result for quality can be acquired using the following;

$$y_q = (S_{w,m}/4 + S_{w,t}/4)/2 \tag{3}$$

where, y_q is the total evaluation value for a target site, $S_{w,m}$ is the sum of normalized weighting values for the means of four quality variables, and $S_{w,t}$ is the sum of normalized weighting values for the trends of four quality variables.

As discussed previously, lineament length density is considered another important factor in determining the location of regional groundwater monitoring stations. These density values can be calculated at each equally spaced point which is a center of unit circle within a study area. To classify the density values, 9 point system is common in statistics and the Natural Break Method was used in this study (Table 3). The Natural Break Method uses Jenk's optimization tool in ArcView GIS software, which minimizes the sum of the variance within each group.

Figure 4 shows a final schematic diagram for a model of the monitoring site selection process including the above three factors. In this case, it is supposed that the importance of groundwater quality monitoring is equal to that of quantity (the

Table 3 Normalized weighting values for nine lineament length density groups using the ranking method

Groups	Straight rank	Weight	Normalized weight
1 (minimum density)	9	1	0.022
2	8	2	0.044
3	7	3	0.067
4	6	4	0.089
5	5	5	0.111
6	4	6	0.133
7	3	7	0.156
8	2	8	0.178
9 (maximum density)	1	9	0.200
Sum		45	

weights are 0.5 and 0.5, respectively) for a convenience of calculation. Of course, the weighting values for quality and quantity can be changed according to the monitoring objectives and priorities by a policy maker or analyzer. ArcView 3.X GIS software was used to illustrate this model.

6 Application to the Milyang District

6.1 Topography and Hydrogeology

The Milyang district was selected for the application of the monitoring site selection model (Fig. 5). The study area is located in the south-eastern region of the Korean peninsula and the area is 802.1 km^2. The northern, western and eastern boundaries surrounding this district show mountainous topographic features including some high mountains with heights over 600 El.m, while the central and southern regions are plain areas which are connected to several rivers and they are mostly below 100 El.m.

The sediments are distributed near the river in the central and southern areas and the average transmissivity is 413.0 m^2/day. On the contrary, the porphyry, granite, and diorite are distributed in the eastern and northern areas and their average transmissivities are about 30 m^2/day for porphyry and 16 m^2/day for granite. Andesite and rhyolite are distributed in the central and western areas and the average transmissivities are about 17 m^2/day for andesite and below 15 m^2/day for rhyolite, respectively. Some sedimentary rocks such as sandstone and shale are partly distributed in the western area and the transmissivity is about 9 m^2/day (Fig. 6; MOCT et al. 2003).

To compare groundwater productivity for each bedrock type, specific capacity data from 97 deep wells were collected (Table 4). The average specific capacities for each hydrogeologic unit do not show any distinct difference and they are lower than 20 m^3/day/m at most wells. This means that aquifer characteristics of the hydrogeologic units are similar in this district and rock type may not be a main factor of groundwater productivity.

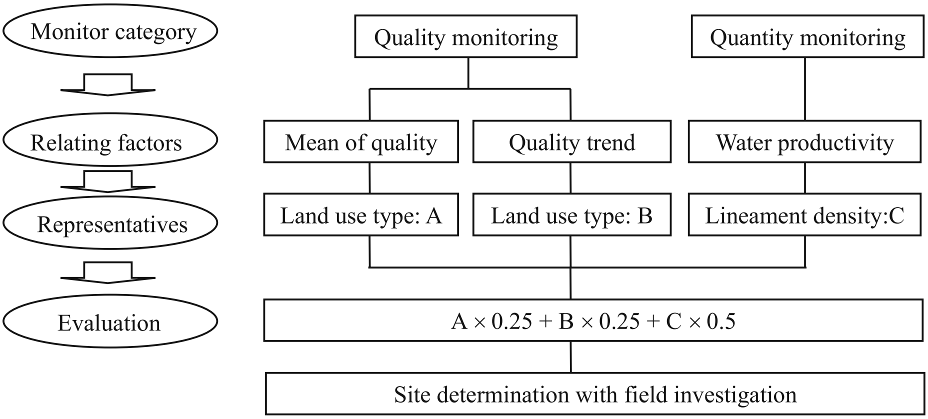


Fig. 4 Proposed procedure to determine the regional groundwater monitoring sites

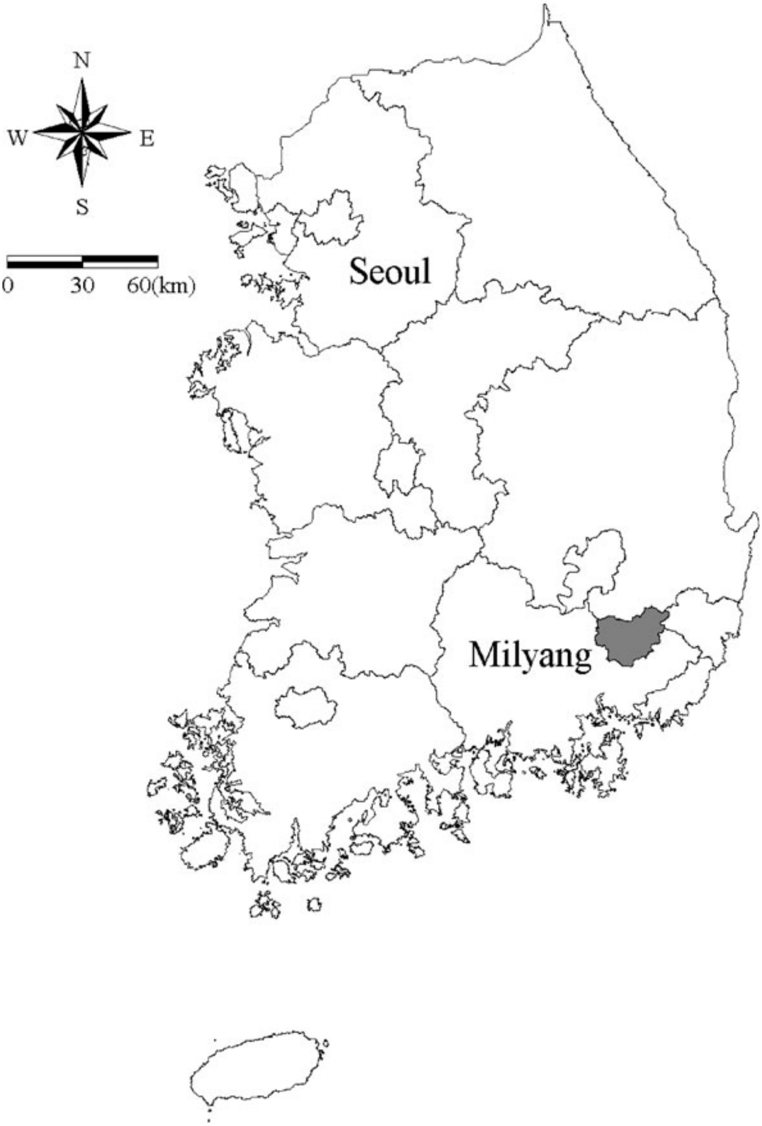


Fig. 5 Location of the Milyang district, South Korea

6.2 Data Preparation

The original land-use map of this district was produced by the Korea National Construction Institute in 1973 and it was modified using a topographic map and a Landsat TM-5 image map ('96.11.22, Row-Path 114–35, 30 × 30 m) and also the supervised classification for six bands was conducted using this satellite image data to make a recent land use map (Fig. 7; MOCT et al. 2003). The six land use types, which are residential urban region, industrial complex, farm production complex, agricultural regions, water and forest, were classified.

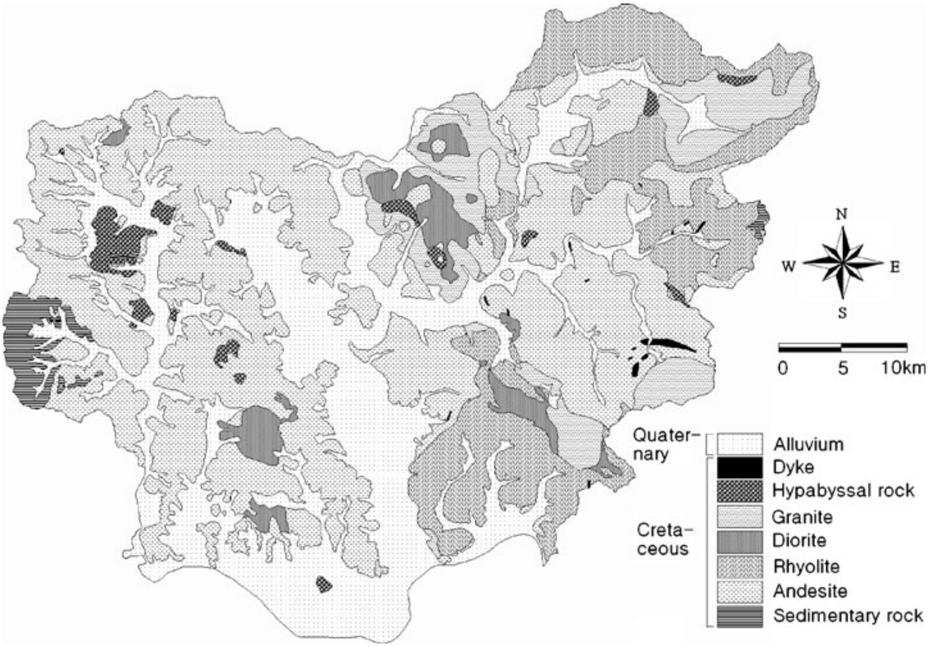


Fig. 6 Hydrogeologic units of Milyang district

Also, the primary extracted lineaments originated from aerial photograph analyses, and these lineaments were modified with the Landsat TM-5 images, shaded relief maps made using DEM data, and a field survey (Fig. 8; Kim et al. 2004b). The systematic grids are constructed for a whole study area to calculate the lineament length density (= lineament length/unit area) within each circle of grid point. The best representative elementary distance of a node (= a radius of circle) is proposed as 1,938 m using the following linear equation which was developed based on the relationship between a lineament length density and the best distance of each node by Kim et al. (2004a).

$$R = 2{,}545.7 - 602.6 \times LLD \tag{4}$$

Table 4 Average specific capacity of deep wells in Milyang district

Hydrogeologic unit	Number of wells	Mean specific capacity (m^3/day/m)	Number of wells for each specific capacity range		
			<20 (m^3/day/m)	20~40	>40
Dyke	–	–	–	–	–
Hypabyssal rock	1	30.9	–	1	–
Granite	17	6.67	16	1	–
Diorite	–	–	–	–	–
Rhyolite	16	5.53	16	–	–
Andesite	59	7.99	55	3	1
Sedimentary rock	4	10.07	3	1	–
Total	97	12.23	90	6	1

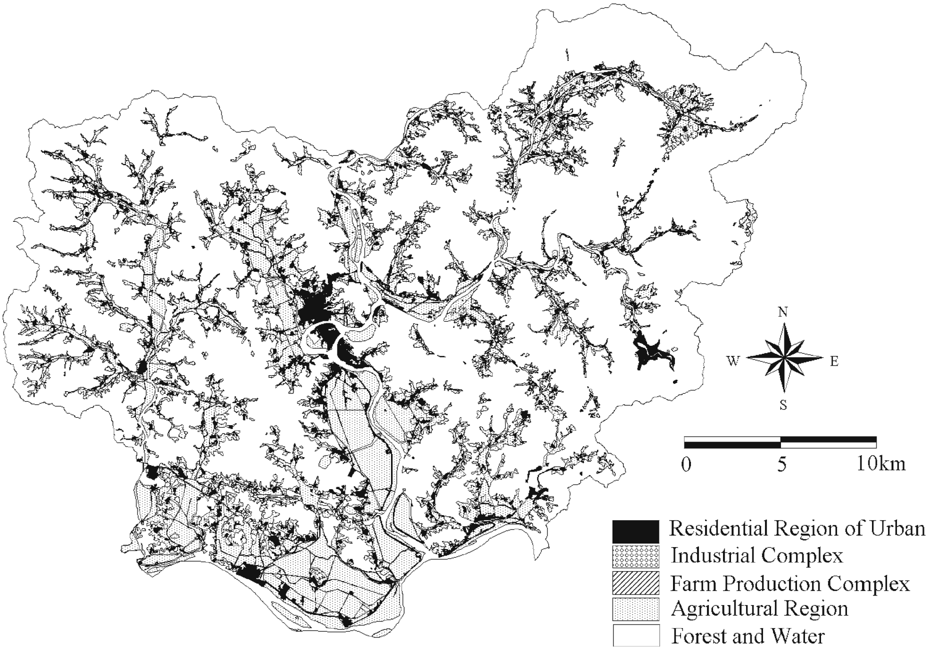


Fig. 7 Land use map of the Milyang district

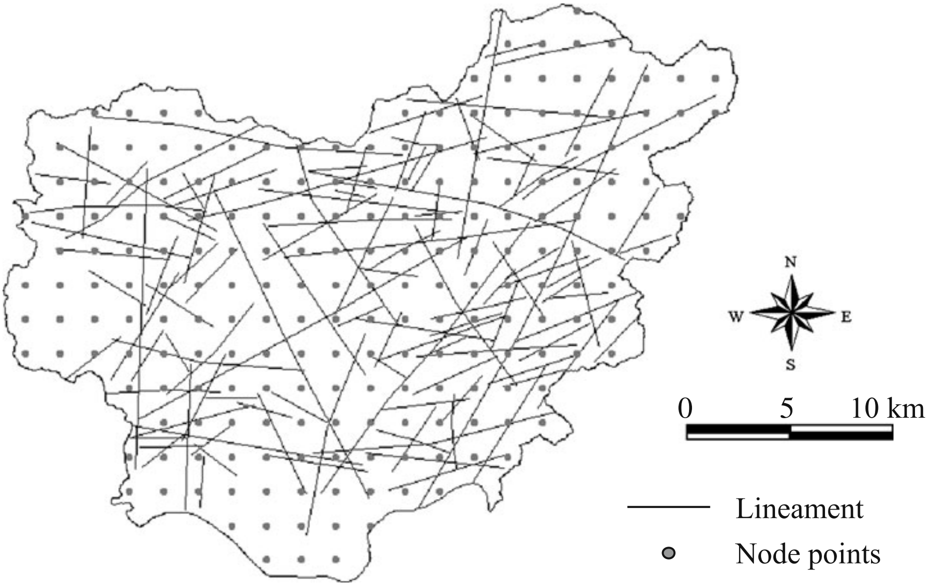


Fig. 8 Lineament map and node distribution within the Milyang district

Here, R is a radius of unit circle (the distance between two nodes) and LLD is a total lineament length density for the whole area.

6.3 Model Application

Table 5 and Fig. 9 show the evaluation results for quality and quantity factors at each node using the proposed GIS model in the previous section. The rank and the circle size explain the priority of groundwater monitoring sites, while considering quantity and quality factors.

6.4 Verification and Limitation

To examine the applicability of this proposed method, the results from two methods, which are the weighting and ranking method of this study and the analytical hierarchy process (AHP) method utilized by Saaty (1980), were compared in this study.

Kim et al. (2007) developed the AHP method for the allocation of regional monitoring wells. The AHP is a technique for multi-criteria decision analysis to support the analysis of complex decisions. It facilitates a quantitative comparison of how effective decision alternatives are in fulfilling multiple criteria relevant to the objective. For allocating the appropriate number of local monitoring stations to a specific district, a method organizing the regional monitoring network was developed based on the analytic hierarchy process using pairwise comparison. Three primary evaluation criteria and eight secondary evaluation criteria determining the optimal number of monitoring stations at specific local districts were selected to reflect each district's hydro-geologic and relevant societal conditions based on an extensive relevant literature review and questionnaires to 93 groundwater experts. The primary evaluation criteria were represented by the main goal of the supplementary groundwater monitoring network and it was explained in detail by the secondary evaluation criteria. The weights of the selected criteria were assigned by the pairwise comparison and pertinent questions to the groundwater experts (Table 6).

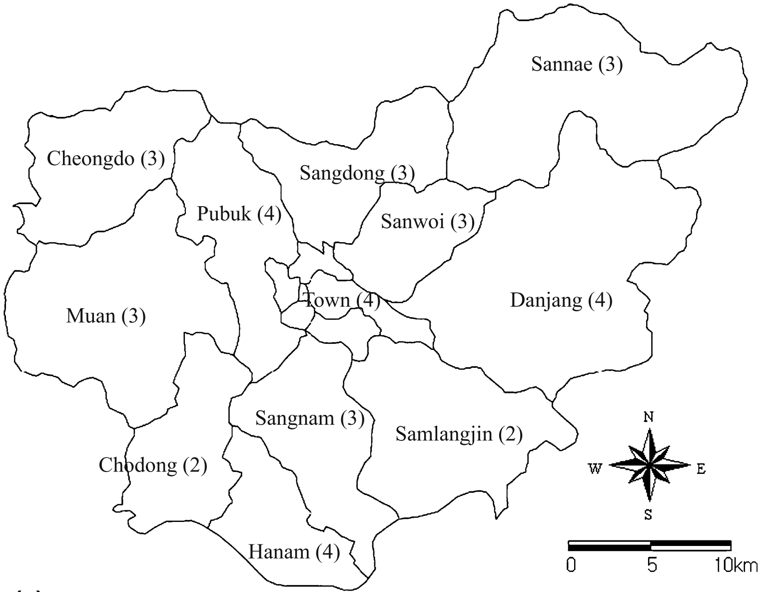
The data related to the eight secondary criteria for each region were collected from the MOCT et al. (2003). On the other hand, the central government had proposed that the total number of groundwater monitoring wells in Milyang district should be at least 38 (MOCT and KOWACO 2002). Using these weights, the optimal number of groundwater monitoring stations for each region (eup and myeon) within the study area was calculated and proposed (Table 7). Here, eup or myeon refers to a county in Korea.

There are some differences between the number of monitoring wells proposed by the AHP method and the weighting and ranking method using GIS tool of this study. As seen in Table 8, the number of sites for monitoring wells was proposed at 36 nodes using the model proposed in this study. The number of total monitoring wells is 38 in this district and two monitoring sites can be selected at other points when considering surface or land use conditions additionally. In this study, Hanam-eup does not meet the monitoring sites criteria as determined by the weighting and ranking method and two sites were allotted to the Hanam-eup area. Also, the number of monitoring wells for each unit area (eup/myeon) is somewhat different between the two methods. The reason is that the density of groundwater wells is too low in Samlangjin-eup and the lineaments can not be defined and drawn in Hanam-eup because that region

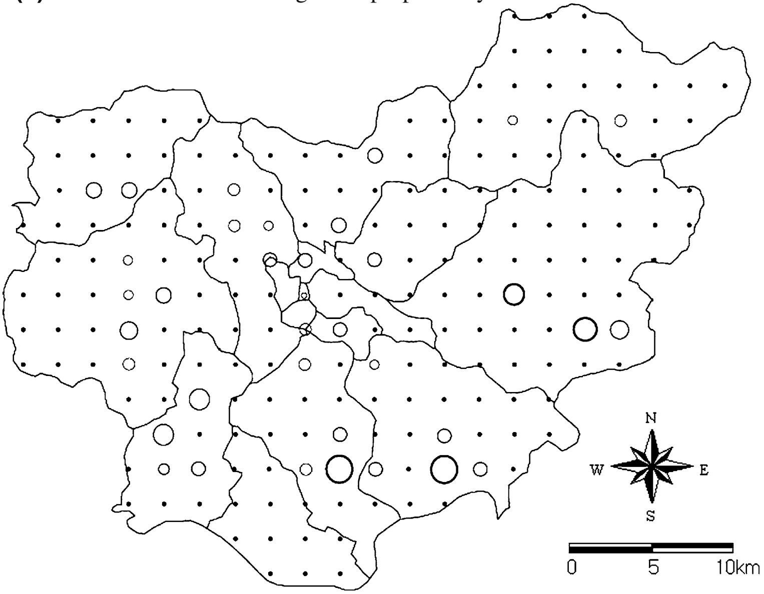
Table 5 Example of quality and quantity evaluations at each node using the weighting method in the Milyang district

Node	*x*	*y*	Evaluation for quality and quantity factors			Total evaluation	Rank
			Mean of quality	Trend of quality	Lineament density		
205	179,665.9	211,761.2	0.383	0.361	0.178	0.2750	1
265	185,479.9	211,761.2	0.383	0.361	0.178	0.2750	1
349	193,231.9	219,513.2	0.383	0.361	0.156	0.2640	3
106	169,975.9	213,699.2	0.240	0.414	0.200	0.2635	4
127	171,913.9	215,637.2	0.240	0.414	0.200	0.2635	4
310	189,355.9	221,451.2	0.240	0.414	0.200	0.2635	4
89	168,037.9	219,513.2	0.383	0.361	0.133	0.2525	7
369	195,169.9	219,513.2	0.383	0.361	0.133	0.2525	7
110	169,975.9	221,451.2	0.240	0.414	0.178	0.2525	9
212	179,665.9	225,327.2	0.240	0.414	0.178	0.2525	9
266	185,479.9	213,699.2	0.240	0.414	0.178	0.2525	9
73	166,099.9	227,265.2	0.240	0.414	0.156	0.2415	12
93	168,037.9	227,265.2	0.240	0.414	0.156	0.2415	12
125	171,913.9	211,761.2	0.240	0.414	0.156	0.2415	12
171	175,789.9	223,389.2	0.383	0.361	0.111	0.2415	12
191	177,727.9	223,389.2	0.383	0.361	0.111	0.2415	12
206	179,665.9	213,699.2	0.240	0.414	0.156	0.2415	12
209	179,665.9	219,513.2	0.383	0.361	0.111	0.2415	12
225	181,603.9	211,761.2	0.240	0.414	0.156	0.2415	12
231	181,603.9	223,389.2	0.240	0.414	0.156	0.2415	12
234	181,603.9	229,203.2	0.240	0.414	0.156	0.2415	12
285	187,417.9	211,761.2	0.240	0.414	0.156	0.2415	12
188	177,727.9	217,575.2	0.383	0.361	0.089	0.2305	23
189	177,727.9	219,513.2	0.383	0.361	0.089	0.2305	23
88	168,037.9	217,575.2	0.240	0.414	0.133	0.2300	25
105	169,975.9	211,761.2	0.240	0.414	0.133	0.2300	25
152	173,851.9	225,327.2	0.240	0.414	0.133	0.2300	25
153	173,851.9	227,265.2	0.240	0.414	0.133	0.2300	25
185	177,727.9	211,761.2	0.240	0.414	0.133	0.2300	25
375	195,169.9	231,141.2	0.240	0.414	0.133	0.2300	25
90	168,037.9	221,451.2	0.240	0.414	0.111	0.2190	31
91	168,037.9	223,389.2	0.240	0.414	0.111	0.2190	31
172	175,789.9	225,327.2	0.240	0.414	0.111	0.2190	31
228	181,603.9	217,575.2	0.240	0.414	0.111	0.2190	31
315	189,355.9	231,141.2	0.240	0.414	0.111	0.2190	31
190	177,727.9	221,451.2	0.383	0.361	0.044	0.2080	36
165	175,789.9	211,761.2	0.240	0.414	0.089	0.2080	37
169	175,789.9	219,513.2	0.240	0.414	0.089	0.2080	37
207	179,665.9	215,637.2	0.240	0.414	0.089	0.2080	37
250	183,541.9	221,451.2	0.240	0.414	0.089	0.2080	37
270	185,479.9	221,451.2	0.240	0.414	0.089	0.2080	37
316	189,355.9	233,079.2	0.240	0.414	0.089	0.2080	37
170	175,789.9	221,451.2	0.296	0.434	0.044	0.2045	43

features a lot of plains and some lineaments are hidden under the land surface. With the exception of these two areas the numbers of monitoring wells proposed by the two methods are very similar.



(a) The number of monitoring wells proposed by the AHP method



(b) The priority of monitoring sites proposed using the weighting method (circle size indicates a priority, the number of circles = 36)

Fig. 9 Evaluation maps for the selection of groundwater monitoring well sites using two different methods in the Milyang district

The AHP method determines only the number of monitoring wells for each eup and myeon area. Therefore, the local government should firmly fix the locations of each monitoring well after additional field investigations for the whole area of

Table 6 Weight values of primary evaluation and secondary evaluation criteria for the AHP method in South Korea

F_i	Weights (FWi)	F_{ij}	Total score (SF_{ij})	Mean of total score (MF_{ij})	Weights (FW_{ij})
F_1	0.38	F_{11}	785	8.53	0.46
		F_{12}	752	8.17	0.36
		F_{13}	657	7.14	0.18
F_2	0.34	F_{21}	674	7.25	0.16
		F_{22}	771	8.29	0.30
		F_{23}	862	9.27	0.54
F_3	0.28	F_{31}	779	8.38	0.66
		F_{32}	692	7.44	0.34

F_i *i*th primary evaluation criterion, F_1 degree of development and amount of groundwater use, F_2 necessity of monitoring whether groundwater is contaminated or not and the contamination is processing, F_3 degree of dependency on groundwater for households, FW_i weight of *i*th primary criterion, F_{ij} *j*th secondary evaluation criterion constituting *i*th primary evaluation criterion, F_{11} number of groundwater wells, F_{12} density of groundwater wells (number/km^2), F_{13} amount of groundwater use (m^3/year), F_{21} number of drinkable wells, F_{22} number of contamination source facilities, F_{23} number of contaminated wells, F_{31} number of households using only groundwater, F_{32} amount of groundwater use for drinking (m^3/year), SF_{ij} total score of *j*th secondary criterion of *i*th primary criterion, MF_{ij} mean value of SF_{ij}, FW_{ij} weight of *j*th secondary criterion of *i*th primary criterion

each eup and myeon. On the other hand, the weighting and ranking method using GIS proposes the importance and priority of groundwater monitoring sites using a weighting value for each node. Therefore, this method is more concrete and specific because it also suggests the order of the monitoring necessity at each node. Additionally, the target area for a field investigation prior to the determination of well site can be smaller; from eup/myeon (average 66.8 km^2) to a unit circle (11.8 km^2 in this case).

To assess a reliability of this model result, RMSE (root mean square error) between the results of AHP method and weighting method was calculated as 1.58

Table 7 Proposed number of groundwater monitoring wells calculated using the AHP method in the Milyang district

Regions	F11	F12	F13	F21	F22	F23	F31	F32	Proposed number of wells
Town	391	13.5	2,393,345	211	129	–	58.2	235,363	4
Samlangjin	100	1.3	1,149,344	59	218	–	58.7	291,800	2
Hanam	472	12.7	1,219,650	49	129	–	95.2	109,000	4
Danjang	103	0.7	1,616,352	72	434	–	100.0	516,960	4
Muan	59	0.6	1,031,544	21	578	–	100.0	198,100	3
Pubuk	199	3.6	2,232,250	46	323	–	100.0	532,820	4
Sannae	65	0.6	1,126,349	44	365	–	100.0	312,600	3
Sanwoi	58	1.6	1,338,235	25	164	–	100.0	168,500	3
Sangnam	96	1.7	2,431,225	56	217	–	100.0	504,960	3
Sangdong	227	4.4	712,951	137	234	–	100.0	230,360	3
Cheongdo	41	0.7	616,531	18	343	–	100.0	215,700	3
Chodong	66	1.4	1,017,250	36	336	–	59.4	324,560	2

Table 8 Comparison of the number of groundwater monitoring wells calculated by the AHP method and the weighting method

Regions	By the AHP method	By the weighting method
Total	38	36 (38)
Town	4	4
Samlangjin-eup	2	5
Hanam-eup	4	0 (2)
Danjang-myeon	4	3
Muan-myeon	3	5
Pubuk-myeon	4	4
Sannae-myeon	3	2
Sanwoi-myeon	3	1
Sangnam-myeon	3	4
Sangdong-myeon	3	2
Cheongdo-myeon	3	2
Chodong-myeon	2	4

and it is lower than 2. This means the number of monitoring wells estimated using the proposed model is reasonable because the range of the number of monitoring wells is from two to five except one region (Sanwoi-myeon).

Of course, some limitations exist with the weighting and ranking method. The extraction and interpretation of lineaments using remote sensing is very difficult in wide plain areas like Hanam-eup and it also contains many uncertainties and differences according to the interpreters and photographing date. However, if the lineaments originated from fractures are extracted thoroughly and cautiously and this method is used together with the AHP method, optimal monitoring sites can be easily selected and the period for additional field investigations can be reduced. Additionally, if most of area is composed of stratified rocks such as shale and sandstone or most of lineaments are distributed along one or two dominant directions, more detailed study for hydraulic features of stratification and weathering zone and tectonic history including stress and strain characteristics may be required. Fortunately, the rocks of this study area are generally massive and the lineaments show a moderately uniform distribution without any strong directional feature.

Additionally, the groundwater wells may have some errors because it is not easy to get an exact data on well productivity, water quality data, lineament location, and many factors, which were used in constructing a model. Some abnormal values or outliers can exist because some wells may be located at any specific condition and therefore statistical approach was introduced in this study.

7 Conclusion and Discussion

As the purpose of the regional groundwater monitoring station is to observe both quality and levels of groundwater, it is efficient to establish the monitoring station at a single site to observe the two items simultaneously. The weighting and ranking method is used for the development of a site selection model. The site selection model, with respect to quality monitoring, uses 4 quality items in Korea: Cl, COD, EC, and NO_3N. The evaluation of monitoring sites for groundwater quality can be calculated by summing up the weighting values of the 4 quality items for the 13 land use types. The same method is adapted in weighting the lineament length density regarding to groundwater quantity. The combination model considering these two factors; quality (land use) and quantity (lineament length density) are developed in this study. By applying the model to the Milyang district, it is revealed that this weighting and ranking method is applicable for selecting the location of monitoring sites and it is more concrete and simple to use than the AHP method. Additionally, a weighting and ranking method using GIS tools can reflect the importance and priority of groundwater monitoring sites by using a weighting value for each node. For these proposed monitoring sites, the local governments can do further investigations to determine whether they are adequate as groundwater monitoring sites in consideration of accessibility, maintenance, physical or chemical conditions within the proposed sites.

References

Andricevic R, Foufoula-Georgiou E (1991) A transfer function approach to sampling network design of groundwater contamination. Water Resour Res 27(10):2759–2769

Ben-Jemaa F, Marino MA, Loaiciga HA (1995) Sampling design for contaminant distribution in lake sediments. J Water Resour Plan Manage ASCE 121(1):71–79

Blickwedel RS, Wood CR (1988) Relation of ground-water quality to land use in the Philadelphia—Camden, New Jersey Area. US Geological Survey Water Resources Investigations Rep. 88–4211, US Department of the Interior, Denver, pp 58

Briz-Kishore BH (1993) Assessment of yield characteristics of granitic aquifers in South India. Groundwater 31:921–928

Daniel CC (1989) Statistical analysis relating well yield to construction practices and siting of wells in the Piedmont and Blue Ridge provinces of North Carolina. US Geological Survey Water Supply Paper 2341-A, USGPO, Denver, Colorado, pp 27

de Olivares GH (1998) Cost effective groundwater quality sampling network design. PhD thesis, University of Vermont, Vermont, pp 158

EPA (1990) Handbook: ground water volume 1: groundwater and contamination, EPA/625/6-90/016a. US Environmental Protection Agency, Washington, DC, pp 144

EPA (1994) Handbook: ground water and wellhead protection, EPA/625/R-94/001. US Environmental Protection Agency, Washington, DC, pp 267

Gibbons RD (1991) Statistical tolerance limits for groundwater monitoring. Groundwater 29: 563–570

Gibbons RD (1994) Statistical methods for groundwater monitoring. Wiley, New York, pp 286

Gilliom RJ, Alley WM, Gurtz ME (1995) Design of the national water quality assessment program: occurrence and distribution of water quality condition. US Geological Survey Circular 1112. US Geological Survey, Sacramento, pp 28

Gustafsson P (1994) Spot satellite data for exploration of fractured aquifers in a semi-arid area in southeastern Botswana. Appl Hydrogeol 2:9–18

Hudak PF, Loaiciga HA, Schoolmaster FA (1993) Application of geographic information systems to groundwater monitoring network design. Water Resour Bull 29:383–390

Jia J, Fisher GW, Dyer JS (1997) Attribute weighting methods and decision quality in the presence of response error: a simulation study. The University of Texas at Austin, Texas, pp 43

Kim GB (2005) Nationwide monitoring and assessment of groundwater in Korea. PhD thesis, Seoul National University, Seoul, Korea, pp 391

Kim GB, Lee JY, Lee KK (2004a) Application of representative elementary area (REA) to lineament density analysis of groundwater implications. Geosci J 8(1):27–42

Kim GB, Lee JY, Lee KK (2004b) Construction of lineament maps related to groundwater occurrence with ArcView and Avenue™ scripts. Comput Geosci 30:1117–1126

Kim JW, Lee JY, Yi MJ, Kim GB, Won JH, Lee KK (2007) Allocating local groundwater monitoring stations for South Korea using an analytic hierarchy process. Hydrogeol J 15:615–632

Knopman DS, Hollyday EF (1993) Variation in specific capacity in fractured rocks, Pennsylvania. Groundwater 31:135–145

Lee YM, Ellis JH (1996) Comparison of algorithms for nonlinear integer optimization: application to monitoring network design. J Environ Eng 122(6):524–531

Lee JY, Yi MJ, Yoo YK, Ahn KH, Kim GB, Won JH (2007) A review of the National Groundwater Monitoring Network in Korea. Hydrol Proced 21:907–919

Loaiciga HA, Charbeneau RJ, Everett LG, Fogg GE, Hobbs BF, Rouhani S (1992) Review of groundwater quality monitoring network design. J Hydraul Eng 118(1):11–37

Mabee SB, Hardcastle KC, Wise DU (1994) A method of collecting and analyzing lineaments for regional-scale fractured-bedrock aquifer studies. Groundwater 32:884–894

Malczewski J (1999) GIS and multicriteria decision analysis. Wiley, New York, pp 178

Meyer PD, Ranjitham R, Valocchi AJ, Eheart JW (1989) Groundwater monitoring network design using coupled Monte Carlo simulation and optimization. In: Proceedings of the 1989 national conference on hydraulics engineering. ASCE, New York, pp 404–409

MOCT (Ministry of Construction and Transportation) (2002) Master plan of groundwater in Korea. Seoul, pp 112

MOCT (Ministry of Construction and Transportation) and KOWACO (Korea Water Resources Corporation) (2002) Installation and management of local groundwater monitoring network: research report. Seoul, Korea, pp 271

MOCT (Ministry of Construction and Transportation) and KOWACO (Korea Water Resources Corporation) (2003a) Report for basic groundwater survey in Cheonan region. Seoul, Korea, pp 400

MOCT (Ministry of Construction and Transportation) and KOWACO (Korea Water Resources Corporation) (2003b) Report for basic groundwater survey in Pohang region. Seoul, Korea, pp 502

MOCT (Ministry of Construction and Transportation), KOWACO (Korea Water Resources Corporation), KORES (Korea Resources Corporation) (2003) Report for basic groundwater survey in Milyang region. Seoul, Korea, pp 230

MOE (Ministry of Environment) (2002) Plan for the management of groundwater quality monitoring stations in 2002. Seoul, Korea, pp 30

Neves MA, Morales N (2007) Structural control over well productivity in the Jundiai River Catchment, Southeastern Brazil. An Acad Bras Cienc 79:307–320

Park YJ, Lee KK, Kim JM (2000) Effects of highly permeable geological discontinuities upon groundwater productivity and well yield. Math Geol 32:605–618

Pope LM, Bruce BW, Rasmussen PP, Millagan CR (2002) Quality of shallow ground water in areas of recent residential and commercial development. US Geological Survey Water Resources Investigation Report 02-4228, US Department of the Interior, Lawrence, pp 67

Risser DW, Siwiec SF (1996) Water quality assessment of the lower Susquehanna river basin: Pennsylvania and Maryland: environmental setting. US Geological Survey Water Resources Investigation Report 94-4245, US Geological Survey, Denver, pp 70

Robinson JL (2002) Ground water quality beneath an urban residential and commercial area, Montgomery, Alabama, 1999–2000. USGS Water Resources Investigation Report 02-4052, US Department of the Interior, Montgomery, pp 37

Saaty TL (1980) The analytic hierarchy process: planning setting priorities, resource allocation. McGraw-Hill, New York, pp 287

Sander P (2007) Lineaments in groundwater exploration: a review of applications and limitations. Hydrogeol J 15:71–74

Sander P, Chesley MM, Minor TB (1996) Groundwater assessment using remote sensing and GIS in a rural groundwater project in Ghana: lessons learned. Hydrogeol J 4:40–49

Sander P, Minor TB, Chesley MM (1997) Ground water exploration based on lineament analysis and reproducibility tests. Groundwater 35:888–894

Siddiqui SH, Parizak RR (1971) Hydrogeologic factors influencing well yields in folded and faulted carbonate rocks in central Pennsylvania. Water Resour Res 7:1295–1312

Sidle WC, Lee PY (1995) Estimating local ground water flow conditions in a granitoid: preliminary assessments in the Waldoboro pluton complex, Maine. Groundwater 33:291–302

Sloto RA (1987) Effect of urbanization on the water resources of eastern Chester County, Pennsylvania. US Geological Survey Water Resources Investigations Report 87-4098, US Department of the Interior, Denver, pp 131

Sophocleous M, Paschetto JE, Olea RA (1982) Groundwater network design for Northwest Kansas using the theory of regionalized variables. Groundwater 20:48–58

Storck P, Eheart JW, Valocchi AJ (1997) A method for the optimal location of monitoring wells for detection of groundwater contamination in three-dimensional heterogeneous aquifers. Water Resour Res 33(9):2081–2088

US Geological Survey (1999) The quality of our nation's water—nutrients and pesticides. US Geological Survey Circular 1225, US Department of the Interior, Reston, pp 82

Van Duijvenbooden, Taat WJ, Gast LFL (1985) The national groundwater quality monitoring network: final report of the installation. Bilthoven report no. 840382001, National Institute of Public Health and Environmental Protection, The Netherlands

Vecchia AV (2003) Water-quality trend analysis and sampling design for streams in North Dakota, 1971–2000. USGS Water Resources Investigation Report 03–4094, US Department of the Interior, Bismarck, pp 73

Waller BG (1983) Effects of land use on ground water quality in the east Everglades, Dade county, Florida. USGS Water Resources Investigations 82–4093, US Department of the Interior, Tallahassee, pp 67