Determining the condition of groundwater in evaluating the need for corrective measures: a case for the national groundwater-monitoring network in South Korea

Jin-Yong Lee · Sang-Ho Moon · Kang-Kun Lee

Abstract Groundwater data (water level, electrical conductivity (EC) and temperature) have been collected since 1995 from the national groundwater-monitoring stations in South Korea. Recently, substantial groundwater-level decline and deterioration of groundwater quality were reported at several stations. Relevant authorities undertook to investigate the groundwater hazards and to devise mitigation measures for selected monitoring stations. However, there were no criteria to determine the status of the groundwater level and EC, compared with historic data. A methodology is presented, which defines the groundwater condition. Using the suggested criteria, water level and EC data are classified into normal, watch and warning levels, leading to different administrative measures and technical investigations. The primary criterion compares the observed values for the evaluation year (e.g. 2003) and the historic values of normal years preceding the evaluation year (e.g. 1996–2002), using box plots. The secondary criterion uses variation trends of the values with the aid of parametric and non-parametric trend tests. Final decisions are dependent on scores assigned to each test. According to the criteria suggested, detailed investigations and mitigation measures for water level decline are required for seven stations and those for water quality are needed for 18 stations because they reside within the warning classification.

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J.-Y. Lee (✉)
Department of Geology,
Kangwon National University,
Chuncheon, 200-701, Republic of Korea
e-mail: hydrolee@kangwon.ac.kr
Tel.: +82-33-2508551
Fax: +82-33-2428550

S.-H. Moon
Groundwater & Geothermal Resources Division,
Korea Institute of Geoscience & Mineral Resources (KIGAM),
Daejeon, 305-350, Republic of Korea

K.-K. Lee
School of Earth and Environmental Sciences,
Seoul National University,
Seoul, 151-742, Republic of Korea

Résumé Des données hydrogéologiques (niveau piézométrique, conductivité électrique (CE) et température) ont été collectées depuis 1995 à partir du réseau national de stations de surveillance des eaux souterraines de la Corée du Sud. Récemment, une baisse substantielle du niveau de l'eau souterraine et une détérioration de la qualité de l'eau ont été signalées sur plusieurs stations de surveillance. Les autorités compétentes ont entrepris d'étudier les risques pour les eaux souterraines et de trouver des mesures de mitigation pour les stations de surveillance sélectionnées. Cependant, aucuns critères n'existaient permettant de déterminer le statut du niveau piézométrique et de la conductivité électrique en comparaison des données historiques. Une méthodologie est présentée et définie les conditions hydrogéologiques. A l'aide des critères proposés, les données de niveaux piézométriques et de conductivités électriques sont classées suivant les niveaux dits normaux, niveaux à surveiller et niveaux d'alerte, conduisant à poursuivre des mesures administratives et des investigations techniques différentes. Le premier critère compare, grâce à des boites à moustache, les valeurs observées pour les années d'évaluation (1996–2002 par exemple). Le deuxième critère utilise les tendances de variation des valeurs à l'aide de tests de tendance paramétriques et non paramétriques. Les décisions finales dépendent des résultats de chaque test. D'après les critère suggérés, sept stations nécessitent des mesures d'investigations détaillées et de mitigation pour la baisse du niveau d'eau, et 18 stations nécessitent des mesures pour la qualité de l'eau car elles se situent dans une zone classée en alerte.

Resumen En las estaciones nacionales de aguas subterráneas de Corea del Sur, se han recogido datos de agua subterránea (niveles piezométricos, conductividad eléctrica (CE) y temperatura) desde 1995. Recientemente, se ha observado en algunas estaciones que el nivel de agua subterránea ha descendido sustancialmente y que se ha producido un deterioro de la calidad de la misma. Las autoridades competentes han decidido emprender la investigación de los riesgos en aguas subterráneas y tomar medidas de mitigación para estaciones seleccionadas. Sin embargo, no había criterio para determinar el estado del nivel piezométrico y la CE, comparados con los datos históricos. Se presenta una metodología que define las condiciones de las aguas subterráneas. Utilizando los

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criterios propuestos, los datos de nivel piezométrico y de CE se han clasificado como normales, en vigilancia o preocupantes, atendiendo a diferentes medidas administrativas e investigaciones técnicas. El criterio primario compara los valores observados para el año de evaluación (por ejemplo, 2003) y los valores históricos de años normales anteriores a este año de evaluación (por ejemplo, 1996–2002), mediante gráficos de caja. El criterio secundario utiliza tendencias de variación de los valores con la ayuda de tests de tendencias paramétricas y no paramétricas. Las decisiones finales dependen de los resultados asignados a cada test. De acuerdo con los criterios sugeridos, se necesitan investigaciones detalladas y medidas de mitigación para el descenso de los niveles en siete estaciones y lo mismo para la calidad del agua en 18 estaciones, que se encuentran en niveles preocupantes.

Keywords Groundwater monitoring · Electrical conductivity · Watch and warning levels · South Korea · Groundwater hazard

Introduction

Since the 1960s, withdrawal of groundwater has drastically increased in South Korea. Groundwater development without proper control and management has resulted in substantial water level decline (groundwater depletion), land subsidence, seawater intrusion and water quality deterioration in the country (Kim et al. 1995; Kim 2005; Lee et al. 2007a). In order to tackle the various groundwater hazards and to sustain the valuable groundwater resources, the South Korean government established the "Groundwater Law" in 1994, in which regulations on groundwater development, basic groundwater surveys, long-term groundwater management plans, and groundwater-monitoring plans were included (Kim et al. 2007). According to the law, central government, namely the Ministry of Construction and Transportation (MOCT), should organize and operate a national groundwater-monitoring network (NGMN) composed of over 320 monitoring stations, which cover the entire country.

KOWACO (Korea Water Resources Corporation, now K-Water), an affiliated organization of MOCT, was in charge of installation and operation of the NGMN. It initiated the installation of the monitoring stations in 1995 and has constructed, on average, 30 monitoring stations every year (Lee et al. 2006a). The total number of the monitoring stations reached 320 in 2005 (Fig. 1), with a density of about one station per 312 km^2 (0.32/100 km^2). The geology of the country is mainly comprised of granite, gneiss, schist, limestone and metamorphic sedimentary rocks in the Precambrian and the Palaeozoic eras while geologic layers in the Cenozoic era are rare (Lee et

Fig. 1 Locations of the national groundwater-monitoring stations in South Korea. Only stations described in this report are marked

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al. 2007a). Most of the rocks show good hydraulic connection within only a small area, and subsequently require many more groundwater-monitoring stations than rocks in areas showing excellent hydraulic connection to a wider extent.

In most cases, two monitoring wells (shallow (~15 m) and deep (~80 m)) exist at each monitoring station and an integrated monitoring probe, measuring water level, electrical conductivity (EC), and water temperature, is installed in each well. Real-time groundwater data are automatically transferred from the station to a host server in KOWACO. From 1995 (start of the NGMN) to 2004, there had been no series review or analysis of the collected groundwater data such as trend analysis and time-series analysis, because interest of relevant authorities was mainly focused on construction of the monitoring stations within the schedule. Only basic statistics were calculated and reported.

Recently, MOCT issued an order for KOWACO to investigate six national groundwater-monitoring stations (NGMS) that have experienced abnormally large water-level decline (3–45 m) over a short period (2–3 years) and to devise a mitigation measure for the substantial decline. Interestingly, selection of the monitoring stations (for the detailed investigation) showing so-called "abnormal water level decline" was mainly based on intuitive evaluation of the groundwater hydrograph of each station (well) and simple calculation for water-level variation (highest level-lowest level) for the entire monitoring period. The monitoring stations (wells) showing a water-level decline over 3 m were simply selected for the detailed investigation. However, the above selection criterion was considered to be somewhat arbitrary. Consequently, a consensus among relevant authorities and hydrogeologists in the country has arisen such that quantitative criteria are necessary to determine whether the water level or EC is normal or abnormal compared with preceding values. In other words, has the groundwater level abnormally dropped or is EC abnormally elevated? Based on the quantitative evaluation of the water-level decline and the increase of EC, relevant administrative or technical measures will be undertaken.

The main objectives of the national groundwater-monitoring network in South Korea are to monitor regional and long-term groundwater variation on a national basis and to establish and revise a national plan for sustainable groundwater development using the monitored groundwater data (Lee et al. 2007a). In addition to these main purposes, each groundwater-monitoring station is used to monitor and represent the local groundwater condition and its variation in the surrounding area, and to identify potential groundwater hazards by analyzing the groundwater data. "Groundwater hazard" in this study indicates groundwater problems that can be caused by water-level decline and groundwater contamination of anthropogenic or natural origin, and which include groundwater depletion, land subsidence, seawater intrusion and abandoned wells. This groundwater hazard may possibly be predicted by regularly analyzing water level, EC and other water quality parameters.

Variation in groundwater levels is dependent on various natural and artificial factors including rainfall and pumping for irrigation or underground building construction (Peters et al. 2005; Lee et al. 2007b). Variation amplitude and pattern are different according to the hydrogeologic settings and topographic conditions. Even though the variations or symptoms (water-level decline or water quality deterioration) at different stations may be the same, recognition of the groundwater hazard and its corresponding remedial measures will vary considerably according to societal and economic conditions of the local province, as well as the hydrogeologic conditions. Consequently, it is difficult to define the groundwater hazard by use of a common quantitative method based on the magnitude and the pattern of the variation. Therefore, the present values must be compared with the historically monitored values. As stated above, the national groundwater-monitoring stations have been constructed since 1995 and the oldest stations have accumulated groundwater data for about 10 years.

For the development of methods to evaluate the conditions of the groundwater level and EC, previous relevant studies or case studies were reviewed. The most useful and appropriate applications were found in the USA (Alley 1985; Schreffler 1997; Taylor and Alley 2001; Prinos et al. 2002; US Geological Survey 2005). In Pennsylvania, USA, groundwater levels are used as one of the indicators of drought; the Pennsylvanian groundwater-level monitoring network has been operated since 1931 and the state government established guidelines regarding water levels for drought control using historic water-level data and the 30-day moving average of current daily water levels. The final decision on the drought condition is dependent on stream flow, precipitation, reservoir level, and the Palmer drought index (Alley 1985), as well as the groundwater levels, and it is classified into four conditions including normal, drought watch, drought warning and drought emergency. Depending on each condition, various relevant measures are undertaken to control water supply.

In Texas, USA, analysis of the water-level measurements is conducted annually and an acceptable annual decline rate is set to prevent groundwater depletion (PGCD 2004). The acceptable decline rates are different with each district depending on aquifer characteristics and groundwater use. To determine the acceptable decline, the last 10-year groundwater-level data, current water levels and the 5-year moving average are used. In one case, the acceptable decline is set at 1.25% of the saturated thickness of the aquifer, which is revised every 5 years. Meanwhile, Pernía and Corral (2001) suggested a piezometric situation index (PSI) to evaluate change in groundwater storage of aquifers using maximum and minimum head levels of preceding and present periods. All these previous cases provided useful information for the development of quantitative methods to urgently determine the condition of groundwater at the groundwater-monitoring stations in South Korea.

Methods

Primary criteria

The primary method of determining the condition of groundwater is to use the groundwater value itself (water level or EC in this case). An 'evaluation year' is established, to which the 'current' condition is related. Statistical characteristics (such as 1st and 3rd quartiles) are derived from the groundwater data of preceding years (e.g. 1996–2002) and the present values of the evaluation year (e.g. 2003) are compared with the statistics. In this method, all groundwater data for the whole monitoring period (after monitoring well installation) or those for some recent years may be used for reference. If the period of the reference data is too long, recent variation trends may not be revealed.

Box plot and annual arithmetic mean (B-1 method)

In this method, historic daily groundwater data of the years preceding the evaluation year are plotted in a box plot and the annual arithmetic mean value (single value of water level or EC) of the evaluation year is superimposed on the box plot (Fig. 2). The mean value is compared with the statistics (percentiles) of the data for preceding years. In this study, 5 step percentiles (<10, 10–<25, 25–75, >75–90, >90 percentile) are adopted. Based on the data point of the evaluation year in the box plot, the groundwater conditions are classified into three levels (normal, watch, warning; Table 1). In cases where the evaluation year water-level mean is higher than the 90th percentile water level of previous years, the groundwater condition is classified as "normal (high)". In some cases, abnormally high groundwater levels may be a problem; elevated water levels can pose a threat to the stability of underground buildings (Lawrence et al. 1998). However,

Table 1 Classification of groundwater condition with data statistics

Statistics (percentile)	Classification	
	Water level	Electrical conductivity
<10	Warning	Normal (low)
10~<25	Watch	
25~75	Normal	Normal
>75~90	Normal (high)	Watch
>90		Warning

in this case, abnormal low water levels compared with historic normal values only are considered to be a groundwater problem (watch or warning levels). In contrast, higher EC concentrations signify a potential groundwater problem such as seawater intrusion and anthropogenic contamination. Consequently, for EC, the classification is reversed compared with water level (see Table 1).

In application of this method, data of abnormal years (<25th percentile for water level or >75th percentile for EC) are excluded from the reference box plot. This method (B-1 method) is the simplest in application. The evaluation can be determined easily and visually; however, the box plot may be largely affected by outliers or missing values, which are inevitable in automatic monitoring systems (Yi et al. 2005). Furthermore, if there are abnormal values in the evaluation year, the single mean value may be biased, which can result in an inappropriate classification result.

Monthly box plot and daily groundwater data (B-2 method)

In the previous method (B-1 method), daily groundwater data for normal years preceding the evaluation year (single box plot) and the annual mean value (single value) of the evaluation year were used. In this method, daily data for each month of preceding years are used to construct 12 box plots and the daily groundwater data for the

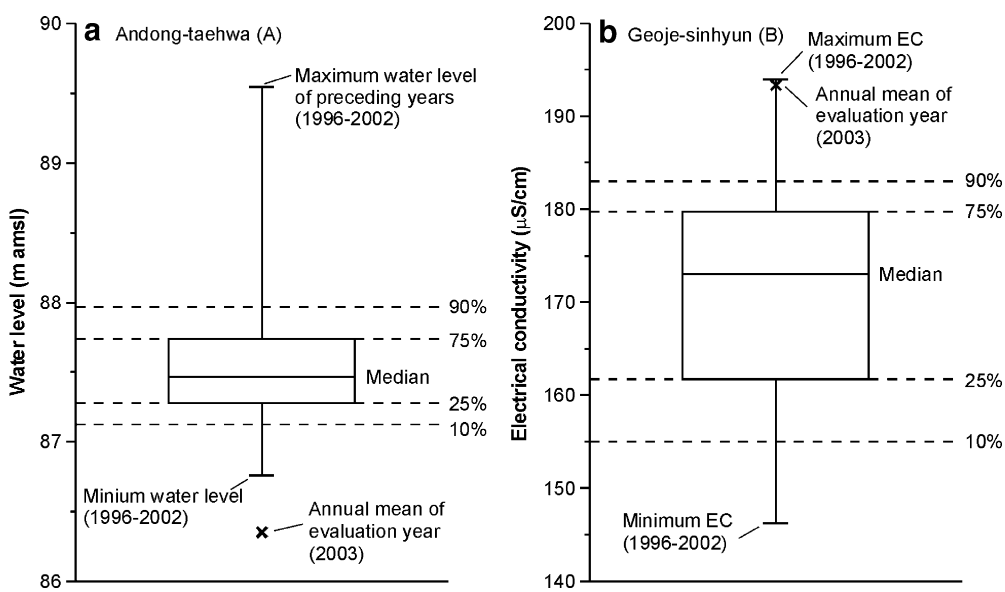

Fig. 2 Box plots of daily groundwater data of preceding years (1996–2002) and annual mean of the evaluation year (2003) for **a** the shallow well (*A*) at Andong-taehwa and **b** the deep well (*B*) at Geoje-sinhyun. The two stations are problematic with respect to water level and electrical conductivity

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evaluation year are superimposed on the box plots (Fig. 3). Unlike the previous method, the evaluation of the groundwater condition is neither straightforward nor easy in this method. So for the quantitative evaluation, a scoring system is recommended based on the statistics of the monthly box plots. For water levels, the lowest value in 1 month is selected as the representative value for that month, and then, according to the position of this representative value in the box plot, a score is assigned to each month (Table 2). For EC data, the highest EC value is selected as the representative value in each month. Using the monthly box plot and the monthly representative value, a score is assigned to every month for water level and for EC. If there are no observed groundwater values (data are missing) in a certain month, an intermediate score (3 in this case) can be assigned. The scoring system may be changed with different cases. In the same manner, scores can be assigned to all 12 months (see Fig. 3) for both water level and EC. Adding the 12 scores together results in a total score. The total score ranges between 12 and 60. This total score can be divided into five groups. According to this division, the groundwater condition can be determined in the same way as the previous method B-1 (Table 3).

Secondary criteria

The secondary methods use variation trends of the groundwater data, instead of the values themselves. There are two common methods to evaluate trends: simple parametric linear regression and non-parametric trend analyses (Kim 2005; Lee et al. 2006b). Representative non-parametric trend analyses include Sen's trend test (Sen 1968) and the Mann-Kendall trend test (Mann 1945; Kendall 1975). In the trend test, data of all monitoring years or those of a few recent years including the evaluation year may be used. However, any obvious trend (decreasing or increasing) does not necessarily imply certain groundwater problems or hazards. Results of these trend tests can be used as secondary evaluation criteria.

Table 2 Scoring system for the B-2 method

Statistics (percentile)	Scores	
	Water level	Electrical conductivity
<10	1	1
10~<25	2	2
25~75	3	3
>75~90	4	4
>90	5	5

Parametric trend test (PT-method)

Times series forecast is based on the statistical trend of data for a certain period. The simplest evaluation method involves fitting the observed data to an appropriate straight line. The linear regression line is established using a least-square method. The goodness of the fit is evaluated by a coefficient of determination (r^2), which is variance (SSR) explained by the regression line, divided by the total variance (SST):

$$SST = \sum (y_i - \bar{y})^2 = \sum (y_i - \hat{y}_i)^2 + \sum (\hat{y}_i - \bar{y})^2 = SSE + SSR \quad (1a)$$

$$r^2 = SSR/SST = 1 - SSE/SST \quad (1b)$$

where $\bar{y}$ is the mean of observed values (y_i) and $\hat{y}_i$ are values estimated using the regression line. However, this method does not treat missing values or outliers appropriately, which can largely affect the trend analysis result (Salmi et al. 2002). In addition, the coefficient of determination does not give any information about confidence level of the trend determination.

For practical application, however, the simple linear regression was adopted in this study using two methods. The first method uses linear regression on a daily basis

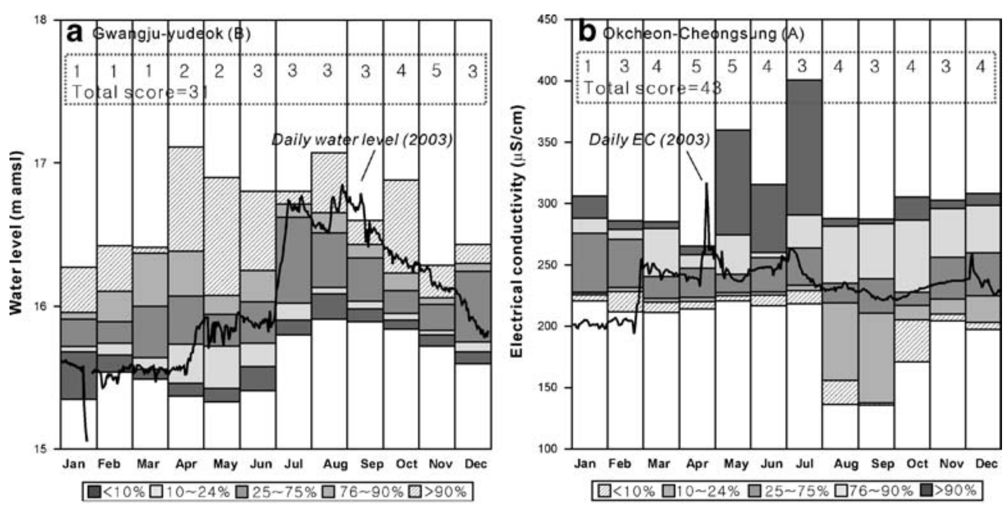

Fig. 3 Box plots of daily groundwater data for each month of preceding years (1996–2002) and daily groundwater data of the evaluation year (2003) for **a** the deep well (*B*) at Gwangju-yudeok, and **b** the shallow well (*A*) at Okcheon-Cheongsung. *Monthly and total scores* are also shown

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Table 3 Classification of groundwater condition with total scores for the B-2 method

Total Score	Classification	
	Water level	Electrical conductivity
<17	Warning	Normal (low)
17~24	Watch	
>24~48	Normal	Normal
>48~55	Normal (high)	Watch
>55		Warning

(LRD) and the second method does the linear regression on a monthly basis (LRM; Fig. 4). Results for the LRD method may be affected when there are missing values or outliers. In the LRM method, a non-parametric statistic and monthly median value can be used instead of the monthly average because the latter may be largely affected by specific outliers. Statistics produced by the linear regression include linear slope and determination coefficient (r^2). The linear slopes showing positive (see Fig. 4a and b), null and negative values respectively imply increasing, no variation and decreasing trends in the groundwater data. Goodness of the linear fit can be evaluated by the determination coefficient while confidence level of the trend cannot be obtained.

The Sen's trend test (NPT-1 method)

As commented above, the conventional linear regression is largely affected by missing values or outliers. However, non-parametric trend tests use rank of the observed values or the slopes of the variation and they appropriately treat the missing values or the outliers (Salmi et al. 2002). The Sen's test and Mann-Kendall test have been widely used in groundwater studies, especially for water quality variation (e.g. Lee and Lee 2003) and they can be appropriately applied to data whose distribution is not normal (Yue and Wang 2002).

Even though the non-parametric trend tests are little affected by the missing values or the outliers, the monthly median was used to minimize potential effects by them. Sen (1968) developed a simple non-parametric method, especially applicable for groundwater data, and it is also robust even when there exist abnormal values, missing values or non-detect values. To obtain Sen's trend estimate, the number (N') of slope estimates (Q) are calculated (Salmi et al. 2002):

$$Q = \frac{x_{i'} - x_i}{i' - i} \quad (2)$$

where $x_{i'}$ and x_i are observed values at times i' and i, respectively, i is consecutive monitoring sequence, $i'>i$ and $N' = n(n-1)/2$ (n=number of observation values). If Qs are obtained, they are newly ordered in their size and the median of the values (S) is calculated:

$$S = Q_{[(N'+1)/2]} \quad (N' = \text{odd}) \quad (3a)$$

$$S = Q_{[(N'/2]} + Q_{[(N'+1)/2]}/2 \quad (N' = \text{even}) \quad (3b)$$

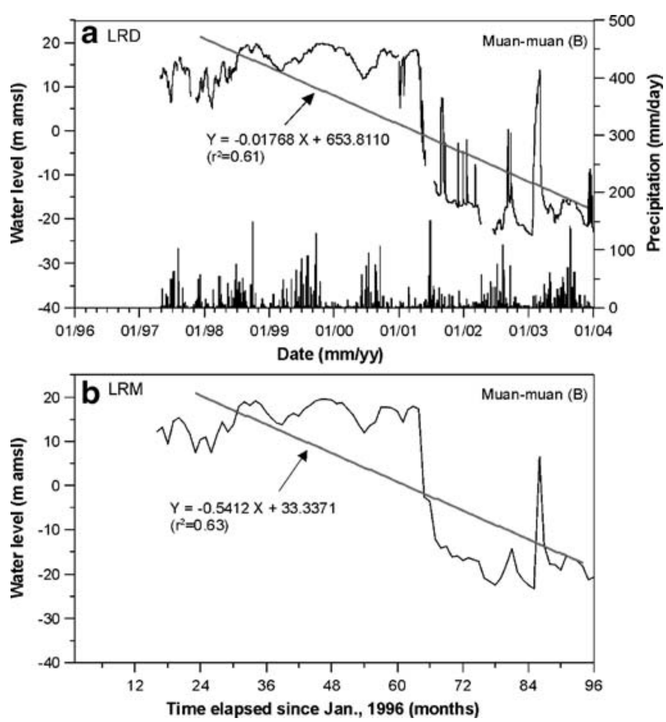

Fig. 4 Linear regression based on **a** daily mean (*LRD*) and **b** monthly median data (*LRM*). Location of the analyzed station is marked in Fig. 1 (*B*: deep well)

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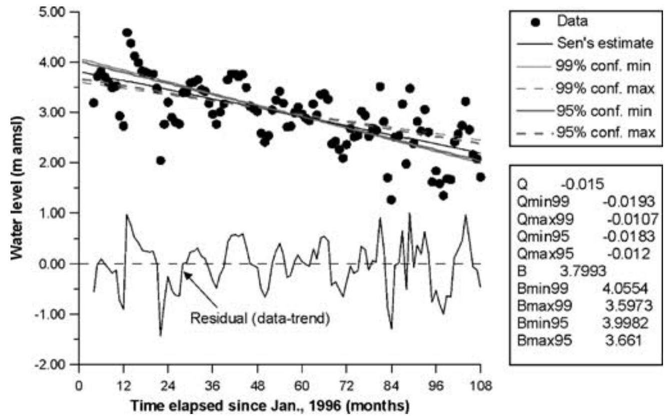

Fig. 5 Result of Sen's trend test for water-level data of Suncheon-pungduk station (for the deep well). *Q* is Sen's slope estimate and *B* is the estimate of the Y intercept based on the linear trend. The water level was decreasing at confidence level of 99%

To validate a hypothesis, variance of S is needed. Gilbert (1987) suggested a modified equation of that of Kendall (1975), calculating variance estimate, which is applicable to data whose number is small:

$$\operatorname{var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p\left(t_p - 1\right)\left(2t_p + 5\right)\right] \tag{4}$$

where t_p is the number of the same observation values or non-detect values and q is the number of such cases. Using these values, confidence intervals (lower M_1 and upper M_2) can be obtained:

$$M_1 = \frac{N' - z_{1-\alpha}[\operatorname{var}(S)]^{1/2}}{2} \tag{5a}$$

$$M_2 = \frac{N' + z_{1-\alpha}[\operatorname{var}(S)]^{1/2}}{2} \tag{5b}$$

where $z_{1-\alpha}$ is (1-α)×100% point of normal distribution.

If Q values of M_1 (lower) and M_2 (upper confidence intervals) do not include zero (0), the null hypothesis (that there is no trend) is rejected, so it is concluded that there is a trend. From the Sen's test, variation trend (increasing, decreasing or no trend), confidence interval and variation slope are obtained (Fig. 5). The result of this trend test may be used as one of the criteria determining the groundwater condition.

The Mann-Kendall trend test (NPT-2 method)

One of methods most widely used for trend identification is the Mann-Kendall trend test along with the previous Sen's test. Pair-wise comparison between the observed values yielding 1 (increasing), −1 (decreasing) or 0 (equivalent) is used in this test. If x_i is an observation value at time $i(1 \le i \le n)$, N' differences, $x_{i'} - x_i$ $(x' > i)$ are produced. Signs of these differences are calculated:

$$\operatorname{sgn}(x_{i'} - x_i) = \begin{cases} 1 & \textit{if } x_{i'} - x_i > 0 \\ 0 & \textit{if } x_{i'} - x_i = 0 \\ -1 & \textit{if } x_{i'} - x_i < 0 \end{cases} \tag{6}$$

and then the Mann-Kendall statistic is calculated as follows (Salmi et al. 2002):

$$S^* = \sum_{i=1}^{n-1} \sum_{i'=i+1} \operatorname{sgn}(x_{i'} - x_i) \tag{7}$$

Using the number of the observation values (n) and the Mann-Kendall statistic, S^*, a probability is obtained about the null hypothesis ($S^*=0$) that there is no trend.

If n is greater than 10, the following Gilbert's equation (Gilbert 1987) can be used assuming normal distribution:

$$z = \begin{cases} \frac{S^*-1}{[\operatorname{var}(S^*)]^{1/2}} & \textit{if } S^* > 0 \\ 0 & \textit{if } S^* = 0 \\ \frac{S^*+1}{[\operatorname{var}(S^*)]^{1/2}} & \textit{if } S^* < 0 \end{cases} \tag{8}$$

Table 4 A scoring system for the combined evaluation method

B-1 method		B-2 method		LRD or LRM		Sen's or Mann-Kendall test[a]	
Subtotal=35		Subtotal=35		Subtotal=15		Subtotal=15	
Percentile	Final score	Score	Final score	Slope	Final score	Trend	Final score
<10	7	<17	7	<−0.1	5	Down	5
10~<25	14	17–24	14	−0.1<S[b]<0.1	10	No	10
25~75	21	>24–48	21	>0.1	15	Up	15
>75~90	28	>48–55	28				
>90	35	>55	35				

[a] 95% confidence interval

[b] Slopes for water level (m/year); EC slopes: <−50, −50<S<50, >50 μS/year, respectively

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In this study, determination of existence of any trend is evaluated at 95 and 99% confidence levels.

Comprehensive final evaluation

In the above, two primary methods using observation values and two secondary methods using variation trend are introduced for the groundwater condition evaluation. However, for the next-step of practical measures, a final decision on the groundwater condition is required, which can be based on any single method above or any combination of them. Results of the final decision are normal, watch, or warning levels for water level or EC.

Application of single method

Single application of the B-1 method is the simplest. Based on the application result, some next-step measures will be undertaken. As stated above, the result of this method may be largely affected by missing values or outliers. The B-2 method is somewhat complicated in practical application, but it can reduce potential errors possibly produced from the use of single annual mean value in the B-1 method. However, if the groundwater data (water level or EC) are frequently fluctuating, applicability of this method may be limited.

Combination of primary and secondary methods

Evaluation methods suggested in the above have their own advantages and also shortcomings. For example, even though the B-2 method yields the normal condition of the groundwater levels, appropriate investigation and mitigation measures may be needed in cases where they are continuously decreasing. Therefore, evaluation of both the groundwater data themselves and their variation trends is sometimes beneficial. Even in this combination evaluation, the primary criteria (methods) are more important than the secondary criteria in respect to hydrogeologic implication. So, relatively larger weight can be given to the primary criteria.

In intuitive consideration of hydrogeologic importance, maximum subtotal scores of 35, 35, 15, and 15 (total=100) are assigned to the B-2, B-1, LRD (or LRM) and Sen's test (or Mann-Kendall test), respectively (Table 4). Therefore, the final total scores range between 24 and 100. In this way, a low score will be obtained if the groundwater levels are low compared with those of preceding years or they are decreasing. However, a high score will be obtained if the water levels are higher than those of the preceding years or they are increasing. In the case of EC, the reverse is applied. So, low scores of water level indicate abnormal condition of the groundwater level, while high scores indicate abnormal condition of the EC. The resultant final total scores determine the groundwater conditions (Table 5). The scoring system can be changed with different cases. For simple application of the non-parametric trend tests, the confidence levels of 95 or 99% may be optionally adopted.

Table 5 Classification of groundwater condition with final total scores for the combined method

Final total scores	Classification	
	Water level	Electrical conductivity
<31	Warning	Normal (low)
31~43	Watch	
>43~81	Normal	Normal
>81~92	Normal (high)	Watch
>92		Warning

Table 6 Application results of the single evaluation method (B-1 and B-2 methods) for the water level and electrical conductivity

	Monitoring wells		Total	Method
	Shallow well	Deep well		
Percentile				
<10	4.5%[a]; 9.0%[b]	2.6%; 7.2%	3.3%; 7.9%	B-1 method
10~<25	7.9%; 12.4%	7.8%; 9.2%	7.8%; 10.3%	
25~50	7.9%; 20.4%	12.3%; 16.3%	10.7%; 17.8%	
>50~75	53.9%; 29.2%	50.0%; 33.3%	51.4%; 31.8%	
>75~90	20.2%; 16.8%	21.4%; 23.5%	21.0%; 21.1%	
>90	5.6%; 12.4%	5.9%; 10.5%	5.8%; 11.1%	
Score				
<17	4.5%; 2.3%	6.5%; 3.3%	5.8%; 2.9%	B-2 method
17~24	20.2%; 3.4%	13.6%; 3.3%	16.1%; 3.3%	
>24~48	71.9%; 62.9%	73.4%; 55.5%	72.8%; 58.3%	
>48~55	2.3%; 20.2%	5.2%; 27.4%	4.1%; 24.8%	
>55	1.1%; 11.2%	1.3%; 10.5%	1.2%; 10.7%	

[a] Proportion for water level

[b] Proportion for electrical conductivity

Application to the national groundwater-monitoring stations in South Korea

To evaluate the applicability of those methods suggested above, the groundwater data obtained from the national groundwater-monitoring stations (128 shallow wells and 236 deep wells) were used. The targeted monitoring period is 1996–2003. Among the total 364 wells, 99 monitoring wells (33 shallow wells and 66 deep wells) whose monitoring period is less than 3 years were finally excluded in the evaluation. Prior to this evaluation, dynamic time series analyses were conducted (Yi et al. 2004, 2005).

Fig. 6 Condition of water level in **a** shallow wells and **b** deep wells, and condition of electrical conductivity in **c** shallow wells and **d** deep wells, determined by the B-1 method. The *dotted lines* are administrative boundaries ▶

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◀**Fig. 7** Condition of water level in **a** shallow wells and **b** deep wells, and condition of electrical conductivity in **c** shallow wells and **d** deep wells, determined by the B-2 method. The *dotted lines* are administrative boundaries

Application results of the single methods

The water-level condition for 2003 (the evaluation year) was evaluated using the groundwater data of 1996–2002. According to the B-1 method, 3.3, and 7.8% of the monitoring wells were classified into the warning (<10 percentile) and watch (10–25 percentile) conditions, respectively, for the groundwater levels (Table 6), and 87.1% of the monitoring wells were classified as normal, including normal (high) condition. In addition, for EC, 21.1 and 11.1% were determined as watch and warning levels, respectively, and 67.8% were normal (Fig. 6). The B-2 method produced somewhat different results. For the water level, the proportions of the warning and watch conditions much increased by 2.5 and 8.3%, respectively (Fig. 7). Frequent fluctuations of water level and EC values resulted in an increase of these negative evaluation results. For EC, the watch condition largely increased while the warning condition slightly decreased. Both of the two methods produced much larger negative evaluation results for EC compared with water level.

Linear regression and trend analysis

Table 7 shows the results of the simple linear regression using daily mean (LRD) and monthly median (LRM) values of water level and EC. As shown in the table, nearly the same proportions of the negative and the positive slopes were obtained for the water levels. However, for EC, somewhat more positive slopes were obtained in the deep wells. The positive slope of the EC variation may indicate deterioration of groundwater quality, to a certain extent, due to recent deeper installation of groundwater wells collecting cleaner water in the country (Lee et al. 2007a). Productive wells are mostly tapped at the deep bedrock aquifer because the shallow alluvial aquifers are poorly developed in the country and the shallow groundwaters are largely contaminated. In the mean time, the analysis results of the LRM method were not significantly different from those of the LRD method.

Table 8 Results of the nonparametric trend analyses for monthly median water levels (WL) and electrical conductivities (EC) for 1996–2003

Wells	Trend	Mann-Kendall test		Sen's test	
		95%[a]	99%	95%	99%
Shallow wells (WL)	Increasing	22.1%[b]	16.8%	22.1%	16.8%
	Decreasing	27.4%	20.0%	27.4%	20.0%
	No trend	50.5%	63.2%	50.5%	63.2%
Deep wells (WL)	Increasing	26.0%	16.0%	26.0%	16.6%
	Decreasing	23.7%	14.8%	23.7%	14.8%
	No trend	50.3%	69.2%	50.3%	68.6%
Shallow wells (EC)	Increasing	29.5%	24.2%	29.5%	24.2%
	Decreasing	32.6%	27.4%	32.6%	28.4%
	No trend	37.9%	48.4%	37.9%	47.4%
Deep wells (EC)	Increasing	42.3%	35.7%	42.8%	36.9%
	Decreasing	26.2%	20.2%	27.4%	20.8%
	No trend	31.5%	44.1%	29.8%	42.3%

[a] Confidence interval

[b] Percentage of wells showing increasing trend among total shallow wells.

Table 8 shows the results of the non-parametric trend analyses (Mann-Kendall and Sen's trend tests) using the monthly median values. Over 50% of the monitoring wells showed no trend (neither increasing nor decreasing) of water levels. Like the results of the linear regression, similar proportions of the shallow and deep wells showed increasing or decreasing trend of water levels at both 95 and 99% confidence levels. These non-parametric trend tests yielded more distinctive division of the trends compared with the linear regressions (only positive or negative slopes). Unlike the water levels, more monitoring wells showed some trends in EC (increasing or decreasing). More shallow wells showed slightly decreasing trends while increasing trends were more dominant in the deep wells. The increase of EC in the deep wells may be derived from recent intensive groundwater development in the deeper bedrock aquifer (KOWACO and KIGAM 2005; Lee et al. 2006b). Distinctive EC rises were observed in low lands of the western coastal areas, which indicated encroachment of seawater (Lee and Song 2007; Lee et al. 2007c).

Application results of the combined method

As described above, the combined method considers both the observed values (water level and EC) themselves and

Table 7 Results of the simple linear regression using daily mean and monthly median values for 1996–2003

Slopes	Water level		Electrical conductivity	
	Shallow wells	Deep wells	Shallow wells	Deep wells
Positive[a]	47.4% (45[c]/95[d])	50.9% (86[c]/169[e])	49.5% (47[f]/95[d])	59.5% (100[f]/168[e])
Negative[a]	52.6% (50/95)	49.1% (83/169)	50.5% (48/95)	40.5% (68/168)
Positive[b]	48.4% (46/95)	52.1% (88/169)	50.5% (48/95)	58.9% (99/168)
Negative[b]	51.6% (49/95)	47.9% (81/169)	49.5% (47/95)	41.4% (69/168)

[a] Slopes for daily mean values

[b] Slopes for monthly median values

[c] Number of wells showing positive slopes for water-level variation

[d] Total number of shallow wells analyzed

[e] Total number of deep wells analyzed

[f] Number of wells showing positive slopes for EC variation

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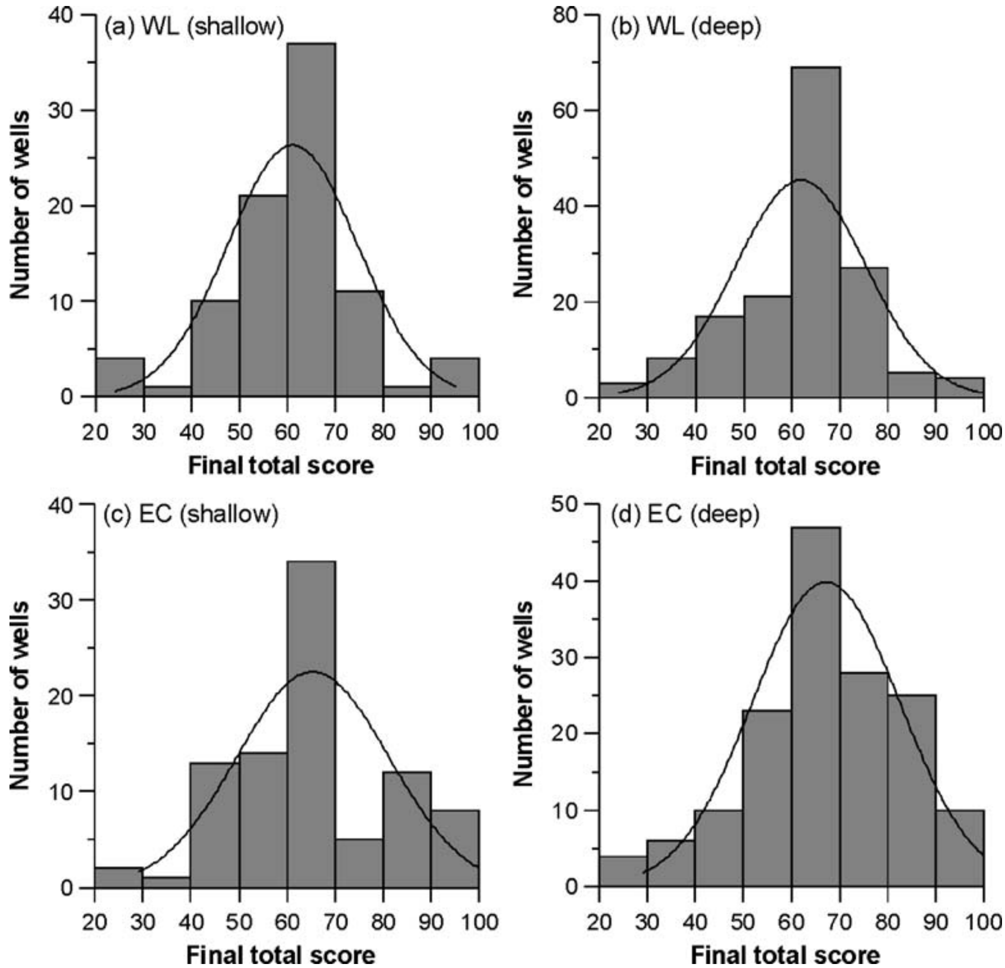

Fig. 8 Distribution of final total scores calculated by the combined evaluation method, which approximates normal distribution

their variation trends. Figure 8 shows final total scores calculated by the combined method. The scores for the water levels are generally normal-distributed while those for EC are slightly positively skewed, which indicates that there are relatively more wells having high scores for EC. Table 9 shows final evaluation results of groundwater conditions classified by the final total scores. For water levels, seven wells (2.9%) are classified as warning condition while 91.3% are normal. According to hydrographs of the wells in warning conditions (Fig. 9), the evaluation results appear sound and reasonable. For EC, 18 wells (7.4%) are classified as warning conditions while 77.3% are normal (see Table 9).

Figure 10 shows EC variations of some wells classified as warning levels. Like the water levels, the evaluation results appear also superficially sound. However, even though the ECs of the evaluation year (2003) are higher than those of preceding years and they show an increasing trend, the EC values of some wells are only low, which are within normal ranges of uncontaminated groundwaters in the country (Lee et al. 2006a). Consequently, some criteria that consider the absolute EC values are required for this combined method in the case of EC.

Summary and conclusions

In this study, some methods were presented to evaluate water level and EC conditions of groundwater-monitoring wells. Based on the evaluation results, certain technical and administrative measures will be undertaken. The methods use a comparison between values of a selected

Table 9 Groundwater conditions determined by the combined method

Condition	Water level			Electrical conductivity		
	Shallow well	Deep well	Total	Shallow well	Deep well	Total
Normal	91.0% (81)[a]	91.5% (140)	91.3%	77.5% (69)	77.1% (118)	77.3%
Watch	4.5% (4)	6.5% (10)	5.8%	13.5% (12)	16.4% (25)	15.3%
Warning	4.5% (4)	2.0% (3)	2.9%	9.0% (8)	6.5% (10)	7.4%

[a] Number of wells showing normal condition

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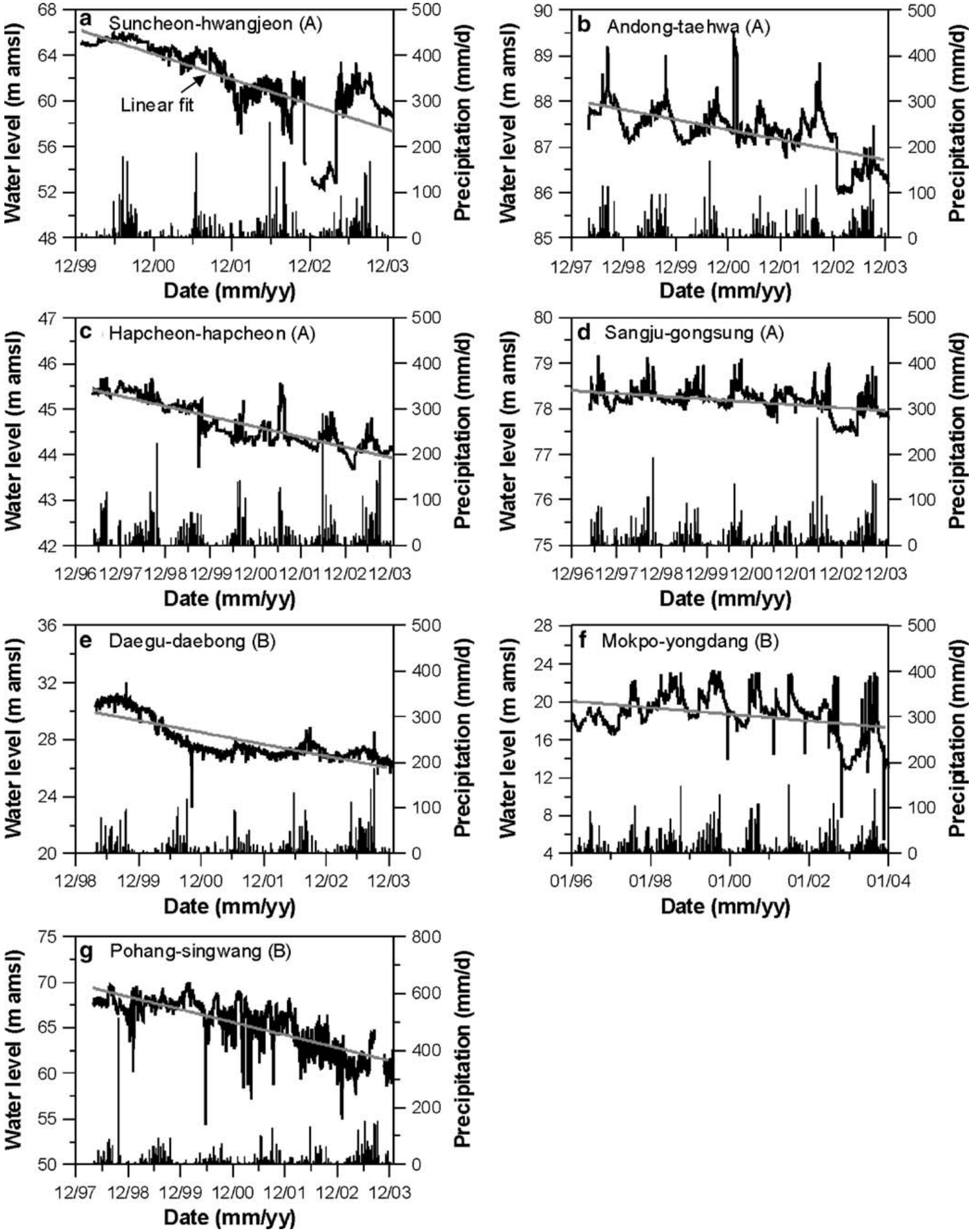

Fig. 9 Water levels of monitoring wells classified as warning conditions. *A* and *B* indicate shallow and deep wells, respectively. *Final total scores* are also marked

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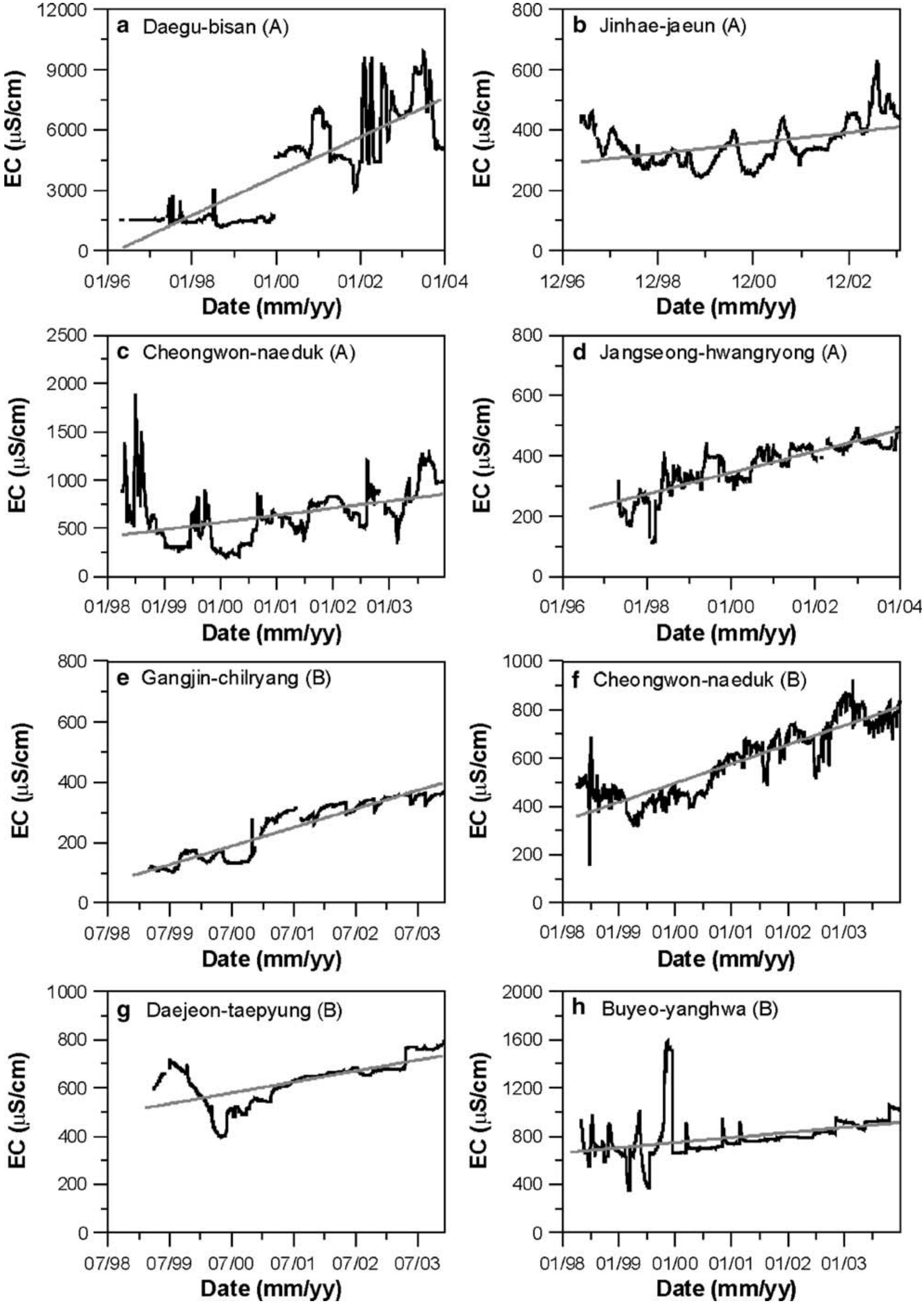

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◀**Fig. 10** Electrical conductivities of some monitoring wells classified as warning conditions. *A* and *B* indicate shallow and deep wells, respectively. *Final total scores* are also marked

evaluation year and those of preceding normal years, and an inter-annual variation trend. The first method (B-1 method) is based on the arithmetic mean of the evaluation year and a box plot for the groundwater values of preceding years, which is the simplest method. The second method (B-2 method) uses all daily values of the evaluation year and 12 monthly box plots of the preceding years. The two methods produced similar results for the groundwater data of the national groundwater-monitoring network in South Korea. However, with these methods, too many wells are classified as warning conditions for water levels and ECs. The warning condition requires detailed field investigation and relevant laboratory analysis. Thus, considering the limited budgets for such analyses, it is not feasible to undertake additional detailed technical or administrative measures at all stations. The last combined method uses variation trend of values as well as the above two methods, in which a scoring (weighting) system is involved. The combined method yielded the most economically reasonable results for water levels. However, in the case of EC, other criteria are also required in order to take account of absolute EC values.

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