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ORIGINAL ARTICLE

Evaluation of groundwater quality in coastal areas: implications for sustainable agriculture

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Abstract Seawater intrusion is a problem in the coastal areas of Korea. Most productive agricultural fields are in the western and southern coastal areas of the country where irrigation predominantly relies on groundwater. Seawater intrusion has affected agricultural productivity. To evaluate progressive encroachment of saline water, the Korean government established a seawater intrusion monitoring well network, especially in the western and southern part of the peninsula. Automatic water levels and EC monitoring and periodic chemical analysis of groundwater help track salinization. Salinization of fresh groundwater is highly associated with groundwater withdrawal. A large proportion of the groundwaters are classified as Na–Cl and Ca–Cl types. The Na–Cl types represent effects of seawater intrusion. The highest EC level was over 1.6 km inland and high Cl values were observed up to 1.2 km inland. Lower ratios of Na/Cl and SO_4/Cl than seawater values indicate the seawater encroachment. A linear relation between Na and Cl represents simple mixing of the fresh groundwater with the seawater. The saline Na–Cl typed groundwaters showed Br/Cl ratios similar to or less than seawater values. The Ca–HCO_3 type groundwaters had the highest Br/Cl ratios. Substantial proportions of the groundwaters showed potential for salinity and should be better managed for sustainable agriculture.

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Introduction

Groundwater development for drinking water, domestic, agricultural and industrial uses in Korea has drastically increased since 1960, along with rapid economic growth (Kim 2005). Increased groundwater development has furthered depletion (water level decline), deterioration of water quality, land subsidence and seawater intrusion throughout the country (Lee et al. 2005, 2006a, b, c, d; Won et al. 2006). According to the official statistics of MOCT (2002), annual groundwater use of the country reached 37,000 million m^3/year in 1998, about 11% of total annual supply. Domestic (50%) and agricultural (42%) uses were dominant among the total groundwater use.

Especially in the western and southern coastal areas of the country, seawater intrusion caused by intensive groundwater pumping threatens sustainable agriculture, which is predominantly rice cultivation. Irrigation is largely dependent on groundwater in these areas and wells are near the shores (Fig. 1; Jeen et al. 2001; Kim et al. 2004). Rice cultivation demands large quantities of water during March–May, which coincides with mid- or end of the very dry season locally. Groundwater pumping is increased. Increased salinity has reduced crop productivity (Lee et al. 2002) and forced abandonment of some wells or entire well fields (Park et al. 2002). Another and more costly clean water source is required.

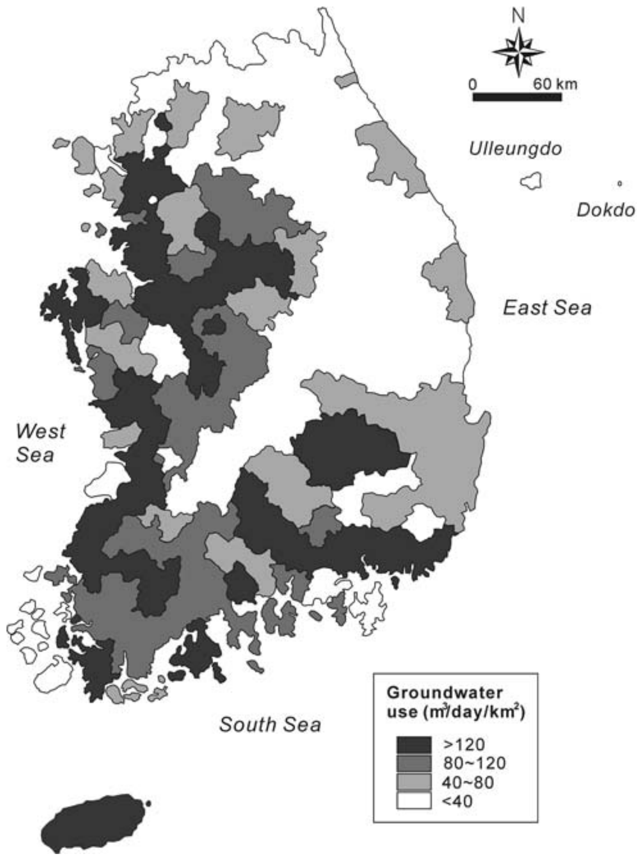


Fig. 1 Distribution of groundwater use per unit area in Korea. Data are obtained from MOCT (2002)

Topographic elevations of the eastern half of the Korean peninsular are high and topographic gradients toward the East Sea are also great, with increased hydraulic gradients. Seawater intrusion has seldom occurred in the eastern coastal areas. The lowlands occupying the western and southern parts of the country are mainly used for rice cultivation (Kim et al. 2006; Lee et al. 2006c).

Monitoring of variations of water levels and water quality along the coastal areas and a seawater intrusion-monitoring program was initiated in 1998 (MAF and KARICO 2004). The KARICO (Korea Agricultural & Rural Infrastructure Corporation) has gradually constructed a seawater intrusion-monitoring network. By 2004, a total of 55 monitoring wells were constructed in 25 western and southern coastal regions. In each monitoring well, water level, electrical conductivity (EC) and water temperature are measured every hour using a multi-probe equipped with a data logger. Data are automatically transferred to a host computer in KARICO. Detailed groundwater chemistry data are obtained from annual groundwater sampling and chemical analysis.

In this study, automatic monitoring data (especially water level and EC) and groundwater chemistry data for 2004 from the seawater intrusion-monitoring network were analyzed and evaluated. A series of ionic ratios were mainly used. Because many of the monitoring wells are still in use, suitability for irrigation was evaluated using salinity (expressed by EC), SAR (sodium adsorption ratio), chloride, sulfate and bicarbonate contents.

Materials and methods

General information

Korea is a peninsular in the northeast of the Asian continent. About 75% of the total land is mountainous (Lee and Hahn 2006). Most of rivers and streams flow from east to west. Rivers in the east are short and steep. The climate is intermediate between continental and oceanic climates. There are four distinctive seasons. Annual precipitation averages 1,260 mm. About 60% of the total precipitation occurs in summer season (Lee and Lee 2000). In the coastal areas, especially in the south, average annual precipitation is increased (1,400–1,800 mm). Mean air temperatures for past 20 years in the western and southern coastal areas are 11–14°C. Those of the coastal areas are slightly higher than the inland areas by 2–3°C.

Seawater intrusion monitoring network

The coastal line is curved and forms a ‘rias’ shape (Park et al. 2002). In each monitoring region, 1–3 wells were constructed (Fig. 2). The monitoring wells are between 19 and 2,000 m from the coast. Prior to well installation, hydrogeologic investigations, including well inventory and geophysical survey, were performed (MAF and KARICO 2004). Depths of the monitoring wells range from 30 to 200 m below surface (Table 1). They correspond to 24–164 m below mean sea level. Most of the wells are actively used for irrigation (Park et al. 2005). Pumping frequencies and rates vary widely.

Hydraulic conductivity of main coastal aquifers ranges between 2.15×10^{-6} and 4.00×10^{-3} cm/s. Thickness varies from 20 to 90 m. Most stratigraphic sequences are reclamation soil, silt, weathered rock and bedrock (schist, gneiss or granite) with fractures (Kim et al. 2003; MAF and KARICO 2004) in varying proportions. Most wells tap the bedrock, so aquifers generally show confined characteristics. Water levels at

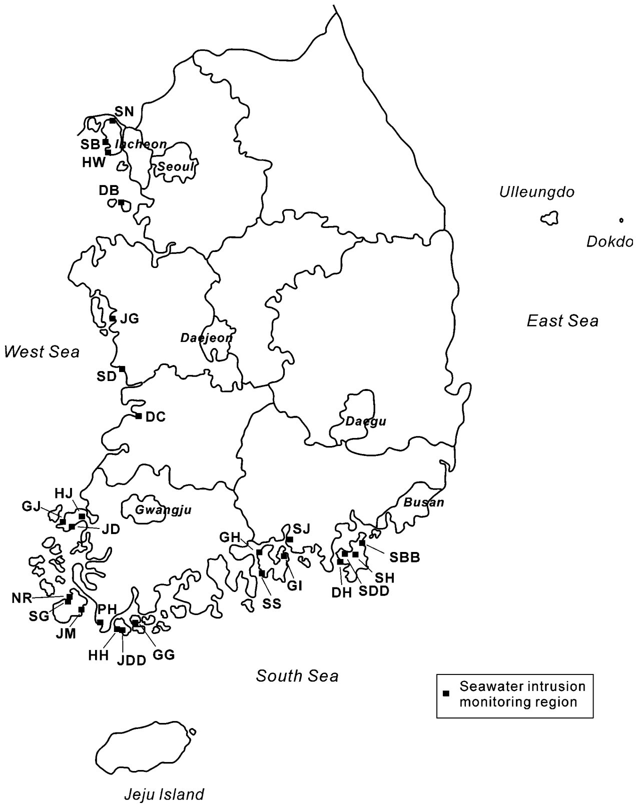


Fig. 2 Locations of the seawater intrusion monitoring regions. In each region, 1–3 monitoring wells having different distances from the coast were installed

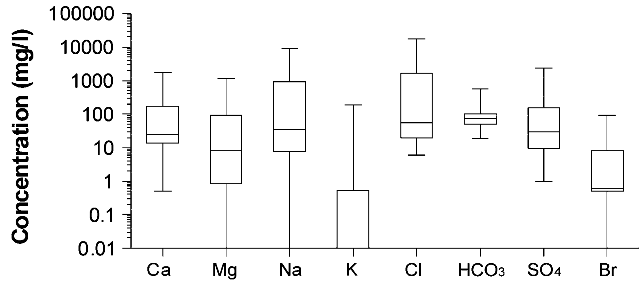


Fig. 3 Box plots of some major constituents

well installation were between –8.06 and 33.80 m above mean sea level, but pumping has lowered water levels by approximately 0.02–29.27 m at present (RRI 2005). The monitoring network will be expanded from 55 wells to 136 by 2011.

EC logging and groundwater chemical analysis

In addition to the water level, EC and water temperature, chemical analysis and vertical EC logging have been conducted every year. For control purposes, chemical analysis results from 2004 annual sampling were used in this study.

Prior to sampling for analysis, groundwater was pumped for about 30 min. Field parameters, including water temperature and EC were determined during pumping using standard probes. Samples for cation analysis were filtered at 0.45 μm and preserved ($pH < 2$) using ultra pure HNO_3 in 125 ml HDPE bottles. Samples for anions were collected in 60 ml HDPE bottles through 0.45 μm filtration. Water samples of 125 ml were also collected for analysis of alkalinity. All samples were stored at 4°C. Anion constituents were analyzed by ion chromatography (IC, DX-120, DIONEX), and other cationic constituents were analyzed by ICP-MS (Ultramass 700, Varian), AA (5100PC, Perkin Elmer) and ICP (ICP-IIIS, Shimadzu) following USEPA standard methods. Alkalinity was determined by potentiometric titration using Gran plots.

Results and discussion

General groundwater chemistry

Concentrations of analyzed constituents are presented as box plots (Fig. 3). Wide ranges (over 3 orders) and great standard deviations occur for most parameters. In particular, concentrations of Na and Cl have ranges of 0.01–9,099.87 and 6.06–17,869.78 mg/l, respectively. Concentrations of Ca, Mg and SO_4 also showed large variations with ranges of 0.50–1,733.05, 0.01–1,173.20 and 0.96–2,350.41 mg/l, respectively. Bicarbonate showed the least variation. These wide distributions indicate that chemical composition is affected by multiple processes, including seawater mixing (Park

Table 1 Physical properties of the seawater intrusion monitoring wells ($n = 55$)

Properties	Mean	Median	Maximum	Minimum	SD
Well depth (m)	83.1	80	200	30	33.3
Sensor depth (m)	44.3	45	76	8	14.9
Distance to sea (m)	525.9	388	2,000	19	446.9
K (cm/s)	6.53×10^{-4}	3.39×10^{-4}	4.00×10^{-3}	2.15×10^{-6}	8.35×10^{-4}
Water level (m, amsl)	2.55	1.34	33.80	–8.06	6.31

et al. 2005). Especially the predominance of Na and Cl indicates strong saline water impact. Of the Cl concentrations, 36.5% exceeded the Korean groundwater standard for agriculture (250 mg/l). Substantial amounts of HCO_3 and Ca reflect contribution by water–rock interaction (Hem 1985; Park et al. 2002). Despite wide ranges of values, most samples showed lognormal density distributions (Fig. 4). The most abnormal distribution was observed for Br concentrations, with very low concentrations.

Cumulative frequency curves for two parameters (Cl and HCO_3) allow differentiation of 'anomalous' values

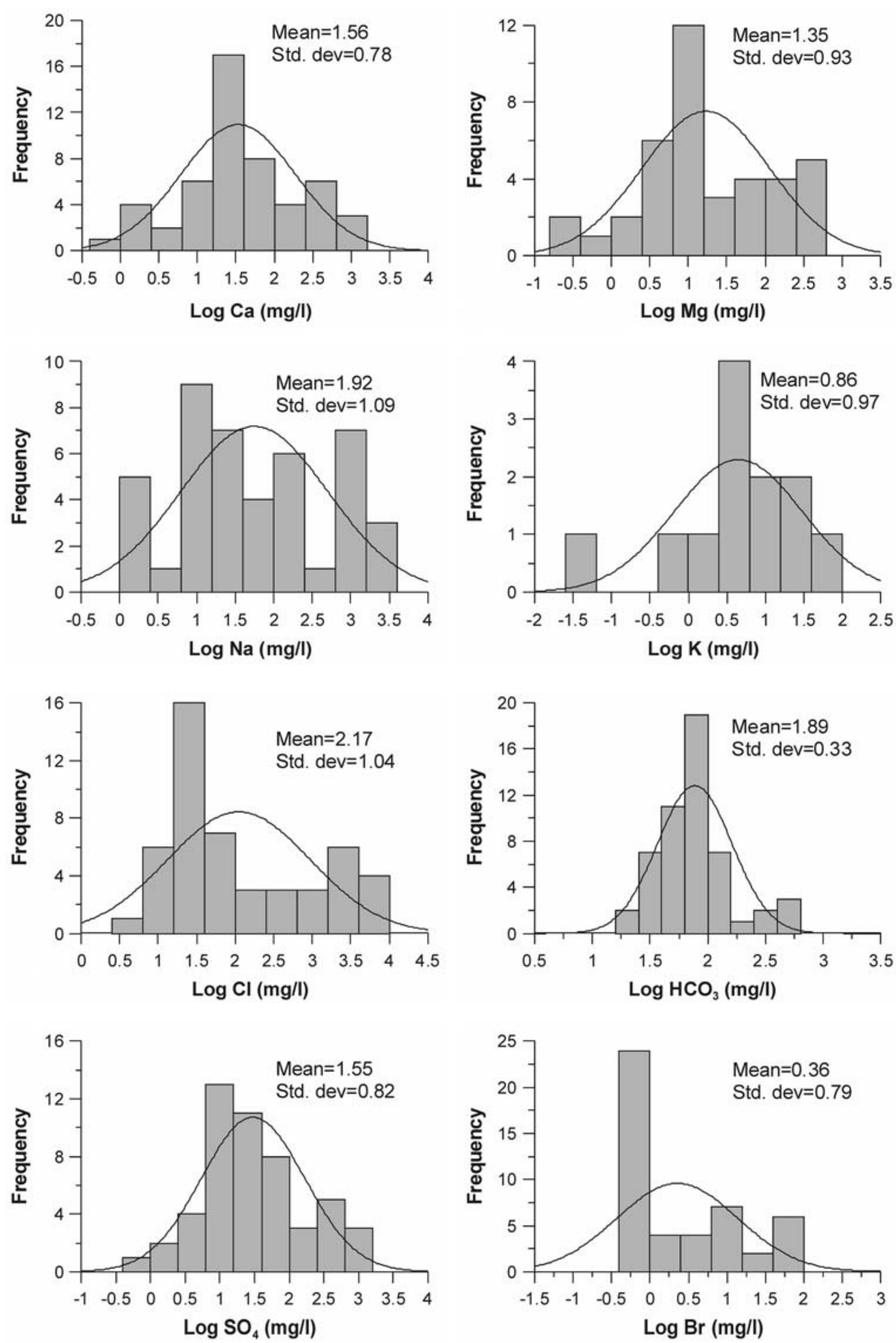


Fig. 4 Distribution of some major ions

from 'background' values (Lepeltier 1969; Sinclair 1974; Park et al. 2002). The two parameters represent effects of seawater mixing (salinization) and water-rock interaction, respectively. The threshold values were calculated as 63 mg/l for Cl and 141 mg/l for HCO_3 (Fig. 5a,b). Based on these thresholds values, the groundwaters can be divided into four classes (Fig. 5c). An estimated 26.9% of the groundwaters are dominantly affected by the salinization process, while only 1.9% were largely influenced by the water–rock interaction. Another 21.2% were affected by both the seawater mixing and the water-rock interaction.

Typical classification of hydrochemical facies for groundwaters is shown in Fig. 6. As expected, although various hydrochemical facies were observed, Ca–Cl and Na–Cl types were dominant. The groundwaters showed paths of hydrochemical evolution, from Ca–HCO_3 type via Ca–Cl type to Na–Cl type; or from Ca–HCO_3 type directly to Na–Cl type. These patterns indicate that the groundwater chemistries are changed by cation exchange reaction, as well as simple mixing (Richter et al. 1993; Appelo and Postma 1999; Jeen et al. 2001). The region of the Ca–Cl type water may be a leading edge of the seawater plume (Vengosh et al. 1991; Appelo and Postma 1999; Jeen et al. 2001). Large proportions of the groundwaters showed Na–Cl type, which generally indicates a strong seawater influence (Pulido-Leboeuf 2004). The Na–HCO_3 type of water represents partly flushed remains of an ancient, confined saline water body (Mercado 1985).

Correlations among analyzed parameters are presented in Table 2. Water temperatures did not show any meaningful correlation. HCO_3 showed the next lowest correlations with other parameters. The EC and Cl were highly positively correlated with most of the other ions (except for HCO_3 and temperature), which

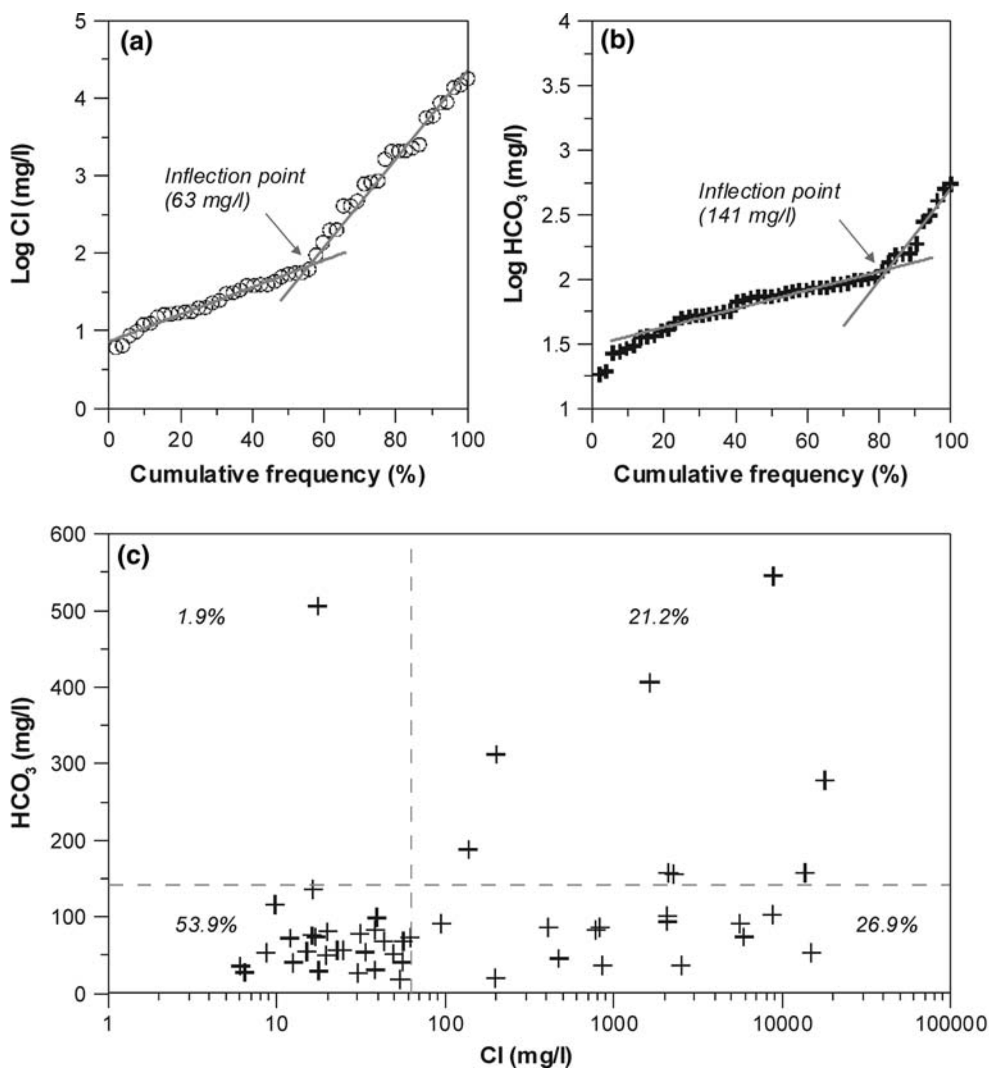


Fig. 5 Cumulative frequency curves for **a** Cl and **b** HCO_3. The inflection points are calculated based on Sinclair (1974). Estimated threshold values can be used to differentiate background from anomalous values. Based on the threshold values, classification of four groundwater types is also shown

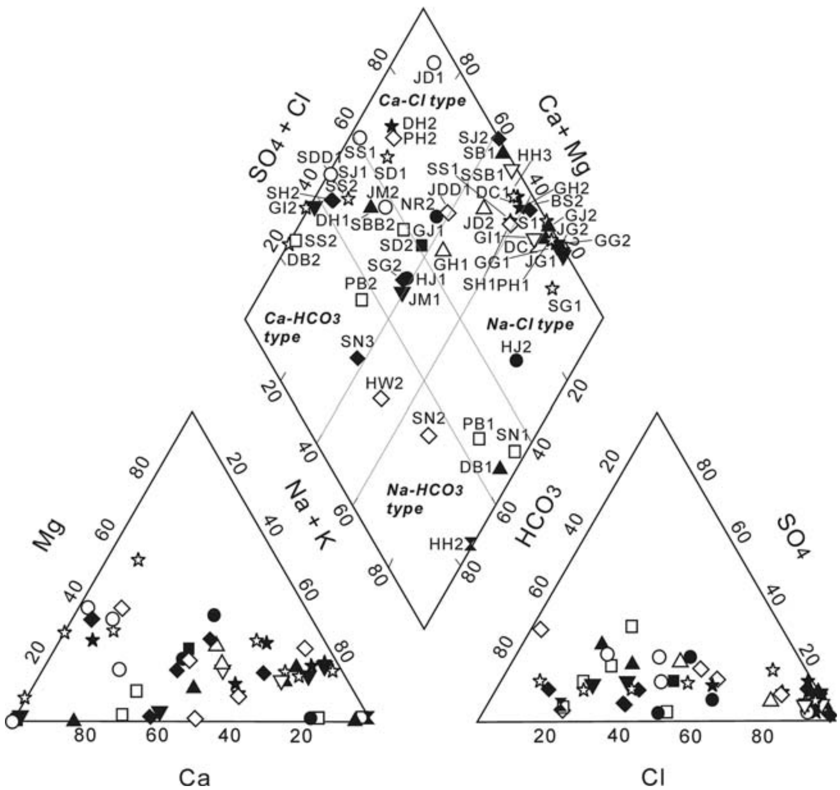


Fig. 6 Piper plots of the groundwater chemistry in 2004

Table 2 Correlations among the physico-chemical parameters of the groundwaters

Paras.	Temp.	EC	Ca	Mg	Na	K	Cl	HCO_3	SO_4	Br
Temp.	1	(0.99)[a]	(0.68)	(0.90)	(0.97)	(0.65)	(0.98)	(0.35)	(0.99)	(0.86)
EC	0.00[b]	1	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)
Ca	0.06	0.67	1	(0.00)	(0.00)	(0.05)	(0.00)	(0.28)	(0.00)	(0.00)
Mg	–0.02	0.89	0.66	1	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)
Na	–0.01	0.88	0.57	0.98	1	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)
K	–0.06	0.72	0.27	0.86	0.89	1	(0.00)	(0.07)	(0.00)	(0.00)
Cl	–0.00	0.90	0.77	0.95	0.93	0.74	1	(0.03)	(0.00)	(0.00)
HCO_3	–0.13	0.35	0.15	0.36	0.38	0.26	0.30	1	(0.04)	(0.02)
SO_4	–0.00	0.88	0.62	0.95	0.96	0.81	0.95	0.29	1	(0.00)
Br	0.03	0.92	0.77	0.94	0.92	0.70	0.97	0.32	0.92	1

[a] Value in parenthesis in the upper triangle of the matrix is probability that they are uncorrelated

[b] Correlation values (in the lower triangle)

indicates that these ions are derived from the same source with a limited composition range (Stoessel 1997; Kim et al. 2003).

Indications of seawater intrusion

Levels of Cl and EC are most simply indicative of seawater intrusion or salinization (Mercado 1985; El Moujabber et al. 2006). Figure 7 shows EC levels and Cl concentrations with distance from the coast. The EC values ranged from 67 to 46,628 μS/cm. Of EC values, 62.9% exceeded the threshold value for differentiating background and anomalous values, 355 μS/cm for EC, indicating saline water or anthropogenic contamination of varying degrees. The higher EC level (>355 μS/cm) reached over 1.6 km inland. In addition, 44.2% of Cl concentrations exceeded the threshold value (63 mg/l) and high Cl values were observed up to 1.2 km inland. The Cl concentrations and EC levels are highly positively associated (see Table 2).

Relations of Cl and EC with water levels and well depths are shown in Fig. 8. Low water levels (<5 m above sea level) generally correspond to high Cl and EC levels. The low water levels are associated with

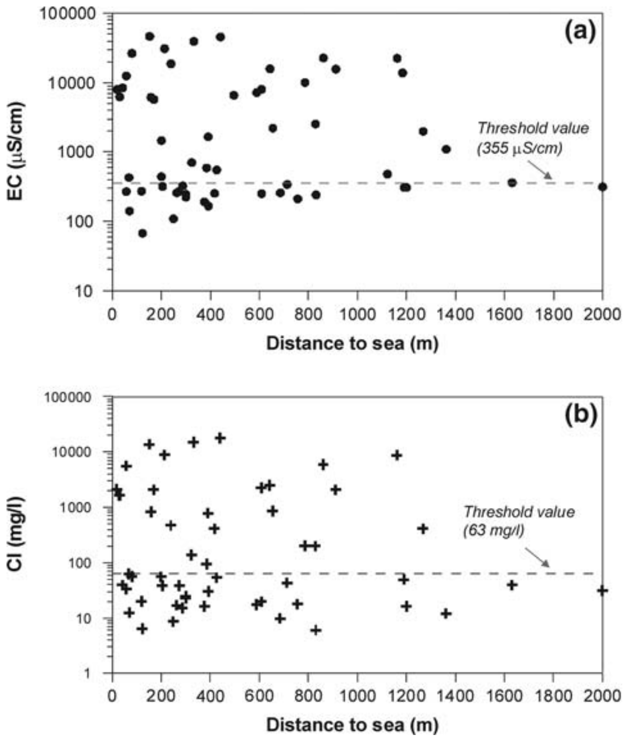
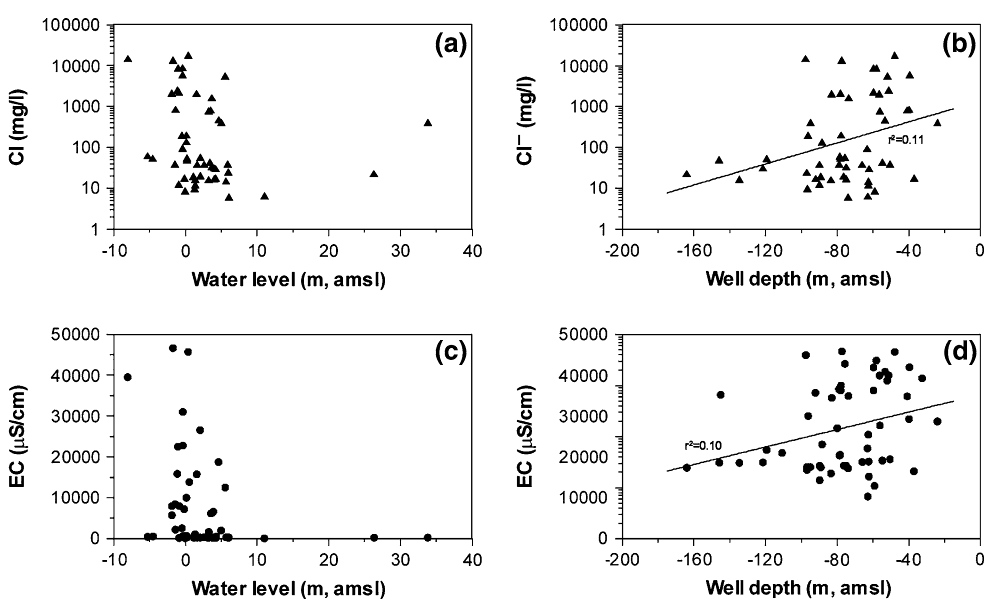


Fig. 7 Levels of electrical conductivity and chloride versus distance of the monitoring wells from the coast

both proximity of the monitoring wells to the coastline and heavy groundwater pumping in the coastal areas (Yakirevich et al. 1998; El Moujabber et al. 2006; Lee et al. 2006c). The depths of the wells tapping the coastal aquifers vary because the fresh water/seawater interface varies. But substantial correlation to well depth was not observed (Fig. 8b, d). On the contrary, the deeper wells showed low Cl and EC levels, indicating bedrock aquifers of low permeability were least affected by the saline waters. One specific depth interval (40–100 m depth below sea level) showed high Cl and EC levels. But within this interval, Cl and EC varied. The intervals are the most permeable in the coastal aquifers, resulting in significant seawater intrusion.

Effects of seawater encroachment have been evaluated by studying a series of ionic ratios (Petalas and Diamantis 1999; Sanchez Martos et al. 1999, 2002; Vengosh et al. 2002; El Moujabber et al. 2006). Figure 9 shows molar ratios of Na/Cl and SO_4/Cl versus Cl concentrations. Conservative seawater–fresh water mixing is expected to show a linear increase in Na and Cl (Sanchez Martos et al. 1999). Ratio values of groundwater less than the seawater ratio (0.86) indicate that fresh groundwaters were contaminated with the saline waters. The Na/Cl ratios ranged from 0.001 to 81.84. For Na/Cl, 73.1% were less than the seawater ratio, while the other 26.9% exceeded the seawater value (Fig. 9a), indicating a large proportion of groundwater was affected by seawater intrusion to some degree. Values close to the seawater ratio indicate recent simple mixing of groundwaters with seawater (Mercado 1985). Very high Na/Cl ratios may be indicative of anthropogenic contamination like fertilizers (Jones et al. 1999). The variation in the molar ratios of SO_4/Cl was evaluated with respect to the distribution of Cl concentrations. Molar ratios (55.8%) less than the seawater value (0.1) indicate contamina-

Fig. 8 Relationship between water levels and Cl and EC levels and those between well depth and Cl^- and EC levels



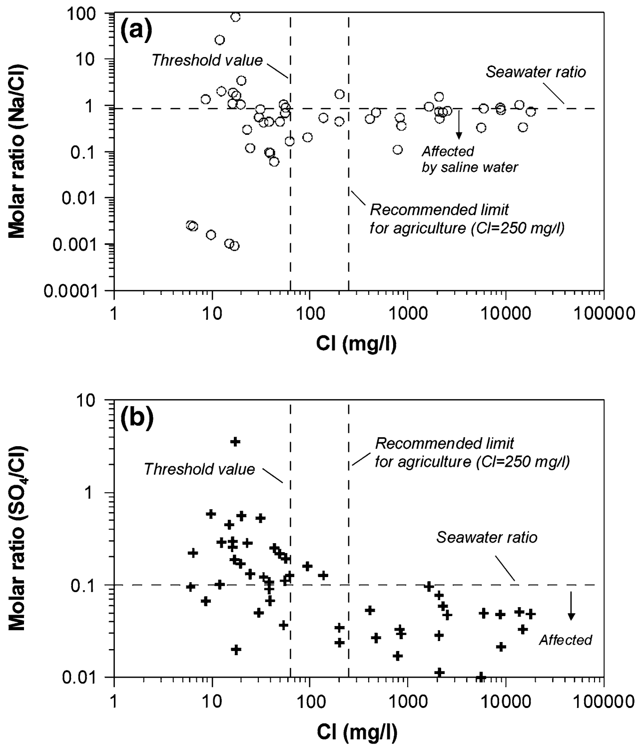


Fig. 9 Molar ratios of Na/Cl and SO_4/Cl versus Cl concentration

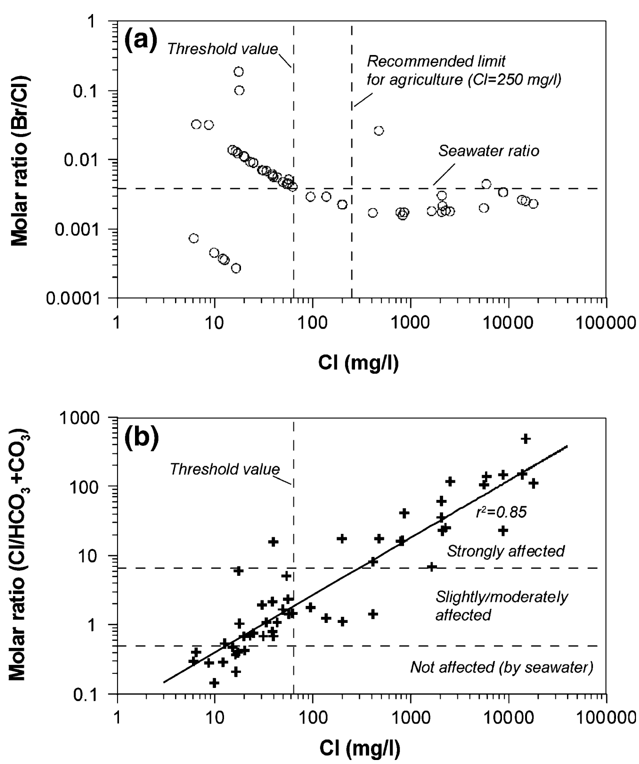


Fig. 10 Molar ratios of Br/Cl and Cl/(HCO_3 + CO_3) versus Cl concentrations

tion with seawater to some extent. The ratios range between 0.01 and 3.54. They generally showed decrease with increase in Cl concentrations.

Other useful ionic ratios are Br/Cl and Cl/HCO_3 + CO_3 (Fig. 10). For Cl concentrations less than the threshold value (63 mg/l), the Br/Cl ratios were larger than the seawater ratio (0.0038), while close to or less than the seawater value for Cl concentrations over 63 mg/l. Thus high Cl and low Br/Cl ratios well represent seawater intrusion. Of the Br/Cl ratios, 50% are smaller than the seawater value. The most salinized Na–Cl type groundwaters showed Br/Cl ratios similar to or less than seawater value. The Ca–Cl type groundwater was less salinized and showed higher Br/Cl ratios with lower Cl concentrations (Jeen et al. 2001). The Ca–HCO_3 type groundwaters showed the highest Br/Cl ratios.

The ratios of Cl/HCO_3 + CO_3 ranged between 0.15 and 488.19 and had strong positive linear relation with Cl concentrations (Fig. 10b). This linear relationship indicates simple mixing of fresh groundwaters with saline waters. Effect of salinization could be classified using the Cl/HCO_3 + CO_3 ratios, which includes <0.5 for unaffected, 0.5–6.6 for slightly and moderately affected and >6.6 for strongly affected (Revelle 1941; Todd 1959). Considering the threshold value of Cl concentration (63 mg/l) and the ratio of Cl/HCO_3 + -CO_3, 36.5% of the groundwaters were strongly affected by the saline water and 7.7% were slightly or moderately affected.

In addition to geochemical data, salinization could also be evaluated by annual EC logging. Figure 11 shows results of vertical EC loggings at some selected monitoring wells. Generally a large increase of EC with time was observed. The transition zones were encountered at 10–30 m below water levels. The progressive increase of EC was attributed to excessive pumping.

Water quality for agriculture

Salinization eventually makes groundwaters inadequate for the growth and productivity of many crops (El Moujabber et al. 2006). Many water quality parameters affect crop growth and productivity, but in this study, suitability of surface irrigation for rice cultivation was evaluated using EC, Na, Ca, Mg, Cl, HCO_3, SO_4 and SAR.

The property of most concern is salinity. EC was used instead of the salinity as an indirect measurement. Soil salinity is the better criterion for evaluating crop growth, but salinity of irrigation water was used in this case because it is easier to measure. For appropriate

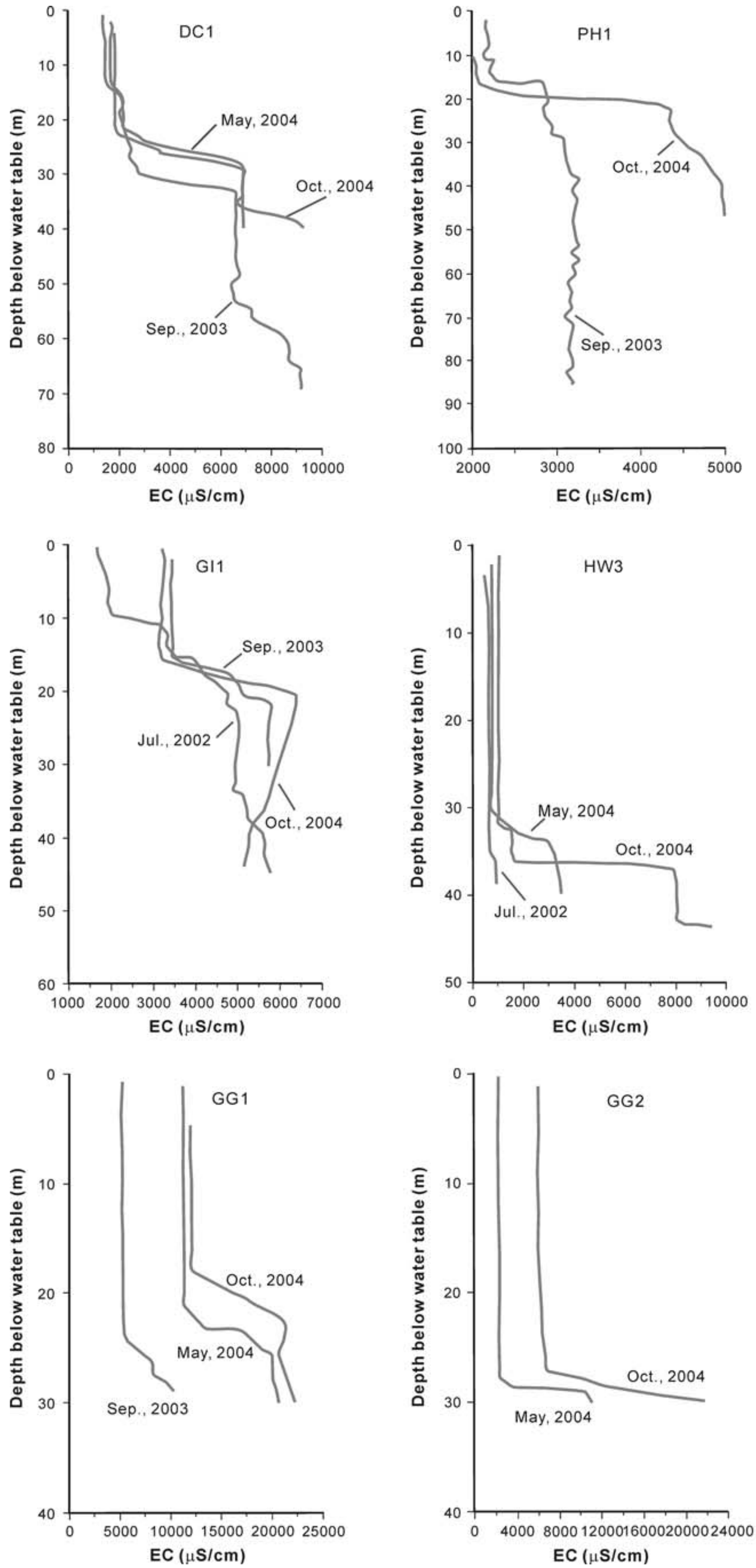


Fig. 11 Vertical EC profiles at some selected monitoring wells

Table 3 Some main criteria of water quality for agricultural irrigation

Parameters	Criteria	Range in this study	Proportion of exceeding (%)	Reference for criteria
EC (μS/cm)	2,000[a]/15,000[b]	67–46,628	42.6/18.5	MAF and KARICO (2004)
Cl (mg/l)	250	6.06–17,869.78	36.5	
SO_4 (mg/l)	50	0.96–2,350.41	34.6	Lee et al. (1999)
HCO_3 (mg/l)	90	18.30–545.34	34.6	Ayers and Westcot (1985),and Hem (1985)
SAR	10	0.001–54.95	23.1	

[a] Recommended value for most of crops

[b] Above which growth of all crops is impossible

growth and productivity of most crops, EC levels should be less than 2,000 μS/cm. But 42.6% of the coastal groundwaters exceeded the recommended EC value, and 18.5% of ECs were greater than 15,000 μS/cm, above which growth is impossible (Table 3).

Salinity levels must consider soil texture and drainage characteristics. The paddy fields of most coastal areas in Korea are largely consisted of silts or silty clay. Because the rice needs a large quantity of water for a long time, drainage conditions are poor. Salinity values of such soils may produce more substantial salt toxicity compared with sandy soil with excellent drainage (Ayers and Westcot 1985).

As a component of the salinity, Cl concentrations were studied. With seawater encroachment, Cl levels of groundwaters in the coastal aquifers should increase. Of the samples, 36.5% exceeded maximum Cl groundwater level (250 mg/l) for agricultural use. Above this level, normal crop growth is not expected. The maximum level for SO_4 for agricultural water is designated at 50 mg/l (Lee et al. 1999); 34.6% of groundwater samples exceeded this level. HCO_3 is not typically a major component of irrigation water and the main concern is damage to leaves of sprinkler irrigated plants. But high HCO_3 content may affect soil permeability by removing soluble Ca. The recommended limit of bicarbonate is 90 mg/l (Ayers and Westcot 1985). In this study, 34.6% of groundwaters exceeded the limit.

The sodium hazard of the irrigation water can be evaluated using SAR from Ca, Mg and Na contents. The combination of specific conductance and SAR is generally used to determine the suitability of water for irrigation. A specific conductance of 2,000 μS/cm at 25°C and an SAR greater than ten represent a high sodium hazard (Hem 1985). The relations between specific conductance and SAR for this study are shown in Fig 12. It is estimated that that there is a high sodium hazard in 21.2% of the groundwater samples. Because rice is moderately tolerant, moderate SAR with low salinity is not a big problem. Higher salinity water (EC > 2,000 μS/cm) with SAR values above ten requires careful management.

Summary and conclusion

Groundwater chemistries in coastal aquifers were evaluated to identify progress of seawater intrusion. Suitability of groundwaters for irrigation was also examined. Data were collected from 55 monitoring wells in the western and southern coastal areas of Korea. From the analysis, conclusions were drawn.

1. Groundwater in the western and southern coastal areas is heavily used for agricultural irrigation. Salinization of fresh groundwater was highly associated with continuous groundwater withdrawal.
2. Distributions of chemical species were very wide but they showed mostly lognormal distribution. The threshold values were estimated as 63 mg/l for Cl and 141 mg/l for HCO_3. Large proportions of the groundwaters were classified as Na–Cl and Ca–Cl types, and the Na–Cl types represented the effect of the seawater intrusion. The region of Ca–Cl type groundwater is the leading edge of the seawater plume.
3. High EC levels reached over 1.6 km inland and high Cl values were observed up to 1.2 km inland. The Cl concentrations and EC levels are highly positively associated. Lower ratios of Na/Cl and SO_4/Cl than the seawater ratios indicated the seawater encroachment. A linear relation between Na and Cl represents simple mixing of fresh groundwater with seawater. The saline Na–Cl typed groundwaters showed Br/Cl ratios similar to or less than the seawater value. Less saline Ca–Cl type groundwater showed higher Br/Cl ratios with lower Cl concentrations. Ca–HCO_3 type groundwaters showed the highest Br/Cl ratios.
4. Some areas showed potential salinity hazard. Of the coastal groundwaters, 42.6% exceeded the

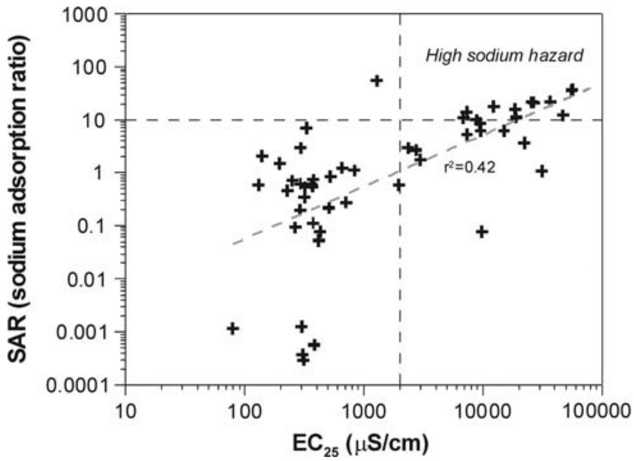


Fig. 12 Relationship between EC at 25°C and SAR value

recommended EC value for agriculture and 18.5% of ECs were greater than 15,000 μS/cm, above which growth of all crops is impractical. In addition, 21.2% of the groundwater samples showed a high sodium hazard. High salinity water with SAR values above ten needs careful management.

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