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Salinization properties of a shallow groundwater in a coastal reclaimed area, Yeonggwang, Korea

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Abstract The need for more agricultural or residential land has encouraged reclamation at the coastal areas of Korea since 1200 AD (approximately). The groundwaters of these reclaimed areas could be expected to reveal hydrogeochemical properties different from those of areas directly affected by seawater intrusion. The purpose of this study, therefore, was to examine the salinization of shallow groundwater in a coastal reclaimed area and to identify the effect of land reclamation on groundwater quality. Major cations and anions, iodide, total organic carbon, δD , $\delta^{18}O$ and $\delta^{13}C$ were measured to assist the hydrogeochemical analysis. Chloride, δD and $\delta^{18}O$ data clearly show that the Na–Cl type water results from mixing of groundwater with seawater. In particular, the δD and $\delta^{18}O$ of Ca + Mg–Cl + NO₃ type groundwaters are close to the meteoric water line, but Na–Cl type waters enriched in chloride are ^{18}O -enriched with respect to the meteoric water line.

Meanwhile, carbon isotopic data and I/Cl ratios strongly suggest that there are various sources of salinity. The $\delta^{13}C$ values of Na–Cl type groundwaters are generally similar to those of Ca + Mg–Cl + NO₃ type waters, which are depleted in ^{13}C with respect to seawater. I/Cl ratios of Na–Cl type groundwater are 10–100 times higher than that of seawater. Because the reclamation has incorporated a large amount of organic matter, it provides optimum conditions for the occurrence of redox processes in the groundwater system. Therefore, the salinization of groundwater in the study area seems to be controlled not only by saltwater intrusion but also by other effects, such as those caused by residual salts and organic matter in the reclaimed sediments.

Keywords Groundwater · Reclaimed area · Seawater intrusion · Salinization · Redox processes

Introduction

Coastal aquifers usually serve as major sources for freshwater supply, such as drinking or irrigation water. Groundwater in the coastal area is relatively vulnerable to the contamination by seawater intrusion, which makes groundwater unsuitable for drinking or irrigation. In addition, heavy pumping and excessive use of near-coast groundwater near the coast can increase the

intrusion of seawater into the aquifer. As saltwater intrusion progresses, groundwaters close to the coast become saline and have to be abandoned. This salinization is the most widespread phenomenon of water contamination and leads to an increase in the content of certain dissolved chemical species such as sodium, chloride, bromide, as well as the overall chemical water composition (Barker et al. 1998; Bear et al. 1999; Cruz and Silva 2000; Giménez and Morell 1997). Because of

the difficulty in restoring the original aquifer properties of groundwaters once contaminated by saltwater, the detection and monitoring of saltwater intrusion are essential in managing the exploitation of these water resources in future. Until recently, most studies on the saline groundwater in Korea have focused on Jeju Island (Choi and Kim 1989; Kim et al. 2003c; Park and Lee 1997).

Starting by about 1200 AD, the need for more agricultural or residential land in the western coastal part of Korea has led to large areas being reclaimed from the sea or tidal flats. Altogether, about 2,000 km² have been reclaimed or about 2% of the total land surface of present Korea, which is 99,000 km² (Koo et al. 1998).

The subsurface system is likely to be altered significantly during reclamation and groundwaters are expected to show properties different from those affected directly by seawater encroachment. Therefore, the purposes of this study are to examine spatial and temporal variations of groundwater chemistry in a coastal aquifer system, which is in a reclaimed area of Korea, and to interpret reasonable processes that control the groundwater chemistry. The chemical compositions of groundwater and isotope data were used to determine factors affecting the hydrogeochemistry of groundwater.

For this research, a western coastal area affected by saltwater intrusion was chosen. The investigated area is a rural village on the western coast of Korea adjacent to the Yellow Sea, at Baeksu-eup and Yumsan-myeon, Yeonggwang-gun. The study area is approximately 35 km² which is between longitudes 126°30'00" and 126°45'00" and latitudes 35°23'00" and 35°30'00" (Fig. 1). The elevation of the study area, most of which is used for cultivation, ranges from 0 to 300 m above mean sea level. The central part is a cultivated plain that adjoins higher land (approximately 300 m above sea level) to the northeast and southeast. Rice is cultivated in 60% of the study area fields near the plain, while many kinds of vegetables and fruits are planted sparsely on the hillsides. Next to the coast, there are salt farms. Therefore, the study area mainly consists of salt farms and residences. The surface hydrology of the region is characterized by the Bulgab stream and another small stream. These streams flow from east to west across the plain, the Bulgab stream with a meandering pattern. The streams and groundwaters have been used as the most important irrigation sources for the nearby paddy fields.

The coastline of the study area has been formed by natural and artificial activities. A comparison of the past geographical maps (1910–1976) made by the National Geography Institute, reveals that the coastal line has changed with time as a result of reclamation (Fig. 1). Like the adjacent areas, the study area has been developed for various agricultural activities and the population has also increased thereafter. Therefore, the extra agricultural or residential space has been reclaimed from

the sea or tidal flats. Due to the lack of historic documents and maps, the exact reclamation history is not known but many local residents and some government publications prove that areas that are almost flat for cultivation have been reclaimed from the sea or muddy beaches.

The topography of the study area can be explained in relation to its geology. The lithology consists of Jurassic granite, mostly biotite granite, and Quaternary alluvium. The granite rocks are distributed in the northeastern and southeastern mountainous parts of the study area. Some faults or lineaments representing the geological structure of the areas cannot be observed at the surface. According to previous studies on this area, there is a good possibility of fracture zones below the surface. The biotite granite is mainly composed of quartz, K-feldspars (chiefly orthoclase), plagioclase, and biotite. The Quaternary deposits are mainly alluvial sediments (Chang and Hwang 1984). A geological profile of monitoring wells established by Korea Institute of Geoscience and Mineral Resources (KIGAM) shows that the sediments are mainly composed of three layers, such as mud, coarse sand and bedrock. The core logging data show that the thickness of mud sediment ranges from 15 to 18 m, the sand layer ranges from 23 to 25 m, and the granite bedrock is below 25 m (Fig. 2).

The climate of the area is temperate. Winter is a cold and dry season, and summer is hot and humid. Spring and autumn are very pleasant with mild temperatures. The monthly average temperature varies from -0.9°C in January to 25.4°C in August (the annual average temperature is 12.8°C). Precipitation also varies seasonally. According to measurements by the Korea Meteorological Administration (KMA), the average annual rainfall for 10 years at the study area is 1,168.6 mm. Rainfall occurs mostly in the period between July and September (the rainy season), when about 67% of the annual rainfall is received, whereas winter is mostly dry. This indicates that the amount of rainfall infiltrating into the aquifer of the study area could show seasonal variation. As a consequence, the lack of recharge during the dry season may allow increased seawater intrusion.

Most domestic wells in the area were developed for drinking water and irrigation. Many groundwaters are primarily extracted from individually owned wells drilled in and around cultivated and residential areas. Because of the developmental costs, most individually owned wells are only drilled to approximately 30 m below surface. According to results of core logging, the main aquifer of the area is thought to be a confined aquifer because the upper part of the aquifer is covered with a mud layer. It is also thought that the sand layer and granite bedrock act as the main aquifers in the area. The general direction of flow of the shallow groundwa-

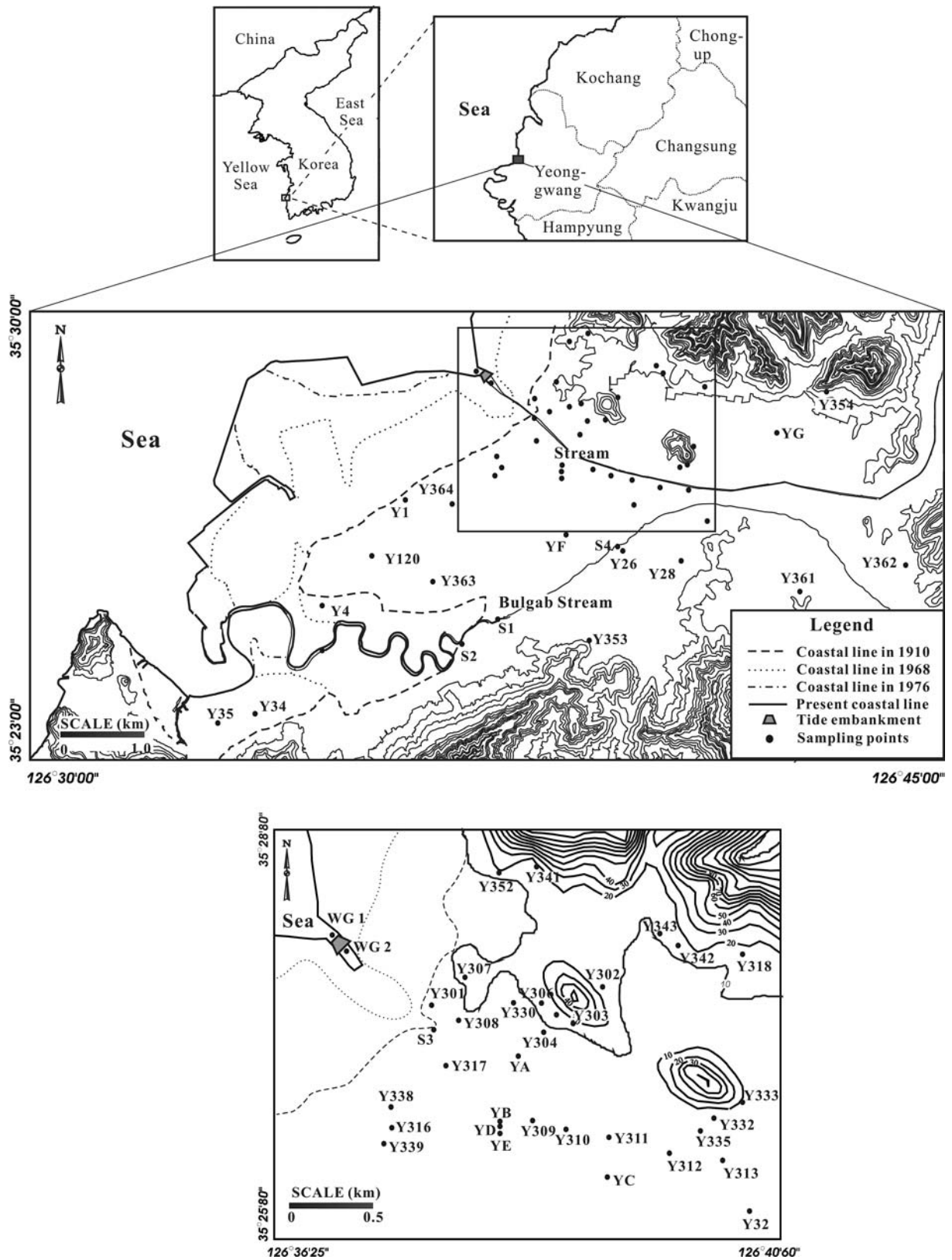


Fig. 1 The geography of the study area and location of groundwater and surface water samples

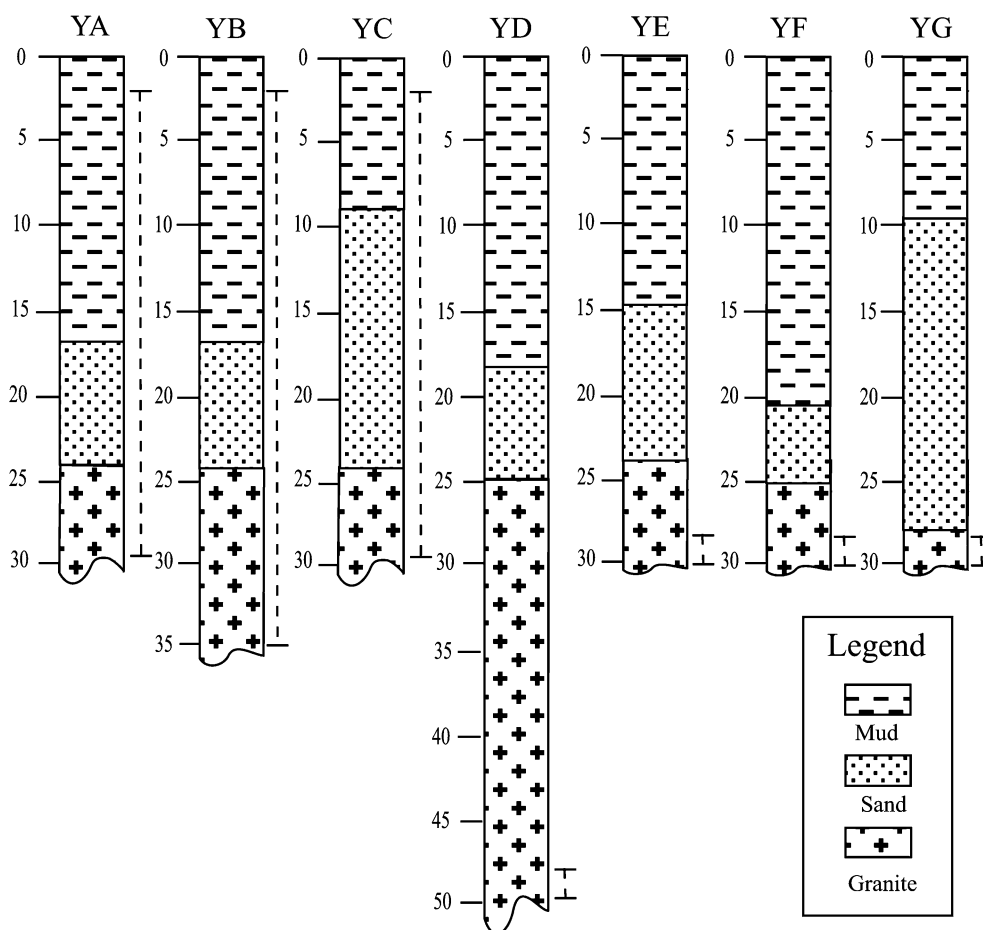


Fig. 2 The profiles of core samples at boreholes YA, YB, YC, YD, YE, YF and YG. The *dash lines* represent screen of wells

ter is affected by the topography of the study area because of the narrowness of the main aquifer. Groundwater in the shallow aquifer is mostly recharged from the nearby mountains. Therefore, the flow velocity of the shallow groundwater of the central plain area must be very low because of its very low hydraulic gradient. Consequently, owing to very slow velocity of groundwater discharge into the sea, saltwater intrusion can occur by virtue of the greater density of seawater. Meanwhile, the flow velocity of the shallow aquifer in the northeastern and southeastern mountainous part must be relatively high owing to its high hydraulic gradient. If the study area is under natural conditions, groundwater in the shallow aquifer will be mostly recharged from the nearby northeastern and southeastern mountainous area, and will usually flow toward the western coastal area. According to previous research in the area, the recharge rate has been estimated at 7.2% (99.3 mm/year) and the transmissivity measured at a well in the granite bedrock area is 1.31 m²/day (KIGAM 1997).

Methods

When there is less groundwater recharge during the dry season, there is more possibility of seawater intrusion. Samples of groundwater, stream and seawater were taken in March 2001, as March is generally dry. As it happened, precipitation in the study area was approximately 16.2 mm in March. To investigate the effect of tidal level change, 44 groundwater samples were collected at a time in this month when there was a big difference between the full and ebb tide. Stream and seawater samples were collected using a bailer. Groundwater samples were collected from local wells, including shallow dug wells as well as boreholes. In the case of dug wells, it was checked if the dug well was being used daily, ensuring that stagnant water was not sampled. All other wells and bores, most of which were constructed with discrete screen intervals, were pumped with either a submersible or a peristaltic pump. At least three well volumes were pumped to waste before col-

lection of a sample to avoid collection of water that had been stagnating in the borehole itself. During purging, the dissolved oxygen (DO), electrical conductivity (EC), pH, redox potential (Eh) and temperature were measured continuously. Purging was considered complete when field parameter measurements stabilize within approximately 10%. Most domestic dug wells, except boreholes developed by KIGAM or wells established by village cooperatives, are only drilled to approximately 30 m below the surface and are in and around cultivated and residential areas. Sampling locations are shown in Fig. 1.

Sampling, preservation and water analyses were performed in accordance with the standard procedures described by APHA (1995). In addition to groundwater sampling, the EC was measured at 1 m intervals down the borehole using YSI 6820 automatic measurement equipment. Prior to sampling, the temperature, pH, Eh and EC were measured using temperature-compensated multi-meters (Orion multi-meter 1230 or Horiba multi-meter D24) in a flow-through cell attached to the pump outlet. Samples were taken for laboratory analyses of major ions and environmental isotopes. Alkalinity was determined by the Gran titration method using 0.1N HCl (Wetzel and Likens 1991). DO was re-measured by Winkler iodometric titration method to compare with the field measurements using the DO-meter (APHA 1995). For analyses of major cations and trace elements, samples were filtered through a 0.45 μm filter and acidified to pH < 2 with HNO_3 (to prevent absorption of cations to the container surface and precipitation of dissolved ions) and collected in polyethylene bottles. Cations and trace elements were analyzed in these solutions by using an inductively-coupled plasma-atomic emission spectrometer (ICP-AES) at the Seoul branch of the Korea Basic Science Institute (KBSI). Prior to analyses of major anions, samples were filtered through 0.45 μm filters without acidification. They were analyzed by Dionex DX-500 Ion Chromatography (IC) in the Geochemistry Laboratory at the School of Earth and Environmental Sciences (SEES), Seoul National University (SNU). Iodide was analyzed using the

UV-visible spectrometer in the Geochemistry Laboratory at the SEES, the SNU, by the method of APHA (1995). Total organic carbon (TOC) samples were preserved using mercury chloride (HgCl_2) to prevent biological activity and were analyzed using the TOC analyzer at the Institute of Environmental Science and Engineering in the SNU (APHA 1995). For analysis of isotopes of δD and $\delta^{18}\text{O}$, samples were collected in scintillation glass vials with conical caps to remove headspace. Analysis of the isotopes of dissolved inorganic carbon (DIC) to obtain $\delta^{13}\text{C}$, the DIC in water samples was precipitated in the field as SrCO_3 by adding $\text{NH}_4\text{OH-SrCl}_2$ solution using the method of Bishop (1990). The precipitates were filtered onto a 0.2 μm glass filter and dried at 105°C in a drying oven in the laboratory. Each δD , $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ was analyzed using a VG prism stable isotope ratio mass spectrometer at the KBSI. The analytical reproducibility was $\pm 0.1\%$ for $\delta^{18}\text{O}$, $\pm 0.1\%$ for δD and $\pm 0.1\%$ for $\delta^{13}\text{C}$, respectively. All isotope data were reported in the usual δ notation relative to the V-SMOW for oxygen and hydrogen and the V-PDB for carbon:

$$\delta(\text{‰}) = \left(\frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}} \right) \times 1000$$

where R represent the ratio $^{18}\text{O}/^{16}\text{O}$, D/H and $^{13}\text{C}/^{12}\text{C}$ ratio of sample and standard for each isotope (Hoefs 1997).

Results and discussions

Hydrogeochemistry

Summaries of the water analyses for the study area are presented in Tables 1 and 2. The data presented have a charge balance between cations and anions within 5%. Data from samples collected in the Bulgab stream or the small stream are given in Table 1. A tide embankment that exists across the mouth of the small stream reaches the sea to examine the effect of the tidal

Table 1 Physical and chemical properties of stream in the study area

| Sample Site | Sampling time | DO (mg/l) | Temp (°C) | EC ($\mu\text{S}/\text{cm}$) | pH | Eh (mV) | Cl (mg/l) | Br (mg/l) | NO_3 (mg/l) | SO_4 (mg/l) | HCO_3 (mg/l) | Na (mg/l) | Mg (mg/l) | K (mg/l) | Ca (mg/l) | Fe (mg/l) | TOC (mg/l) |
|-------------|---------------|-----------|-----------|--------------------------------|------|---------|-----------|-----------|----------------------|----------------------|-----------------------|-----------|-----------|----------|-----------|-----------|------------|
| WG1-1 | Low tide | 12.8 | 7.4 | 1,334 | 8.41 | 379 | 300.3 | 1.0 | 23.7 | 58.3 | 52.5 | 187.9 | 29.2 | 16.6 | 23.4 | ND | 14.8 |
| WG2-1 | Low tide | 12.6 | 8.3 | 630 | 8.32 | 457 | 108.6 | 0.3 | 24.6 | 34.0 | 51.8 | 78.6 | 15.6 | 11.6 | 23.3 | ND | 17.3 |
| WG1-2 | High tide | 4.7 | 13.5 | 37,168 | 8.00 | 221 | 13,791.7 | 54.5 | 7.2 | 1923.6 | 68.0 | 7,814.9 | 1,310.0 | 342.9 | 309.0 | ND | 10.6 |
| WG2-2 | High tide | 14.2 | 9.4 | 17,645 | 7.88 | 260 | 6,796.2 | 17.3 | 14.2 | 789.4 | 53.8 | 3,265.2 | 438.9 | 131.1 | 143.7 | ND | 11.3 |
| S1 | High tide | – | – | 359 | – | – | – | – | – | – | – | – | – | – | – | – | – |
| S2 | High tide | – | – | 431 | – | – | – | – | – | – | – | – | – | – | – | – | – |
| S3 | High tide | – | – | 308 | – | – | – | – | – | – | – | – | – | – | – | – | – |
| S4 | High tide | – | – | 783 | – | – | – | – | – | – | – | – | – | – | – | – | – |

– Indicates no measurement

Table 2 The physio-chemical properties and major ions of groundwater and seawater in the study area

| Sample Site | Depth (m) | Temp (°C) | EC (µS/cm) | Eh (mV) | pH | DO (mg/l) | Cl (mg/l) | NO ₃ (mg/l) | SO ₄ (mg/l) | HCO ₃ (mg/l) | Na (mg/l) | Mg (mg/l) | K (mg/l) | Ca (mg/l) |
|-------------|-----------|-----------|------------|---------|------|-----------|-----------|------------------------|------------------------|-------------------------|-----------|-----------|----------|-----------|
| YA | 30 | 13.9 | 2,000 | 172 | 6.88 | 0.9 | 522.9 | 2.8 | 44.8 | 119.2 | 386.1 | 29.0 | 30.1 | 25.7 |
| YB | 35 | 13.3 | 8,700 | 90 | 7.07 | 0.4 | 2,405.2 | ND | 262.7 | 170.7 | 1,515.1 | 214.1 | 65.6 | 240.5 |
| YC | 30 | 15.0 | 7,100 | 44 | 7.35 | 0.9 | 1,951.1 | ND | 69.2 | 387.3 | 1,307.9 | 210.5 | 66.2 | 82.4 |
| YD | 50 | 13.5 | 19,440 | 115 | 6.7 | 0.8 | 7,485.3 | ND | 819.9 | 123.5 | 3,828.6 | 509.8 | 120.5 | 863.6 |
| YE | 30 | 13.8 | 14,670 | 110 | 6.75 | 0.4 | 4,864.9 | ND | 260.1 | 181.2 | 2,640.3 | 309.2 | 98.3 | 377.7 |
| YF | 30 | 13.6 | 18,040 | 43 | 7.35 | 0.3 | 6,408.7 | ND | 713.2 | 394.6 | 3,958.0 | 331.4 | 132.8 | 153.9 |
| YG | 30 | 15.0 | 567 | 231 | 7.26 | 2.2 | 103.4 | 5.5 | 15.1 | 77.7 | 63.2 | 11.5 | 3.2 | 50.0 |
| Y1 | – | 14.5 | 1,587 | 348 | 7.78 | 3.1 | 233.6 | 159.4 | 99.1 | 130.6 | 256.0 | 46.1 | 39.8 | 103.1 |
| Y4 | – | 14.6 | 2,660 | 185 | 7.98 | 1.9 | 440.8 | 1.5 | 414.0 | 293.0 | 644.5 | 169.9 | 61.1 | 80.0 |
| Y26 | 14 | 14.5 | 18,430 | –29 | 6.98 | 2.1 | 6,516.0 | ND | 354.3 | 154.1 | 3,654.6 | 484.0 | 120.5 | 317.2 |
| Y28 | 18 | 14.5 | 5,960 | –16 | 6.91 | 0.3 | 1,717.1 | ND | 419.8 | 78.6 | 1,348.0 | 61.4 | 33.1 | 37.4 |
| Y32 | – | 14.3 | 255 | 255 | 7.27 | 3.4 | 93.5 | 48.8 | 15.2 | 10.5 | 59.6 | 12.2 | 3.4 | 20.3 |
| Y34 | – | 14.5 | 989 | 65 | 6.74 | 4.1 | 169.6 | 1.3 | 125.1 | 43.8 | 94.3 | 29.7 | 8.4 | 74.1 |
| Y35 | 20 | 13.6 | 403 | 227 | 7.03 | 7.2 | 86.8 | 3.7 | 7.4 | 35.1 | 41.6 | 13.8 | 3.8 | 24.0 |
| Y120 | 12 | 15.2 | 1,037 | 248 | 7.66 | 0.8 | 72.2 | 20.9 | 81.7 | 175.7 | 117.1 | 29.6 | 24.9 | 125.1 |
| Y301 | 10 | 10.7 | 1,367 | 380 | 6.05 | 8.0 | 373.5 | 30.0 | 30.5 | 27.0 | 122.6 | 44.9 | 0.2 | 94.8 |
| Y302 | 15 | 14.9 | 504 | 250 | 6.04 | 1.4 | 100.0 | 0.7 | 19.9 | 46.8 | 53.5 | 23.3 | 0.0 | 24.0 |
| Y303 | 20 | 15.1 | 459 | 246 | 6.41 | 5.2 | 66.6 | 85.2 | 13.9 | 25.4 | 45.8 | 14.7 | 0.0 | 32.7 |
| Y304 | 30 | 15.6 | 841 | 246 | 6.29 | 3.6 | 98.2 | 55.0 | 33.8 | 53.3 | 55.2 | 17.0 | 4.3 | 50.6 |
| Y306 | – | 16.7 | 902 | 219 | 6.73 | 5.0 | 152.8 | 107.7 | 37.7 | 61.0 | 83.8 | 30.1 | 0.1 | 69.4 |
| Y307 | 6 | 11.6 | 1,355 | 384 | 6.1 | 6.2 | 370.4 | 29.8 | 30.4 | 28.7 | 119.4 | 44.7 | 0.2 | 92.6 |
| Y308 | 38 | 14.8 | 461 | 244 | 6.31 | 4.9 | 87.4 | 32.5 | 13.4 | 35.0 | 41.6 | 23.9 | 0.1 | 26.2 |
| Y309 | 9 | 16.0 | 3,389 | 26 | 7.48 | 2.6 | 666.2 | 0.5 | 127.3 | 441.6 | 494.6 | 99.9 | 42.6 | 29.1 |
| Y310 | 22 | 15.3 | 12,570 | 4 | 7.24 | 0.4 | 4,099.1 | ND | 148.5 | 282.9 | 2,638.8 | 284.7 | 109.0 | 129.2 |
| Y311 | 9 | 15.6 | 4,500 | 6 | 7.72 | 0.8 | 1,050.3 | ND | 66.5 | 404.6 | 927.2 | 69.7 | 50.6 | 23.0 |
| Y312 | 5 | 15.0 | 2,660 | 26 | 7.65 | 1.6 | 1,100.6 | ND | 109.6 | 174.8 | 856.9 | 54.7 | 32.8 | 20.8 |
| Y313 | 5 | 15.5 | 1,967 | 82 | 7.45 | 1.6 | 524.1 | 4.7 | 28.3 | 89.5 | 405.5 | 35.1 | 19.2 | 23.1 |
| Y317 | 25 | 16.7 | 998 | 214 | 7.74 | 3.1 | 97.1 | 177.9 | 73.6 | 100.7 | 64.6 | 37.3 | 11.5 | 99.7 |
| Y318 | 60 | 17.2 | 375 | 329 | 6.73 | 7.2 | 22.6 | 18.0 | 5.1 | 42.2 | 16.4 | 4.3 | 2.6 | 12.3 |
| Y330 | – | 17.8 | 596 | 586 | 6.25 | 5.9 | 97.3 | 69.7 | 14.1 | 50.9 | 44.8 | 19.6 | 4.8 | 35.7 |
| Y332 | – | 16.4 | 1,660 | 44 | 7.45 | 4.8 | 341.7 | 1.9 | 39.4 | 281.5 | 254.5 | 28.2 | 20.3 | 10.8 |
| Y335 | – | 16.3 | 2,374 | 114 | 7.18 | 2.3 | 657.8 | 1.0 | 49.9 | 195.0 | 405.3 | 40.5 | 22.7 | 15.6 |
| Y338 | – | 15.7 | 999 | 306 | 7.99 | 4.2 | 112.8 | 135.9 | 134.7 | 55.6 | 68.0 | 30.2 | 12.2 | 80.7 |
| Y339 | 10 | 15.8 | 1,795 | 223 | 7.21 | 0.8 | 193.3 | 248.4 | 133.6 | 197.4 | 131.1 | 52.1 | 115.6 | 120.0 |
| Y341 | 12 | 13.4 | 629 | 224 | 6.44 | 6.0 | 110.5 | 71.5 | 17.3 | 35.6 | 64.6 | 17.3 | 4.6 | 43.1 |
| Y342 | – | 17.3 | 864 | 358 | 6.20 | 3.9 | 118.2 | 84.6 | 41.4 | 141.6 | 48.1 | 20.0 | 3.6 | 77.0 |
| Y343 | – | 17.4 | 583 | 246 | 6.50 | 5.8 | 55.2 | 112.3 | 24.1 | 73.1 | 48.2 | 18.6 | 3.0 | 39.7 |
| Y352 | 12 | 12.5 | 678 | 69 | 6.38 | 2.8 | 130.5 | 85.3 | 18.2 | 32.5 | 61.8 | 25.3 | 6.4 | 52.1 |
| Y353 | 27 | 13.3 | 215 | 265 | 6.60 | 4.6 | 32.9 | 15.3 | 12.5 | 20.9 | 38.5 | 0.0 | 0.0 | 22.7 |
| Y354 | 10 | 11.4 | 256 | 255 | 6.80 | 6.6 | 37.4 | 35.3 | 18.4 | 13.7 | 21.2 | 7.8 | 6.9 | 18.6 |
| Y361 | – | 11.6 | 729 | 324 | 7.17 | 4.1 | 126.8 | 86.5 | 22.9 | 48.8 | 37.2 | 9.5 | 13.7 | 26.6 |
| Y362 | – | 10.5 | 395 | 351 | 7.28 | 5.4 | 74.0 | 29.1 | 6.6 | 48.8 | 27.3 | 2.8 | 0.8 | 17.4 |
| Y363 | – | 15.4 | 1,470 | 289 | 7.50 | 4.5 | 146.8 | 221.1 | 95.4 | 189.2 | 53.8 | 29.3 | 27.6 | 106.1 |
| Y364 | – | 14.9 | 1,057 | 303 | 7.79 | 2.0 | 66.0 | 13.9 | 62.4 | 347.8 | 33.4 | 18.2 | 40.5 | 70.0 |
| Sea | – | – | 39,390 | 385 | 7.47 | 5.9 | 14,408.2 | ND | 1,951.2 | 100.5 | 8,868.3 | 1,482.9 | 300.9 | 304.6 |

ND Not detected

– Indicates no measurement

cycle on water quality, WG samples were collected between high and low tides, twice daily, on both sides of the tide embankment. The TDS of WG samples at high tide are higher than those at low tide, indicating that seawater is influencing surface water behind the embankment in the high tidal period. This result implies that there is a possibility of seawater intruding subsurface of the study area during high tide. The EC values of inland stream water, at sites S1, S2, S3, and S4, were measured and samples collected just after high tide. Results here show that seawater did not directly

intrude inland along stream channels. A summary of the March 2001 groundwater and seawater analyses is presented in Table 2. The compositions of the groundwaters showed a broad range with the locations. Observation wells YA, YB, YC, YD, YE, YF, and YG were boreholes established by the KIGAM and other wells were developed by individuals or village cooperatives. Although the depth of some wells could not be measured, most individually owned wells are thought to have been drilled to within only 30 m below the surface and not to bedrock, owing to higher costs.

Therefore, it is thought that most wells in the study area are screened within the shallow aquifer.

The analytical data show considerable variation in the concentrations of components. The chemical composition of groundwater changes from the hillsides to the plain. The value of EC ranges from 215 to 19,440 $\mu\text{S}/\text{cm}$. The chloride concentrations of the groundwater samples range from 22.6 to 7,485.3 mg/l. Because of the unreactivity of chloride, chloride is a good guide to mixing proportions. The groundwater over a large part of the study area is not suitable for drinking or irrigation water, based on the 250 mg-Cl/l guideline for potable water (Izbicki 1996). Sodium is the most abundant cation in seawater. It showed trends similar to chloride. The lowest value is 16.4 and the highest value is 3,828.6 mg/l. Because the calcium content of seawater is not very high, high calcium values might be attributed to calcite dissolution or cation-exchange reactions accompanying saltwater intrusion. The calcium concentration is as high as 863.6 mg/l and as low as 6.3 mg/l. Magnesium concentrations generally have a similar trend to calcium. Because magnesium is the second most abundant cation in seawater, the main source of magnesium might be seawater. The highest value of the study area is 509.8 mg/l and the lowest value is 4.3 mg/l.

Because the groundwaters are likely to be affected by agricultural activities and seawater intrusion, two chemical components, chloride and nitrate, were chosen to represent these influences and examine their spatial variation. The spatial distribution of major elements mainly depends on the distance from the coastal line, topography, geology, and groundwater flow direction. The spatial variations of chloride and nitrate concentrations are shown in Fig. 3a, b.

As shown in Fig. 3a, the central plain has relatively high chloride concentrations compared to the near-shore area or area with high elevation. Higher chloride concentrations in groundwater are observed in the wells of about 2–3 km inland area, far from the coastline. Meanwhile, according to Fig 3b, the central plain area has relatively lower concentrations for nitrate than the near-shore area. According to these results, the groundwaters in the central plain area are characterized by higher concentrations of chloride compared with those in other areas such as seashore or hilly areas. Also, it seems that some groundwaters at the seashore or the hilly areas with high nitrate concentrations are often affected by contamination induced by human activities, including agricultural activities.

To observe the major components that influence groundwater quality, the relationship between total dissolved solids (TDS) and major ions in the groundwaters were plotted (Figs. 4, 5). The plot shows that most ions are positively correlated with TDS. In particular, Na, Cl, and Mg show a strong correlation

($r^2=0.9880$, 0.9932 , and 0.9403 , respectively) with TDS, indicating that such ions are derived from the same source of saline waters. Because these components, Na, Cl and Mg, are dominant in seawater, this implies that salinization of this area is closely connected with seawater. Meanwhile, in the case of nitrate, two trends can be identified ($r^2=0.4646$ and 0.5016), correlated with TDS on the graph. This means that two reactions with respect to nitrate are possible, one with a relatively constant nitrate concentration with respect to TDS and the other with an increasing pattern of nitrate concentrations with respect to TDS. In general, it has been known that nitrate is an indicator of anthropogenic contamination in most groundwaters. Moreover, it is thought that nitrate is a widespread contaminant in groundwater systems affected by agricultural activities (Kacaroglu and Gunay 1997; Kim et al. 2003b). Owing to its shallowness, the aquifer of the study area is highly susceptible to pollution from irrigation activities. Therefore, it is fairly certain that the increasing pattern ($r^2=0.4646$) of nitrate concentrations with respect to TDS originates from irrigation of cultivated areas.

Because nitrate constituted a significant percentage of the total ion concentration for some part of the study area, piper diagrams were modified to include nitrate (Kim et al. 2003b; Song et al. 1999). If fresh groundwater is simply mixed with seawater, the groundwater on the modified piper diagram will be plotted with seawater. In fact, it shows that the chemical composition of the groundwaters can be divided into two main types except for one sample (Fig. 6). Each water type had different ranges in chemical components, such as sodium, calcium, magnesium, chloride, and nitrate. Using the pattern on the figure, the groundwaters were classified into two groups, namely the Na–Cl type and the Ca + Mg–Cl + NO_3 type. The major ion trends of the Na–Cl type are $\text{Na}^+ > \text{Mg}^{2+} > \text{Ca}^{2+} > \text{K}^+$ and $\text{Cl}^- > \text{HCO}_3^- > \text{SO}_4^{2-}$. In contrast, those of Ca + Mg–Cl– NO_3 type are $\text{Na}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ or $\text{Ca}^{2+} > \text{Na}^+ > \text{Mg}^{2+} > \text{K}^+$ and $\text{Cl}^- > \text{NO}_3^- > \text{HCO}_3^- > \text{SO}_4^{2-}$ or $\text{NO}_3^- > \text{Cl}^- > \text{HCO}_3^- > \text{SO}_4^{2-}$. Because Na–Cl type groundwaters plotted along with seawater, it is certain that Na–Cl type groundwaters are mainly a result of mixing with seawater. Meanwhile, Ca + Mg–Cl + NO_3 type groundwaters may result from two possibilities, one of which is the effect of cultivation. About 54% of the Ca + Mg–Cl + NO_3 type groundwater has more NO_3^- than the maximum amount of 45 mg/l permitted by the US Environmental Protection Agency (US EPA 2003), which means that NO_3^- has severely contaminated this type of groundwater. Because this Ca + Mg–Cl + NO_3 type groundwater has a high concentration of NO_3^- , Cl^- , K^+ , Ca^{2+} and Mg^{2+} , NO_3^- likely comes from anthropogenic sources such as chemical fertilizers. Another possible reaction is cation exchange reaction with aquifer minerals. According to previous research, it is known

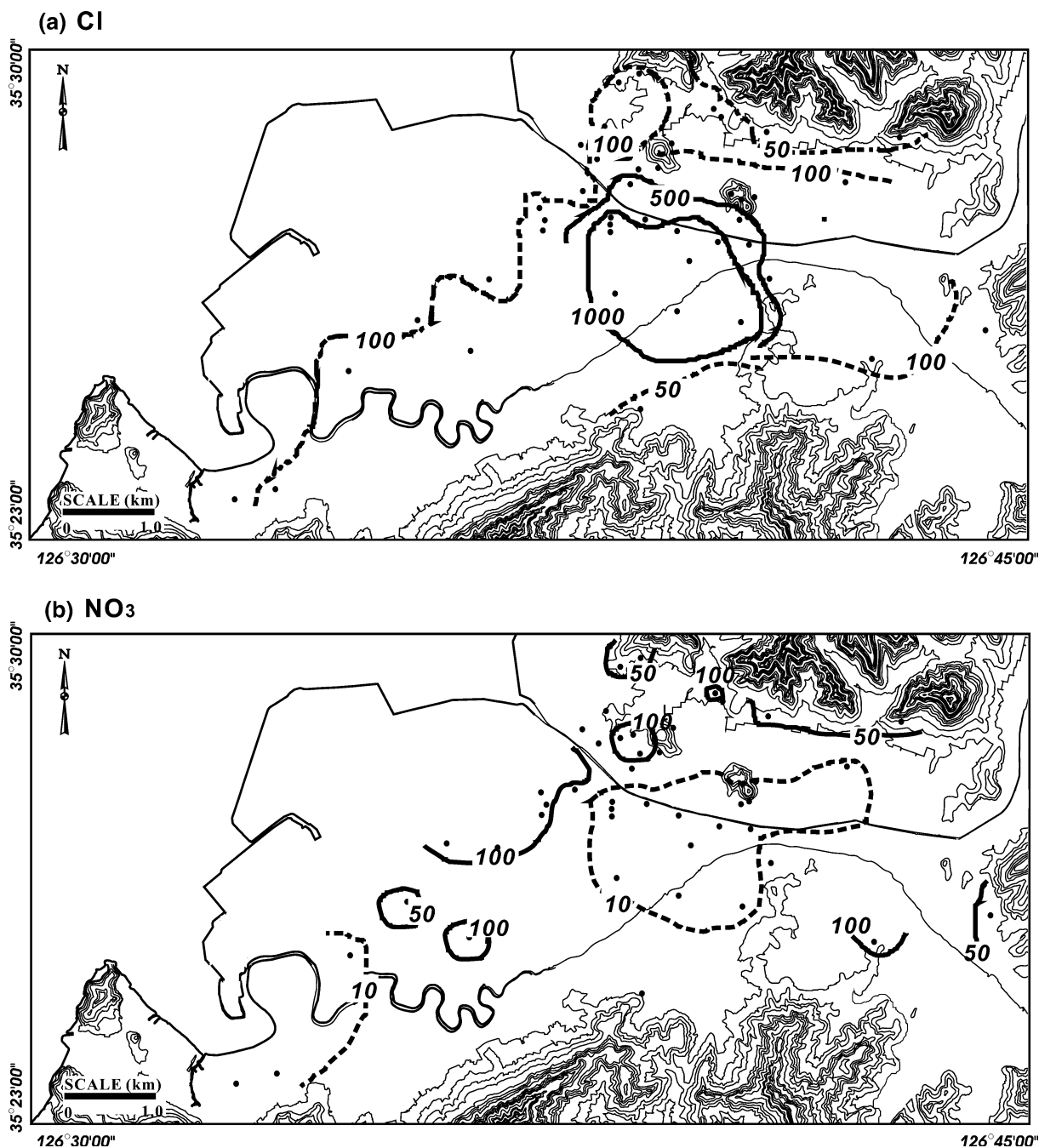


Fig. 3 a Spatial distribution of chloride concentration in the groundwater. b Spatial distribution of nitrate concentration in the groundwater

that the salinization process is often linked to cation-exchange reactions (Appelo and Postma 1993; Cruz and Silva 2000). These ion-exchange processes account for the enrichment or depletion of the cations involved in the reactions. Freshwater in coastal areas is usually dominated by Ca^{2+} . Therefore, the cation exchange sites on the surfaces of material in the aquifer are mostly occupied by calcium ions. In seawater, Na^+ and Cl^- are

the dominant ions, and sediment in contact with seawater will have adsorbed Na^+ for a large part. When seawater intrudes in a coastal aquifer an exchange reaction of cations takes place as follows:

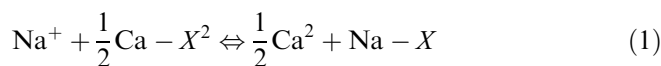


Fig. 4 The diagrams of variations between TDS (total dissolved solid) and cations (K, Na, Ca, Mg) in the groundwater of the study area

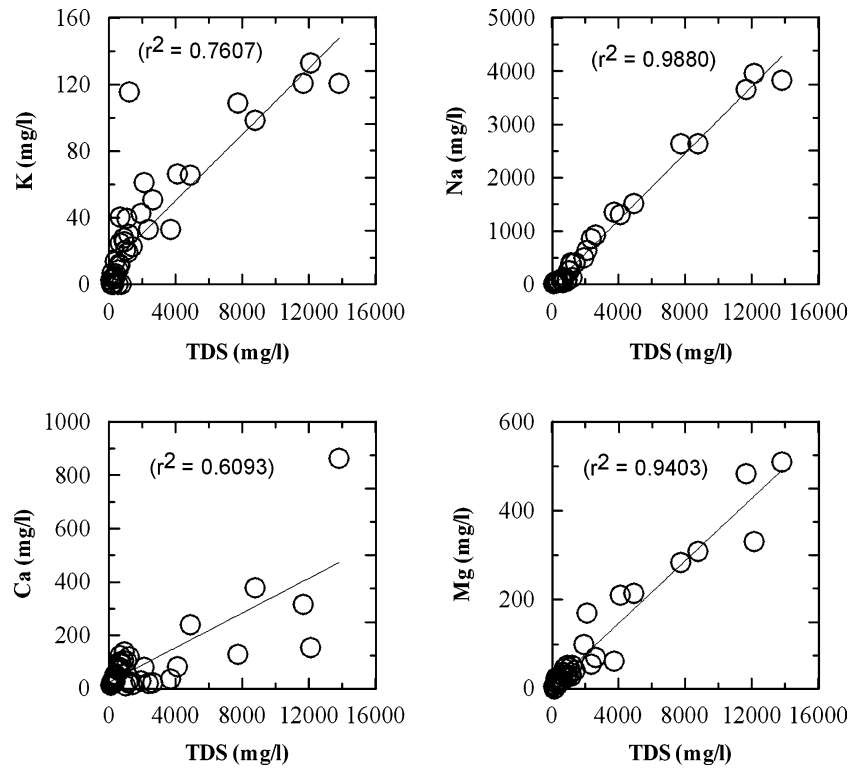


Fig. 5 The diagrams of variations between TDS (total dissolved oxygen) and anions (NO_3 , SO_4 , Cl, HCO_3) in the groundwater of the study area

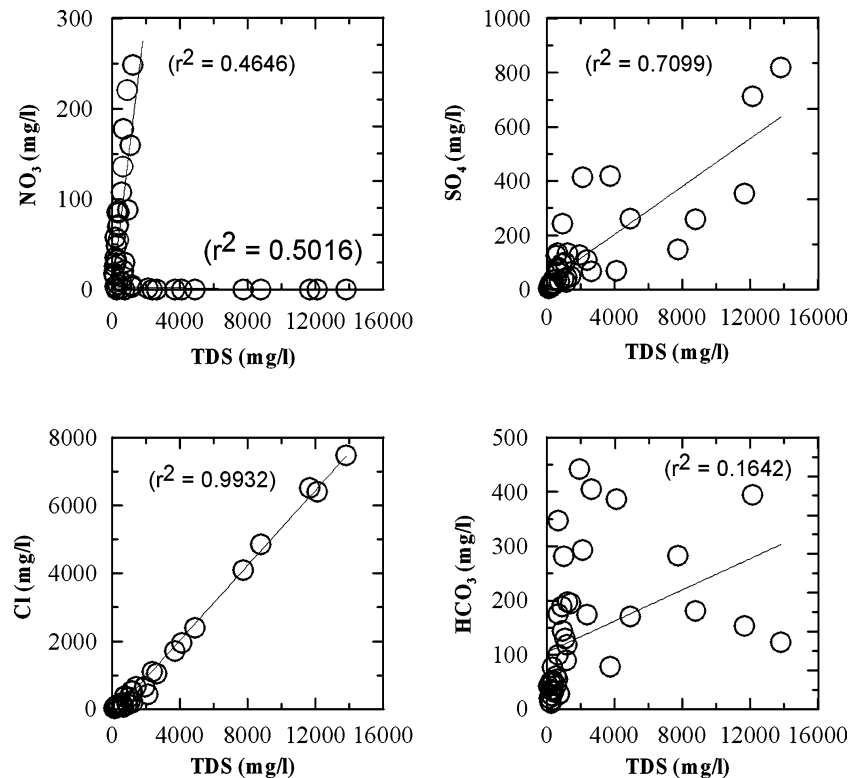
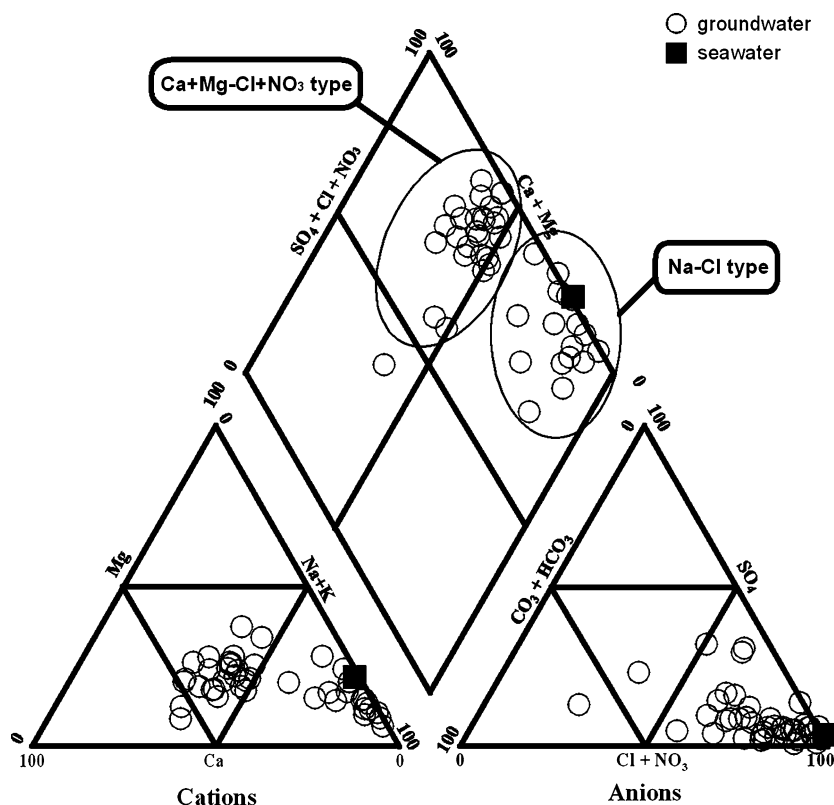


Fig. 6 Modified Piper diagram of the groundwater samples in the study area. NO_3 has been added to the $\text{SO}_4 + \text{Cl}$ side of the ion rhombus and the Cl side of the anion triangle



where X indicates the soil exchanger (site). By Eq. 1, Na^+ is taken up by the exchanger and Ca^{2+} is consequently released into the water phase. The groundwater quality changes from Na-Cl type to Ca + Mg-Cl + NO_3 type water.

To examine the spatial distribution of these groundwater types, these groundwater groups were plotted according to location and topography of the wells (Fig. 7). While groundwater near the seashore area, in general, belongs to the Na-Cl type groundwater

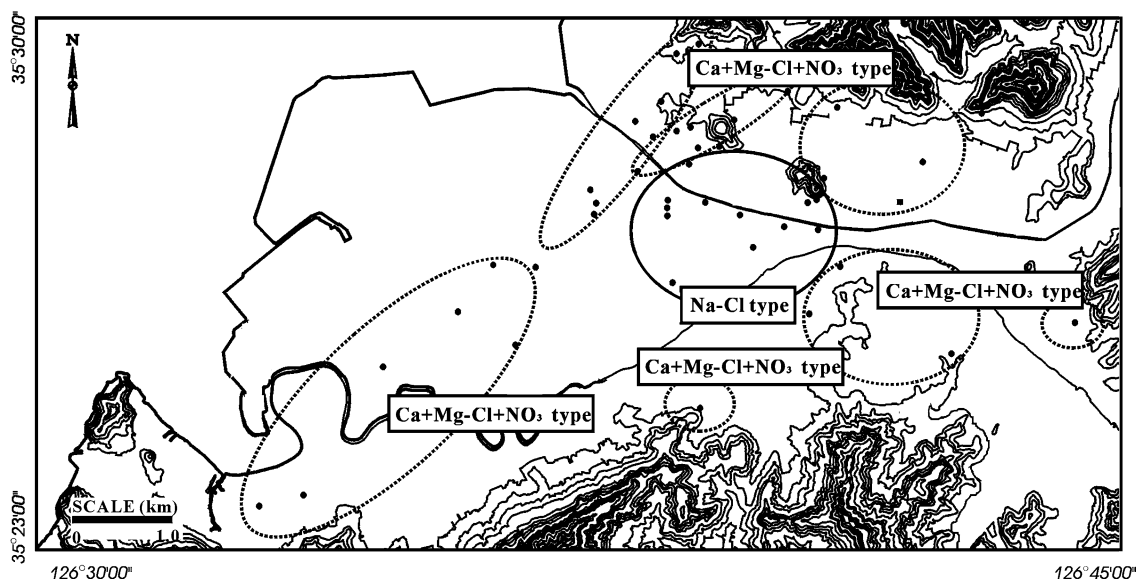


Fig. 7 The two classified water types of groundwater samples on a geographic contour map of the study area. The first group is the Na-Cl type, and the second is the Ca + Mg-Cl + NO_3 type

(Giménez and Morell 1997; Kim et al. 2003a), in this case groundwaters of the central plain area show Na–Cl type. Meanwhile, groundwaters at the seashore or hilly areas inland belong to the Ca + Mg–Cl + NO₃ type. To examine in detail the degree of salinization in the central plain, the EC was measured with depth. The YD and YE boreholes in the central plain were selected for this investigation (Table 2). Most of the components concentrations and EC values of the YD borehole, with a depth of 50 m, are higher than those of YE borehole, which has a depth of 30 m. These results mean that the salinization is more serious at deeper levels and into the bedrock.

Environmental isotopes

Hydrogen, oxygen, and carbon stable isotopes were used to determine the origin of the saline groundwater in the study area. Generally, seawater has δD and $\delta^{18}O$ values close to 0‰, because standard mean ocean water (SMOW) is taken as the standard reference value. Freshwater is generally lighter than seawater because of fractionation processes that occur during evaporation of seawater and the subsequent condensation that leads to precipitation (Hoefs 1997). Generally, groundwater affected by seawater has a higher value of δD and $\delta^{18}O$ than that of freshwater (Izbicki 1996). Therefore, groundwater oxygen and hydrogen isotope data can provide important information on the salinization processes in the coastal aquifers. The results of $\delta^{18}O$ and δD analyses over the area are presented in Table 3, and Fig. 8 shows the hydrogen and oxygen stable isotopic compositions of the groundwater and seawater. From Table 3, $\delta^{18}O$ ratios ranged from –8.1 to –4.2‰, and δD ratios ranged from –57 to –28‰. The $\delta^{18}O$ and δD values of local seawater are –0.7 and –6.2‰, respectively. The δD and $\delta^{18}O$ compositions of Ca + Mg–Cl + NO₃ type groundwater are close to the Global Meteoric Water Line (GMWL), but Na–Cl type groundwaters are enriched in ¹⁸O, compared to Ca + Mg–Cl + NO₃ type groundwater. The Na–Cl type

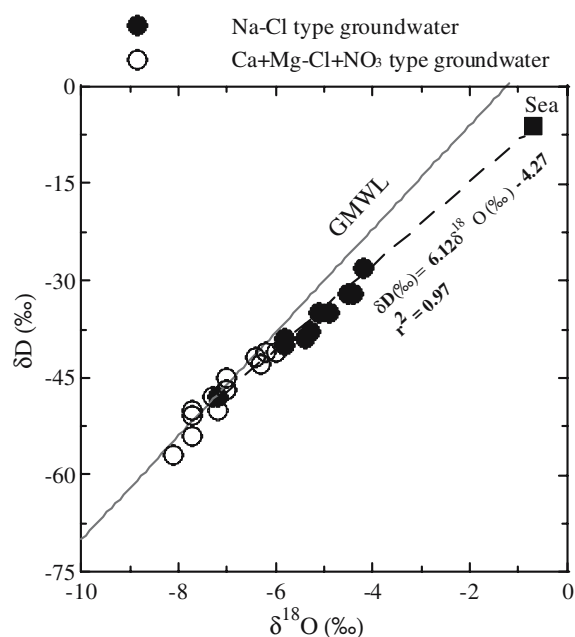


Fig. 8 Plots of δD versus $\delta^{18}O$ for groundwater in the study area. Closed circles Na–Cl type groundwaters; open circles Ca + Mg–Cl + NO₃ type groundwaters

groundwaters lie below the GMWL ($\delta D = \delta^{18}O + 10$; Craig 1961) and the Ca + Mg–Cl + NO₃ type groundwater is in agreement with the GMWL. The Na–Cl type groundwaters plot around a line having a slope of 6.12, considerably lower than for the GMWL. Such a low slope can be produced by evaporation and/or mixing of groundwater and seawater. In this case, the latter seems more likely to be the cause. Therefore, the Na–Cl type groundwaters have a mixed origin of seawater and fresh groundwater, while Ca + Mg–Cl + NO₃ type groundwaters have a fresh groundwater origin from meteoric water.

Carbon isotope ratios ($\delta^{13}C$) of DIC are usually used as a monitoring tool to determine redox processes (Aggarwal et al. 1997; Kim et al. 2003a; Landmeyer et al. 1996). Based on the composition of δD and $\delta^{18}O$, Na–Cl

Table 3 The isotopic data for groundwater and seawater in the study area

| Sample | YA | YB | YC | YD | YE | YF | YG | Y1 | Y4 | Y26 | Y32 | Y34 | Y120 |
|--------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| $\delta^{18}O$ (‰) | –6.1 | –5.4 | –4.4 | –5.3 | –5.8 | –5.1 | –7.2 | –7.0 | –5.8 | –4.2 | –7.7 | –6.2 | –8.1 |
| δD (‰) | –35.0 | –39.0 | –32.0 | –38.0 | –39.0 | –35.0 | –50.0 | –47.0 | –40.0 | –28.0 | –50.0 | –41.0 | –57.0 |
| $\delta^{13}C$ (‰) | –17.9 | –15.2 | –16.5 | –15.7 | –17.1 | –17.8 | –16.9 | – | –14.2 | –15.6 | –18.5 | – | – |
| Sample | Y301 | Y302 | Y303 | Y307 | Y308 | Y310 | Y311 | Y312 | Y317 | Y341 | Y353 | Y354 | Sea |
| $\delta^{18}O$ (‰) | – | –6.3 | –7.0 | –7.0 | –6.0 | –4.5 | –4.9 | –7.2 | –7.7 | –6.4 | –7.3 | –7.7 | –0.7 |
| δD (‰) | – | –43.0 | –45.0 | –47.0 | –41.0 | –32.0 | –35.0 | –48.0 | –54.0 | –42.0 | –48.0 | –51.0 | –6.2 |
| $\delta^{13}C$ (‰) | –18.5 | –23.7 | –19.3 | –18.9 | – | –17.7 | –16.0 | –15.3 | –12.9 | –19.9 | – | –19.6 | –4.7 |

– Indicates no measurement

type groundwaters reveal a mixed origin of seawater and fresh groundwater. Therefore, if the groundwater of the study area, in the absence of carbonate rock such as limestone, is influenced by seawater, the $\delta^{13}\text{C}$ composition in the Na-Cl type groundwaters is expected to have a higher value than in the Ca+Mg-Cl+NO₃ type groundwaters and is expected to show similar values to the $\delta^{13}\text{C}$ of seawater. However, the measured values of $\delta^{13}\text{C}$ in the Na-Cl type groundwaters show similar values to the Ca+Mg-Cl+NO₃ type groundwaters (Table 3). Generally, seawater has a value of $\delta^{13}\text{C}$ close to 0‰ and groundwaters have a range of -12.9 to -24.9‰. The $\delta^{13}\text{C}$ values of Na-Cl type groundwaters have ranges of -17.8 to -15.6‰, similar to those of Ca+Mg-Cl+NO₃ type groundwaters (Table 3; Fig. 9). These results suggest that ¹³C in Na-Cl type groundwaters has been depleted by another mechanism. When redox processes occur, the CO₂ pressure increases as a by-product of microbial respiration, which in turn increases alkalinity and decreases $\delta^{13}\text{C}$. Therefore, carbon isotope composition provides further distinctive evidence of redox processes in Na-Cl type groundwaters of the central area. According to previous research (Barker et al. 1998), mixing of saline and fresh water in estuaries results in high rates of biological productivity and sediments will be rich in organic matter. Sediments in estuaries contain large quantities of organic matter due to the high biological productivity in the water column. High rates of microbial metabolism within the sediments cause a rapid depletion in O₂ and a lowering of Eh, resulting in the black anoxic muds (Barker et al. 1998).

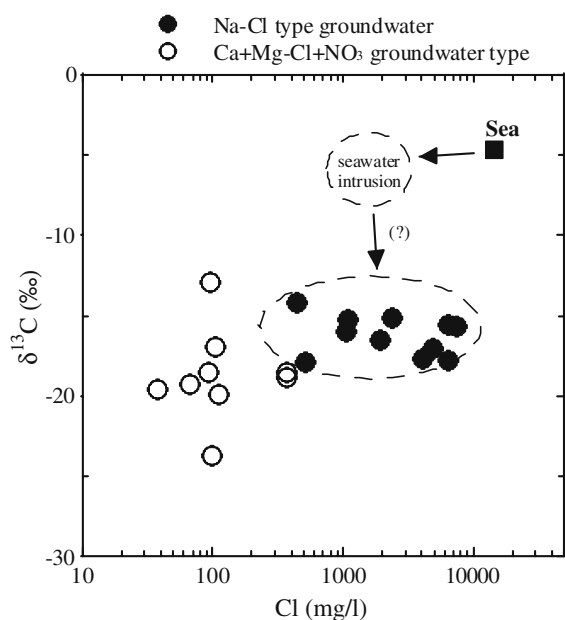


Fig. 9 Plots of $\delta^{13}\text{C}$ versus Cl for groundwater in the study area. Closed circles Na-Cl type groundwaters; open circles Ca+Mg-Cl+NO₃ type groundwaters

Because the study area has a lot of reclaimed land, it is certain that much organic matter was comprised into the reclaimed areas. The depletion in ¹³C of the groundwaters is suggested to be due to the reduction of marine organic matter in a reclaimed land.

Iodide properties

Iodide in groundwaters and seawater was analyzed to examine in detail the effect of the reduction of the study area (Table 4). Iodide is generally of marine origin and is specially enriched in corals or marine plants such as seaweeds. Therefore, iodide tends to be adsorbed on organic matters, Fe-oxides or Fe-hydroxides in marine sediments accumulated from corals or seaweeds (Stoesell 1997; Tellam 1995). Salinization in most coastal aquifers is frequently related to the movement of modern seawater, but there are other potential sources, such as paleomarine water and connate water. Many researchers have tried to distinguish modern seawater from paleomarine water (Lloyd et al. 1982; Sukhija et al. 1996). The use of minor ions can be an effective approach to identifying saline groundwater types. Among the components, iodide (I⁻) can be a valuable characteristic in identifying modern and ancient seawater and formation waters, because iodide can be leached out of aquifer material and may increase in groundwaters with time (Lloyd et al. 1982; Sukhija et al. 1996). Iodide, unlike chloride and boron, is generally reactive in most groundwater environments. Therefore, the enrichment of iodide in groundwater indicates a long residence time for the saline water. Such residence-time dependent processes can provide an indicator of paleomarine waters.

The relationship of iodide versus TOC and Fe is shown on Table 4 and Fig. 10. Iodide concentrations of Na-Cl type groundwaters are higher than those of Ca+Mg-Cl+NO₃ type groundwaters. In particular, the iodide concentrations of Na-Cl type groundwaters are positively correlated with TOC. It suggests that iodide has been lost during organic decomposition in reduction environment. Usually, iodide is subject to release and diagenetic redistribution during organic matter decomposition in a reducing environment (Kim et al. 2003a; Lloyd et al. 1982; Sukhija et al. 1996).

The I/Cl value provides information on groundwater residence time and so the types of salinity occurrences and whether these are related to modern or ancient seawater intrusion. The I/Cl value increases as a result of contact with an ancient marine body (Lloyd et al. 1982; Sukhija et al. 1996). Therefore, I versus Cl and I/Cl ratios versus Cl relationships for the groundwater samples were investigated (Fig. 11). Most of Ca+Mg-Cl+NO₃ type groundwaters are characterized by iodide depletion with respect to seawater, but some Na-Cl type

Table 4 The hydrochemical data with relation to iodide of the groundwaters and seawater

| Sample Site | I (mg/l) | TOC (mg/l) | Fe (mg/l) | Cl (mg/l) | I/Cl | Sample Site | I (mg/l) | TOC (mg/l) | Fe (mg/l) | Cl (mg/l) | I/Cl |
|-------------|----------|------------|-----------|-----------|----------|-------------|----------|------------|-----------|-----------|----------|
| YA | 0.031 | 16.4 | 1.79 | 522.9 | 5.93E-05 | Y308 | 0.009 | 9.7 | ND | 87.4 | 1.03E-04 |
| YB | 0.272 | 20.4 | 1.41 | 2,405.2 | 1.13E-04 | Y309 | 0.160 | 16.5 | 1.00 | 666.2 | 2.40E-04 |
| YC | 0.156 | 16.2 | 2.13 | 1,951.1 | 8.00E-05 | Y311 | 0.307 | 29.6 | 1.19 | 1,050.3 | 2.92E-04 |
| YD | 0.155 | 11.0 | 1.06 | 7,485.3 | 2.07E-05 | Y312 | 0.112 | 22.0 | 0.79 | 1,100.6 | 1.02E-04 |
| YE | 0.149 | 15.9 | 4.94 | 4,864.9 | 3.06E-05 | Y313 | 0.031 | 11.9 | 3.20 | 524.1 | 5.91E-05 |
| YF | 0.136 | 19.9 | 3.29 | 6,408.7 | 2.12E-05 | Y317 | 0.031 | 17.6 | ND | 97.1 | 3.19E-04 |
| YG | 0.005 | 6.8 | 0.33 | 103.4 | 4.84E-05 | Y318 | 0.001 | 4.0 | ND | 22.6 | 4.42E-05 |
| Y1 | 0.011 | 2.0 | ND | 233.6 | 4.71E-05 | Y330 | 0.008 | 28.6 | ND | 97.3 | 8.22E-05 |
| Y4 | 0.055 | 9.2 | 0.57 | 440.8 | 1.25E-04 | Y332 | 0.049 | 12.6 | 0.81 | 341.7 | 1.43E-04 |
| Y26 | 0.119 | 15.5 | 19.10 | 6,516.0 | 1.83E-05 | Y335 | 0.082 | 9.5 | 0.09 | 657.8 | 1.25E-04 |
| Y28 | 0.061 | 12.6 | 3.14 | 1,717.1 | 3.55E-05 | Y338 | 0.023 | 3.8 | 0.26 | 112.8 | 2.04E-04 |
| Y32 | 0.006 | 3.6 | 0.01 | 93.5 | 6.42E-05 | Y339 | 0.018 | 27.1 | ND | 193.3 | 9.31E-05 |
| Y120 | 0.009 | 20.0 | 0.10 | 72.2 | 1.25E-04 | Y341 | 0.005 | 16.2 | ND | 110.5 | 4.52E-05 |
| Y301 | 0.014 | 16.4 | 0.06 | 373.5 | 3.75E-05 | Y342 | 0.003 | 12.7 | ND | 118.2 | 2.54E-05 |
| Y302 | 0.011 | 15.2 | 0.40 | 100.0 | 1.10E-04 | Y343 | 0.001 | 5.4 | ND | 55.2 | 1.81E-05 |
| Y303 | 0.047 | 11.6 | ND | 66.6 | 7.06E-04 | Y353 | 0.003 | 11.0 | ND | 32.9 | 9.12E-05 |
| Y306 | 0.061 | 10.4 | ND | 152.8 | 3.99E-04 | Y354 | 0.003 | 4.6 | 0.01 | 37.4 | 8.02E-05 |
| Y307 | 0.009 | 15.0 | ND | 370.4 | 2.43E-05 | Sea | 0.096 | 14.9 | 0.14 | 14,408.2 | 6.66E-06 |

ND Not detected

groundwaters are characterized by iodide enrichment with respect to seawater. Moreover, I/Cl values of groundwater in the study area are about 10–100 times larger than that of seawater. In particular, the I/Cl ratios of Na–Cl type groundwaters are distinctively higher than that of seawater, suggesting that the Na–Cl type groundwaters have mainly resulted from interaction with connate saltwater or formation water. Similarly, the I/Cl ratios of Ca + Mg–Cl + NO₃ type groundwaters are higher than that of seawater. The study area has been changed by the reclamation of the tidal flats or sea, with the possibility of incorporation of large amounts of organic matter and old seawater. Due to the decomposition of the organic matter in a reducing environment, iodide has been subject to release and redistribution. Therefore, it is thought that the Na–Cl type groundwaters of the central area show higher I/Cl ratios owing to the decomposition of organic matter. Similarly, Ca + Mg–Cl + NO₃ type groundwaters also show higher

I/Cl ratios. However, this resulted from comparatively low Cl concentrations of the Ca + Mg–Cl + NO₃ type groundwaters, because the Ca + Mg–Cl + NO₃ type groundwaters have a sufficient supply of recharge water from the surface. Therefore, owing to the different chemical properties of easily leached chloride and strongly adsorbed iodide, it is thought that Ca + Mg–Cl + NO₃ type groundwaters show higher I/Cl ratios because of their low Cl concentrations. It seems that distribution of iodide is controlled by residual salts or reduction of organic matter in a reducing environment. This is strongly supported by the evidence from study of the carbon isotope data discussed above.

Conclusions

The purpose of this study was to examine the salinization of groundwater in a coastal reclaimed area and to

Fig. 10 **a** Plots of iodide versus total organic carbon (TOC) for groundwater in the study area. **b** Plots of iodide versus total Fe for groundwater in the study area. Closed circles Na–Cl type; open circles Ca + Mg–Cl + NO₃ type

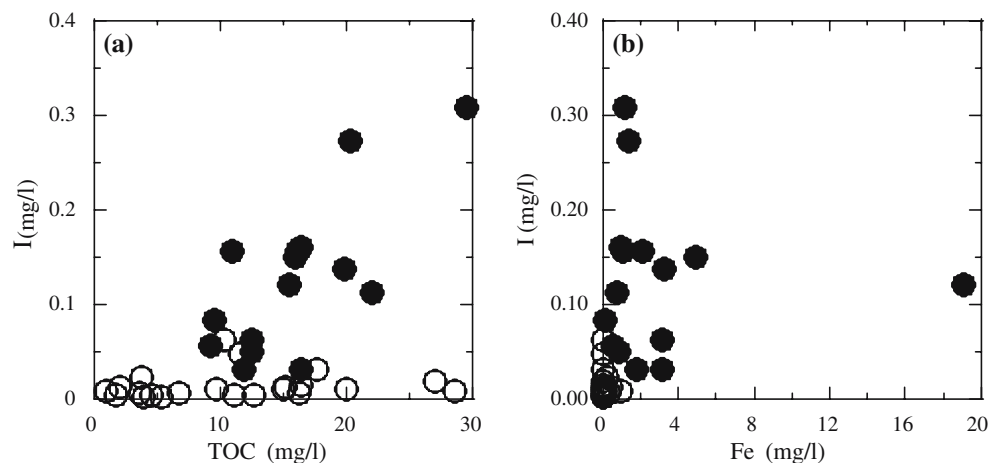
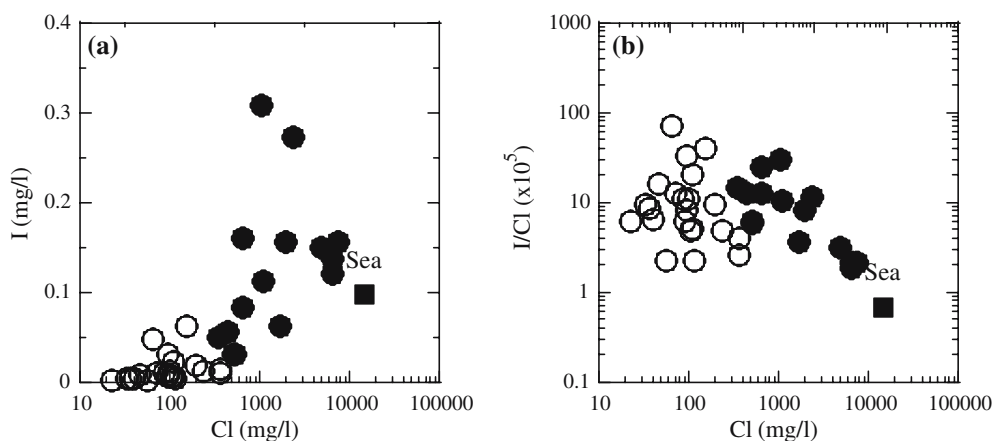


Fig. 11 a Plots of iodide versus chloride for groundwater in the study area. **b** Plots of iodide versus ratio of I/Cl for groundwater in the study area. *Closed circles* Na–Cl type; *open circles* Ca + Mg–Cl + NO₃ type; *closed square* seawater sample



identify the effect of land reclamation on groundwater quality. The hydrogeochemical characteristics of groundwater in the study area comprise two main types, Na–Cl and Ca + Mg–Cl + NO₃. These two water types could be distinguished by various chemical characteristics (e.g. Na⁺, Ca²⁺, Mg²⁺, Cl⁻, NO₃⁻, I⁻, total Fe and TOC). The groundwaters are affected by three major factors, these being seawater intrusion, fertilizers and redox processes.

The Ca + Mg–Cl + NO₃ type groundwaters are mostly localized in the near-shore area or areas at high elevation. They have a high concentration of NO₃⁻ and Ca²⁺. The Ca + Mg–Cl + NO₃ type groundwaters define two different mechanisms of groundwater evolution. The first mechanism is contamination with fertilizer. The high concentrations of nitrate accord with the intensive agricultural activity in the study area. Nitrate likely comes from anthropogenic sources such as chemical fertilizers. Another possible mechanism is cation exchange reactions with aquifer minerals.

The Na–Cl type groundwaters are usually distributed in the central plain about 2–3 km inland far from the coastline. They show high chemical concentrations, of the stable isotopes, only ¹⁸O are enriched with respect to the meteoric water line. Meanwhile, δ¹³C values are

depleted in ¹³C with respect to seawater. Iodide concentrations are positively correlated with TOC, and the iodide concentration is higher than that of seawater. Moreover, I/Cl ratios are 10–100 times higher than that of seawater.

Because the reclamation has resulted in a large amount of organic matter being buried, it is likely that the study area provides conditions for the occurrence of redox processes. Therefore, the salinization of the groundwater seems to be controlled by not only salt-water intrusion but by other effects such as reduction of marine organic matter. The EC values in Na–Cl type boreholes in the central area show that the EC values of the groundwater at depth or in bedrock are higher than those of shallower groundwater. Therefore, most Na–Cl type groundwaters in a central area are under the influence of redox processes in the shallow aquifer, such as the sand layer. Meanwhile, Na–Cl type groundwater is under the influence of the upconing or connate saline water at depth.

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