

# Groundwater flow system under a rapidly urbanizing coastal city as determined by hydrogeochemistry

著者	Kagabu Makoto, Shimada Jun, Delinom Robert, Tsujimura Maki, Taniguchi Makoto
journal or publication title	Journal of Asian earth sciences
volume	40
number	1
page range	226-239
year	2011-01
権利	(C) 2010 Elsevier Ltd.
URL	<a href="http://hdl.handle.net/2241/107853">http://hdl.handle.net/2241/107853</a>

doi: 10.1016/j.jseaes.2010.07.012

Groundwater flow system under a rapidly urbanizing coastal city as  
determined by hydrogeochemistry

Makoto Kagabu<sup>1\*</sup>, Jun Shimada<sup>1</sup>, Robert Delinom<sup>2</sup>, Maki Tsujimura<sup>3</sup>, Makoto  
Taniguchi<sup>4</sup>

<sup>1</sup> Graduate School of Science and Technology, Kumamoto University, 2-39-1  
Kurokami, Kumamoto 860-8555, Japan.

<sup>2</sup> Research Center for Geotechnology, Indonesian Institute of Sciences, Jln Cisit  
Sangkuriang, Bandung 40135, Indonesia

<sup>3</sup> Graduate School of Life and Environmental Sciences, Tsukuba University, 1-1-1  
Tennodai, Tsukuba, 305-8571, Japan

<sup>4</sup> Research Institute for Humanity and Nature, 457-4 Motoyama Kamigamo, Kita-ku,  
Kyoto 603-8047, Japan

\*Corresponding author

**Makoto Kagabu**

Email address: m.kagabu@es.sci.kumamoto-u.ac.jp

+81-96-342-3419

Submitted to:

**Journal of Asian Earth Sciences**

30 March, 2010

Resubmitted to:

**Journal of Asian Earth Sciences**

19 July, 2010

## Abstract

In the Jakarta area (Indonesia), excessive groundwater pumping due to the rapidly increasing population has caused groundwater-related problems such as brackish water contamination in coastal areas and land subsidence. In this study, we adopted multiple hydrogeochemical techniques to demonstrate the groundwater flow system in the Jakarta area. Although almost all groundwater existing in the Jakarta basin is recharged at similar elevations, the water quality and residence time demonstrates a clear difference between the shallow and deep aquifers. Due to the rapid decrease in the groundwater potential in urban areas, we found that the seawater intrusion and the shallow and deep groundwaters are mixing, a conclusion confirmed by major ions,  $\text{Br}^-:\text{Cl}^-$  ratios, and chlorofluorocarbon (CFC)-12 analysis. Spring water and groundwater samples collected from the southern mountainside area show younger age characteristics with high concentrations of  $^{14}\text{C}$  and  $\text{Ca-HCO}_3$  type water chemistry. We estimated the residence times of these groundwaters within 45 years under piston flow conditions by tritium analysis. Also, these groundwater ages can be limited to 20 to 30 years with piston flow evaluated by CFCs. Moreover, due to the magnitude of the CFC-12 concentration, we can use a pseudo age-indicator in this field study, because we found a positive correlation between the major type of water chemistry and the CFC-12 concentration.

Keywords: groundwater flow system; hydrogeochemistry; excessive groundwater pumping; groundwater age tracer; Jakarta, Indonesia

### 1. Introduction

Groundwater is an indispensable drinking water resource in developing cities, especially in places where no public water supply exists because of an inadequate infrastructure or a poor economic situation. Subsurface environmental problems, such as land subsidence due to excessive abstraction and groundwater contamination, have occurred consecutively in large Asian cities (Foster and Chilton, 2003) with some time lag between each city. Most of these growing Asian mega-cities are located in coastal areas (Jiang *et al.*, 2001) where basement geologies are composed of quaternary marine or fluvial unconsolidated deposits. Jakarta, the capital city of Indonesia, is one of the

cities that suffer from groundwater related problems.

35 Researchers have recently conducted hydrogeochemical studies of the Jakarta Groundwater Basin. Delinom *et al.* (2009) classified regional groundwater into hydrochemical groups on the basis of major ion chemistry by using Stiff diagrams. Umezawa *et al.* (2008) and Onodera *et al.* (2008) showed nitrate contamination in agricultural fields and mentioned the possibility of seawater intrusion into groundwater in coastal areas. Lubis *et al.* (2008) identified recharge and discharge areas by groundwater temperature profile measurements in deep observation wells. However, an integrated  
40 study that employs multiple hydrogeochemical techniques has not yet been performed in the Jakarta groundwater basin.

Urbanization has obviously had a significant impact on the water demand in this area. Since only 30% of the city's potable water supply demand is met by surface water (Delinom, 2008), people are increasingly turning to the groundwater resources of the  
45 basin. Reliance on groundwater as a water resource is common, and the demand has reputedly reached 76% (Bakker, 2007). In addition to the city's need for potable water, the continued development of the industrial sector has also increased the pressure on this resource. Under these situations, it is necessary to understand the groundwater flow system for its sustainable use.

50 This study describes the groundwater flow system in the Jakarta Groundwater Basin on the basis of the multiple hydrogeochemical techniques such as stable isotopes ( $\delta D$  and  $\delta^{18}O$ ), water chemistry by major ions,  $Br^-:Cl^-$  ratio, tritium,  $^{14}C$ , and chlorofluorocarbon (CFC) analyses.

## 55 2. Study area

The South China Sea borders Jakarta, the capital city of the Republic of Indonesia, to the north (Fig. 1a). The province of Jakarta (DKI Jakarta;  $6^{\circ}00'-6^{\circ}20''$  S,  $106^{\circ}42'-107^{\circ}00''$  E) has a surface area of approximately  $652 \text{ km}^2$  and a humid tropical climate that is significantly influenced by monsoon winds. The long-term mean annual  
60 rainfall in this city ranges between 1,500 and 2,500 mm/year, with a dry season ( $<100$  mm/month) that lasts 7–8 months in coastal areas, 2–4 months at elevations of 30–50 m above sea level (asl), and less at higher elevations. Peak rainfall usually occurs

throughout the region in January, while the least rainfall occurs between June and August. The long-term mean monthly temperature ranges between 26°C and 28°C, and the mean  
65 annual air temperature is 27°C. The mean potential evapotranspiration for the Jakarta region is 1,606 mm/year (Tambunan, 2007).

The overall population of Jakarta increased significantly in the 20th century, from about 100,000 in 1900 to more than 9 million in 1995. Most of the population increase occurred in the last 20 years of the 20th century (Han and Basuki, 2001).

70 The Jakarta Groundwater Basin, in which the city of Jakarta resides, is one of the most developed basins in Indonesia. The aquifer system in this basin is classified (upper to lower order) into the following five zones (Fachri *et al.*, 2003).

Zone 1 is a shallow aquifer layer composed of sandstone, conglomerate, and claystone.

75 Zones 2 and 4 are aquiclude layers composed of claystone with sand infixes.

Zone 3 is a deep aquifer layer composed of sandstone with infixes of breccias and claystone.

Zone 5 is the basement of the Jakarta Groundwater Basin, composed of impermeable rocks such as limestone and claystone.

80 The components of the aquifer, such as sandstone and conglomerate, are connected to each other (Martodjodjo, 1984; Assegaf, 1998). The deep aquifer under the urban area is about 150-m thick. The vertical cross section of the local hydrogeology along the line (A-A') in Fig. 1a (south to north) is shown in Figs. 6 and 10. In this paper, we classified the groundwater samples collected from the wells into 5 zones on the basis of screen  
85 existing elevation.

### 3. Sampling and Methodology

We collected 46 groundwater, 5 spring water, 2 hot spring, and 3 river water samples between February and March, 2008 (Fig. 1a). The Groundwater samples were collected  
90 from observation wells, production wells, and dug wells.

Temperature, pH, and electric conductivity (EC) of the water samples collected in this study were measured in the field by using a portable EC/pH meter (WM-22EP, TOA DKK, Japan). Samples for stable isotope ( $\delta^{18}\text{O}$  and  $\delta\text{D}$ ) and major ion ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,

Mg<sup>2+</sup>, Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, and SO<sub>4</sub><sup>2-</sup>) analyses were collected in 100-mL polyethylene bottles at  
95 the hydrology laboratory of Kumamoto University.

We analyzed the major ions by ion chromatography (Compact IC 761, Metrohm, Switzerland) with the analytical error typically within 10%; the alkalinity titration could be substituted for the activity of HCO<sub>3</sub><sup>-</sup>. Stable isotope ratios and D/H ratios of water were determined by the CO<sub>2</sub> equilibration method and the chromium-reduction method,  
100 respectively, followed by analysis by using a Thermo Electron Delta S mass spectrometer (USA). Hydrogen and oxygen isotope ratios were expressed using δD and δ<sup>18</sup>O, respectively, where  $\delta = ((R_{\text{sample}}/R_{\text{standard}}) - 1)1000$  (‰) and R is the ratio of <sup>2</sup>H/<sup>1</sup>H or <sup>18</sup>O/<sup>16</sup>O in either the sample water (R<sub>sample</sub>) or the Standard Mean Ocean Water (R<sub>standard</sub>). We reported isotopic compositions in the standard δ-notation (‰) as deviations from the  
105 Vienna Standard Mean Ocean Water standard (V-SMOW; Craig, 1961). The analytical error was ±0.1‰ for δ<sup>18</sup>O and ±1.0‰ for δD. Tritium determinations were performed using a liquid scintillation counter (TRI-CARB2750TR/LL, Perkin-Elmer Co., USA) subsequent to electrolytic enrichment. The results were reported as tritium units (T.U.), i.e., one atom of tritium in 10<sup>18</sup> atoms of hydrogen, with a maximum error of 0.7 T.U.  
110 Groundwater samples for CFC analysis were collected in triplicate and stored in glass bottles sealed with metal lined caps (Busenberg and Plummer, 1992). We analyzed the CFCs by closed system purge and trap gas chromatography by using an electron capture detector (GC-8A, Shimadzu, Japan). Water samples for CFCs were analyzed in triplicate, and the values were reported only if the concentrations of at least two measurements were  
115 within 10% for concentrations above 100 pg/kg. Below 100 pg/kg concentrations, the values were reported only if at least two measurements were within 20 pg/kg of each other (Johnston *et al.*, 1998). The analytical uncertainty associated with CFC analysis was less than 5%. <sup>14</sup>C assays conducted using the accelerator mass spectrometer (AMS) required approximately 5 mg C (Clark and Fritz, 1997). We collected groundwater  
120 samples in 1-L glass bottles, which we filled and allowed to overflow for several minutes. The samples were made alkaline (pH>10) by adding 5 mL 10 N NaOH solution to convert all dissolved inorganic carbon species to carbonate (CO<sub>3</sub><sup>2-</sup>), which precipitated with the dissolved Ba<sup>2+</sup> added as 20 mL of saturated BaCl<sub>2</sub>·2H<sub>2</sub>O (450 g/L). Finally, we collected 50 cc BaCO<sub>3</sub> precipitates in an amber glass bottle. Prior to <sup>14</sup>C analysis, the

125 BaCO<sub>3</sub> precipitates were freeze-dried for 24 h before being sent to the Center for  
Chronological Research at Nagoya University for analysis. <sup>14</sup>C measurements were  
confirmed with graphite pellets using a High Voltage Engineering Europe (HVEE)  
<sup>14</sup>C-Accelerator Mass Spectrometry (AMS) system (Model 4130-AMS). One-sigma <sup>14</sup>C  
130 dating uncertainties typically ranged from ±20 to ±40 years for materials younger than  
8000 BP, depending on absolute <sup>14</sup>C ages or <sup>14</sup>C counting uncertainties. Background  
levels associated with the <sup>14</sup>C-AMS system ranged from 52 to 54 ka BP for pure graphite  
powder (Nakamura *et al.*, 2004).

#### 4. Results

##### 135 4.1. Groundwater potential

We obtained groundwater potential data from 30 observation wells in the study area  
for the period from 1985 (oldest) to the present. The spatial distribution of groundwater  
potential was estimated on the basis of the observation well data. Figure 2 shows the  
groundwater potential of the deep aquifer for the years 1985, 1990, 1997, 2000, 2004, and  
140 2008. In 1985, the depression area was located in the northeast of the Jakarta area and the  
groundwater potential was -15 m. The depression area then expanded, moving toward  
central Jakarta prior to moving to the northwest of the city in 2008 when it was -25 m.  
Note that the movement of the depression area was associated with a decline in  
groundwater potential, implying a disturbance in the groundwater flow system.

145 Below, we discuss the observed tendency in groundwater potential at 18 observation  
wells, which have been monitored continuously for a minimum of 10 years. Figure 3  
shows the groundwater potential in each well in 1982 relative to that in 2005. As shown  
in the figure, three general tendencies were apparent in groundwater potentials:  
“long-term steady,” “long-term declining,” and “sharply declining.” The locations of the  
150 wells exhibiting these tendencies are plotted on in Fig. 4. The figure shows that the  
declining tendencies are most apparent in the central part of Jakarta; wells exhibiting the  
sharply declining trait predominated in the central district. On the other hand, wells  
exhibiting the long-term steady tendency were located around the coastal areas and  
southern part of the study area.

155

## 4.2. Major ions

Table 1 lists the results of the major ion analyses, and Fig. 5 plots them on a Piper diagram, referring to the concentrations of hydrogeochemical components. Figure 6 shows the distribution of the stiff diagram along a cross section that passed through the central Jakarta area (A-A'; Fig. 1a). The depth of the screen at each sampling point was projected to this cross section from the coast along the topographical profile.

In the Piper diagram of Fig. 5, samples collected from spring and river waters are of the Ca-HCO<sub>3</sub>-type. Therefore, waters in upstream areas can be recognized as those with juvenile features; they are not much affected by human activities. Many shallow groundwaters (zones 1 and 2) are also of the Ca-HCO<sub>3</sub>-type. However, shallow groundwater in the middle stream area possessed high NO<sub>3</sub><sup>-</sup> concentrations, as shown in Fig. 6 (G31, G35, G43, and G45), especially those within the areas of high agricultural activity, located between the urbanized and mountain areas (Fig. 1b). On the other hand, the deep groundwater (zones 3 to 5) was of the Na-HCO<sub>3</sub>-type, as shown in Fig. 5 (Group I) and Fig. 6 (G7, G28, G30, G32, G37, G44, and G46). However, the samples collected from the coastal area (G8 and G10) were of the Na-Cl-type, as shown in Fig. 5 (Group II) and Fig. 6. This type of groundwater displayed seawater intrusion. Samples located near the coast and slightly further inland (G6, G11, G14, G25, and G27) occupied an intermediate position between the deep groundwater (Group I) and seawater intrusion wells (Group II) (Group III, Fig. 5). These results imply that seawater intrusion is encroaching on inland aquifers. Though the samples H2 and G20, located about 40 km inland from the coast line, were also of the Na-Cl-type (Fig. 5), this result may be due to the geological setting, including the local fault system (Delinom *et al.*, 2009).

According to the results of the major ion analyses, Ca-HCO<sub>3</sub>-type groundwaters mainly recharge the aquifer in the upstream area, and this water changes to the Na-HCO<sub>3</sub> type as it flows in the northern, deeper direction. This change can be explained by the cation exchange reaction ( $\text{Na}^+ \leftrightarrow \text{Ca}^{2+}$ ) (Appelo and Postma, 2005). A similar tendency occurs in the groundwater flow system of the Osaka basin (Yamanaka *et al.*, 2005).

## 4.3. Bromide:chloride ratio of groundwater in Jakarta

Bromide and chloride are particularly good indicators of seawater intrusion, because



both these ions are chemically conserved in natural aqueous environments. Both ions also move freely in the subsurface. Similar  $\text{Br}^-:\text{Cl}^-$  ratios in groundwater and seawater indicate that seawater is a source of chloride. Dissimilar ratios in groundwater and seawater indicate that chloride is derived, at least in part, from another chloride source (Fetter, 1993).

We determined the nitrogen concentrations in order to indicate the possible presence of another chloride source in the groundwater. Nitrate and chloride commonly occur together in groundwater contaminated by sewage effluent. Potential sources of sewage contamination of the groundwater in the study area include residential septic systems and public sewer lines. Contamination of groundwater by nitrate from fertilizers might also result in elevated chloride concentrations (Richter and Kreitler, 1993).

Figure 7 plots the  $\text{Br}^-:\text{Cl}^-$  ratios and corresponding chloride concentrations. Two trend lines are included for comparison. One is the theoretical  $\text{Br}^-:\text{Cl}^-$  ratio of seawater based on a study by Drever (1988) (equivalent to the  $\text{Br}^-:\text{Cl}^-$  ratio in seawater). The other is the assumed trend line of the chloride contamination from the anthropogenic source based on the study by Andreasen and Fleck (1997). This trend line represents the native groundwater affected by an anthropogenic chloride source. Also plotted in the figure, the  $\text{NO}_3^-$  concentration (mg/L) shows the potential contamination.

The  $\text{Br}^-:\text{Cl}^-$  ratios were similar to the seawater ratio with a high chloride concentration in samples collected from the coastal area (G6, G8, G10, G11, G13, G25, and G27). Since these samples show the Na- $\text{HCO}_3$  to the Na-Cl type (Figs. 5 and 6), the seawater was the primary source of chloride.

Shallow groundwater samples were scattered along the anthropogenic line with high  $\text{NO}_3^-$  concentrations and low  $\text{Br}^-:\text{Cl}^-$  ratios. These results support the nitrate contamination caused by fertilizers in dry fields, reported by Umezawa *et al.* (2008).

#### 4.4. Stable isotopes

Figure 8 shows the relationship between  $\delta^{18}\text{O}$  and  $\delta\text{D}$ . This figure displays the local meteoric water line (LMWL), which is generated from the precipitation in Bogor, the southern part of the study area. The LMWL is expressed as  $\delta\text{D} = 7.6\delta^{18}\text{O} + 10$ , based on the 20 times term sampling of local precipitation from November 2006 to

October 2007.

Spring and river water samples located in the southern mountainside area are mostly plotted above the LMWL and relatively depleted positions, implying that these waters were recharged at relatively higher elevations, i.e., mountain areas. On the other hand, despite being collected from different depths, 76.1% of the groundwater samples in the study area had stable isotopes that could be plotted within a narrow range ( $-5.6$  to  $-6.5\text{‰}$   $\delta^{18}\text{O}$  and  $-30$  to  $-40\text{‰}$   $\delta\text{D}$ ). Besides, this range occupies a somewhat more depleted position than that of the weighted average precipitation value, indicating that the groundwater in the shallow and deep aquifers in the Jakarta basin is recharged at approximately the same elevation, which is higher than that of Bogor city. These recharge characteristics are consistent with the groundwater flow determined by the temperature-depth profile analysis of the groundwater, which shows that the recharge area is distributed in the hills and uplands that are located on the periphery of the Jakarta Groundwater Basin (Lubis *et al.*, 2008).

Deep groundwater samples collected near the coast (G8 and G10) were enriched in their isotopic compositions and somehow deviated from the LMWL as their data was plotted mostly along the trend line toward SMOW, possibly affecting the seawater intrusion into the groundwater. Hot spring water located inland (H2) also deviated distinctly.

#### 4.5. Tritium

Tritium contents of the groundwater samples collected in this study were small values and demonstrated small variations, ranging from 0.5 to 1.4 T.U. (N = 18; Table 1). When we considered the simple piston flow, the tritium concentrations in the groundwater could be estimated on the basis of the tritium concentrations in the local precipitation, corrected by the radioactive decay with a half life of 12.4 years. Figure 9 shows the tritium concentrations of the precipitation in Jakarta ( $6^{\circ} 10' 48''$  S,  $106^{\circ} 49' 48''$  E, asl 8 m) and Tokyo ( $35^{\circ} 40' 48''$  N,  $139^{\circ} 46' 12''$  E, asl 4 m) (IAEA/WMO, 2004). Although tritium data for the precipitation in Jakarta after 1993 is not available, its decreasing trend is quite similar to that in Tokyo. However, the overall tritium concentration of the precipitation in Jakarta is lower than that in Tokyo because of the latitude effect on the tritium content. This figure also plots the maximum and minimum

250 tritium concentrations in the groundwater of this study area and expresses the decay of  
the tritium content in the groundwater as dashed lines. The recharge year of groundwater  
is normally estimated at the point of intersection of the groundwater tritium decay line  
and the tritium content in the local precipitation (De Vries and Simmers, 2002;  
Bolsunovsky and Bondareva, 2003; Marechal and Etcheverry, 2003; Hosono *et al.*,  
255 2008).

Since the overall tritium concentration of the precipitation in Jakarta is low, it is  
rather difficult to estimate the exact groundwater age. However, it may be possible to  
determine the recharge year of the groundwater samples, which were recharged before or  
after the 1960s when it is assumed that there was no recharge due to unusually low  
260 tritium concentrations in the precipitation as compared to the general tendency. For  
instance, the lowest tritium concentration in the H2 sample had no point of intersection  
with the precipitation and the decay line. That is, it must have recharged before the 1960s.  
On the other hand, since the sample with the largest tritium concentration (S5) had many  
points of intersection, it recharged after the 1960s (residence time is assigned to within 45  
265 years). However, we should note that tritium analysis possesses certain analytical errors.

#### 4.6. $^{14}\text{C}$ concentration

Table 1 lists the  $^{14}\text{C}$  concentrations (in pmC), and Fig. 10 shows the distribution of  
 $^{14}\text{C}$  concentrations along a cross section (A-A'; Fig. 1a).  $^{14}\text{C}$  concentration in shallow  
270 groundwater (zone 1) was around 100 pmC, indicating that these groundwater samples  
possessed a modern (younger) component. Deep groundwater (zone 3) along the cross  
section had relatively smaller concentrations than its shallow counterpart. The upper  
portion of Zone 3 and upstream areas had relatively large pmC as compared to the lower  
portion of this zone and downstream areas. In particular, samples collected from under  
275 the urban area (G6, G7, and G28) showed low pmC content, reflecting that these  
groundwater samples may possess older components. Samples collected from zone 5  
(G11) demonstrated considerably low pmC content; it could be considered stagnant water.  
Hot spring water located inland (H2) also showed considerably low pmC content.

#### 280 4.7. CFC-12 concentration

CFCs are useful tools for tracing and dating post-1945 groundwater (Busenberg and

Plummer, 1992; Plummer *et al.*, 2000; Plummer *et al.*, 2001). We, therefore, employed CFCs as a marker for young groundwater, because the release of CFCs into the atmosphere only started after the 1940s (USGS, 2010). Consequently, if groundwater  
285 possesses some dissolved CFCs, it was recharged after the 1940s. In this study, we used CFC-12 because of its stability in the subsurface environment (Plummer *et al.*, 1998). Figure 10 shows the distribution of CFC-12 (mg/L) along the cross section. Since the shallow groundwater (Zone 1) showed a large CFC-12 concentration, it can be considered modern (young) and was recharged after the 1940s. This result is consistent with those  
290 obtained from the <sup>14</sup>C concentration. On the other hand, the deep groundwater (zones 3 and 5) had low concentrations, and some wells possessed concentrations below the detection limit. However, because some deep groundwater samples collected from under the urban area (G6, G8, and G28) somehow possessed CFC-12 concentrations, the shallow (young) groundwater and/or present seawater component might be introduced  
295 into the deeper aquifer. The driving force of this forced groundwater movement is the excessive groundwater pumping in the central urban area, corresponding to the rapid urbanization.

## 5. Discussion

300 Based on the results of the hydrogeochemical data, this study area can be divided into two areas: the northern Jakarta plain area and the southern mountainside spring water area. The latter area includes one deep groundwater sampling point (G1). In this section, we discuss the groundwater flow system in each area.

### 305 5.1. Groundwater flow system in the northern Jakarta plain area

According to the results of the stable isotope analyses (Fig. 8), almost all groundwater in the Jakarta plain was recharged at similar surface elevations. Subsequent to recharging, groundwater flow is divided into two major aquifers: shallow and deep, confirmed by the stratification of the local geology.

310 Although the river water and many shallow groundwater samples displayed Ca-HCO<sub>3</sub>-type water chemistry, the shallow groundwater in the southern area's dry field showed clear nitrate contamination, which is mostly due to artificial fertilizers, including agrochemicals, from agricultural activities. Umezawa *et al.* (2008) confirmed via stable N

and O isotopes in  $\text{NO}_3^-$  that the nitrate contamination in this area is caused by the  
315 application of fertilizers and by household effluents. According to these results, we can  
assume that most parts of the  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  proportions in the Piper diagram are due to  
the agricultural activities utilizing excessive fertilizers, agrochemicals, and, to a lesser  
degree, household effluents.

The  $\text{Br}^-:\text{Cl}^-$  ratios versus the chloride and  $\text{NO}_3^-$  concentrations (Fig. 7)  
320 demonstrated that the shallow groundwater deviated from the  $\text{Br}/\text{Cl}$ 's seawater mixing  
line with a relatively high  $\text{NO}_3^-$  concentration. It affected the nitrate contamination  
caused by fertilizers in dry fields, and both the  $\text{Br}^-$  and  $\text{Cl}^-$  ions probably come from  
fertilizers. However, seawater is the primary source of chloride in the groundwater  
samples collected from the coastal area. These results are consistent with the groundwater  
325 samples collected from the coastal area (G8 and G10), which displayed Na-Cl-type water  
chemistry with high dissolved ion concentrations.

Because the CFC-12 concentration in some groundwater samples was greater than  
that of the past CFC concentrations in the Northern Hemisphere's atmosphere, which is  
contaminated, we could not evaluate the exact residence time of the groundwater.  
330 However, since CFC-12 was detected in the shallow groundwater, it was recharged after  
the 1940s. This fact is consistent with the high  $^{14}\text{C}$  concentration (Fig. 10), which  
represented the modern groundwater component.

Deep groundwater had Na- $\text{HCO}_3$ -type water chemistry, suggesting that the chemical  
evolution during the groundwater flow process changed from the original Ca- $\text{HCO}_3$ -type  
335 shallow water chemistry, indicating that it had a relatively long residence time than the  
shallower groundwater. This result is consistent with the  $^{14}\text{C}$  and CFC-12 contents; the  
 $^{14}\text{C}$  of the deep groundwater was apparently much older than that of the shallower  
groundwater, and the CFC-12 concentration in the deep groundwater was near or lower  
than the detection limit, implying that it was at least older than the 1940s. However, we  
340 found somewhat high CFC-12 concentrations in some deep groundwater samples, mostly  
collected under the well developed urban area (G6, G8, and G28) where the groundwater  
depression zone is located (Fig. 10), implying that the young groundwater component  
intruded from the shallow aquifer or that seawater was present due to excessive pumping  
of groundwater in the urban area.

345 According to the distribution on the delta diagram of stable isotopes, two  
groundwater samples located near the coast (G8 and G10) and the hot spring water  
sample (H2) deviated from the LMWL in the heavy isotopic direction. Excluding this  
hot spring water, which is located about 40 km inland from the coastal line and has a  
different type of flow system from that of the remainder of the studied groundwater  
350 region, the isotopic enriched coastal groundwater (G8 and G10) was due to mixing  
with seawater. The Cl- $\delta^{18}\text{O}$  relationship shown in Fig. 11 clearly supports seawater  
mixing, and the water chemistry of this water (Na-Cl type; Figs. 5, 6) is another  
evidence for this mixing process. Although the hot spring water sample (H2) also fell  
along the seawater mixing line in Fig. 11, its position in the delta diagram of Fig. 8  
355 clearly demonstrates that there was no intrusion of modern seawater. The considerably  
low  $^{14}\text{C}$  concentrations (apparent  $^{14}\text{C}$  age is approximately 47,000 years) and the  
different mixing line in the delta diagram, which seems to have oxygen-shifted  
seawater as its end member component, might suggest that this hot spring water  
recharged during a different climatic period. The local geological setting also  
360 suggested the contribution of fossil sea water to this hot spring (Delinom *et al.*, 2009).

## 5.2. Groundwater flow system in southern mountainside spring water area

All spring water samples collected from the southern mountainside area were the  
Ca-HCO<sub>3</sub>-type water chemistry, and one deep groundwater sample (G1) was also the  
365 Ca-HCO<sub>3</sub>-type. Its residence time was clearly shorter than that of the deep groundwater  
in the northern Jakarta plain. This short residence time was consistent with the modern  
 $^{14}\text{C}$  age and the evidence of modern CFC-12 concentrations in the groundwater of this  
area.

Unlike the shallow groundwater in the northern Jakarta basin, spring water samples  
370 (S1 to S5) and the deep groundwater sample (G1) were not affected by the anthropogenic  
contamination caused by urban CFCs. We evaluated groundwater residence time by CFC  
concentrations. As there was no clear difference in the atmospheric CFC concentration  
between North America and low latitude countries (e.g., Samoa and Barbados; Cunnold  
*et al.*, 1997), to evaluate CFC age, we adopted the time series trend of atmospheric CFC  
375 concentrations in the Northern Hemisphere's atmosphere in this study. The binary mixing  
model was adopted to evaluate the groundwater flow process for the CFC age estimation,

either only by the piston flow with no dilution, mixing during the flow process, or mixing with some other water resource during its flow process. We used the relationship between CFC-12 and CFC-113 (Fig. 12) to evaluate this process, diluted by mixing with old, CFC-free water (Plummer *et al.*, 2001).

Since almost all groundwater samples obtained from the southern mountainside area approximately fell on the piston flow line (Fig. 12), the groundwater residence time could be evaluated by assigning the recharge temperature and the elevation of each sample, 18.0°C and 1500 m, which are the rough estimations for the recharge temperature and the elevation, respectively. Table 1 lists the results of the apparent recharge year of each water sample. The residence time of these groundwater samples was 20 to 30 years.

This relatively young groundwater age was consistent with that obtained from the tritium analysis; S2, S5, and G1 were recharged after the 1960s (residence time assigned to within 45 years by using the piston flow model).

390

### 5.3. Relationship between water chemistry and CFC-12

Because the CFC-12 concentration in some groundwater samples was contaminated, we could not estimate the exact residence time of the groundwater. However, the relationship between the major water chemistry type and the CFC-12 concentration seemed to have a positive tendency. The magnitude of the CFC-12 concentration could be considered as a function of a younger age indicator in this field of study. Figure 13 shows the CFC-12 concentrations overlaid on the Piper diagram of the groundwater in the study area. Both the groundwater collected from the mountainside and the shallow groundwater collected from the Jakarta plain showed relatively short residence times, indicated by their Ca-HCO<sub>3</sub>-type water chemistries and their relatively high CFC-12 concentrations. On the other hand, the deep groundwater in the Jakarta plain represented by the Na-HCO<sub>3</sub>-type water chemistry showed relatively long residence times and low CFC-12 content.

395

400

## 405 6. Conclusion

We studied the groundwater flow system in the Jakarta area by hydrogeochemical techniques such as stable isotopes ( $\delta D$  and  $\delta^{18}O$ ), water chemistry by major ions, Br<sup>-</sup>:Cl<sup>-</sup> ratio, tritium, <sup>14</sup>C, and CFC analyses. Based on the results of major ion and stable isotope

analyses, the study area was divided into two parts: the northern Jakarta plain area and  
410 the southern mountainside spring water area.

In the southern mountainside spring water area, groundwater samples had juvenile  
features with Ca-HCO<sub>3</sub>-type water chemistry, which is not much affected by  
anthropogenic contamination. Since the concentrations of CFC-12 demonstrated no  
contamination characteristics from excessive urban CFCs, we could evaluate the  
415 groundwater residence times, and all groundwater samples, including the spring water  
and deep groundwater samples in this area, showed residence times of 20 to 30 years  
under piston flow conditions. These groundwater ages are consistent with those of the  
tritium analysis, and groundwater ages could be limited by CFCs.

In the northern Jakarta plain area, although hydrogeochemical characteristics  
420 showed various water chemistries depending on the aquifer depths, almost all (shallow  
and deep) groundwater samples recharged at similar elevations. In the shallow  
groundwater, groundwater samples were characterized by Ca-HCO<sub>3</sub>-type water chemistry,  
but some groundwater samples collected near dry agricultural fields displayed nitrate  
contamination related to the agricultural activities. This finding was supported by both  
425 stable N and O isotope content in NO<sub>3</sub><sup>-</sup> (Umezawa *et al.*, 2007) and the Br<sup>-</sup>:Cl<sup>-</sup> ratios in  
the groundwater samples. On the other hand, the deep groundwater samples had  
Na-HCO<sub>3</sub>-type water chemistry, influenced by cation exchange during its flowing process  
in the aquifer. However, the groundwater collected from the coastal area had Na-Cl-type  
water chemistry and was affected by seawater intrusion, caused by over pumping in the  
430 urban area. This result was also supported by the Br<sup>-</sup>:Cl<sup>-</sup> ratio, shown along the mixing  
line with sea water.

The difference in hydrogeochemistry between shallow and deep groundwater  
samples implied a difference in the relative residence times of their respective  
groundwaters, and this result was supported by the results of the <sup>14</sup>C and CFC-12  
435 analyses. Concentrations of <sup>14</sup>C and CFC-12 were higher (and, thus, the groundwater was  
younger) in the shallow aquifer while lower (and older) in the deep aquifer.

Even in the deep aquifer, we detected CFC-12 particularly under the urban area  
where the groundwater potential depression zone is located, suggesting that the recent  
shallow, younger groundwater intruded into the deeper aquifer because of excessive  
440 groundwater pumping, corresponding with rapid urbanization.



Since we found a positive correlation between the major type of water chemistry and the CFC-12 concentration, the magnitude of the CFC-12 concentration can be used as a pseudo-young age indicator in this field of study.

This study clearly reveals the groundwater flow system of the Jakarta area by  
445 integrating several hydrogeochemical components. Since the excessive groundwater  
pumping disturbs the subsurface environment, including the groundwater mixing of  
the shallow and deep aquifers and seawater intrusion in the coastal area, it is  
necessary to construct frameworks for the management of local groundwater resources,  
including pumping regulations and effective artificial recharge for the groundwater  
450 aquifer.

#### Acknowledgments

We thank the staff of the Indonesia Institute of Sciences (LIPI) for sampling.  
F. Lubis (LIPI) gave us the information on well locations. We also appreciate the  
455 support of T. Nakamura (Nagoya University) for analyzing  $^{14}\text{C}$ . This research was  
funded by the project “Human Impacts on Urban Subsurface Environment,” Research  
Institute for Humanity and Nature (RIHN).

#### References

- 460 Andreasen D. C., Fleck W. B. (1997) Use of Bromide:Chloride Ratios to Differentiate  
Potential Sources of Chloride in a Shallow, Unconfined Aquifer Affected by  
Brackish-Water Intrusion. *Hydrogeology Journal*, 5, 2, 17–26.
- Appelo C. A. J., Postma D. (2005) Ion exchange. In: Appelo C.A.J., Postma D., editors.  
Geochemistry, groundwater and pollution. *AA Balkema Publishers, Leiden*, 241–309.
- 465 Assegaf A. (1998) Hidrodinamika Airtanah Alamiah Cekungan Jakarta, MSc Thesis,  
Geological Engineering Dept., Bandung Institute of Technology, Indonesia.
- Bakker K. (2007) Trickle Down? Private sector participation and the pro-poor water  
supply debate in Jakarta, Indonesia. *Geoforum*, 38, 5, 855–868.
- Bolsunovsky A. Y., Bondareva L. G. (2003) Tritium in surface water of the Yenisei River  
470 basin. *Journal of Environmental Radioactivity*, 66, 285–294.
- Busenberg E., Plummer L. N. (1992) Use of chlorofluorocarbons (CCl<sub>3</sub>F and CCl<sub>2</sub>F<sub>2</sub>) as  
hydrologic tracers and age-dating tools: the alluvium and terrace system of central

Oklahoma. *Water Resour. Res.*, 28, 2257–2283.

- Clark I. D., Fritz P. (1997) *Environmental isotopes in hydrogeology*. Lewis Publishers.  
475 328p. United States.
- Craig H. (1961) Isotope variations in meteoric waters. *Science*, 133, 1702-1703.
- Cunnold D. M., Weiss R. R., Prinn R. G., Hartley D., Simmonds P. G., Fraser P. J., Miller  
B., Alyea F. N., and Porter L. (1997) GAGE/AGAGE measurements indicating  
reductions in global emissions of CCl<sub>3</sub>F and CC<sub>1</sub><sub>2</sub>F<sub>2</sub> in 1992-1994. *Journal of*  
480 *Geophysical Research*, 102, 1259–1269.
- De Vries J. J., Simmers I. (2002) Groundwater recharge: an overview of processes and  
challenges. *Hydrogeology Journal*, 10, 5–17.
- Delinom R. M. (2008) Groundwater management issues in the Greater Jakarta area,  
Indonesia. *Proceedings of International Workshop on Integrated Watershed*  
485 *Management for Sustainable Water Use in h Humid Tropical Region, JSPS-DGHE*  
*Joint Research Project*, 8, 40–54.
- Delinom R. M., Delinom A. A., Hasanuddin Z. A., Makoto T., Dadan S., Rachmat F. L.,  
Eko Y. (2009) The contribution of human activities to subsurface environment  
degradation in Greater Jakarta Area, Indonesia. *Science of the Total Environment*,  
490 407, 3129–3141. doi:10.1016/j.scitotenv.2008.10.003.
- Drever J. I. (1988) *The Geochemistry of Natural Waters*, second ed. Prentice Hall, Inc.
- Fachri M., Djuhaeni, L. M. Hutasoit and A. M. Ramdhan (2003) Stratigraphy and  
hydrostratigraphy in Jakarta groundwater basin (in Indonesian). *Bull Geol Bandung*  
*Instit Technol*, 34, 169–189.
- 495 Fetter C. W. (1993) *Contaminant hydrogeology*. New York, Macmillan Publishing Co.,  
458p.
- Foster S. S. D., Chilton P. J. (2003) Groundwater: the process and global significance of  
aquifer degradation. *Philosophical Transactions of the Royal Society of London*  
*Series B-Biological Sciences*, 358, 1957–1972.
- 500 Han, S. S., Basuki A. (2001) The spatial pattern of land values in Jakarta. *Urban Studies*  
38(10): 1841–1857.
- Hosono T., Ikawa R., Shimada J., Nakano T., Saito M., Onodera S., Lee K., and  
Taniguchi M. (2008) Human impacts on groundwater flow and contamination  
deduced by multiple isotopes in Seoul City, South Korea. *Science of the Total*

- 505 *Environment*, 407, 3189–3197.
- IAEA/WMO (2004) Global network of isotopes in precipitation. The GNIP database. Accessible at: <http://isohis.iaea.org>.
- Jiang Y., Kirkman H., and Hua A. (2001) Megacity development: managing impacts on marine environments. *Ocean and Coastal Management*, 44, 293–318.
- 510 Johnston C. T., Cook P. G., Frapce S. K., Plummer L. N., Busenberg E., and Blackport R. J. (1998) Ground water age and nitrate distribution within a glacial aquifer beneath a thick unsaturated zone. *Ground Water*, 36, 171–180.
- Lubis R. F., Sakura Y., and Delinom R. M. (2008) Groundwater recharge and discharge processes in the Jakarta groundwater basin, Indonesia. *Hydrogeology Journal*, 16,
- 515 927–938.
- Marechal J. C., Etcheverry D. E. (2003) The use of  $^3\text{H}$  and  $^{18}\text{O}$  tracers to characterize water inflows in Alpine tunnels. *Applied Geochemistry*, 18, 339–51.
- Martodjodjo S. (1984) Evolusi Cekungan Bogor, Jawa Barat. PhD Dissertation, Bandung Institute of Technology, unpublished.
- 520 Nakamura T., Niu E., Oda H., Ikeda A., Minami M., Ohta T., and Oda T. (2004) High precision  $^{14}\text{C}$  measurements with the HVEE Tandatron AMS system at Nagoya University. *Nuclear Instruments and Methods in Physics Research B* 223–224, 124–129.
- Onodera S., Saito M., Sawano M., Hosono T., Taniguchi M., Shimada J., Umezawa Y.,
- 525 Lubis R. F., Buapeng S., and Delinom R. (2008) Effects of intensive urbanization on the intrusion of shallow groundwater into deep groundwater: Examples from Bangkok and Jakarta. *Science of the Total Environment*, 404, 401–410.
- Plummer L. N., Busenberg E., Böhlke J. K., Nelms D. L., Michel R. L., and Schlosser P. (2001) Groundwater residence times in Shenandoah National Park, Blue Ridge
- 530 Mountains, Virginia, USA: a multi-tracer approach. *Chemical Geology*, 179, 93–111.
- Plummer L. N., Rupert M. G., Busenberg E., and Schlosser P. (2000) Age of Irrigation Water in Ground Water from the Eastern Snake River Plain Aquifer, South-Central Idaho. *Ground Water*, 38, 264–283.
- 535 Plummer L. N., Busenberg E., Drenkard S., Schlosser P., McConnell J. B., Michel R. L.,

- Ekwurzal B., Weppernig R., McConnell J. B., and Michel R. L. (1998) Flow of river water into a karstic limestone aquifer-2. Dating the young fraction in groundwater mixtures in the Upper Floridan aquifer near Valdosta, Georgia. *Applied Geochemistry*, 13, 1017–1043.
- 540 Richter B. C., Kreitler C. W. (1993) Geochemical techniques for identifying sources of ground-water salinization. *Boca Raton, FL, C. K. Smoley*, 258p.
- Tambunan M. P. (2007) Flooding area in the Jakarta province on February 2 to 4 2007. *Proceedings of Asian Association on Remote Sensing (ACRS) 2007*.
- Umezawa Y., Hosono T., Onodera S., Siringan F., Buapeng S., Delinom R., Yoshimizu
- 545 C., Tayasu I., Nagata T., and Taniguchi M. (2008) The source and mechanisms controlling nitrate and ammonium contaminations in groundwater at developing Asian-Mega cities, Metro Manila, Bangkok and Jakarta. *Science of the Total Environment*, 407, 3219–3231.
- USGS (2010) The Reston Chlorofluorocarbon Laboratory Accessible at:
- 550 [http://water.usgs.gov/lab/software/air\\_curve/](http://water.usgs.gov/lab/software/air_curve/).
- Yamanaka M., Nakano T., and Tase N. (2005) Hydrogeochemical evolution of confined groundwater in northeastern Osaka Basin, Japan: estimation of confined groundwater flux based on a cation exchange mass balance method. *Applied Geochemistry*, 20, 295–316.

### Figure and Table Captions

**Figure 1** Maps showing (a) study area and sampling locations and (b) the land use divided into eight components. A cross line (A-A') in Fig. 1a corresponds to the cross sections in Fig. 6 and 10.

**Figure 2** Historical change in the spatial distribution of groundwater potential. Unit of the potential is meters above sea level.

**Figure 3** Trends in groundwater levels between 1982 and 2005 (N = 18).

**Figure 4** Distribution of trends in groundwater fluctuation.

**Figure 5** Piper diagram for the major ions.

**Figure 6** Vertical distribution of the stiff diagram along a cross sections shown in Fig. 1a.

**Figure 7** Relationship between the  $\text{Br}^-:\text{Cl}^-$  ratios and the  $\text{Cl}^-$  and  $\text{NO}_3^-$  concentrations.

**Figure 8** Relationship between  $\delta^{18}\text{O}$  and  $\delta\text{D}$  in all water samples.

**Figure 9** Tritium concentrations of the precipitation in Jakarta and Tokyo and water samples showed maximum and minimum concentrations in this study. Dashed lines indicate tritium concentration of sampled groundwater at the time of recharge, assuming a piston flow model and a half life of 12.4 years.

**Figure 10** Vertical distribution of  $^{14}\text{C}$  and CFC-12 concentrations along a cross sections shown in Fig. 1a.

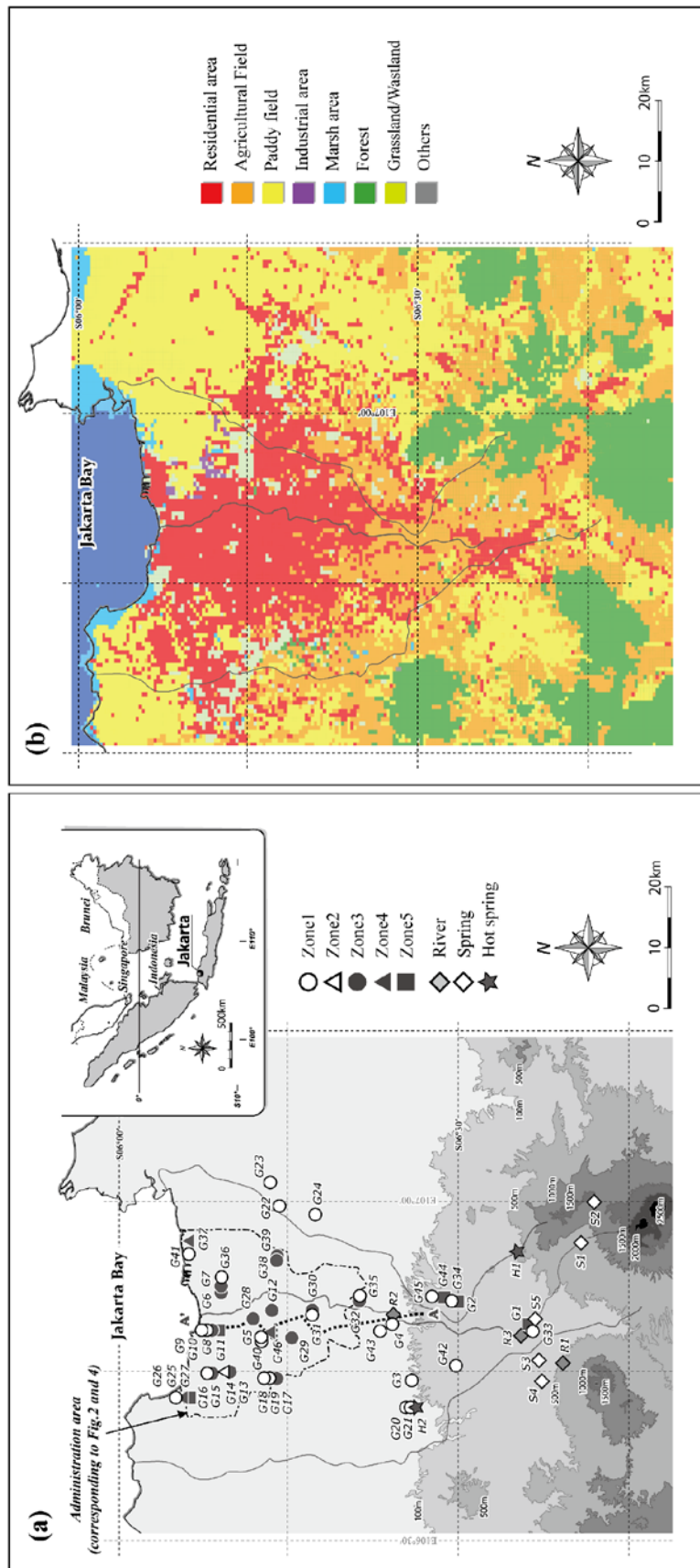
**Figure 11** Relationship between the  $\text{Cl}^-$  concentration and  $\delta^{18}\text{O}$ .

**Figure 12** Plots comparing CFC-12 and CFC-113 concentrations in water in pptv by piston flow (solid curve) and by binary mixtures of young water (recharged in 2000, 1995, 1990, 1985, 1980, and 1975) with old, CFC-free water (dashed lines).

**Figure 13** CFC-12 concentration overlaid on the Piper diagram.

**Table 1** Results of chemical and isotopic analyses.

**Fig. 1**



**Fig. 2**

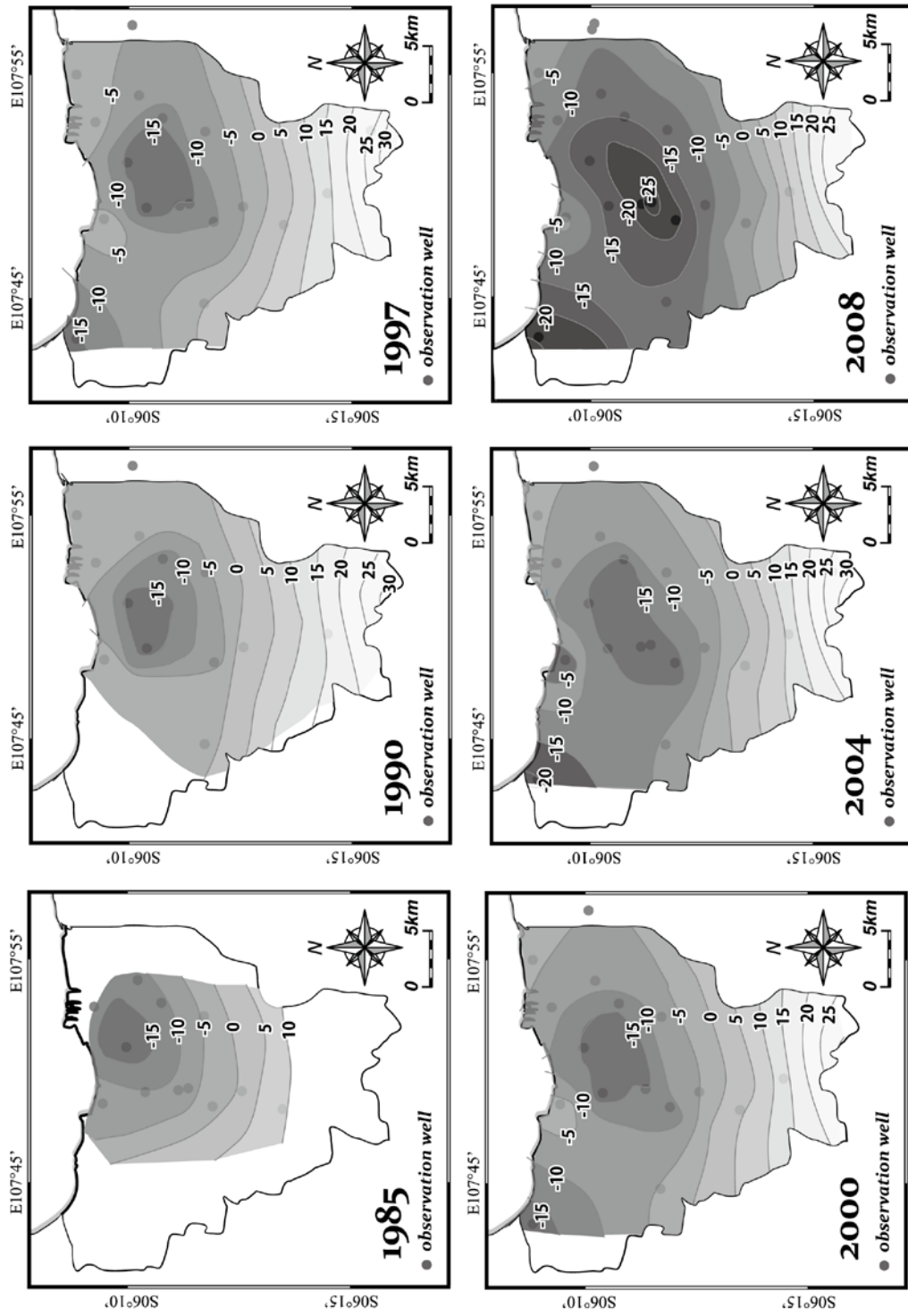
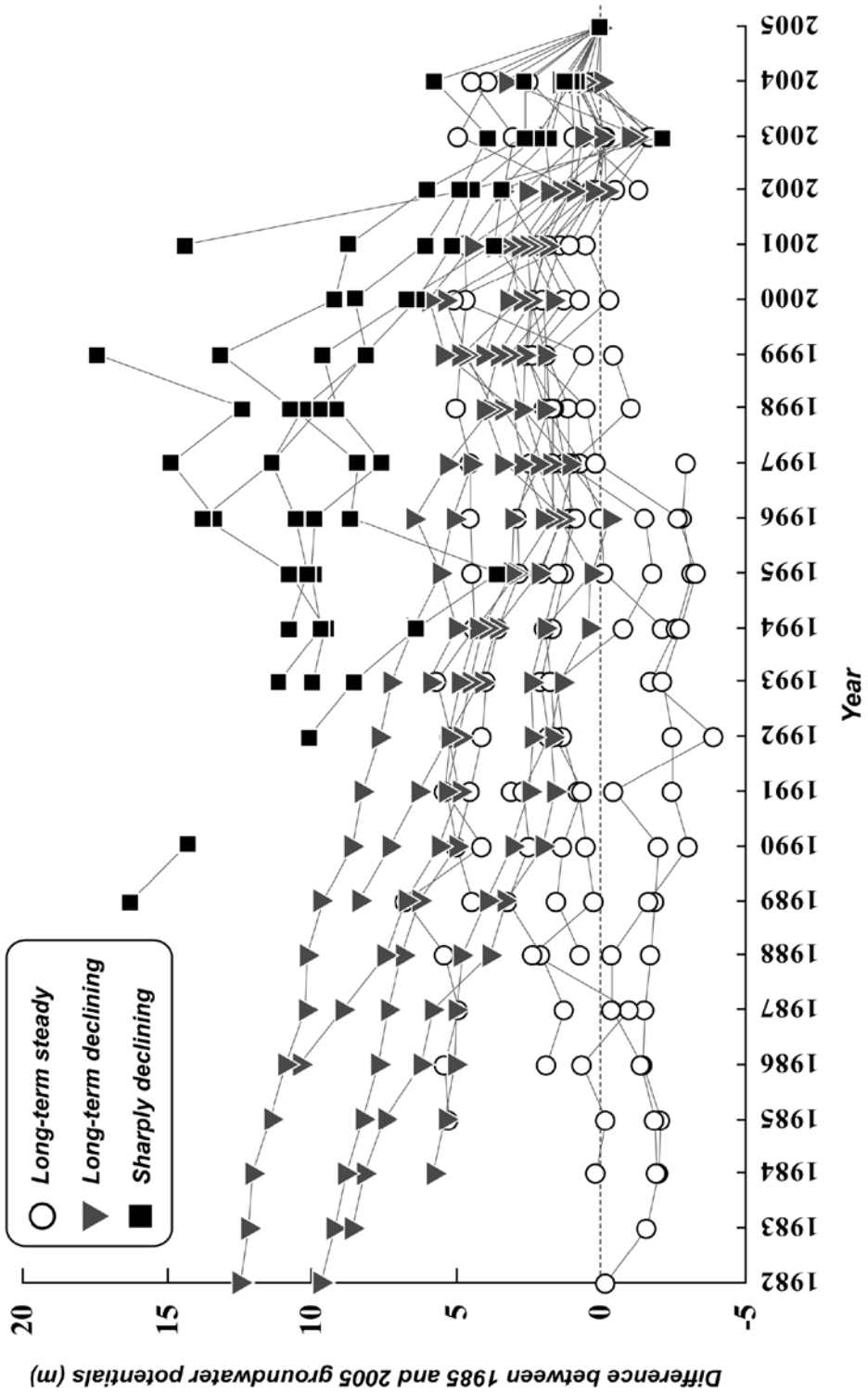
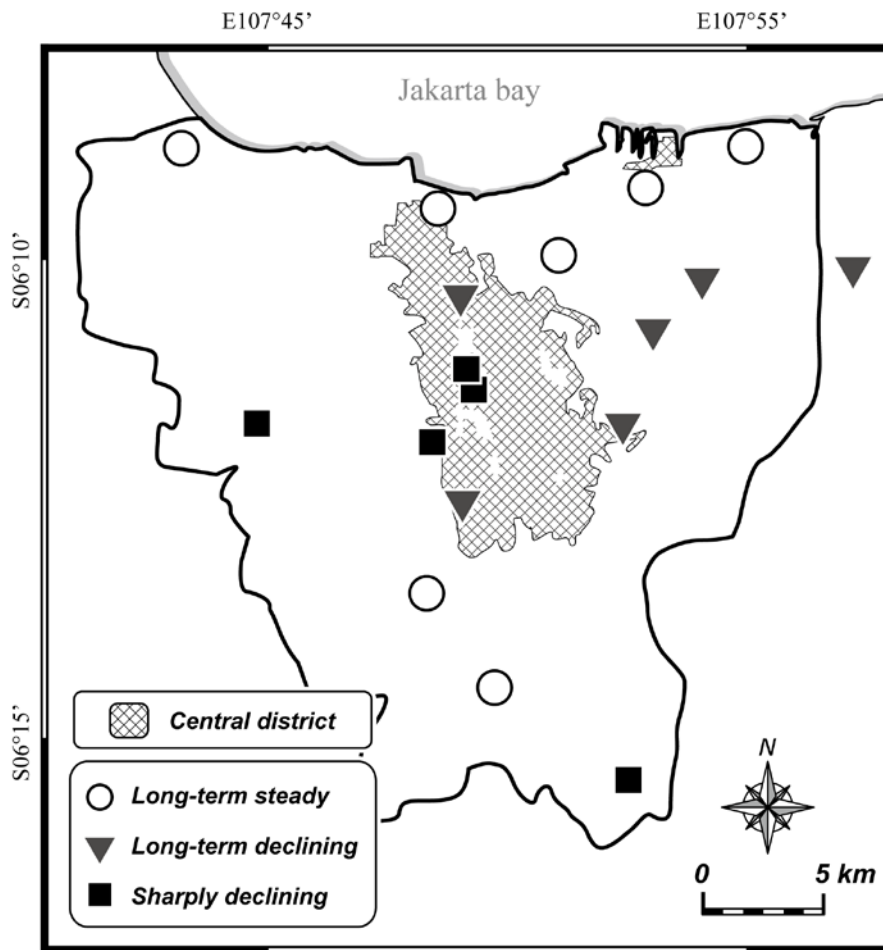


Fig. 3



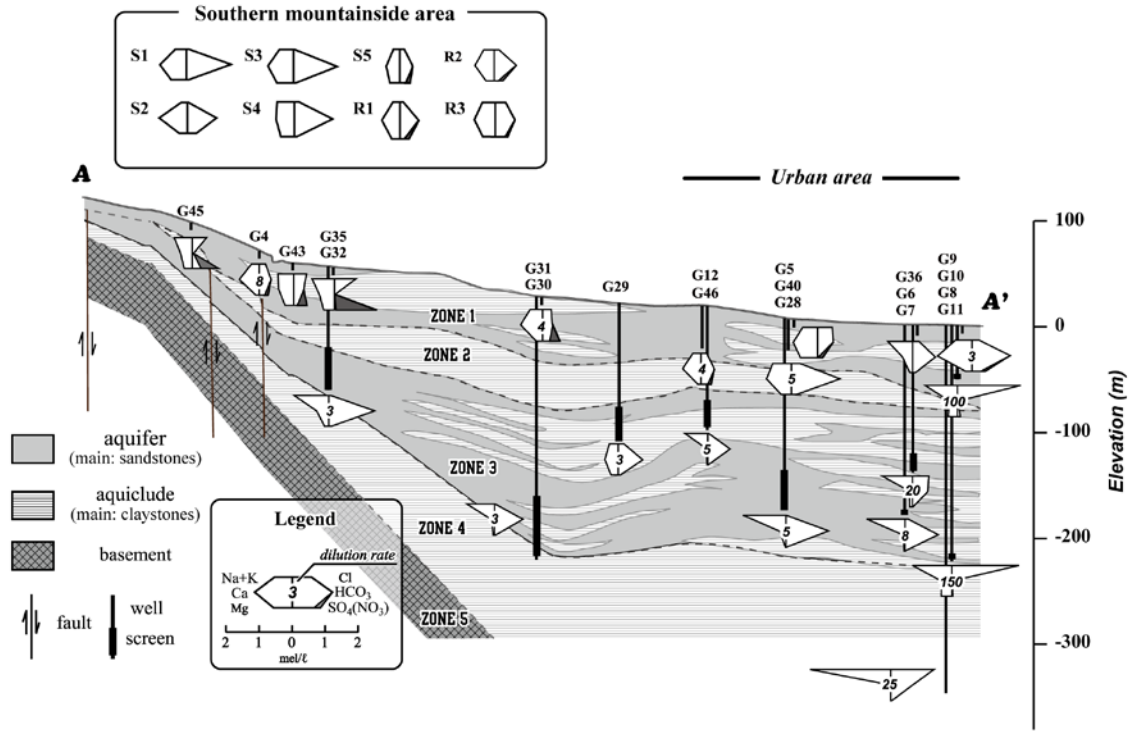


**Fig. 4**





**Fig. 6**



**Fig. 7**

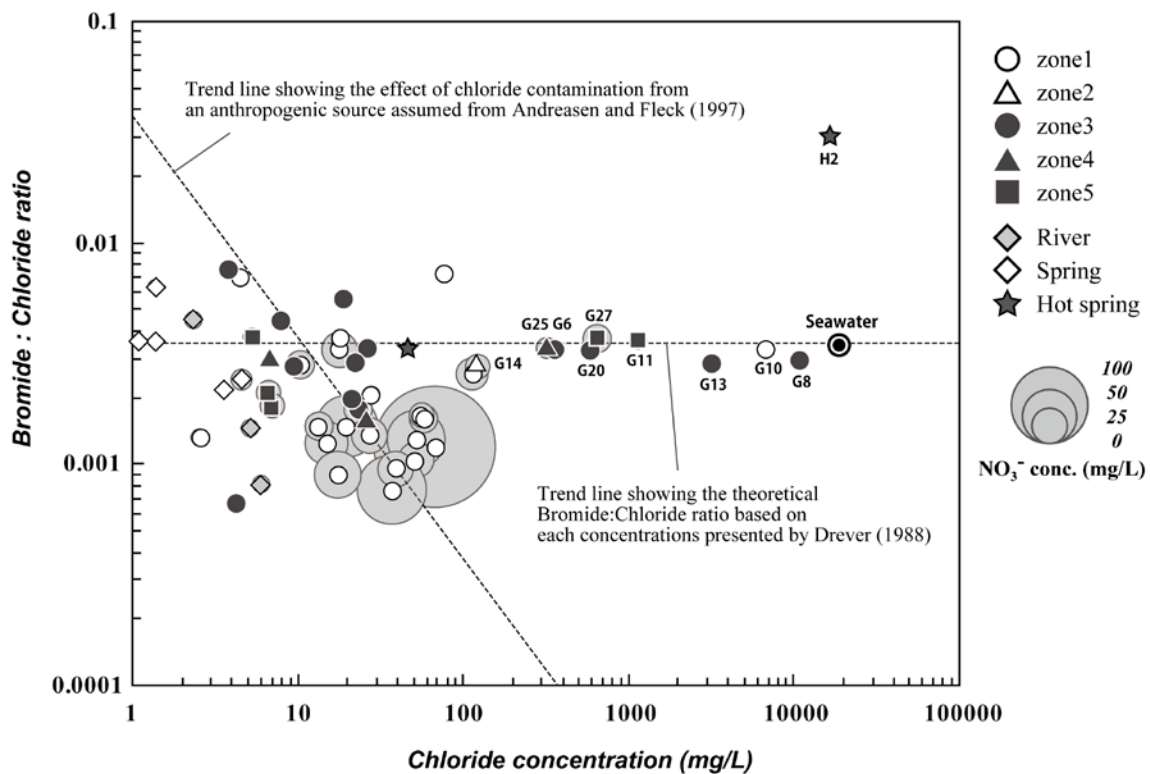


Fig. 8

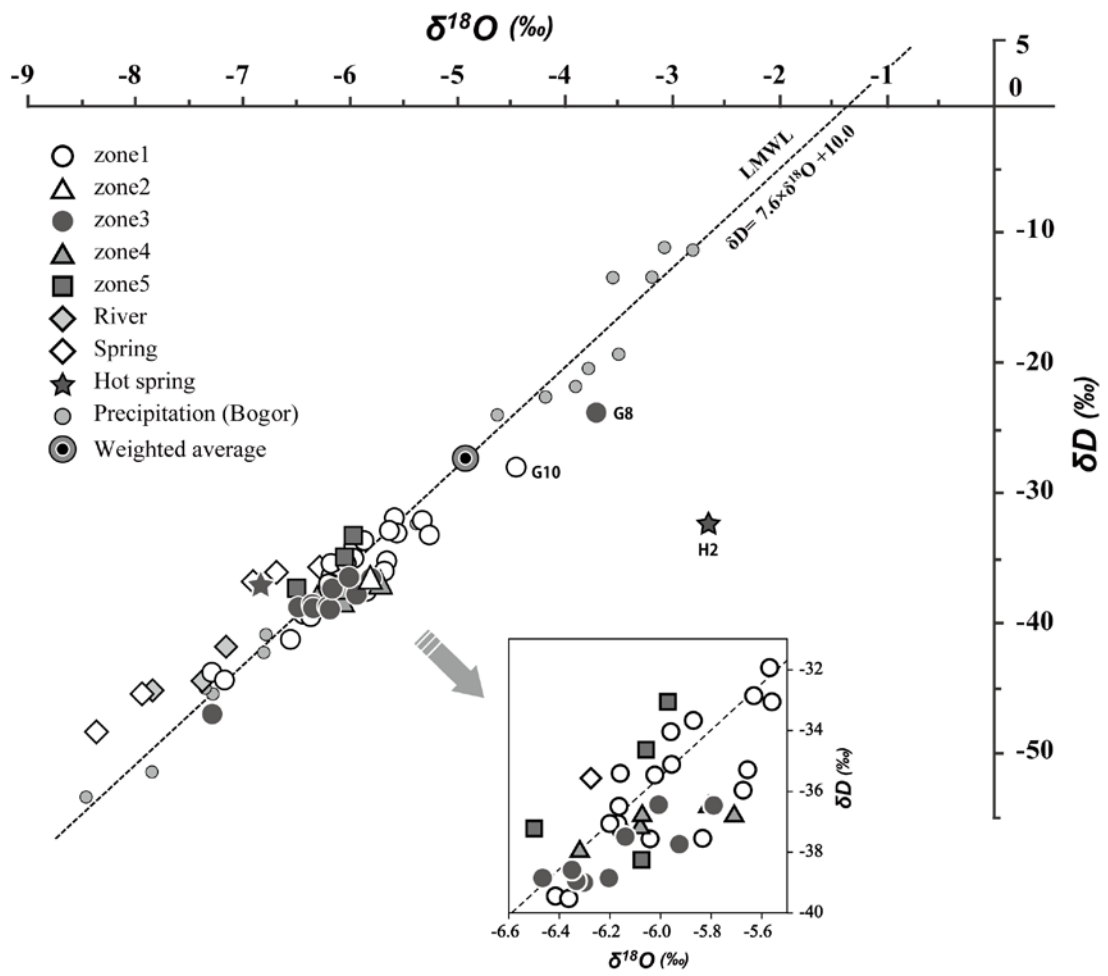
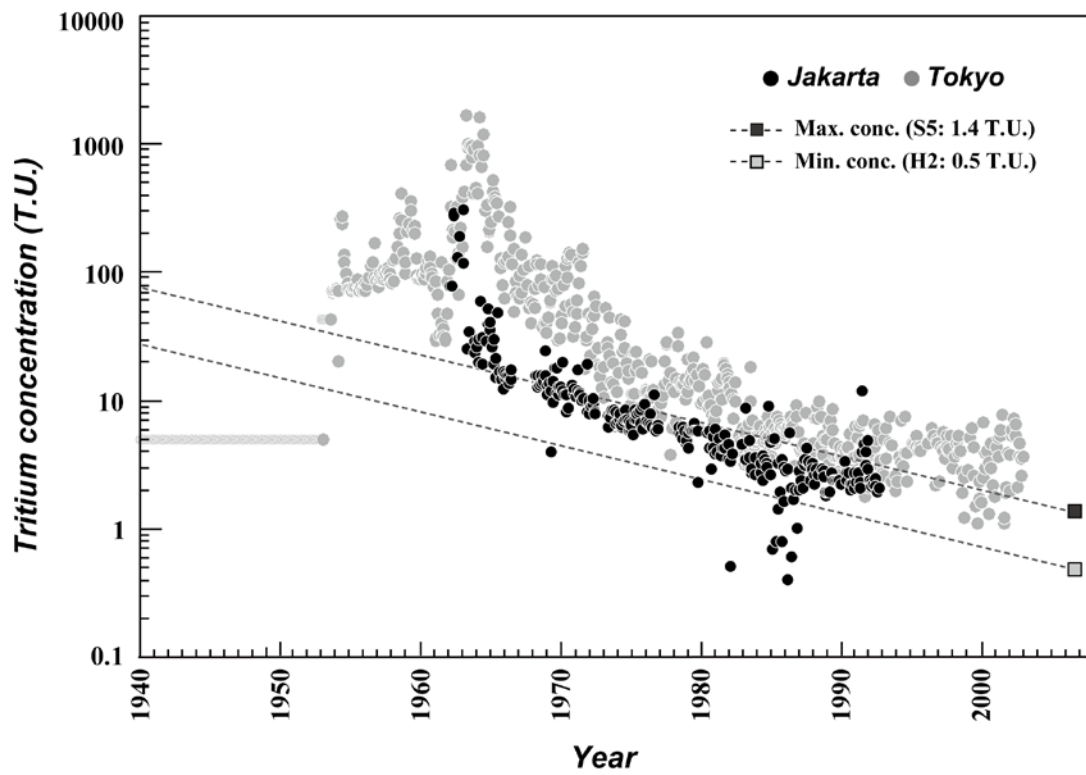


Fig. 9



**Fig. 10**

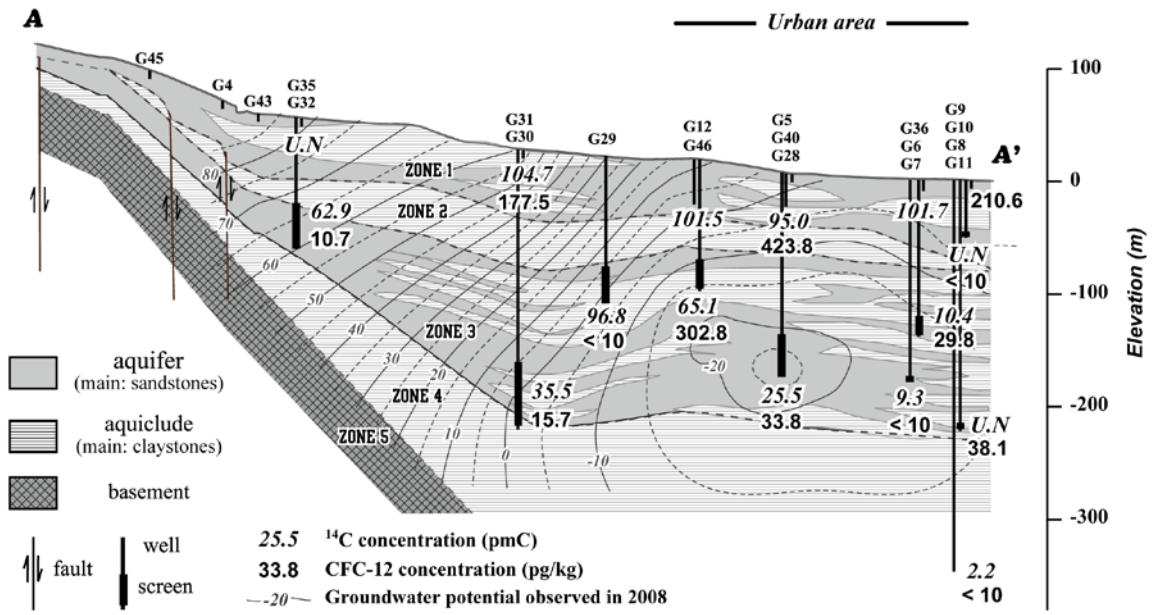


Fig. 11

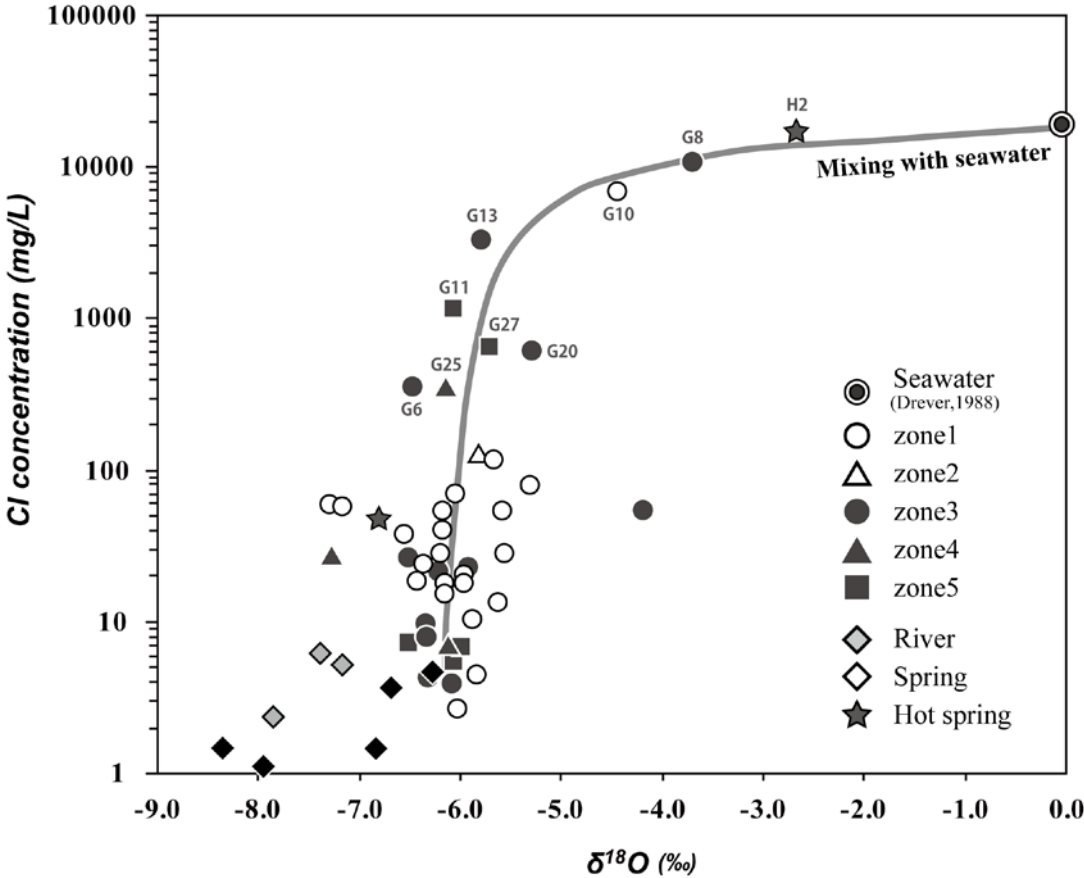
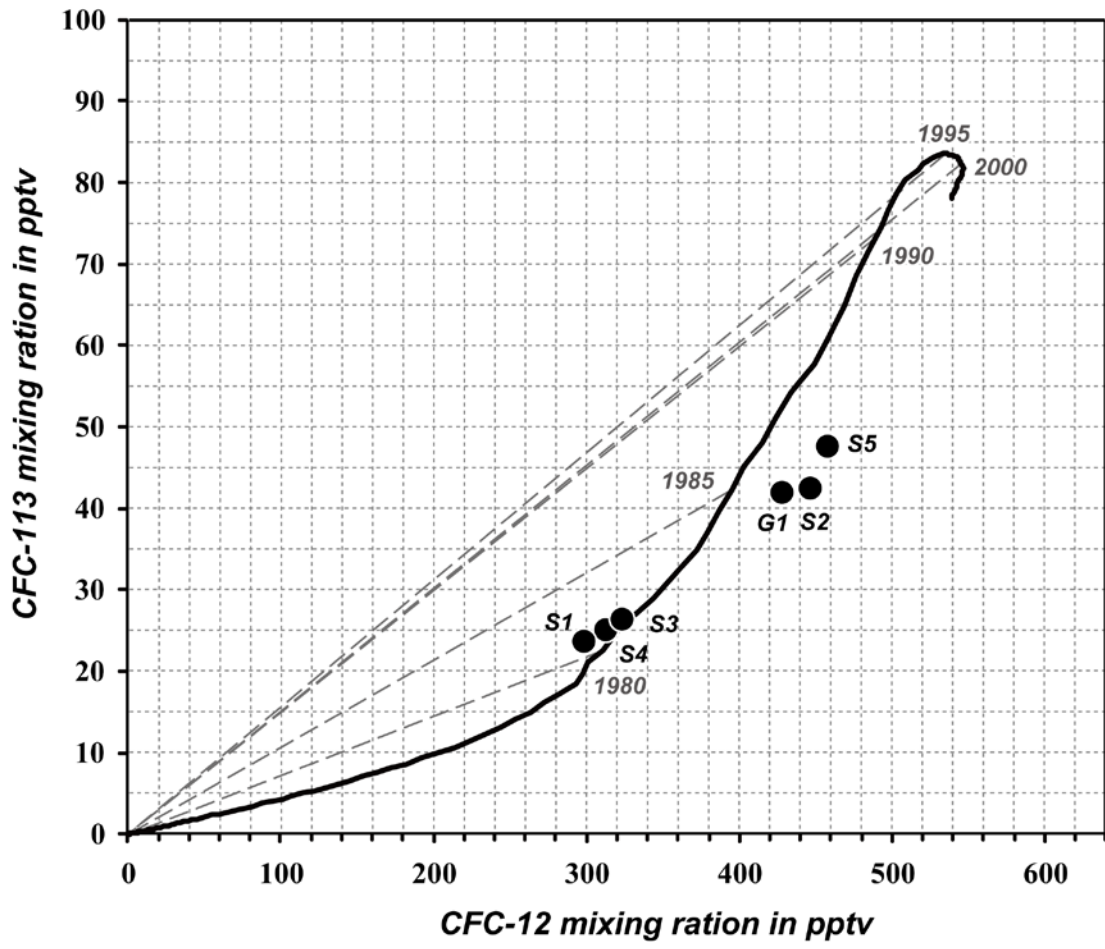
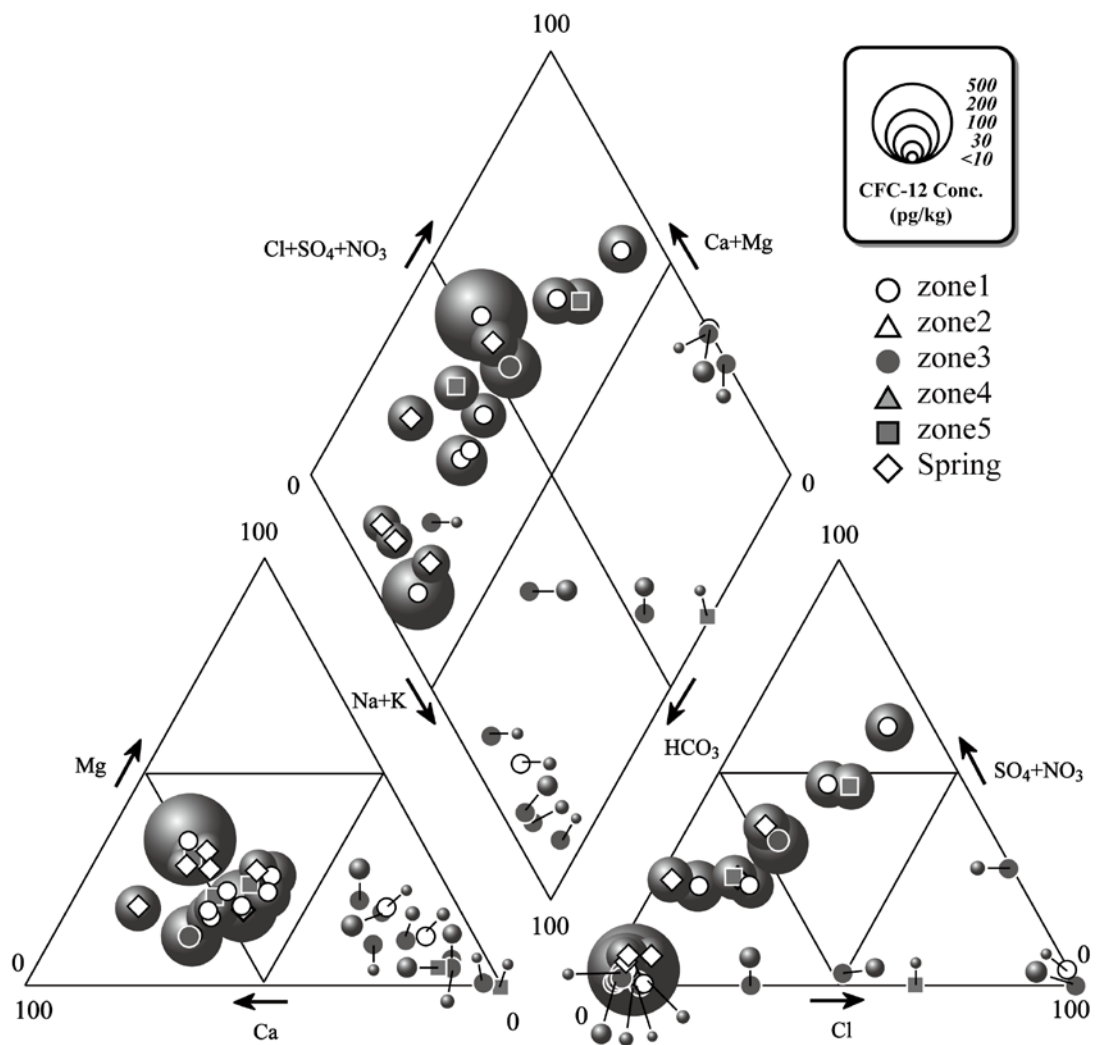




Fig. 12



**Fig. 13**



# Table 1

**Table 1** Results of chemical and isotopic analysis

Sampling Location No.	Sample type	Well depth (m)	Temp. (°C)	pH	EC (µS/cm)	Cl <sup>-</sup> (mg/l)	NO <sub>3</sub> <sup>-</sup> (mg/l)	SO <sub>4</sub> <sup>2-</sup> (mg/l)	HCO <sub>3</sub> <sup>-</sup> (mg/l)	Na <sup>+</sup> (mg/l)	K <sup>+</sup> (mg/l)	Mg <sup>2+</sup> (mg/l)	Ca <sup>2+</sup> (mg/l)	Water type	Br <sup>-</sup> /Cl <sup>-</sup> ratio	δ <sup>18</sup> O (‰)	δD (‰)	Tritium (T.U.)	<sup>14</sup> C (pmC)	<sup>14</sup> C (apparent age)	CFC-12 (pg/kg)	CFC-12 (apparent residence time in year)	
G1	GW	150	26.6	5.8	129	6.7	12.3	6.1	46.6	4.8	0.9	4.5	12.1	Ca type	0.0021	-6.0	-33.1	1.3 ± 0.4	106.4	-500	161.2	21.5	
G2	GW	80	27.4	5.8	75	7.1	11.2	6.4	9.8	6.3	0.4	2.2	6.4	Ca type	0.0018	-6.5	-37.2	1.0 ± 0.4	105.3	-412			
G3	GW	9	27.5	5.1	152	20.0	63.9	0.5	7.4	10.9	0.5	4.7	13.9	Ca type	0.0015	-6.0	-34.1						
G4	GW	4	28.7	6.3	634	52.7	57.4	59.1	166.8	42.8	6.9	8.0	99.8	Ca type	0.0013	-5.6	-31.9	0.7 ± 0.6					
G5	GW	4	28.2	5.5	210	18.1	17.3	1.4	31.9	6.3	1.5	4.8	17.5	Ca type		-5.7	-36.0						
G6	GW	140	31.1	8.3	1897	352.7	0.0	27.2	566.6	416.4	11.9	16.6	32.3	Na type	0.0033	-6.5	-38.8	0.8 ± 0.3	104.8	18183	29.8	<10	
G7	GW	180	31.2	8.7	755	26.6	4.1	0.0	495.5	208.1	9.9	1.3	7.0	Na type	0.0033	-6.3	-39.0		9.3	19043	<10		
G8	GW	225	32.2	7.0	22900	10875.2	0.0	32.4	0.0	3851.3	277.2	541.8	856.1	Na type	0.0029	-3.7	-23.8	0.8 ± 0.3	UN		210.6	<10	
G9	GW	3	26.5	7.6	430	17.9	23.1	38.8	208.5	29.8	9.1	7.2	61.4	Ca type	0.0033	-6.2	-37.3						
G10	GW	50	30.9	6.8	14370	6798.7	0.0	347.1	0.0	2198.3	140.5	333.8	446.5	Na type	0.0033	-4.4	-28.1		UN				
G11	GW	350	36.0	8.1	3920	1136.6	7.2	3.7	983.7	6.5	2391.2	0.0	5.6	Na type	0.0036	-6.1	-38.3		2.2	30766	<10		
G12	GW	40	28.5	6.7	420	23.5	17.0	40.3	93.2	19.6	8.3	5.3	44.9	Ca type	0.0017	-6.4	-39.5	0.5 ± 0.3	101.5	-117	302.8		
G13	GW	150	31.0	6.3	10780	3250.0	0.0	1684.6	0.0	1942.6	20.5	145.8	344.7	Na type	0.0028	-5.8	-36.5	0.5 ± 0.1	UN		17.0		
G14	GW	70	27.3	7.4	1062	123.7	13.1	96.4	291.9	167.3	9.4	6.5	68.3	Na type	0.0027	-5.8	-36.5						
G15	GW	250	29.2	7.4	664													0.9 ± 0.6					
G16	GW	4	26.6	7.1	746	58.6	14.4	81.7	284.5	64.5	13.3	23.4	110.8	Ca type	0.0016	-7.3	-43.9	0.7 ± 0.3	103.6	-285	163.3		
G17	GW	123	30.7	8.8	169	22.4	0.3	0.1	80.9	24.0	5.8	4.9	8.0	Na type	0.0029	-5.9	-37.7	0.5 ± 0.2	96.9	251	36.1		
G18	GW	8	28.4	6.5	405	52.6	23.3	21.7	132.5	16.4	11.1	10.9	64.4	Ca type	0.0010	-6.2	-36.5	1.0 ± 0.3	99.9	7			
G19	GW	50	28.2	6.5	463	39.6	22.8	25.6	130.0	17.2	10.3	8.7	57.6	Ca type	0.0009	-6.2	-37.1		99.8	13			
G20	GW	30	28.9	6.6	2460	600.9	0.0	7.5	257.6	378.5	49.9	11.7	69.7	Na type	0.0033	-5.3	-32.9	0.8 ± 0.4					
G21	GW	3	24.8	7.0	1330																		
G22	GW	20	28.9	7.2	180	2.6	6.6	3.8	55.2	1.8	3.4	1.7	16.4	Ca type	0.0013	-6.0	-35.5						
G23	GW	13	29.8	6.4	423	18.1	0.0	5.1	179.1	14.1	4.5	10.3	45.6	Ca type	0.0037	-6.4	-39.4						
G24	GW	32	29.5	6.9	329	4.5	1.6	0.8	164.4	11.5	4.1	8.9	33.2	Ca type	0.0069	-5.8	-37.5						
G25	GW	200	31.3	8.7	2350	341.2	10.0	0.0	1047.4	612.9	15.3	3.0	0.0	Na type	0.0033	-6.1	-37.5		6.6	21796			
G26	GW	4	26.5	7.1	1385	56.4	11.1	77.4	363.0	64.9	15.1	23.5	106.6	Ca type	0.0016	-7.2	-44.4						
G27	GW	250	31.0	7.5	3570	643.9	14.9	1226.5	899.4	61.9	10.6	10.6	34.9	Na type	0.0037	-5.7	-36.8		2.9	28522			
G28	GW	150	30.3	8.2	495	8.0	2.8	3.0	382.7	139.1	10.7	3.6	16.9	Na type	0.0044	-6.3	-38.6	0.9 ± 0.3	25.5	10973	33.8		
G29	GW	125	30.9	6.9	332	18.9	0.0	0.0	130.0	17.3	3.9	7.3	25.3	Ca type	0.0055	-6.0	-36.4		96.8	263	<10		
G30	GW	253	31.1	7.2	302	3.8	1.3	1.2	152.1	55.4	2.7	1.4	4.9	Na type	0.0076	-6.1	-37.1		35.5	8320	15.7		
G31	GW	8	28.1	6.2	435	37.6	78.1	38.6	73.6	35.0	1.9	9.8	53.7	Ca type	0.0008	-6.5	-41.2		104.7	-365	177.5		
G32	GW	120	29.7	8.3	270	4.3	5.2	1.5	198.7	48.7	5.5	4.0	14.6	Na type	0.0007	-6.3	-37.9		62.9	3724	<10		
G33	GW	12	27.5	5.7	127	10.4	16.0	7.2	35.6	5.0	0.0	5.4	12.4	Ca type	0.0028	-5.9	-33.7		107.5	-583	685.1		
G34	GW	12	27.1	5.2	163	17.8	37.1	19.9	8.6	14.0	0.2	4.9	11.2	Na type	0.0009	-6.0	-35.1		102.5	-195	185.7		
G35	GW	9	27.7	3.9	483	68.3	239.2	2.3	0.0	45.1	2.2	11.7	26.6	Na type	0.0012	-6.0	-37.6		UN				
G36	GW	4	28.6	7.4	1467	114.9	19.2	35.3	598.5	210.3	9.6	28.5	71.8	Na type	0.0025	-5.7	-35.3		101.7	-137			
G37	GW	250	31.5	7.8	377	26.5	3.1	13.4	169.3	62.0	10.7	4.0	23.9	Na type	0.0015	-7.3	-47.0		101.9	-148	171.8		
G38	GW	130	30.9	7.2	265	9.6	1.3	0.6	179.1	21.6	3.0	9.2	28.8	Ca type	0.0027	-6.3	-38.9		98.1	155			
G39	GW	80	30.3	7.0	325	21.3	2.4	1.4	203.6	24.6	4.1	10.1	39.3	Ca type	0.0020	-6.2	-38.8		99.1	69			
G40	GW	31	29.6	7.5	486	27.9	5.6	33.2	392.5	40.1	8.0	12.6	50.1	Ca type	0.0020	-6.2	-37.1		95.0	416	423.8		
G41	GW	1	28.7	7.4	78.4	78.4	0.8	9.0	635.3	54.4	2.6	4.5	6.3	Na type	0.0071	-5.3	-32.1		96.5	285	14.0		
G42	GW	15	28.7	4.4	118	27.6	25.3	1.0	2.5	13.2	0.9	1.7	5.1	Na type	0.0013	-5.6	-33.0						
G43	GW	15	27.4	5.4	102	13.5	13.9	8.7	19.6	10.0	0.9	3.0	8.7	Na type	0.0015	-5.6	-32.9		22.9	11831			
G44	GW	80	27.9	8.3	431	5.4	5.3	1.6	321.3	120.2	9.8	0.9	4.6	Na type	0.0037	-6.1	-34.6						
G45	GW	10	27.9	4.6	145	15.2	32.3	14.2	1.2	11.5	1.5	2.9	7.4	Na type	0.0012	-6.2	-35.4						
G46	GW	150	31.3	11.1	521	6.8	0.7	9.1	206.1	72.6	11.0	0.1	2.6	Na type	0.0029	-6.1	-36.8		65.1	3450			
R1	River		21.1	7.6	130	2.3	6.8	5.8	30.7	3.4	1.4	2.5	8.8	Ca type	0.0045	-7.8	-45.2	1.0 ± 0.5					
R2	River		25.7	7.1	861	5.3	7.6	6.2	40.5	5.9	1.7	2.9	11.3	Ca type	0.0014	-7.2	-41.7						
R3	River		23.1	7.6	740	6.0	7.4	6.8	36.8	6.8	9.0	3.1	12.8	Ca type	0.0008	-7.4	-44.5						
S1	Spring		20.1	7.4	149	1.4	3.6	1.8	84.6	5.9	2.6	5.4	16.2	Ca type	0.0063	-8.4	-48.4						
S2	Spring		18.1	7.3	125	1.1	3.3	12.5	55.2	3.7	1.0	2.8	16.9	Ca type	0.0036	-7.9	-45.5	0.8 ± 0.7					
S3	Spring		22.9	7.1	132	1.4	3.3	2.0	74.8	6.8	2.6	4.6	13.4	Ca type	0.0036	-6.8	-37.0						
S4	Spring		22.7	6.5	126	3.7	3.3	1.4	66.2	9.2	2.4	4.3	9.9	Ca type	0.0021	-6.7	-36.1						
S5	Spring		26.1	5.6	77	4.6	8.6	7.4	22.1	3.9	0.7	3.2	7.5	Ca type	0.0024	-6.3	-35.6	1.4 ± 0.6					
H1	Hot Spring		51.5	7.5	1552	46.4	0.0	534.6	120.2	98.1	2.4	9.8	249.8	Ca type	0.0033	-6.8	-37.2	0.5 ± 0.4	33.9	8691	172.2	20.5	
H2	Hot Spring		38.3	6.3	41000	16620.4	0.0	0.0	291.9	7519.6	654.8	376.8	1654.0	Na type	0.0303	-2.7	-32.6	0.5 ± 0.3	0.3	47197			

GW: groundwater from wells, UN: values was unmeasurable