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GROUNDWATER CHARACTERISTICS IN JAKARTA AREA, INDONESIA

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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 understand groundwater characteristic in the Jakarta area. Although almost all groundwater existing in the Jakarta basin is recharged at similar elevations, the water quality and apparent residence time demonstrates a clear difference between the shallow and deep aquifers.

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Due to the rapid decrease in the groundwater potential in urban areas, we found that the seawater intrusion in shallow aquifer and the shallow and deep groundwaters are mixing, a conclusion confirmed by major ions, $Br^-:Cl^-$ ratios and chlorofluorocarbon (CFC)-12 analysis.

Keywords : groundwater hydrogeochemistry, excessive groundwater pumping, chlorofluoro carbon (CFC), Jakarta, Indonesia

ABSTRAK Di Jakarta, Indonesia, pemompaan airtanah yang terus menerus karena penambahan jumlah penduduk telah menyebabkan terjadinya beberapa masalah yang berhubungan dengan sumberdaya air, seperti adanya kontaminasi air payau di sekitar pantai dan penurunan muka tanah. Dalam penelitian ini, telah digunakan berbagai teknik kimia airtanah untuk mengetahui karakteristik dari airtanah di Daerah Jakarta. Meskipun hampir semua airtanah di Jakarta diresapkan pada ketinggian yang sama, kualitas air dan waktu tinggal memperlihatkan perbedaan yang jelas antara akifer dangkal dan akifer dalam. Karena adanya penurunan airtanah potesial yang cepat di daerah perkotaan, ditemukan bahwa intrusi airlaut dalam airtanah bebas dan adanya percampuran antara airtanah bebas dan tertekan, kesimpulan ini dikonfirmasi oleh ion utama, rasio $Br^-:Cl^-$ dan analisis chlorofluorocarbon (CFC)-12.

Kata Kunci: airtanah, hidrogeokimia, pemompaan airtanah berlebih, Khlorofluoro karbon (CFC), Jakarta, Indonesia

INTRODUCTION

Subsurface environmental problems, such as land subsidence due to excessive groundwater 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. 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 study that employs multiple hydrogeochemical techniques has not yet been performed in the Jakarta groundwater basin.

STUDY AREA

The Java Sea borders Jakarta, the capital city of the Republic of Indonesia, to the north (Fig. 1a). The province of Jakarta (DKI Jakarta; 6°00'-6°20" S, 106°42'-107°00" E) has a surface area of approximately 652 km² and a humid tropical climate that is significantly influenced by monsoon winds. The long-term mean annual 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 annual air temperature is 27°C. The mean potential evapotranspiration for the Jakarta region is 1,606 mm/year (Tambunan, 2007).

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.

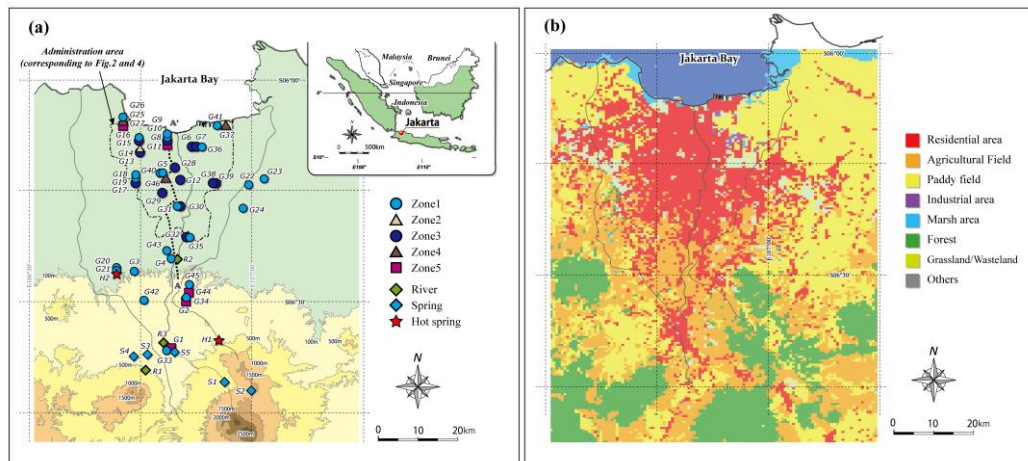


Figure 1 Maps showing (a) study area and sampling locations and (b) the land use divided into eight components. A cross line (A-A') in Fig. 1a corresponds to the cross sections in Figs. 4 and 7.

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.

The vertical cross section of the local hydrogeology along the line (A-A') in Fig. 1a (south to north) is shown in Figs. 4 and 7.

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 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 δD) and major ion (Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Cl^- , NO_3^- , and SO_4^{2-}) analyses were collected in 100-mL polyethylene bottles at 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_3^- . Stable isotope ratios and D/H ratios of water were determined by the CO_2 equilibration method and the chromium-reduction method, respectively, followed by analysis by using a Thermo Electron Delta S mass spectrometer (USA). Hydrogen and oxygen isotope ratios were expressed using δD and $\delta^{18}\text{O}$, respectively, where $\delta = ((R_{\text{sample}}/R_{\text{standard}}) - 1)1000$ (‰) and R is the ratio of $^2\text{H}/^1\text{H}$ or $^{18}\text{O}/^{16}\text{O}$ in either the sample water (R_{sample}) or the Standard Mean Ocean Water (R_{standard}). We reported isotopic compositions in

the standard δ -notation (‰) as deviations from the Vienna Standard Mean Ocean Water standard (V-SMOW; Craig, 1961). The analytical error was ± 0.1 ‰ for $\delta^{18}\text{O}$ and ± 1.0 ‰ for δD . 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 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%.

RESULTS

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 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.

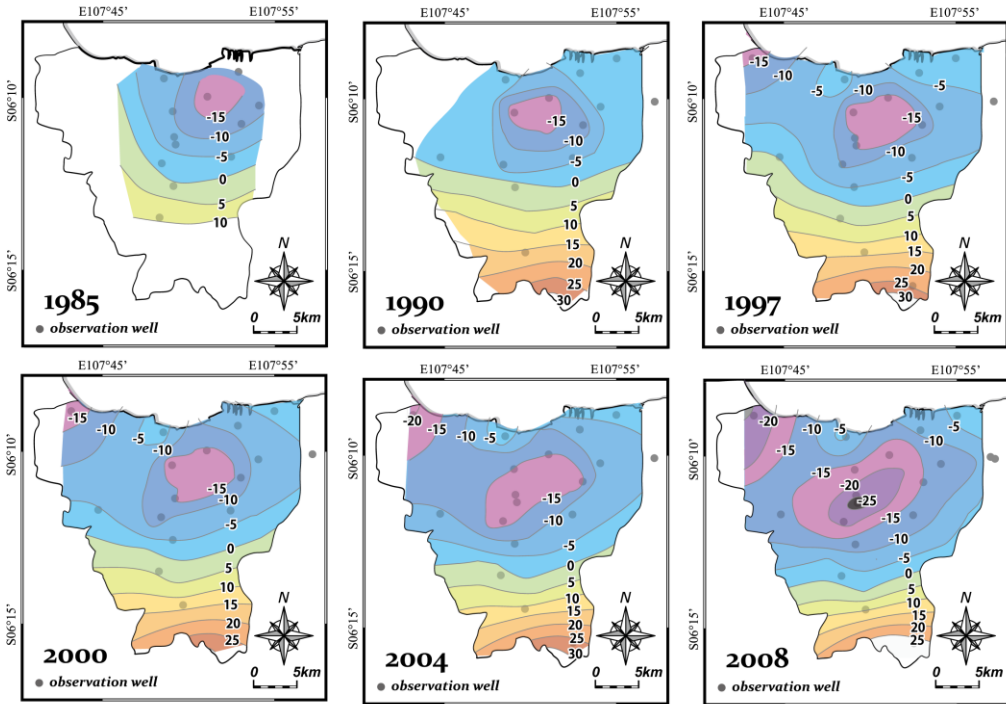


Figure 2 Historical change in the spatial distribution of groundwater potential. Unit of the potential is meters above sea level.

Major ions

Fig. 3 plots a Piper diagram, referring to the concentrations of hydrogeochemical components of groundwater samples which collected in this study. Figure 4 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. 3, samples collected from spring and river waters are of the Ca-HCO_3 -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_3 -type. However, shallow groundwater in the middle stream area possessed high NO_3^- concentrations, as shown in Fig. 4 (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_3 -type, as shown in Fig. 3 (Group I) and Fig. 4 (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. 3 (Group II) and Fig. 4. 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. 3). 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. 3),

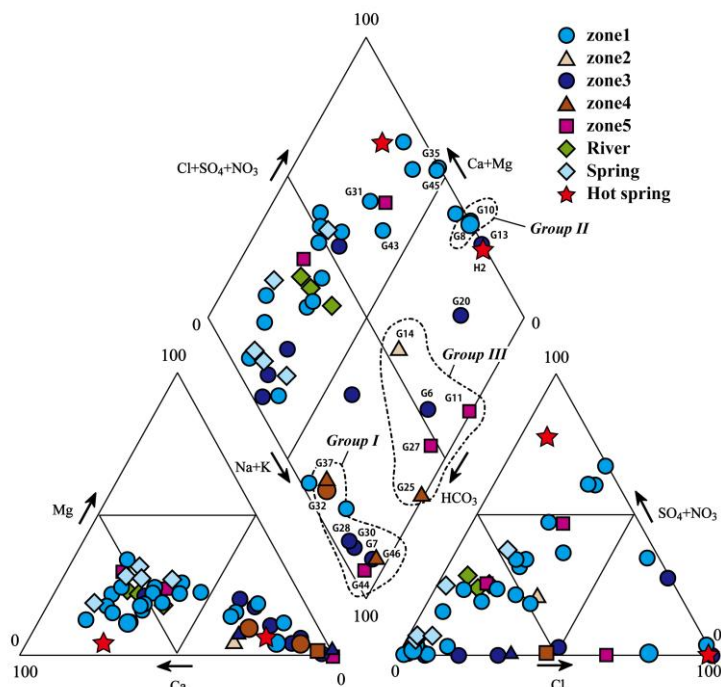


Figure 3 Piper diagram for the major ions.

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-HCO₃-type groundwaters mainly recharge the aquifer in the upstream area, and this water changes to the Na-HCO₃ 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).

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 Br⁻: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 5 plots the Br⁻:Cl⁻ ratios and corresponding chloride concentrations. Two trend lines are included for comparison. One is the theoretical Br⁻:Cl⁻ ratio of seawater based on a study by Drever (1988) (equivalent to the Br⁻: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).

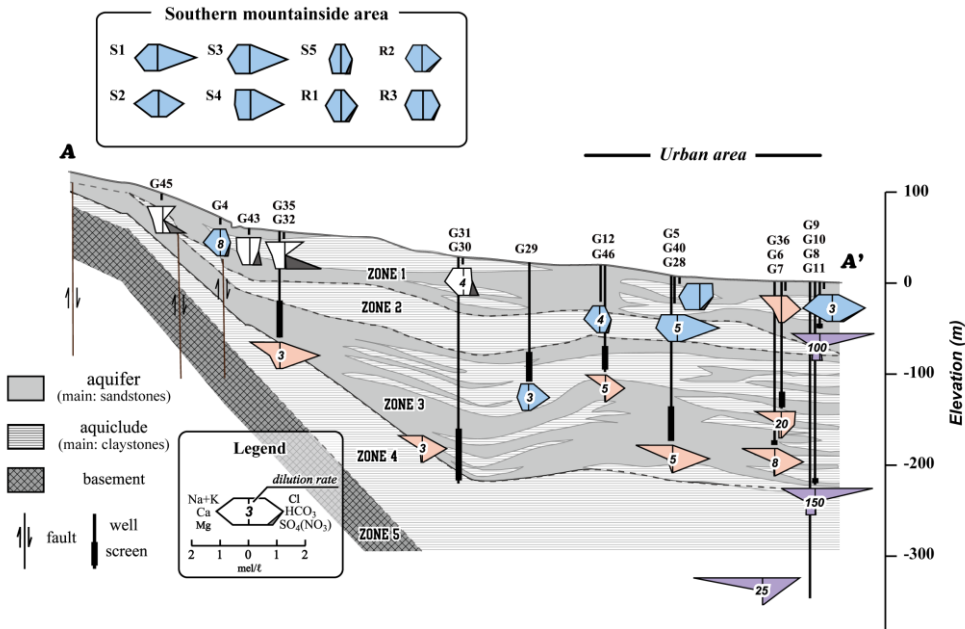


Figure 4 Vertical distribution of the stiff diagram along a cross sections shown in Fig. 1a.

This trend line represents the native groundwater affected by an anthropogenic chloride source. Also plotted in the figure, the 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- HCO_3^- to the Na-Cl type (Figs. 3 and 5), the seawater was the primary source of chloride.

Shallow groundwater samples were scattered along the anthropogenic line with high 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).

Stable isotopes

Figure 6 shows the relationship between $\delta^{18}\text{O}$ and δD . 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‰ $\delta^{18}\text{O}$ and -30 to -40‰ δD). 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).

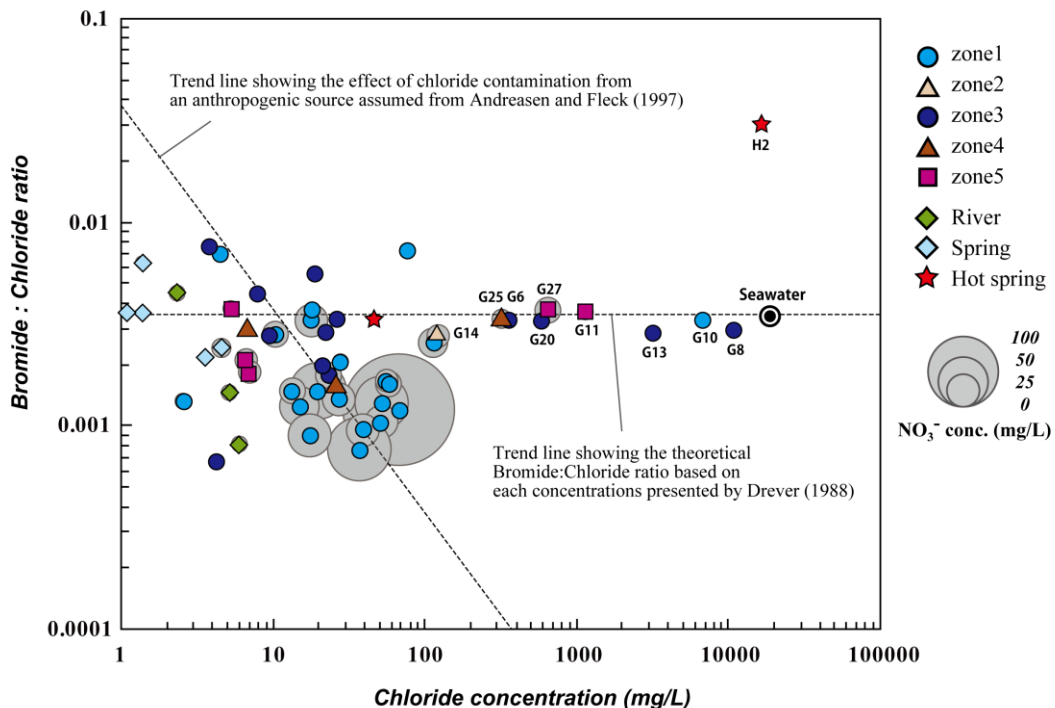


Figure 5 Relationship between the $Br^-:Cl^-$ ratios and the Cl^- and NO_3^- concentrations.

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 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 7 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. 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 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.

DISCUSSION

According to the results of the stable isotope analyses (Fig. 6), 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.

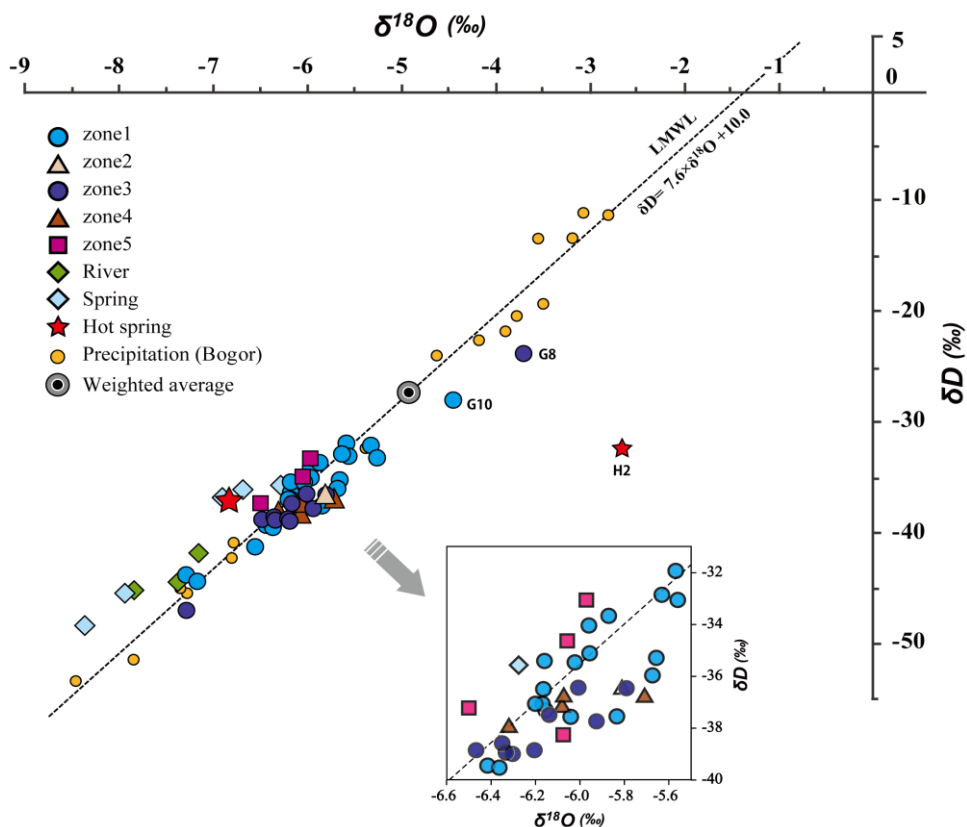


Figure 6 Relationship between $\delta^{18}\text{O}$ and δD in all water samples.

Although the river water and many shallow groundwater samples displayed Ca-HCO_3 -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 NO_3^- that the nitrate contamination in this area is caused by the application of fertilizers and by household effluents. According to these results, we can assume that most parts of the Cl^- and 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 NO_3^- concentrations (Fig. 5) demonstrated that the shallow groundwater deviated from the Br/Cl 's seawater mixing line with a relatively high NO_3^- concentration. It affected the nitrate contamination caused by fertilizers in dry fields, and both the Br^- and 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 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. However, since CFC-12 was detected in the shallow groundwater, it was recharged after the 1940s.

CONCLUSION

We studied the groundwater characteristics in the Jakarta area by hydrogeochemical techniques such as stable isotopes (δD and $\delta^{18}O$), water

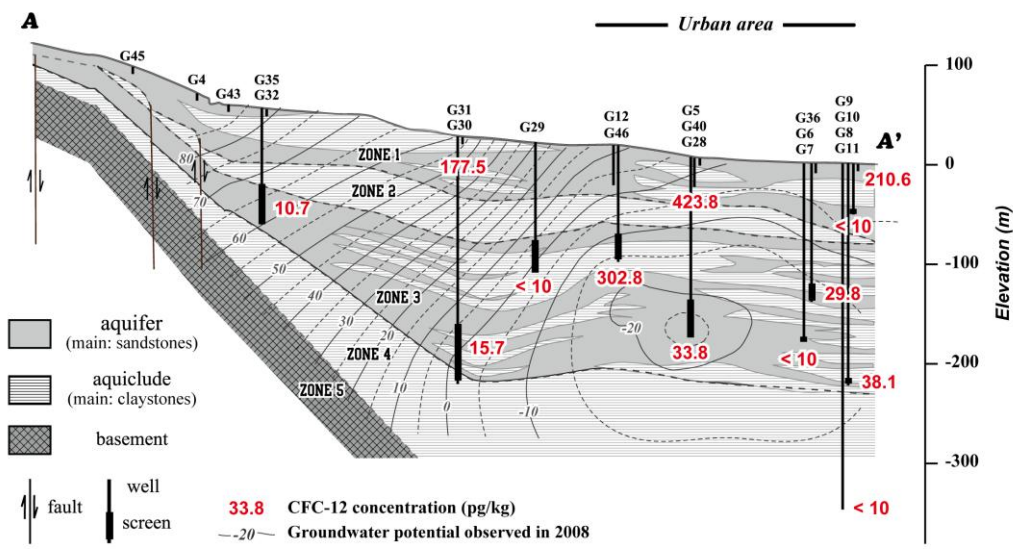


Figure 7 Vertical distribution of CFC-12 concentrations along a cross sections shown in Fig. 1a.

Deep groundwater had Na-HCO₃-type water chemistry, suggesting that the chemical evolution during the groundwater flow process changed from the original Ca-HCO₃-type shallow water chemistry, indicating that it had a relatively long residence time than the shallower groundwater. This result is consistent with the CFC-12 contents; 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 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. 7), 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.

chemistry by major ions, Br⁻:Cl⁻ ratio, and CFC analyses.

In the Jakarta area, although hydrogeochemical characteristics 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-HCO₃-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 stable N and O isotope content in NO₃⁻ (Umezawa *et al.*, 2008) and the Br⁻:Cl⁻ ratios in the groundwater samples. On the other hand, the deep groundwater samples had Na-HCO₃-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 urban area. This result was also supported by the $\text{Br}^-:\text{Cl}^-$ 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 CFC-12 analyses. Concentrations of 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 groundwater pumping, corresponding with rapid urbanization.

This study clearly reveals the groundwater characteristics of the Jakarta area by 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 aquifer.

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