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Groundwater Flow and Its Isotopic Evolution in Deep Aquifer of Jakarta Groundwater Basin

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Abstract— **Jakarta Groundwater Basin is the Quaternary basin and has three zones of the aquifer, where the deepest aquifer is confined aquifer (Aquifer III). Stable isotope ^{18}O and ^{2}H (Deuterium/D) in this research studied to see its evolution, particularly in this deep groundwater. Isotopic evolution is studied to determine the distribution patterns of distribution and factors that may control in the evolution process. The research method was sampling of groundwater from bore wells that tap water from the Aquifer III, and then tested for the content of stable isotope and its TDS. Analyses have been done by using primary data and some secondary data of stable isotope and TDS data. The results showed that the isotopic evolution occurs in the deep aquifer, influenced by the action of water on rock minerals along groundwater flow. In general, isotopic enrichment occurs in line with groundwater flow, where the content of the stable isotope is heavier toward the north. This isotope enrichment related to the isotopic fractionation processes, which may be occur because of the limestone that consists of the aquifer III and Tertiary limestone of Klapanunggal and Bojongmanik Formations. Increasing of TDS in deep groundwater is followed by increasing of the isotope δ^{18}O content, but it is unclear followed by an increasing of δD. Increasing of isotope content of groundwater in the aquifer is influenced by the groundwater flow velocity, where the rapid flow may occurred in the central part of the research area indicated by contours that curve northward, especially on the δ^{18}O distribution contour pattern.**

Keywords- deep groundwater, stable isotope, evolution

I. INTRODUCTION (HEADING 1)

Jakarta Groundwater Basin is formed by Quaternary deposit which is unconformable overlaid of Tertiary basement rocks. According to regional physiography, this basin is located in the Coastal Plain area of Jakarta, Bogor Anticlinorium and Quaternary Volcanoes physiographic units (Fig. 1) [1]. Groundwater is quite abundant available in this basin, but sometimes saline / brackish groundwater can be found. Brackish groundwater is also found even in the deep aquifer. Groundwater in the basin has a wide variety of chemical types and characteristics of the isotope. Chemical and isotopic characteristics are associated with genetic of groundwater. Isotopic evolution of deep groundwater in the basin can be studied to understand the genetic flow of groundwater.

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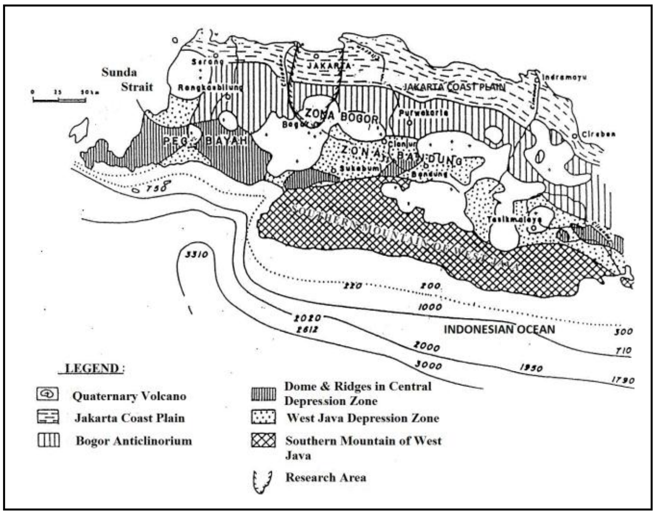

Figure 1. Jakarta Groundwater Basin in physiographic map of West Java [1].

High salinity of groundwater in Jakarta has been formed prior to human disturbance at a considerable distance from sea water (fossil water) [2]. For the deep aquifer, the water salinity was caused by a combination of connate Pleistocene and Holocene vertical infiltration of sea water. This opinion was supported by the analysis of hydrochemistry as well as ^{18}O and ^{2}H isotopes [3].

Studies on stable isotope in Jakarta Groundwater Basin have been done by several researchers, among others, using statistical methods to identify the presence of sea water intrusion [4]. Meanwhile, use of natural isotope data has also been used to determine the source of groundwater in Jakarta includes groundwater recharge and leakage even though not related to the existence of saline groundwater [5].

The author has been analyzed the stable isotopes which include oxygen-18 (^{18}O) and deuterium (^{2}H or D) to determine the isotopic composition of the groundwater. The isotope analysis would be expected to note the things that relate to the groundwater flow pattern and its isotopic evolution, particularly in the deep aquifer. Deep groundwater in this paper is the groundwater which is flow in deep, confined aquifer (Aquifer III) according to the division from Soekardi (1982) in [6].

II. METHOD

To determine the isotopic evolution of groundwater in the basin it needs to know the content of stable isotope ^{18}O and ^{2}H (deuterium) because these isotopes can be an indicator of groundwater resources [7]. TDS of groundwater chemistry data were also used to support the isotopic analysis of the evolution.

Secondary data were used to analyze groundwater flow and isotopic evolution include geological data (surface and subsurface), hydrogeological data (groundwater level) as well as isotope groundwater data. The primary data collected from an sample of deep groundwater drawn from Sunter bore well. Furthermore, groundwater samples were tested content of isotopes in the Hydrology Laboratory, National Atomic Energy Agency, in Jakarta. Compilation of secondary and primary data was conducted to determine the evolution of groundwater isotopes in the studied aquifer.

III. REGIONAL GEOLOGY

Jakarta Groundwater Basin is the Quaternary basin with a thickness of 250 m which deposited in a marine, delta and fluvial environments [8]. The upper part of Quaternary sediment consists of Upper Pleistocene alluvial fan deposits that were exposed in the southern part of the basin, while in the north it consists of Holocene marine and non marine sediments.

Jakarta Groundwater Basin stratigraphy made [9] based on the compilation of the Geological Map of Jakarta and Karawang Sheet. Rock constituent of groundwater aquifers are generally Quaternary sediments of young volcanoes debris, river and beach sediments, unconformable overlaid Tertiary rocks. Tertiary rock outcrops which limit Jakarta Groundwater Basin are located on the west - southwest namely Serpong, Genteng, Bojongmanik Formations and Mt. Dago basalt intrusion; in the south around Bogor found Klapanunggal Formation and in the southeastern region found Serpong, Jatiluhur and Klapanunggal Formations outcrops. Some of these rock formations composed of Tertiary carbonate rocks. For example, Bojongmanik Formation composed of sandstone, claystone with limestone intercalation. Klapanunggal Formations composed of limestone reefs.

Quaternary sediments boundary in Jakarta Groundwater Basin in three dimensions is not clear. Bore well data indicate Tertiary rocks at a depth of 69.50 m in Babakan. Based on geological maps and bore well data the bottom limit of Quaternary sediments seen as uneven but like horst and graben blocks of Bogor to Depok that deeper to the north - northeast [9].

The division of the aquifer system in Jakarta Groundwater Basin generally refers to Soekardi (1982) in [6] as follows.

1. Group of free aquifer (Aquifer I) at a depth of 0-40 m.
2. Group of upper confined aquifer (Aquifer II) at a depth of 40-140 m.
3. Group of lower confined aquifer (Aquifer III) at a depth of 140-250 m.

This aquifer division performed by the marine facies clay layers that separate the three aquifers system.

The groundwater level of Aquifer III in Jakarta in 1995 at Kosambi Coast - Pluit area suspected to be under the sea level, while in the Tanjung Priok - Marunda estimated between 0-5 m (above sea level/asl) [10]. The groundwater level at the central part of the research areas such as Tangerang approximately 10 m (asl), Gambir -10 to -20 m (asl), Pulogadung between 0 to -5 m (asl) and Bekasi between 10 to 15 m (asl). The southern part of the study area have groundwater level ranged between 20 to 50 m (asl), at Serpong between 30 to 35 m (asl), Pasarminggu between 25 to 30 m (asl) and Depok approximately 50 m (asl) (Fig. 2).

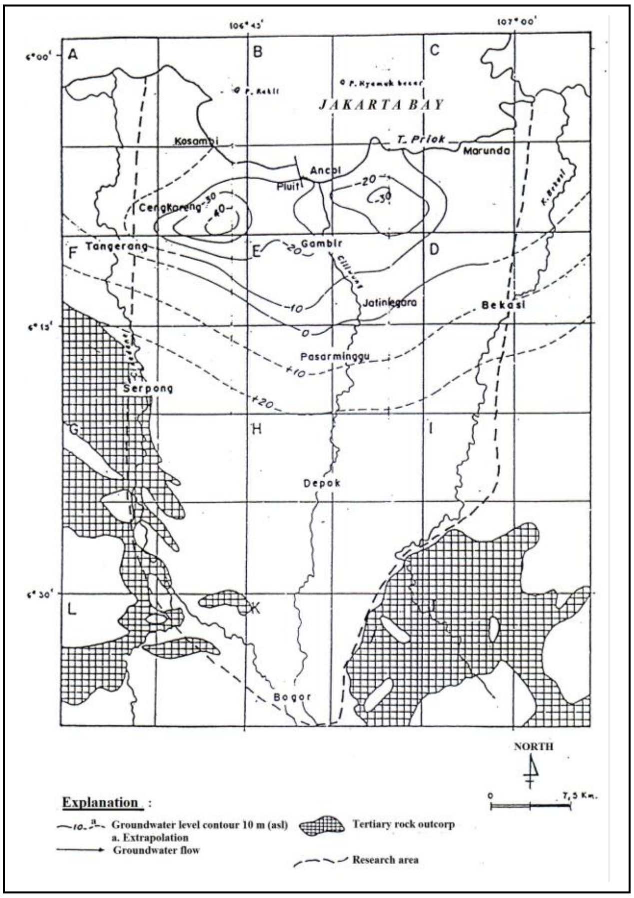

Figure 2. Groundwater table map of Aquifer III [10].

Deep groundwater flow in the Aquifer III of Jakarta Groundwater Basin generally runs from south to north, with some depression cone in the northern part of the basin. This means that the recharge of groundwater in the aquifer III comes from the south. By calculating the difference of the $\delta^{18}O$ and δD of groundwater contents to rain water, the recharge zone for the Aquifer III known to be in the area slopes Mt. Salak at an altitude of 977 to 1537 m in the south basin [11].

Based on the old well data from 1904 until 1922, it is known that the high saline groundwater is already exists in Jakarta area before groundwater drilling conducted on a large scale in 1960 [2]. The spread of saline / brackish groundwater in 1996 can be seen on the iso-chloride map [3]. The distribution of saline/brackish groundwater in Aquifer III limited in several places include Kapuk, Ancol and north Gambir areas by forming a circular pattern.

IV. BASIC THEORY

Isotopes are elements that have the same atomic but different mass numbers. An example is the three isotopes of hydrogen: ${}_1^1H$, ${}_1^2H$, ${}_1^3H$. Isotope abundance measured by the standard deviation ratio according to Fritz and Fontes (1980) in [15] as follows.

$$\delta = \frac{(Rsample - Rstandard)}{Rstandard} \; x\, 1000$$

δ = standard deviation (‰)
R = isotopic ratio, example: ${}^{18}O/{}^{16}O$

This study used ${}^{18}O$ and D (deuterium) isotopes. These isotopes are often used in the study of chemical processes. ${}^{18}O$ and D are non-radioactive, stable isotopes and mainly serve as an indicator of groundwater resources [7].

Relationship between $\delta^{18}O$ and δD precipitation water follows the meteoric water line equation. From the results of a global investigation [12] it was obtained an equation for meteoric water line as $\delta D = 8\, \delta^{18}O + 10$ ‰.

Isotopic fractionation process in precipitation is a process that depends on the temperature [13]. Thus, if there are changes in seasonal temperature at somewhere it will look their stable isotope composition variation of precipitation where the light value occurs in the cold months. For the same reasons precipitation will also has a light isotope content in the polar regions / high latitudes, in places further away from the sea as well as in places with higher elevation.

Source of groundwater is meteoric water. Groundwater with the isotope composition at meteoric water line comes from the atmosphere and is not affected by other isotopic process. Deviation from the meteoric water line shows the isotopic fractionation processes, which can occur due to the exchange with rock minerals (IAEA 1983) in [14], [15]. Thus, the deviation can be examined to determine the processes that occur during the evolution of groundwater in an area.

The $\delta^{18}O$ and δD values has been used to determine the genesis of saline groundwater from oil fields in Illinois, Michigan, Alberta and Gulf Coast [14]. The results of this study indicate that the genesis of saline groundwater is not necessarily connate water but can be derived from local recharge which subsequently evolved. This conclusion is drawn on the basis of the following facts as follows.

1. The relationship between TDS with $\delta^{18}O$ and δD.

   Increasing TDS followed by increasing of heavier isotope content of groundwater, especially on the $\delta^{18}O$. Extrapolation of data $\delta^{18}O$ towards groundwater with low salinity will be in touch with local meteoric water isotope composition and not to the value of the seawater isotope. This indicates that the saline groundwater is not connate water. From this fact, it was concluded that the original groundwater which occurred since the time of marine sedimentation has been missed for compaction and then flushing occurs.

2. The relationship between $\delta^{18}O$ and δD.

   Plotting between these two values indicates that the groundwater with the lowest salinity meteoric comes near to water line, whereas groundwater with higher salinity indicates $\delta^{18}O$ enrichment. The relationship between $\delta^{18}O$ against δD showed that saline groundwater studied form the regression line which is not cut the point of sea water, which means groundwater was not associated with sea water. Groundwater studied showed great $\delta^{18}O$ enrichment, while enrichment δD were relative small.

Change in the $\delta^{18}O$ groundwater composition mainly caused by the isotope exchange that occurs between limestone and groundwater. Clayton (1959) laboratory experiments showed that the isotope exchange between water with calcite much faster than silicate [14]. Thus it can be expected that the exchange of oxygen between water against the limestone is a dominant factor in saline groundwater.

Limestone that influence on the isotope value in rocks diagenetic environment has also been investigated. Petrographic and stable isotope geochemistry in the limestone formations of El Abra in Mexico showed its diagenetic environment. The $\delta^{18}O$ values range from -12.41 to -4.02 ‰ in these rocks indicate meteoric diagenesis [16].

Changes δD of groundwater may be caused by isotope exchange with hydrogen bearing minerals such as gypsum and clay minerals or hydrocarbons. However, fundamental data concerning the exchange between δD and the three materials haven’t been established yet, so it is difficult to determine the cause of the δD groundwater change. In addition, the variation of the value in one area is not large, so it is concluded that this exchange is not significant [14].

In rural area, isotope exchange between rainwater and humidity can slightly shift the values of deuterium excess. In high relief, the interaction between rainfall and orographic clouds can shift the values of deuterium excess significantly. The slope lower of LMWL could be due to the high value of the deuterium excess of a higher place and associated with orographic precipitation than evaporation during the rain fall. The results obtained showed that local orographic features can significantly alter the isotopic composition of precipitation [17].

Other researchers give the possibility of changes in isotope for membrane filtration. Phillips and Bentley (1987) in [18] considered that membrane filtration (reverse osmosis) can enrich $\delta^{18}O$ and δD, while Graf *et al*, 1965 in [14] explained that this process is associated with increasing of δD.

V. RESULT AND DISCUSSION

A. Isotope Data

The primary data representing deep groundwater of Aquifer III took from bore well at Sunter in 1997 [19]. This sample has been taken in the well which constructed with a telescope system so the groundwater in each aquifer zones did not be mixed. In addition to the primary data this study was also used secondary data [10], [4]. These data are presented in Table 1 below.

TABLE I. DEEP GROUNDWATER (AQUIFER III) ISOTOPE DATA OF JAKARTA GROUNDWATER BASIN.TABLE TYPE STYLES

No.	$\delta^{18}O$ (‰)	δD (‰)	TDS (eq/l)	Source
1	-5.55	-31.5	0.113	[19]
2	-5.85	-35.17	0.037	[10]
3	-5,73	-30,52	0.020	
4	-5.7	-35.2	No data	[4]
5	-5.81	-35.6		
6	-6.22	-34.3		
7	-5.9	-32.6		
8	-5.91	-34.4		
9	-6.19	-35.9		
10	-6.19	-37.3		
11	-5.5	-32.3		
12	-6.23	-37		
13	-6.69	-33.7		
14	-4.91	-31.5		
15	-6.18	-37.5		
16	-6.16	-37.9		
17	-6.59	-38		
18	-6	-35.9		
19	-6.23	-33.3		
20	-5.83	-33.5		
21	-6.14	-38.5		
22	-6.02	-36.7		
23	-6.21	-35		
24	-6.18	-37.7		
25	-6.57	-38.5		

Sea water : $\delta^{18}O$ = -1.23‰; δD = -6.45‰ [4]

B. Relation of $\delta^{18}O$ and δD to TDS

The increasing of the isotope content can be associated with salinity increasing (TDS) of groundwater [14]. Basically, the salinity is same as TDS of groundwater [20]. Relations between TDS against $\delta^{18}O$ and δD in deep groundwater (Aquifer III) form a line with gradient 2.55 (Fig. 3). The gradient of this line is also included in the range of groundwater gradient as in [14] which means that also showed a good relationship between increasing of TDS with increasing of $\delta^{18}O$. This is also supported by a correlation of 0.83. Bad correlation between TDS against δD (0.14) showed that increasing of δD is not related with the increasing of TDS.

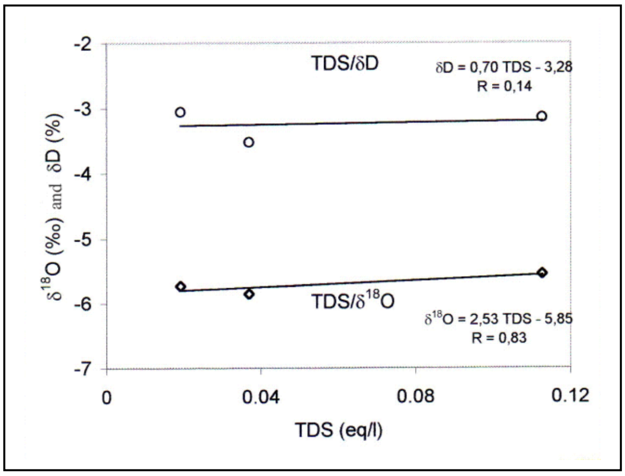

Figure 3. Relation of $\delta^{18}O$ and δD to TDS of deep groundwater in Jakarta Groundwater Basin.

C. Relation between $\delta^{18}O$ and δD

Local meteoric water line (LMWL) for the Jakarta-Bogor area was created by the National Atomic Energy Agency in [5] that δD = 7.98 $\delta^{18}O$ + 14.14 (Fig.4). The regression line of groundwater isotopes in Aquifer III runs far from LMWL. The regression line in this aquifer has equation as δD = 3.94 $\delta^{18}O$ – 11.44. With gradient 3.94 then extrapolating the regression line for Aquifer III will not intersect with the point of sea water, which means that the saline groundwater in this aquifer is not connate water nor derived from mixing with sea water.

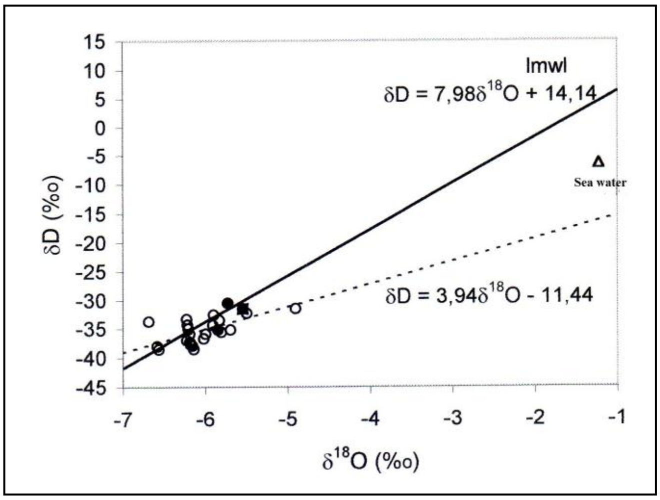

Figure 4. Relation between $\delta^{18}O$ and δD in deep groundwater (Aquifer III). Notes: ○ [17]; ● [10]; ■ primary data [18]

Increasing of $\delta^{18}O$ relatively to local meteoric line can be caused by carbonate minerals [14], [21]. Calcareous rocks are thought to cause an increasing of groundwater $\delta^{18}O$ in the study area include limestone. From the research [22] known that in some places limestone consists of the Aquifer III, and may result the increasing of $\delta^{18}O$ groundwater. In addition, the limestone also presents in the Tertiary rocks of Klapanunggal and Bojongmanik Formations. Thus there would be interpreted that deep groundwater recharge water also through the Tertiary limestone.

The gentle sloping gradient of relationship line between $\delta^{18}O$ and δD of Aquifer III shows that there was increasing of $\delta^{18}O$ groundwater without significant increasing of δD. This indicates that the groundwater in the aquifer comes from meteoric water with isotopic exchange by calcite [14].

In contrast to the evolution of $\delta^{18}O$ then evolution of δD is less obvious [18]. This is confirmed by the statement that δD is not affected by the reaction of the aquifer material at low temperature [19]. Therefore, the content of δD of groundwater studied is not clearly indicates an increasing to LMWL (Fig. 4).

In the research area, δD fractionation may occur due to isotopic exchange between water with H_2S which can be derived from the reduction of sulfate or gypsum. The presence of gypsum known from XRD analysis of rocks from Sunter and Tongkol bore wells [23].

Membrane filtration process in the micro-pore clay system can affect the increasing of δD in the study area [24], [14]. This increasing may occur considering the number of clay as a medium for ion filtration process. However, membrane filtration is easier occur in a deep aquifer because this process requires high pressure, which is equivalent to `depth of 1.6 km sediment [24]. Filtration membrane does not really matter in sedimentary rocks which are less than 1 km depth [20].

D. Distribution of Groundwater Isotopic Content

$\delta^{18}O$ contour of groundwater in the Aquifer III form an patterns that juts into the north at central area (Fig. 5) with anomalies in the form of centralization in the northeastern of research area. The amount of $\delta^{18}O$ content of this aquifer is -6.69 ‰ to -4.91 ‰.

The content of the studied groundwater isotopes were generally more and more heavy from south to north. Water recharge comes from the south with light $\delta^{18}O$ characteristics. Furthermore $\delta^{18}O$ content of groundwater becomes heavier because of the evolution that occurs due to the reaction of groundwater against limestone.

The increasing of $\delta^{18}O$ groundwater content is affected by the flow velocity. Rapid groundwater flow may occurred in the central part of the research area marked by relatively protrudes contour to the north. In the northeastern part of the study area occurred circle contour containing heavy $\delta^{18}O$ (-4.91‰). It is believed to be related to the presence of limestone known in bore wells nearby [22].

Increasing of $\delta^{18}O$ and δD contents from south to north were conformable with groundwater flow. Contour patterns in some places on the δD distribution map (Fig. 6) seemed more concave to the south. This shape differences may be caused by groundwater flow speed difference where in the southward trending contour pattern, the area have relatively slow groundwater flow. Rapid groundwater flow is expected to occur in several places marked with contour that juts into the north. This is particularly evident on the $\delta^{18}O$ distribution contour map, but at a δD distribution map there are some variations. Thus, the evolution δD is less clear pattern, and this evolution is usually not affected by the reaction of the aquifer material at low temperature [20] as happened in the studied basin.

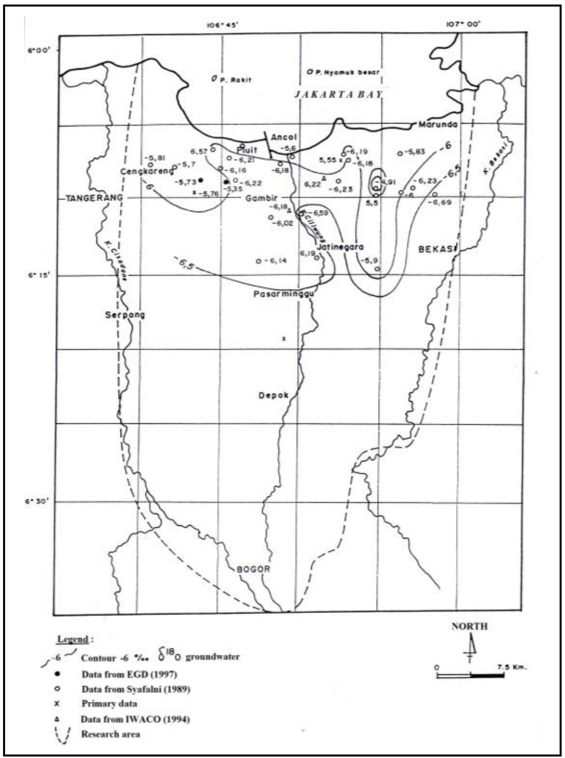

Figure 5. Contour map of $\delta^{18}O$ of deep groundwater in Aquifer III.

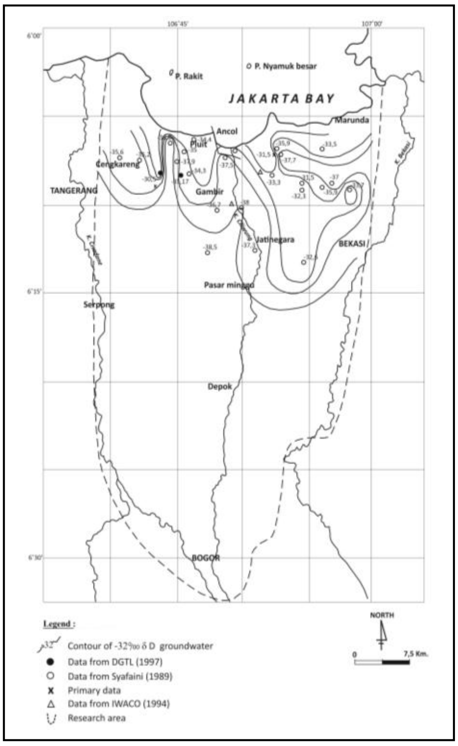

Figure 6. Contour map of δD of deep groundwater in Aquifer III.

VI. CONCLUSION

Evolution of ^{18}O and ^{2}H (D) stable isotopes has been studied in deep groundwater of Jakarta Groundwater Basin. In this basin, deep groundwater flow generally runs from south to north, with some concentration in the northern part of the basin. Isotopic evolution influenced by the reaction of water on rock minerals along groundwater flow. Isotopic enrichment occurs in harmony with groundwater flow, where the stable isotope content is generally heavier towards the north. Stable isotope enrichment is in association with isotopic fractionation processes. The fractionation process may occur because of the limestone that consist of aquifer III and Tertiary limestone of Klapanunggal and Bojongmanik Formations. The increasing of TDS of deep groundwater is followed by the increasing of $\delta^{18}O$ isotopes content, but it is unclear followed by the increasing of δD. Increasing of the isotope content of groundwater in the aquifer is influenced by the speed of groundwater flow. Rapid groundwater flow may occur in the central part of the research area marked by contours that juts into the north. Pattern indented contour is more clearly seen in the $\delta^{18}O$ distribution contour map, while this pattern on δD distribution maps is more varied.

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