GROUNDWATER FLOW SYSTEM OF BANDUNG BASIN BASED ON HYDRAULIC HEAD, SUBSURFACE TEMPERATURE, AND STABLE ISOTOPES

Robert M. Delinom and Ade Suriadarma

ABSTRACT To recognize the groundwater flow system in the Bandung Basin, two main methods of regional groundwater flow delineation were employed: hydraulic heads and tracers. Two different environmental tracers, i.e. subsurface temperature and stable isotope were applied. The measured temperatures and stable isotope compositions from 19 observation wells lead to the recognition of three types of flow systems within the Bandung Basin i.e., shallow, intermediate and deep groundwater flow system. The recharge area is located in the hills and upland which form the periphery of the plain. The summit area of the southern mountainous complex might have represented the highest recharge area. No indication was found for water being recharged at higher elevation in the northern part of the basin which means the recharged water in the Mount Tangkuban Parahu area did not reach the Bandung Plain. This study clearly demonstrates the usefulness of these environmental tracers and hydraulic head measurement in identification of the groundwater flow system of a certain area.

Keywords: Bandung Basin, groundwater flow system, subsurface temperature, environmental tracers, stable isotope, hydraulic head.

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ABSTRAK *Untuk mengetahui sistem pergerakan airatanah di Cekungan Bandung, pengukuran muka airatanah dan analisis pelacakan dilakukan. Dua pelacak lingkungan yang berbeda, yaitu suhu bawah permukaan dan isotop stabil digunakan. Hasil pengukuran suhu dan komposisi isotop stabil telah mengenali adanya tiga tipe pergerakan airtanah di Cekungan Bandung, yaitu sistem dangkal, pertengahan, dan dalam. Daerah imbuhan terletak di daerah perbukitan dan tinggian yang mengelilingi cekungan. Puncak pegunungan di sebelah Selatan merupakan daerah imbuhan dengan elevasi tertinggi. Tak ada indikasi bahwa air yang terimbuh dari Gn. Tangkuban Parahu sampai ke Dataran Bandung. Penelitian ini secara jelas memperlihatkan kegunaan dari analisis pelacak lingkungan dan pengukuran muka airtanah dalam mengidentifikasi sistem pergerakan airtanah di suatu daerah.*

Kata kunci : *Cekungan Bandung, sistem pergerakan airtanah, suhu bawah permukaan, pelacak lingkungan, isotop stabil, muka airtanah.*

INTRODUCTION

In the Bandung Basin (Fig.1), whereas the City of Bandung is located, human activities have influenced the groundwater condition of the area. So far, not many groundwater studies have been carried out in this area. Therefore, the chance for detecting new groundwater phenomena is quite plausible. It is one of the most developed basins in Indonesia as Bandung City is located within the basin. It covers an area of around 2,670 km2 which in 1997 had a population of around six millions.

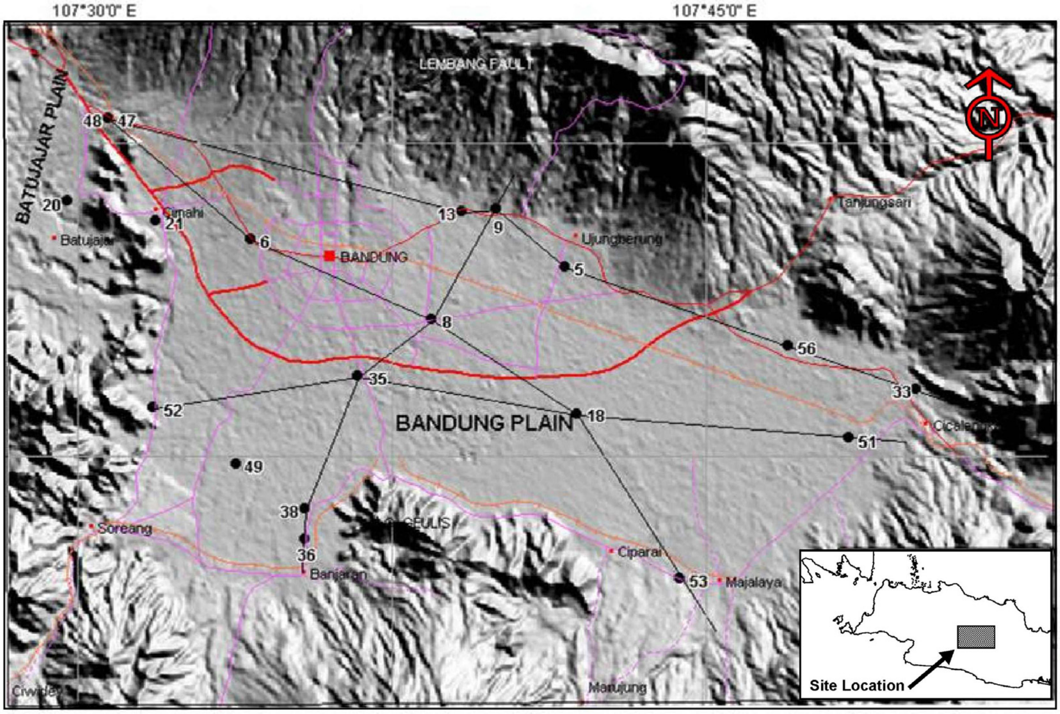


Fig. 1. Bandung Basin Site Area and Monitoring Wells Locations.

This basin is located in the West Java Province, Indonesia, with an elevation ranges between 660 and 2,750 m above sea level. It is surrounded by the Burangrang-Tangkubanperahu Mountain Complex to the North and the Wayang-Windu-Mandalawangi Mountain Complex to the South. The basin was constructed by the unconsolidated and undifferentiated Quaternary volcanic products and lake deposits dried up ca. 16-20 ka ago (Dam et al, 1996).

Some normal faults mark its eastern and western, northern and southern borders (Silitonga, 1972; Koesoemadinata, R.P. and Hartono, 1981; Alzwar et al, 1992). The Bandung Plain is situated at an elevation of about 660 - 675 m asl. The Bandung Plain has a more or less elliptical shape, with axes of approximately 35 km and 15 km in east-west and north-south direction respectively.

Two fundamental causes for groundwater's active role in nature are its ability to interact with the ambient environment and the systematized spatial distribution of its flow (Tóth, 1999). Under natural condition, the groundwater flow regime is controlled by the driving force, the recharge rate, and the groundwater flow region resulting in a relationship between the local groundwater flow to the regional groundwater flow (Shimada et al., 1993). It is often disturbed by human industrial activities such as pumpage, irrigation, and drainage. The driving force of groundwater flow is gravitation, and can be thought as a potential flow through porous media under laminar flow condition. Three methods are typically used to delineate groundwater flow in a regional system: measuring heads, numerical simulation, and tracers. In this study, two different environmental tracers, i.e. groundwater temperature and stable isotopes, combined with hydraulic head condition, have been utilized in order to study the groundwater flow system in Bandung Basin area.

The purpose of this study is to define the regional groundwater flow system of the Bandung basin using the distribution of subsurface temperature and hydraulic heads and the stable isotope content of the samples. The subsurface temperature and hydraulic head were measured in observation wells which were extensively distributed throughout the basinal area and the samples were collected from a specified depth in each of the monitoring wells. It is expected that this study will demonstrate the potential of the use of subsurface temperature and isotopes in tracing regional groundwater flow.

Hydraulic Head and Groundwater Heat Flow

Gravity is the dominant driving force for groundwater to flow. Water flows from high elevation to low elevation and from high pressure to low pressure, and gradients in potential energy (hydraulic head) drives groundwater flow. From the hydraulic head, the information about the where and how fast the ground water is flowing and the amount of water involved can be deducted. By definition, hydraulic head is the sum of pressure head and elevation head or the difference between the land surface elevation and depth to water in certain area (Freeze and Cherry, 1979). In this paper the second definition has been applied in the analysis of groundwater flow.

There are some studies (Cartwright, 1970; Sakura, 1978; Sakura, 1993; and Dim et al, 2000), where temperature data were used to understand the groundwater flow system in a basin. The basic theory is that heat can be transported in a porous medium by way of three processes: conduction, convection, and radiation. The most important groundwater movement process in an aquifer is the convection process, as the convective alteration can cause the groundwater geothermal to increase with increasing depth in the recharge area and decrease in the discharge area (Domenico and Palciauskas, 1973). If it is assumed that the groundwater temperature in the well is equal to the surrounding subsurface temperature, we can get a one-dimensional view of the groundwater distribution by profiling the water temperature in the well. This is most important point for water temperature analysis when compared to other physically based measurements or tracer techniques.

Subsurface temperature distribution is affected by heat conduction and heat advection due to groundwater flow. There are some hydrological studies in which the groundwater flow system is estimated from subsurface temperature distribution in basins or plains (Uchida et al., 1999; and Sakura, 1993). Based on the results of these studies, it could be concluded that the subsurface temperature in the recharge area is much lower than in the discharge area at the same elevation. Temperature profiles measured in wells show a decreasing temperature gradient with depth in the recharge area and increasing temperature gradient with depth in the discharge area (Taniguchi et al., 1999).

Stable Isotopes

An intimate knowledge of the source areas is necessary to evaluate and protect groundwater resources. While chemical and isotope analysis have been extensively used for groundwater tracing, Tyler et al (2000) emphasized the maximum benefit derived from any investigation using stable isotope data will be obtained when integrated with water level, chemical, and other relevant data. Such a synthesis will produce more reliable conceptual models of the groundwater system of both local and regional scale.

It has been recognized that the use of environmental isotopes contribute to such investigation, complementing geochemistry, and physical hydrogeology. The stable isotopic composition of water is modified by meteoric processes, for this reason the recharge waters in a specific environment will have a characteristic isotopic signature that serves as a natural tracer for the provenance of groundwater. The radioisotope decay provides us with a measure of circulation time, and the groundwater renew ability, while stable isotopes provide much more information than only indications of groundwater provenance and age (Clark and Fritz. 1998). It has been generally known that natural water contains, in addition to hydrogen (H) of mass 1 (^1H) and oxygen of mass 16 (^{16}O), small amounts of the stable isotope of hydrogen (^2H, deuterium D), the stable isotopes of oxygen (^{17}O and ^{18}O), and the radioisotope tritium (^3H, T). The unstable oxygen isotopes (^{14}O, ^{15}O, and ^{19}O) have such short half-lives that they are of no importance (Matthess and Harvey, 1982). As a stable isotope does not spontaneously disintegrate by any know mode of decay, it can be used as a groundwater tracer. In this case, the abundance of D and ^{18}O was used in tracing of groundwater flow in the Bandung Basin.

STUDY AREA GEOLOGICAL SETTING

Generally, the morphology of the island of Java is dominated by a belt of Quaternary strato-volcanoes, with a number of summits rising above 3,000 m. This volcanic belts rest upon a basement of shallow marine strata of Tertiary age, interbedded with volcanogenic sediments. According to Engelen and Kloosterman (1996), structurally, three E-W trending zones can be distinguished on Java:

1. a northern zone comprising low hilly areas of folded Tertiary strata, and Quaternary coastal lowlands bordering the Java Sea;
2. A central structurally depressed but topographically high zone, filled with Quaternary volcanics. The majority of the great volcanic cones lie within this structural zone;
3. A southern zone of uplifted and tilted plateaus of Tertiary strata dissected and rimmed by narrow patchy coastal lowlands.

The Bandung Basin belongs to the second structural region and is part of a chain of depressions in West Java, which is called the Bandung Zone (Bemmelen, 1949). The Bandung Zone can be regarded as a graben-like longitudinal belt of intramontane depressions, extending through the center of West Java. To the north, it is bordered by the Bogor Zone, an anticlinal ridge structure composed of Neogene strata and volcanic intrusions. To the south the Bandung Zone is bordered by northern slope of the Southern Mountains. Here, the transition is marked by a series of Quaternary volcanoes including the G. Patuha, G. Tilu, G. Malabar, and G. Mandalawangi (Figure. 2).

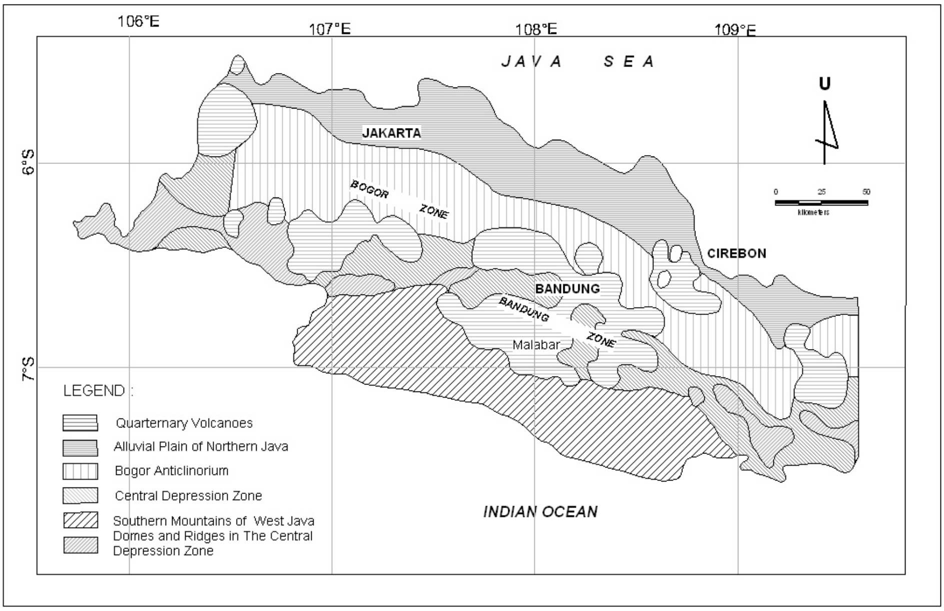


Fig. 2. Tectono-physiografic map of West Java (after Bemmelen, 1949).

Geologically, the development of the Sunda Volcano into G. Tangkuban Parahu has been an important factor in the history of the Bandung Basin. Bemmelen (1934, 1949) recognized three eruption phases of Tangkuban Parahu after the first collapse, separated by two other phases of collapse and faulting along the Lembang Fault.

Generally, the subsurface of the Bandung Basin comprises horizontal Quaternary deposits consisting of floodplain deposits, channel deposits (as lenses), lake deposits, lake fan deposits, Bandung (clastic) fan deposits, and alluvial fan deposits representing the oldest products. Therefore, the aquifer mostly comprises deposits of channels and lenses.

Some shallow aquifers can be found in the floodplain deposits. Deeper aquifers located in the foot slope of the hilly area which encircle the Bandung Basin. In the center of the basin, the deeper aquifer should be very scarce with very low transmissivity. Detail of the Geological Map of Bandung is shown on Figure 3 and is modified after Dam (1992).

During the last 20 years an important number of studies, concerning the geology and geomorphology of the Bandung Basin and its surrounding area, have been carried out, following the early work by Bemmelen (1934, 1949).

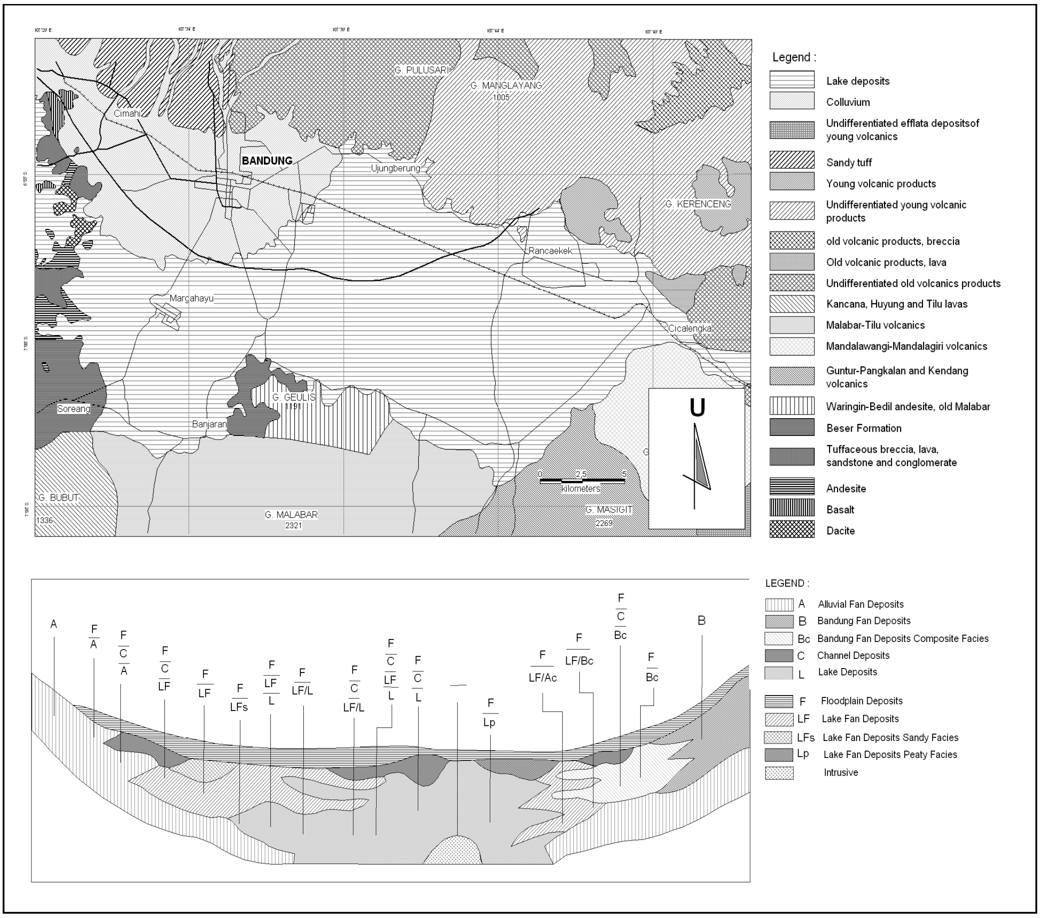


Fig. 3. Bandung Basin Geological Map and its Cross-section (Dam, 1992).

METHODOLOGY

In this study, the thermal profiles and hydraulic heads in 19 monitoring wells of various depths (20 – 200m) were measured. Measurements were carried out from June to July 2002. A digital thermistor thermometer of 0.01°C precision which was attached to a 300 m long cable measured the subsurface temperature at 2 m intervals from the static water level to the bottom of the hole. The wells were drilled exclusively to monitor groundwater level and subsidence caused by groundwater withdrawal. They are therefore ideal for thermal studies as they had attained a steady-state thermal condition as the time elapsed since their construction was quite a long period. The well's water levels were measured in order to get the hydraulic head condition distribution within the whole basin. The hydraulic head value, was then plotted in a cross-section to derive the direction of the groundwater flow in the Bandung Basin

Water samples for stable isotope analysis were collected from the screen openings of the observation wells. Water samples were collected in 100 mL polyethylene bottles that were well capped to prevent evaporation. Oxygen 18 and deuterium data were obtained by CO_2 equilibration at a constant temperature of 25°C and zinc reduction at 420°C, respectively, before measurements by mass spectroscopy on a Finnigan Mat 251 delta S apparatus. Results were expressed in ‰ deviation from the Vienna Standard Mean Ocean Water (VSMOW) and will be referred to as $\delta^{18}O$ and δD. Duplicate sample analysis showed measurement accuracy of ± 0.1‰ and ± 1‰ for both $\delta^{18}O$ and δD, respectively.

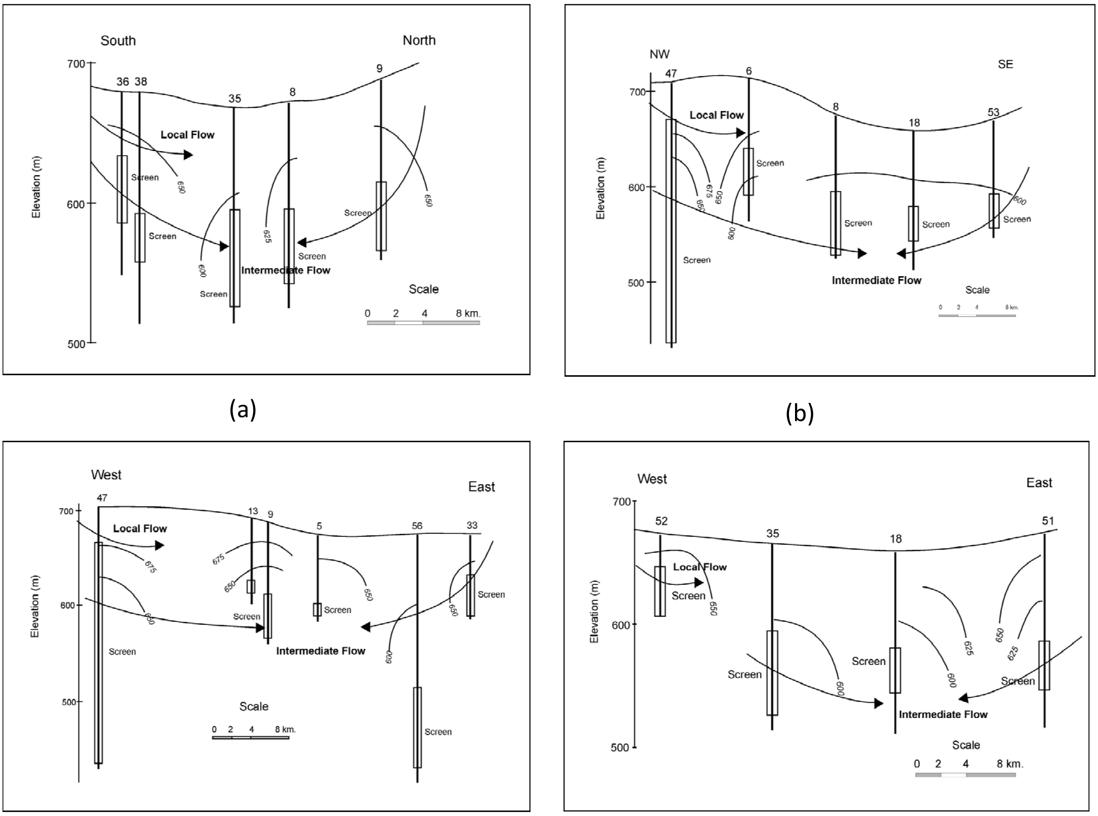
RESULTS

None of the visited monitoring wells were found to be in a good condition. All wells have already been silting up either by sediment material in the water or by debris from the well's wall. The worst conditions were found in well number 48 and 49. In well 48, the total depth (TD) should be 65 m but during the field visit, the measured depth was only 23 m. While in well 49, TD should be 130 m, but the measured depth reached only 36 m. The deepest measurement was executed in well 56; the measurement reached a depth of 200 m out of a drilled TD of 270 m. For wells where measurement could not reach the screen area, the water sample(s) for isotope analysis was (were) collected from the greatest possible depth which could be reached (well 49 and 52) or from production wells in the near surroundings (well 47, 05, and 09).

Distribution of hydraulic head

The hydraulic head of each monitoring well was measured during the field work. In order to get an overview of the hydraulic condition, two dimension models were constructed along four cross sections (I, II, III, and IV), see Figure 1. Figure 4.a show the vertical 2-D distribution of hydraulic head along cross section (I) which could represent the hydraulic head of the South – North segment of the basin. It shows that the hydraulic head is high in the area near the foot-slope of the hills and low in the lowland area. The same phenomenon was observed in cross-sections II, III, and IV (Figure 4b, 4c, and 4d). All areas with high hydraulic heads are located in areas with relatively high elevation and gradually decrease from highland to lowland. Especially in the lowland which is located in the central part of the plain (wells 35 and 8), hydraulic heads are surprisingly very low.

To the east (well no. 18), the condition is better as the hydraulic head is still high as this area is relatively untouched by human activity. To the south-east (well no. 53), in the Majalaya area, the drop of the hydraulic head has already happened, as the hydraulic head in this area is lower than the hydraulic head in well no.18, although its elevation is higher (Figure 4.b). These distributions shows that the groundwater water flow in this area exists, being recharged in the upland and the foot-slope of the hills and discharged at the lowland in the central part of the Bandung Basin.



(a)

(b)

(c)

(d)

Fig.4. 2D Vertical Distribution of Hydraulic Head in the Bandung Basin.

Distribution of subsurface temperature

On Figure 5, Taniguchi et al 1999, depicts a two-dimensional groundwater temperature distribution scheme under the condition of regional groundwater flow showing a concave shape in the recharge area where the downward water flux dominates and a convex shape in the discharge area where the upward flow of the groundwater dominates. It also shows the isothermal lines in the two-dimensional groundwater flow system. The temperature profiles and thermal regimes in the vertical two-dimensional cross-section are also shown in this figure under both the effects of surface warming and regional groundwater flow.

In order to illustrate the convective and conductive heat flow of the Bandung Basin, 4 cross sections, which were the same as those depicting hydraulic head, of two dimensional (2-D) subsurface temperatures were constructed. Cross section (I), Figure 6a, shows that subsurface temperature in the southern part of the area (wells nos. 36 and 38) is more complicated as the surface temperature has already influenced the water in the well to a depth greater than it should be. Nevertheless, the remnant 2-D subsurface temperature shows that the discharge area occurred in the central part of the basin. Cross section II, a NW – SE section, Figure 6b, shows the ideal heat flow configuration as high temperature coincides with the discharge area and low temperature corresponds with recharge area.

In general, all cross sections show that subsurface temperature in this area is low in the upland and the foot-slope of the hills surrounding the plain, and high in the lowland located in the central part of the plain. Except for the extreme high temperature in wells nos. 51, 53, and 56 which reflect the influence of intrusive rocks of the G. Manglayang volcanic cone (?) complex, the G. Bukitjarian volcanic neck, and the G. Geulis volcanic complex. In this case, although the site is located at a higher altitude than the central part of the plain, the temperature is also high. But compared to the neighboring area s, the temperature analysis can still be considered reliable for the prediction of the direction of groundwater flow in this area.

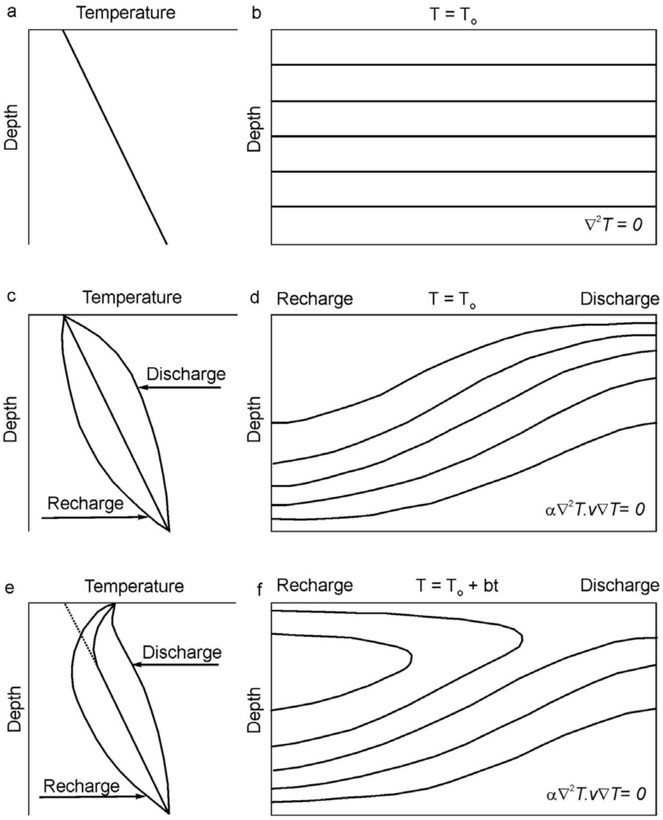
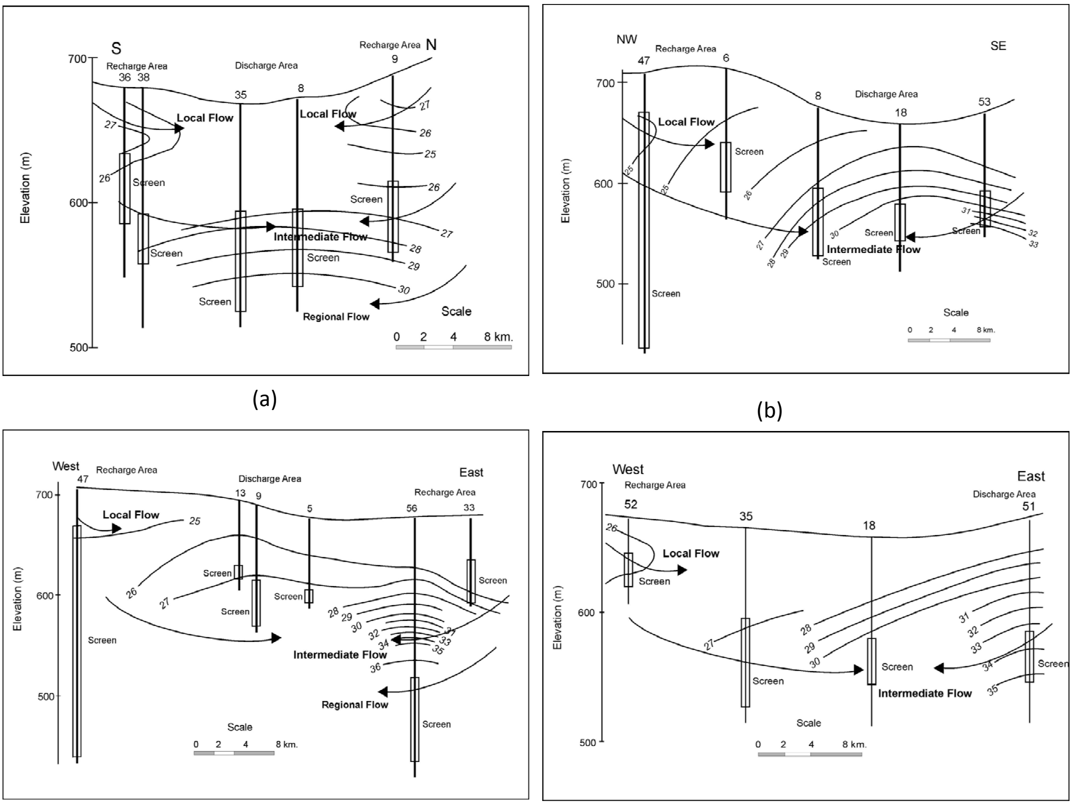


Fig. 5. Schematic diagrams of the groundwater flow system and subsurface thermal regime under the condition of (a) and (b) no groundwater flow, (c) and (d) regional groundwater flow, and (e) and (F) regional groundwater flow with surface warming. Note; T, T_0 and t are subsurface temperature, constant surface temperature and time respectively. After Taniguchi et al. (1999).



(a) (b)

(c) (d)

Fig.6. 2D Vertical Distribution of Sub-surface Temperature in the Bandung Basin.

Stable isotopes

It is well known that stable isotope ratios (δD, $\delta^{18}O$) in precipitation are mostly affected by the temperature condition during which the raindrops were produced). Thus there exist seasonal, latitudinal, and altitudinal changes in the stable isotopic composition of precipitation. Therefore, each type of raindrop will contribute a different stable isotope composition the groundwater. Hydrogen and oxygen stable isotopes are ideal tracers for identifying the origin of groundwater because they make up the water molecules and are sensitive to physical processes. The source of recharge can be identified from the stable isotope signature in the water. Therefore, the groundwater flow system in a certain area can be characterized. The stable isotope data (Figure 7) shows that all samples can be classified into four main groups. Group A samples representing deep groundwater which has the lightest isotopic composition indicating the influence of a high altitude recharge area (up to 2000 m in height difference), comprising the Malabar – Patuha Mountain Complex that occupies the mountainous area South of the Bandung Basin. Group B, represents the intermediate groundwater flow, as the isotopic composition is slightly heavier than that of Group A. The recharge area of this group is considered to be located in the slope area of the Northern Mountainous Complex up to the scarp of Lembang Fault. Delinom (2009) concluded that the Lembang Fault blocked the groundwater flow to the Bandung Basin. Group C and Group D signify the shallower groundwater flow of local groundwater systems.

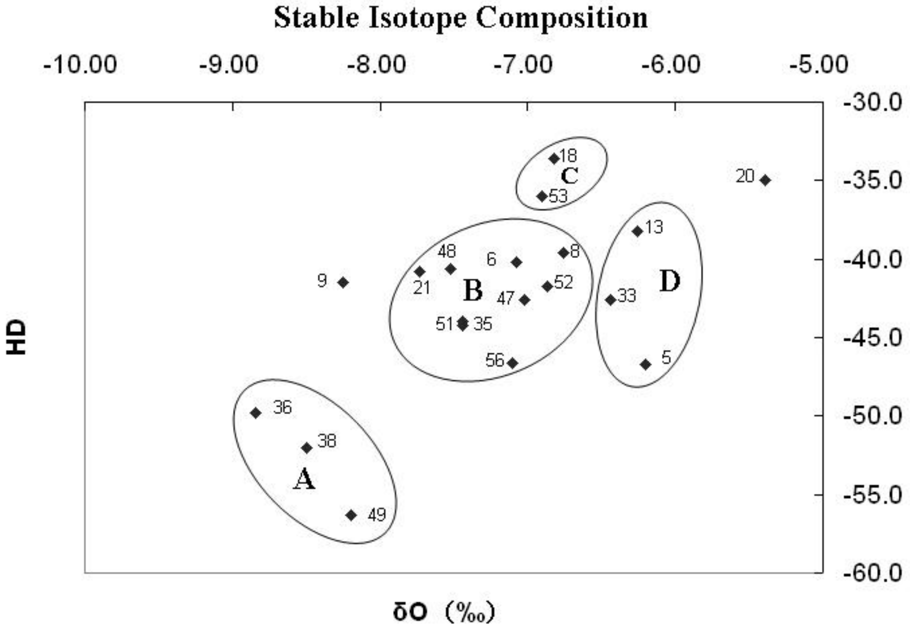


Fig. 7. Stable Isotope Composition (D) and ^{18} O of the Bandung Basin Area.

The difference between these two groups is due to the influence of the type of rainfall and type of vegetation in the surrounding area. Group C indicates that the recharge infiltrated through dry land cultivation while the recharge of group D infiltrated through irrigated paddy fields. As stable isotopes in group C are heavier than those of Group D, taking also into consideration the depth of the aquifer, it is concluded that this group belongs to the shallow groundwater flow system.

The two dimensional vertical subsurface distribution of oxygen isotopes show the existence of shallow, intermediate, and deep flow systems (Figure 8). The shallow system recharges and discharges in the vicinity of wells nos. 13, 33, and 5.

Summary and Discussion

The measured subsurface temperature data have been compiled into four vertical 2-D subsurface temperature distribution schemes. These lines of cross-section were also used in constructing the 2-D distribution model of hydraulic head and stable isotopes. The 12 cross-sections combined with the horizontal temperature gradient distribution, provided sufficient data for the construction of the groundwater flow system of the Bandung Basin.

It is recognized that the groundwater flows from the higher hydraulic head to the lower hydraulic head. Figure 4a shows the distribution of hydraulic head in an S – N direction. The lowest hydraulic head was found in well no. 35, while in the wells which are located near the plain boundary show higher hydraulic heads. This suggests that the groundwater flows from the area of higher elevation to the central part of the basin.

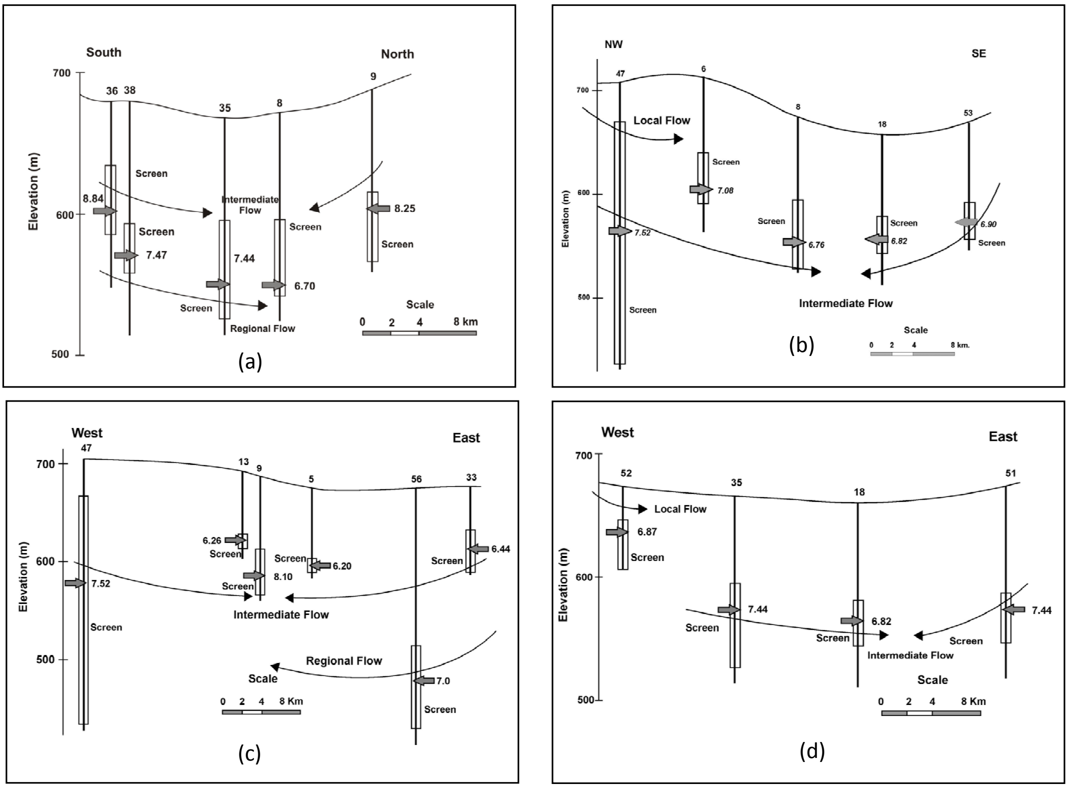


Fig.8. 2D Vertical Distribution of Stable Isotopes in the Bandung Basin

The vertical distribution of the groundwater temperature as shown on Figure 6a represents the temperature distribution in an S -N direction. In the southern part, represented by wells nos. 36 and 38, the measurement did not record a good vertical temperature profile as this area is located in the transition between recharge and discharge area. The best results were recorded in cross section II, as it shows the high temperature located in the plain area while lower temperatures were observed in the hilly area. This represents the ideal groundwater distribution of the area. In general, all cross sections illustrated that lowland has a high temperature, while high temperatures were observed in the hilly and upland areas. Stable isotope analysis based on 19 samples showed that the groundwater recharged from four different areas. Among those 19 samples, two samples showed stable isotope composition anomalies; these are the samples from wells nos. 9 and 20. The sample from well 20 shows the heaviest composition of stable isotopes. This means that extensive evaporation occurred before infiltration took place. Anyhow, geographically this well is not located inside the Bandung Plain proper, but it is actually located in the Batujajar Plain. Therefore, this well will not be used in any analysis. Well 9 are supposed to belong to the intermediate group (Group B) as its deuterium stable isotope falls within the range of this group. The lower value of the oxygen stable isotope is possibly due to the absence of temperature influence from the groundwater flow as it seems that the groundwater flowed through a paleo-river channel. In the areas which have high infiltration at the top of alluvium fan (Wells nos. 5, 13 and 33), the shallow groundwater is mostly recharged through local precipitation.

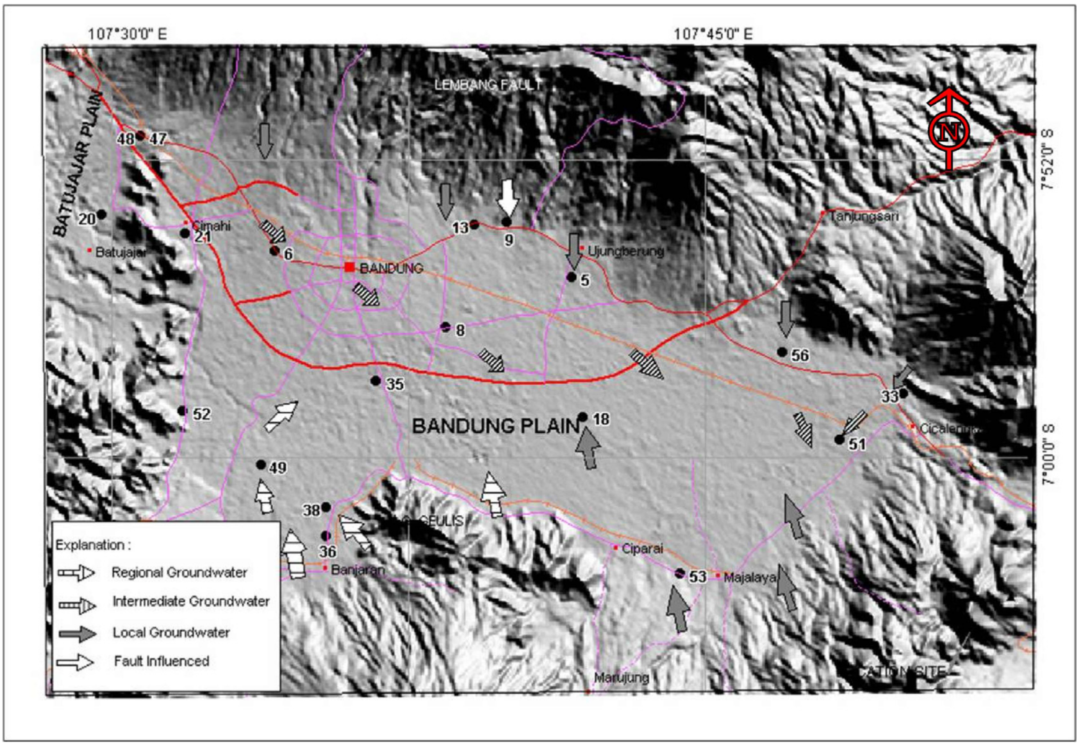


Fig. 9. Horizontal Groundwater flow Direction of Bandung Basin

In the area where the infiltration rate ranges from intermediate to low rates, shallow groundwater shows an intermediate isotopic composition as a result of mixing between groundwater recharged by precipitation and infiltration in paddy fields (wells nos. 52 and 18). Based on Deuterium and Oxygen stable isotope composition in the Bandung Basin, the groundwater flow in this area can be classified into shallow, intermediate, and deep groundwater systems. The difference of the stable isotope composition of these three flow systems reflects difference in altitude of recharge area.

Concluding Remarks

In this study, the identification of the groundwater flow system in the Bandung Basin using subsurface temperature, gradient subsurface temperature, hydraulic head, and D and ^{18}O stable isotope composition appeared to be very satisfying.

The measured temperature data and stable isotope compositions from 19 observation wells lead us to the classification into three types of flow systems that exist within the Bandung Basin i.e., shallow, intermediate and deep groundwater flow system. The two shallow systems mostly recharged in the lower part of the mountainous slope in the North, East and Southeast of the basin, and discharged in the shallow area within the basin. The intermediate system mostly recharged in the upper part of the Northern Mountainous Slope and flowed from the western part of the basin (Cimahi area), passing through Bandung City and discharged in the southern part of Rancaekek. The deep system recharged from the top of the Malabar Mountainous Complex in the South, passing through Banjaran and Margahayu and discharged in the area around the Citarum River Valley in the vicinity of Dayeuhkolot and Soreang. Some of the groundwater then joined the intermediate groundwater flow and together discharged in the Rancaekek area.

In general, all data showed that the recharge area is distributed in the hills and upland areas located along the periphery of the plain. The highest recharge area was estimated to take place on the summits of the Southern Mountainous Complex as the lightest stable isotope composition was found in the area around Banjaran, at the foot-slope of this mountain complex. No indication was found of higher elevation water recharge in the northern part of the basin which means the water recharged in the Mount Tangkuban Parahu area did not reach the Bandung Plain. The recharge in the northern part of the basin mostly came from intermediate elevation and filled the intermediate flow system. Two local groundwater flow system discharged from foot - slope of the hills distributed along the periphery.

In order to obtain a complete view of the groundwater flow system in the Bandung Basin, one overlaying GIS technique, intersect, has been utilized. The configuration of the overall groundwater flow system in the Bandung basin is depicted see Figure 9.

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