The hydrogeology of the volcanic spring belt, east slope of Gunung Ciremai, West Java, Indonesia

D. ERWIN IRAWAN[1], AND DENY JUANDA PURADIMAJA[2]

Department of Geology, Institut Teknologi dan Sains Bandung, Jl. Ir. H. Juanda No. 215, 40135 Bandung, Indonesia (e-mail: r-win@centrin.net.id)
[2]Department of Geology, Institut Teknologi Bandung, Jl. Ganesha No. 10, 40132 Bandung, Indonesia (e-mail: denyjp@bdg.centrin.net.id*,* denyjp@gc.itb.ac.id *)*

Abstract: A hydrogeological study of the spring belt of Gunung Ciremai, Kuningan Regency, West Java Province, aimed to determine the recharge-discharge system, based on geological mapping and groundwater characterisation. Observation on 21 springs shows three spring zones: Zone 1: 100-250 masl, lahar aquifer with large and continuous inter-boulder voids forming micro-canals with permeability of 1.26-2.53 cm/min, Zone 2: 250-650 masl, lava flow fracture aquifer with a permeability of 0.5-1.2 cm/min (the highest spring concentration), and Zone 3: 650-1250 masl, pyroclastic breccias with large and continuous inter-boulder voids forming micro-canals with permeability of 1.5 cm/min. A regional potentiometric map shows radial flow, with two major directions: SW-NE with 0.4 gradient in the Linggarjati Area and NW-SE with 0.3 gradient in the Cibulan Area. Groundwater flow is parallel to ridge orientation.

Chemical analysis indicates three types: mesothermic, low conductivity, bicarbonate; hypothermic, low conductivity, bicarbonate; hyperthermic, high conductivity, NaK-bicarbonate. Type 1 and type 2 are similar to rain water, with local recharge-discharge system (3 months residence time). Type 3 is influenced by extensive Na and K enrichment from volcanic gasses. This water is a non-local recharge-discharge system.

This study shows that the recharge-discharge system is controlled by three factors. First factor: the change of rock distribution causes largest spring distribution at Zone 2 (250 – 650 masl). Elevations lower than 1250 masl are the discharge area, while higher than 1250 masl is recharge area. The second factor: fracture zone controls the level of spring discharge. The third factor: the weathering processes is very intensive, resulting in thick residual soil and high final infiltration rates, which gives a high potential to store and to be infiltrated by rain water and surface water.

Résumé: Une identification de la system d'alimentation/recharge-decharge des aquiferes du terrain volcaniques a ete etudiee dans la partie east du Mont de Ciremai, Kuningan-Ouest Java, Indonesie. Ce travail basee sur l'observation des emergences/sources, analyse d'hydrochimie, et analyse des courbes hydroisohypses. On peut distinguer 3 zone des emergences with de la position au-dessus de la niveau la mer: a)Zone-1: situee entre 100-250 m, aquifere des terains volcanique lahar avec micro canal, b)Zone-2: situee entre 250-650 m, aquifere des terains volcanique lave fissuree, c)Zone-3: situee entre 650-1250 m, aquifere des terains volcanique pyroclastique avec micro canal.

D'apres de la carthographie des courbes hydroisohypses, montre l'ecoulement dans la nappe libre est radial ecoulement avec 2 direction principaux: SO – NE, gradient hydraulique 40 % a la partie -1 (Linggarjati) et 30% a la partie -2 (Cibulan). Cependant, basee sur d'analyse hydrochimie, on peut distinguer l'influence des eaux meteoriques avec de local d'alimention (temps de sejour: 3 mois). Ce system d'alimentation influencee avec trois aspect principaux: distribution des roches, type du fractures, et d'alteration des roches qui sont controlee zone d'alimentation/recharge situee au-dessus de 1250 m et de la zone de la decharge en bas de 1250 m.

Keywords: springs, hydrogeological controls, fractures, environmental protection

INTRODUCTION

The 'Ring of Fire' in Indonesia

Indonesia is a part of the 'Ring of Fire', consisting of almost 128 volcanoes. 13 – 17% of the world's volcanoes are located in Indonesia. Such a number of volcanoes makes Indonesia one of the most important countries for solving volcano problems. A subduction zone lies across the country forming the volcanic belt. Most of them are strato volcanos (Figure 1). Hundreds of volcanoes produce volcanic deposits which cover 33,000 km^2 or one sixth of Indonesia's land (Department of Mining and Energy 1979).

Among the 128 volcanoes, there are 73 active ones (Table 1) with a distribution as described in Table 1 (Department of Mining and Energy 1979). Some of the active volcanoes on Java are plotted in Figure 2.

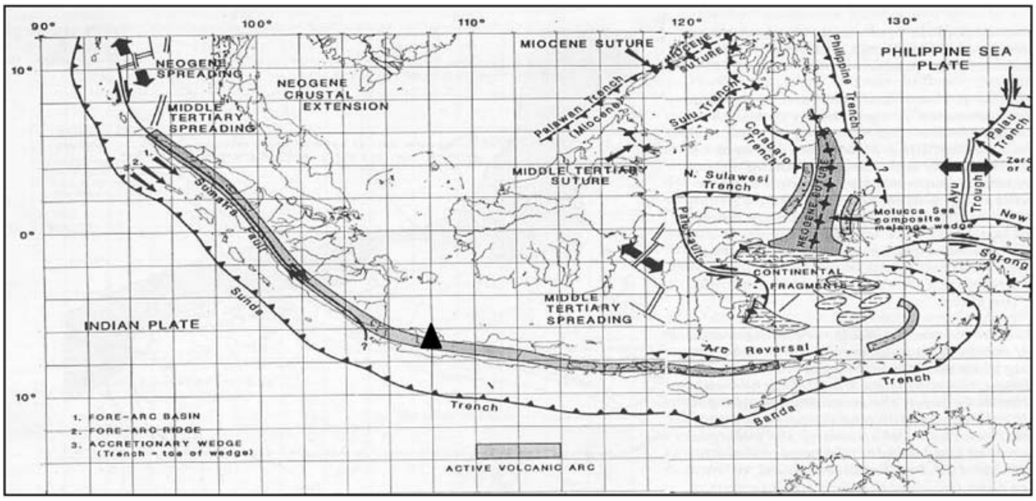
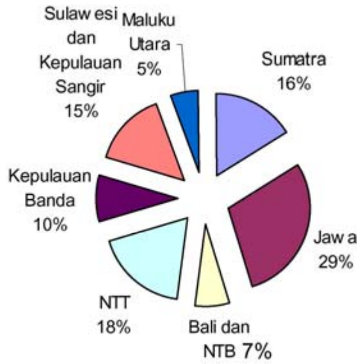


Figure 1. Active volcanic belt in Indonesia. These Quartenary strato volcanoes are widely spread on Sumatra, Java, Bali, Nusa Tenggara, Sulawesi etc (IAGI, 1989). The triangle shows the location of Gunung Ciremai (3072 masl elevation).

Table 1. Distribution of volcano in Indonesia (Department of Mining and Energy 1979)

Number of volcanoes	Location
21 (29%)	Jawa (Java)
12 (16%)	Sumatra
5 (7%)	Bali and Nusa Tenggara Barat (West Nusa Tenggara)
13 (18%)	East Nusa Tenggara
7 (10%)	Banda island
11 (15%)	Sulawesi and Sangir island
4 (5%)	Maluku Utara (North Mollucas)



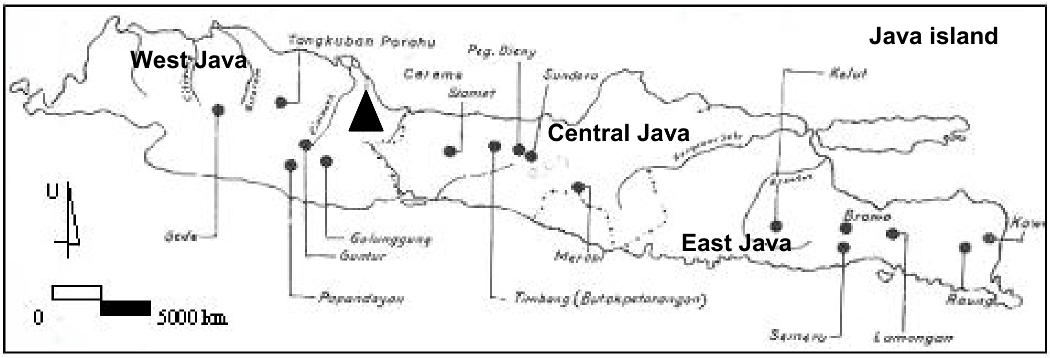


Figure 2. The distribution of 17 active volcano in Java (Department of Mining and Energy 1979). The triangle is Gunung Ciremai.

Overview of spring potential in volcanic deposit aquifer

Volcanic deposits play a role as productive aquifers, as shown by the emergence of springs with enormous discharge and excellent quality. The aquifer results from the pore space system as well as the fracture system. For example, on Gunung Ciremai (Figure 2), there are 13 springs among hundreds with variable discharge, from 80 l/sec (litre/second) up to 1000 l/sec.

A large number of volcanoes in Indonesia should be a research material and inspiration in terms of macro and/or spesific research in the field of volcanic disaster, volcanic resources, etc. Concerning the conservation issues, identifying and delineating the groundwater basin should be placed at the early step in order to determine the suitable groundwater conservation plans. According to Mandel & Shiftan (1981), the delineation of groundwater systems aims to determine:

1). the recognition of the hydrogeological boundaries enclosing the system, 2). the mechanisms of recharge, and discharge, along with the flow paths of groundwater from recharge areas to discharge areas.This study will be interesting because of the variation of volcanic deposits.

Objectives

The objectives of this research are to characterise the hydrogeological system and groundwater flow pattern of Gunung Ciremai. This will help to delineate hydrogeological boundaries of the volcanic deposits and the recharge-discharge system, spesifically in strato volcanoes.

GENERAL HYDROGEOLOGY

Location

Gunung Ciremai is a strato volcano with an elevation of 3072 masl, is situated 20 km south of Cirebon, Kuningan Regency, West Java Province, Indonesia (Figure 3). Its radius from the peak to the foot slope is about 10 km. Gunung Ciremai is a strato volcano, composed of lava and pyroclastic material at the top and main body and laharic breccia on the footslope. The main body of Gunung Ciremai is divided in to 2 administrative area, Majalengka Regency and Kuningan Regency:

1. from the top to the west slope is under Majalengka Regency Administration
2. from the top to the east slope is under Kuningan Regency Administration

The higly productive groundwater reservoir is used to provide the water supply of Majalengka Regency, Kuningan Regency, and Cirebon Regency. This important role has forced the administration to manage the sustainability of the groundwater supply through environmental protection measures. Other problems have arisen since there are many registered and non-registered volcanic sand mining activities on Gunung Ciremai.

The location was selected because of the large amount of groundwater which form a spring belt with no less than 300 springs, discharging over 1500 l/sec of water. The scientific interest is to determine the hydrogeological conditions and the recharge – discharge system, which control such large amounts of spring discharge.

Previous research in identifying the volcanic deposit distribution has been carried out by Situmorang (1995). According to Situmorang (1995), regionally, all of volcanic deposits exposed were produced by four generations of eruption. However, based on its position and the rock dip, the observed rocks was produced by the last eruption.

The regional aquifer system on Gunung Ciremai area is divided into three systems:

1. Superficial Alluvium,
2. Quartenary Volcanics (Young Volcanics)
3. Tertiary sedimentary system.

Surficial alluvium system is thin aquifer composed of loose sand. It is located at the footslope spreading in to the low land. Groundwater is stored in the pore system. Volcanic system is an heterogen aquifer with high productivity. The heterogenity is caused by vertical and lateral variations. This system lies from the top to footslope, in form of porous soil weathering and fractured fresh rocks. The Tertiary Sediments System lies under the volcanic system. The system is composed of non productive aquifer. Groundwater is stored in porous soil weathering and clayish sand; also micro fractures of fresh rock. It flows in local pattern and limited discharge.

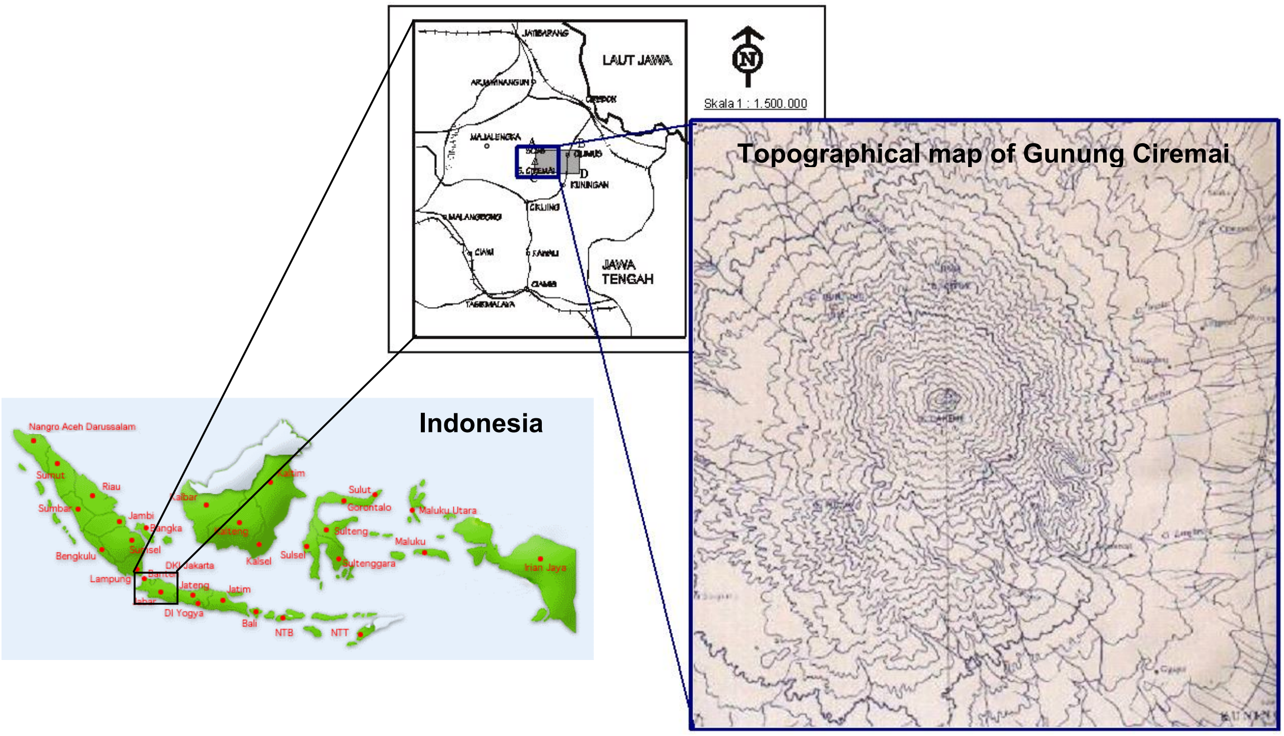


Figure 3. Location and topographical map of Gunung Ciremai.

Spring spatial distribution

On the east slope of Gunung Ciremai there is a spring belt, with variable discharge. Spring emergence with respect to elevation is not equally distributed on the slope, as shown in Figure 4.

The figure shows that there are 3 zones of spring belt:

- Zone 1 : 100-250 masl
- Zone 2 : 250-650 masl (the highest spring concentration)
- Zone 3 : 650-1250 masl

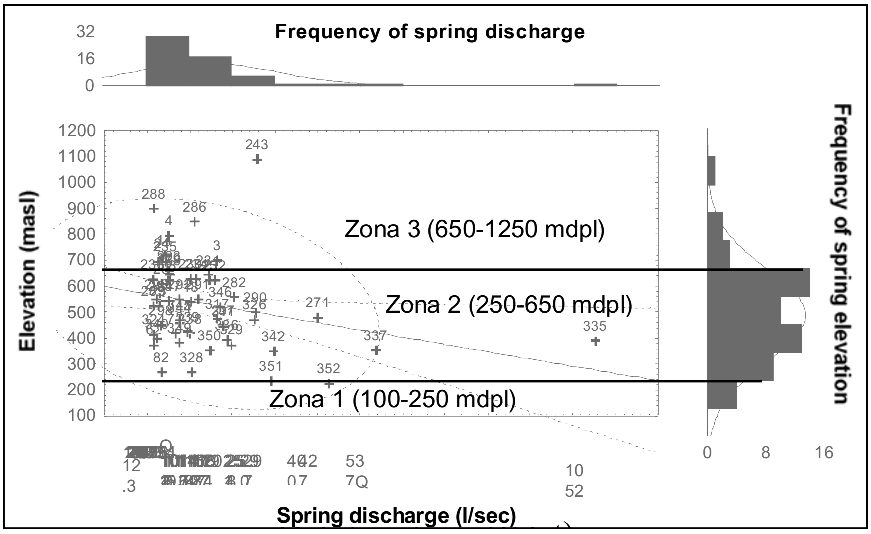


Figure 4. Distribution of the spring belt**.**

The auifer system has been simulated in 2D on the NW-SE and W-E slope of Gunung Ciremai (Figure 5). In the simulation, the aquifer system is simplified into two systems:

1. Productive Young Volcanic System
2. Impermeable Tertiary Sediment System as basement.

According to the simulation on the SW-NE section, the high concentration of spring discharge is at 100 to 400 masl, with a local and subregional flow system. Low concentration emerges at below 100 masl. The high concentration of springs at 250-650 masl is controlled by the occurence of a slope break at the elevation of 800 masl. The slope break is formed by a lithological change, from lava (at an elevaton higher than 750 masl) to laharic breccia (at an elevation lower than 750 masl).

A rather similar situation can be seen in the W-E section; the figure shows a spring zone at 100 masl to 750 masl. This zone is controlled by a slope break at about 750 – 800 masl. Groundwater flow is presumably a local flow system. All of the flow system shows normal pH and high EC. This is characteristic of meteoric water interacting with highly mineralised aquifers.

METHODS

The hydrogeological condition is a combination of two main aspects: the solid and the fluid. The solid aspect comprises the material and the geometry of an aquifer and the hydraulic properties of the aquifer; the fluid aspect involves the hydraulic behaviour of the groundwater. Therefore, two complementary methods have been carried out in this study:

1. Surface mapping of the volcanic aquifer system at 1 : 25.000 scale, to identify the geometry of the aquifer and the hydraulic properties of the soil (unconfined aquifer). The data were obtained from observations of 21 springs and volcanic rock exposures; these were supported by 10 field permeability measurements.
2. Flow net analysis, to identify the groundwater flow system. The analyzed systems were:
   a. Regional flow in the Linggarjati and Cibulan areas;
   b. Detailed flow at the Cibulan spring area. The flow net analysis was based on water table measurement at dug wells and springs.

OBSERVATION

Observations were made at 21 spring locations, all of which are fracture springs. Based on spring and exposure observations, three aquifer units were identified: pyroclastic breccia, lava, and laharic breccia units. The distribution of the aquifer units is shown in Table 2 and Figure 6.

Distribution of springs and lithology

All of the observed aquifers are unconfined. Based on their elevations, springs on the east slope of Gunung Ciremai can be divided into three zones as follows:

1. Volcanic core facies is distributed at 3050-3100 masl, consisting of andesite to dacite rock. This facies is impermeable;
2. Volcanic Proximal facies is distributed at 650-3050 masl and consists of:
   a) Proximal 1 at 1250–3050 masl, composed of impermeable pyroclastic flow and fall deposits with andesite boulders and tuff matrices;
   b) Proximal 2, composed of permeable andesite to dacite lava flows at 650 – 1250 masl. In Proximal 2 facies, there is Spring Zone 1 with three springs which discharge a total of 98 l/sec. The estimated thickness is at least 100 m.
3. Volcanic Distal facies is distributed at 100–650 masl and consists of permeable laharic breccia, with small to large andesite to dacite boulders in a tuff and volcanic sand matrix. The rock is fractured with unidentified dimension and geometry, which sets up a good permeability. In this facies, there is Spring Zone 2 which consists of 18 springs with a total discharge 1063 l/sec. The estimated thickness is at least 100 m.

The morphology of Gunung Ciremai is controlled by changes of rock distribution. Such a condition forms two slope breaks at 750 masl (4^o difference) and 1350 masl (19^o difference). The summary of the hydrogeological conditions is presented in Table 2 and Figure 6.

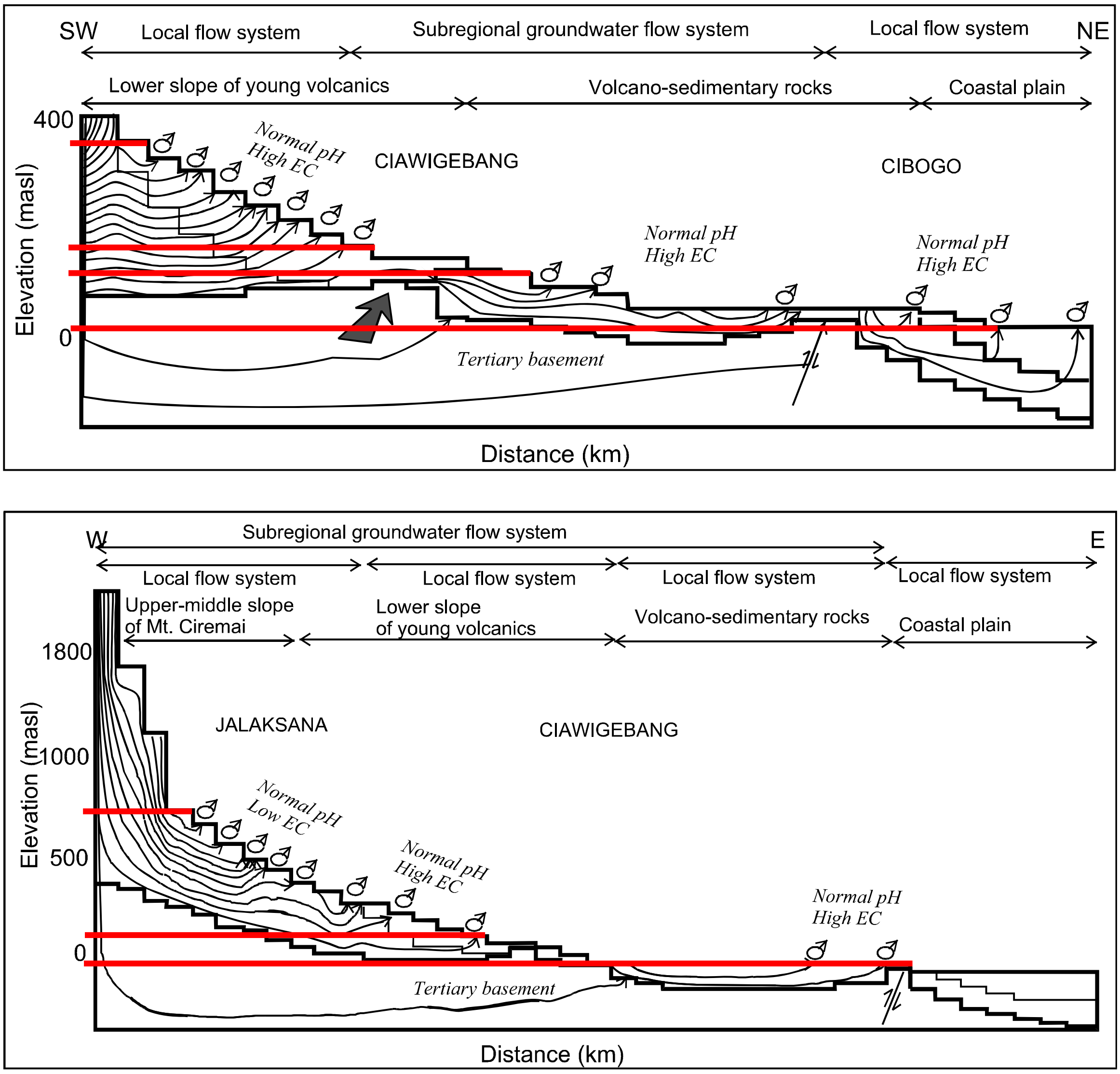


Figure 5. Two dimensional numerical simulation of groundwater flow.

Thickness and final infiltration rate for residual soil

The intensity of weathering processes in the study area is very high, resulting in thick residual soil. The thickness of residual soil ranges from 2 to nearly 10 m. Such thick residual soil is a high potential to store and to infiltrate rain and surface water into the aquifer.

Infiltration tests (according to Chow et.al. 1964, Miyazaki 1993) are carried out to verify the final infiltration rate of residual soils. Residual soils from lahars show the largest values of 1.26–2.53 cm/min, followed by residual soils from pyroclastic breccias at 1.5 cm/min, and from lava flows at 0.5–1.2 cm/min. High final infiltration rates (Linsley & Franzini, 1978) indicate the high capacity of residual soils to be infiltrated by rain water and surface water.

Intensity of macro fracture

The fracture zone controls the level of spring discharge. A sketch of the fractures system is depicted in Figure 7. There are two genetic types of fractures:

a) Fractures on lava flows

The fractures are constituted of cooling joints which form narrow openings in the rock. The pattern of the joints is unsystemmatic, with many orientations as follows: N63^{0}E, N90^{0}E, N117^{0}E.

b) Fractures on laharic breccias

The fractures are continuous in the rock. At Cibulan spring, the orientation of fractures is N93^{0}E, which is in the same direction as the ridge.

Chemical Analysis

Chemical analysis indicates that rain water has a low conductivity and bicarbonate composition. Groundwater samples are classified into three types: Mesothermic, low conductivity, bicarbonate; Hypothermic, low conductivity, bicarbonate; Hyperthermic, high conductivity, NaK-bicarbonate. Type 1 and type 2 are similar to rain water, with local recharge-discharge system [3 months residence time]. Type 3 is influenced by extensive Na and K enrichment from volcanic gasses. This water is a non-local recharge-discharge system.

Groundwater Flow Pattern

A regional isophreatic map covers two spring areas: Linggarjati and Cibulan. The Linggarjati spring area emerges from a lava flow, discharging 80 l/sec of groundwater; while the Cibulan spring area is located at the edge of a ridge, and discharges, overall, 400 l/sec of groundwater.

- The groundwater flow pattern in the Linggarjati area is SW-NE with 0.4 gradient and 0.6 slope inclination. The flow appears to be deviated.
- The groundwater flow pattern in the Cibulan spring area shows a NW-SE direction with 0.3 gradient and 0.4 slope inclination. The isophreatic contour shows a straight pattern.

ANALYSIS AND INTERPRETATION

According to Freeze & Cherry (1979), morphology and geology controls the distribution of potentiometric conditions. Many variations of potentiometric pattern produces a varied input-output system of groundwater flow. Another view from Purbohadiwijoyo (1965) indicates that spring distribution is strongly controlled by 3 types of geological condition:

- Type 1 At the slope break of volcano. Groundwater moves from the recharge area to the discharge area at slope break, forming a spring belt;
- Type 2 At the contact between the aquifer and an intrusion as a boundary. Groundwater emerges in the form of a contact spring at the contact between the aquifer and the intrusion;
- Type 3 In the volcanic rock coastal zone, which only occurs for near-sea volcanoes. Groundwater moves from the recharge area to the coastal zone. Springs can emerge either above sea level or below sea level and are known as underwater springs.

At Gunung Ciremai, the change of slope angle controls the hydraulic flow of the unconfined groundwater to develop spring belts in the area, with the largest spring in Zone 2 (250–650 masl). On the other hand, on the upper slope (1250–3100 masl), there are no spring occurrences. Therefore, it can be concluded that the elevation lower than 1250 masl is a discharge area, while the elevation higher than 1250 masl is a recharge area.

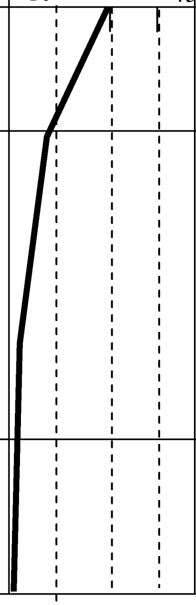
At a larger scale, the volcanic deposit distribution forms morphological features of ridges and valleys. Such features function as passageways for groundwater (Figure 8) The analysis is proven by some spring discharges from ridge edges, with potential lines matching the topographical contour. The ridge consists of a 10 m thickness of laharic breccia deposit, which plays a role as a productive aquifer.

Based on the observations, there are three hydrogeological factors which control spring distribution, spring discharge and groundwater flow pattern as follows: the distribution of lithology and morphology; the intensity of macro fracturing; the thickness and final infiltration rate of the residual soil. The details of each factor are described below.

Fractures on lava flow

The fractures consist of cooling joints which form narrow openings in the rock. The pattern of the joints is unsystematic, with many orientations as follows: N63^{0}E, N90^{0}E, N117^{0}E. The orientation of the fractures controls the deviated groundwater flow pattern.

Table 2. Summary of hydrogeological conditions

Volcanic facies (according to McPhie et al. 1993)	Description		Slope	Spring			Physical and hydraulic properties
	Symbol	Lithology	10° 20° 30° 45°	Zone	Number	Discharge (L/s)	
Volcanic Core (3050 masl-estimated 3100 masl)		Volcanic neck, consists of andesites to dacite		-	0	0	Impermeable rock with less, no other data is available
Volcanic Proximal (650 – 3050 masl)							
Volcanic Proximal 1 (1250 – 3050 masl)		Pyroclastic fall and pyroclastic flow. Consists of andesite boulder and tuff matrices		-	0	0	Impermeable rock, high infiltration rate of soil 1.5 cm/min, no other data is available
Volcanic Proximal 2 (650 – 1250 masl)		Lava flow. Consists of andesite to dacite lava		1	3	98 (class 1-3)*	Permeable, secondary permeability: cooling/sheeting joint with unsystematic pattern, thick residual soil (2-5 m), final infiltration rate of 0.5 – 1.2 cm/min
Volcanic Distal (100 – 650 masl)		Laharic breccia. Consists of andesite to dacite boulder with tuff and volcanic sand matrices.		2	18	1063 (class 1-3)*	Permeable, secondary permeability: fractured with isolated pattern, thick residual soil (2-5 m), final infiltration rate of 1.26 – 2.53 cm/min

* according to Meinzer classification of spring discharge (Todd 1980)

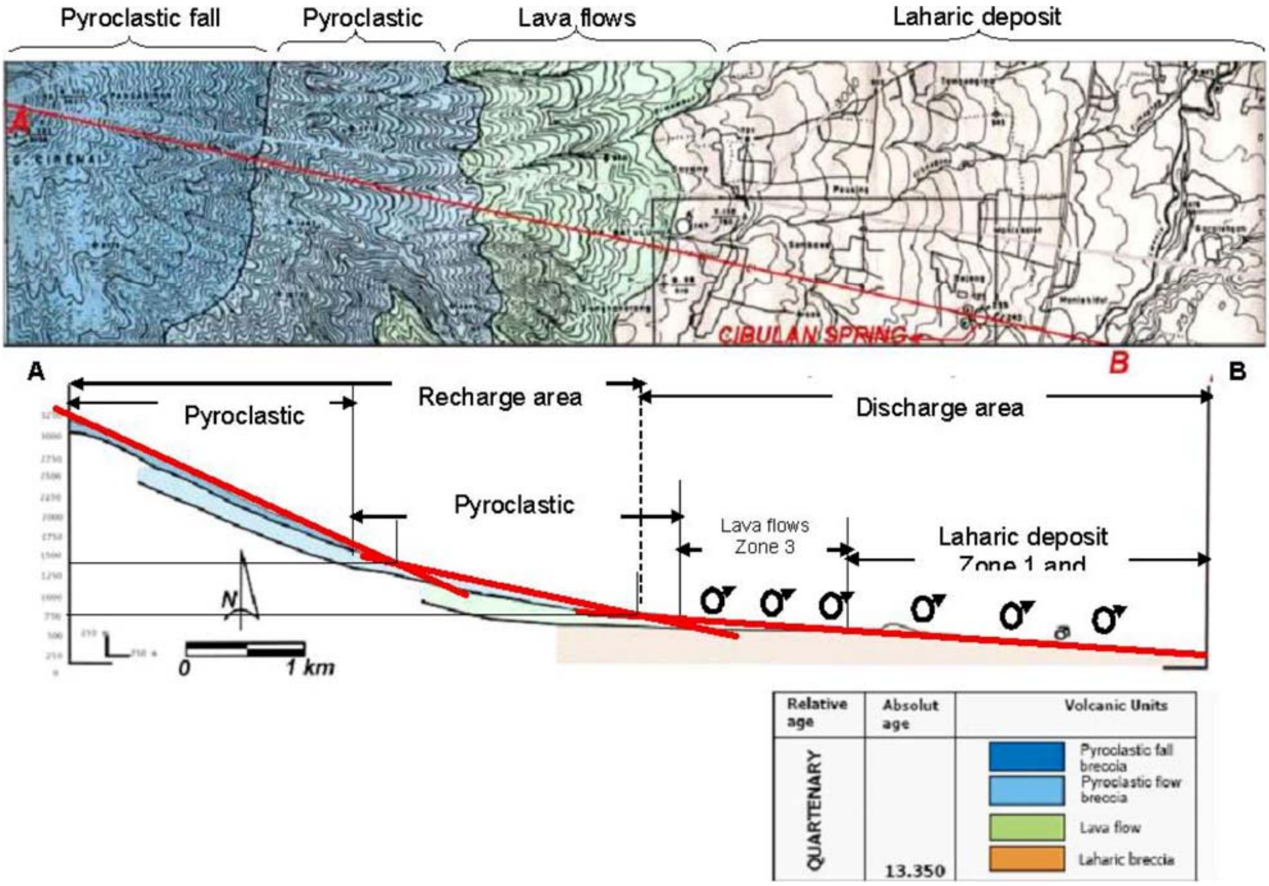


Figure 6. Volcanic Deposit Distribution. Laharic breccia is deposited at the lowest elevation (100-650 masl). In the upperpart, a series of lava flows are deposited at 650–1250 masl of elevation and a series of pyroclastics (flow and fall) is deposited at 1250–3100 masl elevation. The change of rock type, from lava flows to pyroclastic breccia, forms two slope breaks at 750 masl (4^{o} difference) and 1350 masl (19^{o} difference). Zone 1 consists of three spring observations with total discharge 98 l/sec. Zone 2 consists of 13 spring observations with total discharge 1063 l/sec.

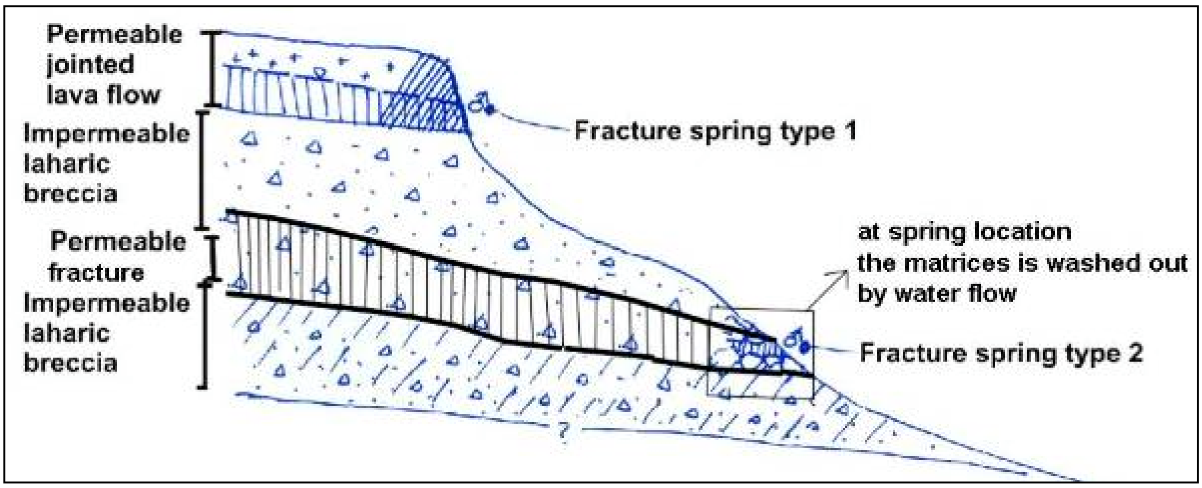


Figure 7. Fractures on lava flows and laharic breccia. There are two spring systems at this location. The upper spring occurs in lava flows aquifer and emerges from fractures of cooling joints. The lower spring occurs in laharic breccia and emerges from fractures of large and continuous inter-boulder voids (canal spring).

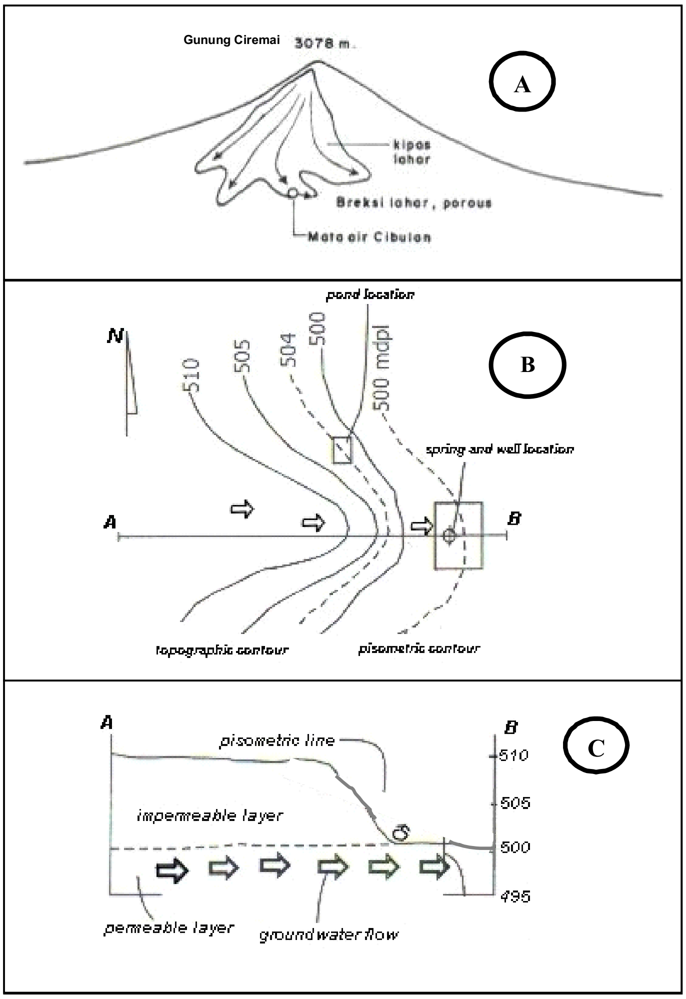


Figure 8. The three figures show the situation of the Cibulan spring area, the isophreatic map, and the section of groundwater flow: A. Location of Cibulan spring; B. The isophreatic and groundwater flow at the ridge; C. The cross section of Cibulan spring (400 l/sec).

Fractures on laharic breccia

The fractures is in form of micro canals, formed by large and continuous inter-boulder voids. This canal stretches following rock distribution. At Cibulan spring, the orientation of canal is N93^{0}E, which is in the same direction as the ridge. The unidirection fracture controls isolated groundwater flow pattern.

CONCLUSIONS

Results from 21 observations have shown that spring distribution, spring discharge and groundwater flow pattern are controlled by three hydrogeological factors as follows: distribution of lithology and morphology; intensity of macro fracturing; thickness and final infiltration rate of residual soils.

First factor: the change of rock distribution from lava to laharic breccia produces slope breaks at 750 masl (4^o difference), while changes from pyroclastic flow and fall generates a slope break at 1350 masl (19^o difference). The change of slope angle controls the hydraulics of the unconfined groundwater to develop the largest spring distribution at Zone 2 (250 – 650 masl). Elevations lower than 1250 masl are a discharge area, while higher than 1250 masl is a recharge area. The morphological features of ridges and valleys control groundwater flow patterns. This fact is indicated by the similarity of the topographical contour and potential contour. The similarity controls parallel groundwater flow with ridge orientation.

Second factor: fracture and continuous voids zones control the level of spring discharge in volcanic terrain. The fracture of large and continuous inter-boulder voids occurs on the laharic breccia. The voids form micro-canals, which also controls the isolated groundwater flow. On the other hand, fractures on the lava flows are in the form of cooling joints with an unsystematic pattern, which controls the divergent groundwater water flow.

Third factor: the weathering processes in the study area is very intensive, resulting in thick residual soils and high final infiltration rates, which give a high potential to store and to be infiltrated by rain water and surface water.

Understanding of the recharge-discharge system of volcanic hydrogeology can assist the authorities to determine the right programme for environmental protection.

Corresponding author: Mr Dasapta Erwin Irawan, Institut Teknologi Dan Sains Bandung, Jl Ir.H. Juanda No. 254, Bandung, West Java Province, 40135, Indonesia. Tel: +62 222501541. Email: r-win@centrin.net.id .

REFERENCES

CHOW, V.T. (Ed). 1964. *Handbook of applied hydrology*. McGraw-Hill, New York. 12.1-12.30.

DEPARTMENT OF MINING AND ENERGY. 1979. *Data dasar Gunung Api Indonesia*, Department of Mining and Energy. (in Indonesian)

FREEZE, R.A. & CHERRY, J.A. 1979. *Groundwater*. Prentice-Hall, Englewood Cliffs, New Jersey.

IAGI (INDONESIAN GEOLOGISTS ASSOCIATION). 1989. *The geology of Indonesia*. Special Edition of Majalah IAGI (in Indonesian)

LINSLEY, R.K. & FRANZINI, J.B. 1978. *Water resources engineering*. Mcgraw-Hill, New York.

MANDEL, S. & SHIFTAN, Z.L. 1981. *Groundwater resources: investigation and development*. Academic Press, New York.

McPHIE, J., DOYLE, M. & ALLEN, R. 1993. *Volcanic textures*. University of Tasmania, Australia.

MIYAZAKI, T. 1993. *Water flow in soils*. Marcel Dekker Inc, New York. 29–45

PURBOHADIWIJOYO. 1965. *Hydrogeology of Stratovolcanoes*. International Association of Hydrogeologists, Memoirs Congress of Hannover

SITUMORANG. 1995. *Peta geologi Gunung Ciremai*. Directorate of Volcanology. (in Indonesian)

TODD, D.K. 1980. *Groundwater hydrology. 2nd Edition*. John Wiley, New York.