Journal of Hydrology 376 (2009) 221–234

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Hydrogeochemistry of volcanic hydrogeology based on cluster analysis of Mount Ciremai, West Java, Indonesia

Dasapta Erwin Irawan [a,*], Deny Juanda Puradimaja [a], Sudarto Notosiswoyo [b], Prihadi Soemintadiredja [a]

[a] Research Group on Applied Geology, Faculty of Earth Sciences and Technology, Institut Teknologi Bandung, Jl. Ganesha No. 10, 40132 Bandung, Indonesia
[b] Research Group on Earth Resources Exploration, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jl. Ganesha No. 10, 40132 Bandung, Indonesia

ARTICLE INFO

Article history:
Received 22 July 2008
Received in revised form 9 July 2009
Accepted 11 July 2009

This manuscript was handled by L. Charlet, Editor-in-Chief, with the assistance of Sheng Yue, Associate Editor

Keywords:
Hydrochemistry
Volcanic hydrogeology
Multivariate analysis

SUMMARY

Hydrogeochemical analysis has been conducted on 119 spring locations to portray volcanic hydrogeological system of Mount Ciremai, West Java, Indonesia. Cluster analysis on 14 parameters has extracted three clusters. Cluster 1 (112 springs) is distinguished by normal temperatures, low TDS, EC, and high bicarbonate concentrations. Cluster 2 (five springs) has moderately high temperature, TDS, EC, and high concentration of chloride. Cluster 3 (two springs) exhibits high temperature, anomalous high TDS, EC, and chloride concentration.

Three hydrogeological systems have been pictured based on the 3 clusters consecutively. The 1st system is developed in shallow unconfined aquifer, with domination of high bicarbonate (4.2 me/L) meteoric water. The 2nd system is predominated with mixing processes, between groundwater in unconfined aquifer and hot groundwater from deeper aquifers. The 3rd system is primarily dominated by groundwater flow from deep formation. The hot – deep seated groundwater flow also carries mud particles. It has anomalous high TDS (>1000 mg/L), EC (515 μS/cm), and chloride (99 me/L) from interaction between groundwater with clay formations, interpreted as Kaliwangu Formation.

Introduction

Indonesia is part of ring of fire, in form of volcanic belt with almost 128 volcanoes or 13–17% of total volcanoes in the world. The volcanic belt with focussing on Java Island is presented in Fig. 1. These volcanoes produce volcanic deposit cover a total area of 33,000 km^2 or one sixth of Indonesia's land (Dept. of Mining and Energy, 1979). In terms of hydrogeology, the volcanic deposits perform as productive aquifer. Such high productivity is shown by the emergence of spring belt at the foot slopes with enormous discharge and excellent quality. The aquifers come as porous system as well as fracture system. For example, at Ciremai volcano, there are at least 119 springs with variable discharge, from 10 L/s to nearly 100 L/s (Bapeda Kuningan, 2002).

This paper describes a hydrogeological assessment method to extract the geological control to groundwater springs. It is important in order to build a conceptual hydrogeological model of volcanic system at Ciremai. The methods are established using cluster analysis on hydrochemical parameters, measured at 119 groundwater springs.

Problem statement and objective

On Java island of Indonesia, the water demand increases due to the growing population and rising of water consumption (Puradimaja et al., 2002). The island has an area of 138,793 km^2, with population of around 128 million people. The population had been doubled in the last four decades. Therefore, the density is around 1000 people per sq. km (Runtunuwu and Pawitan, 2008, op.cit Bapeda Kuningan, 2002). On the other side, the Indonesian islands receive abundant precipitation, ranging from 2000 to 4000 mm/year. In March 2009 for instance, the average precipitation in Java Island reached 300 mm (BKMG, 2009), which is not well distributed.

However, the water resources are not well-managed yet. On the slopes of volcanoes for example, the upslope movement of habitation and agriculture should have changed the water budget of particular region. Other problem is the productive zone of hydrogeological system has not been identified and understood in details.

The objective of this research is to clarify the geological control to groundwater system based on hydrochemical parameters from spring water samples. The hydrochemical parameters are analyzed using basic statistical and cluster analysis to extract the groupings of groundwater samples. Given the relatively complex setting and geological history of the study area, the analysis is expected to help distinguish the role of geological and hydrogeological parameters on this evolution.

* Corresponding author. Tel.: +62 8122041446; fax: +62 224238545.
E-mail addresses: erwin@gc.itb.ac.id (D.E. Irawan), sudarto@mining.itb.ac.id (S. Notosiswoyo).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2009.07.033

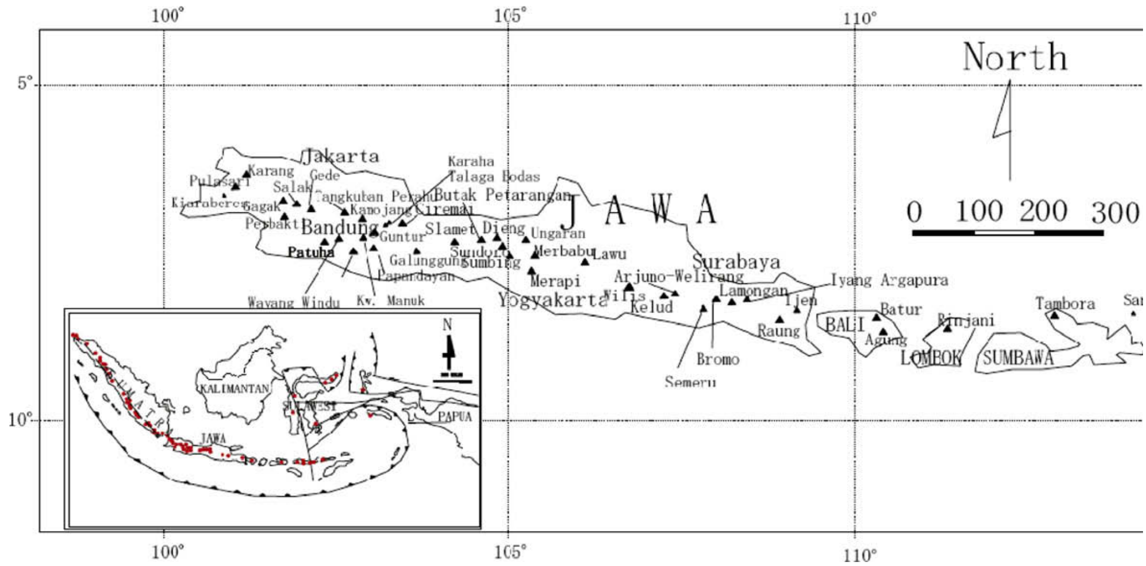

Fig. 1. The volcanic arc of Indonesia focussing in Java Island (Dept. Pertambangan dan Energi, 1979).

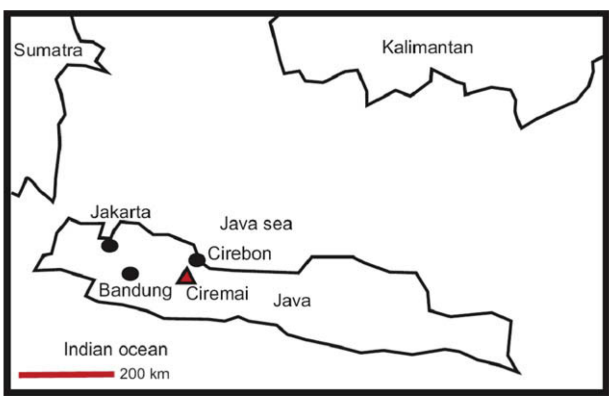

Fig. 2. Map of the study area. Red triangle indicates the location of Mount Ciremai. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Literature review

Hydrogeological background

Ciremai is a solitaire-strato volcano with elevation of 3072 masl, situated in Majalengka (west flank) and Kuningan Regency (East flank) (Fig. 2), 20 km south of Cirebon. Its peak lies at 6°53′30″ latitude and 108°24′00″ longitude. The diameter of this volcano, from the peak to the foot slope is about 10 km. Many studies have been conducted at the area, consists of regional geology and hydrogeology in large scale. More detail study still has not been done. Situmorang (1995) has published volcanic geological map of Ciremai (Fig. 3). According to the author, Ciremai has erupted five times since the 1600s, in: 1698, 1772, 1775, 1805, and 1937. The eruption interval was 3–112 years. Those eruptions produced 22 types of volcanic deposit, consists of: 11 layers of lava flows and 11 layers of pyroclastic materials. Pyroclastic breccias consist of andesite fragments planted in tuff lithic and tuff crystal. Lava flow consists of andesite composition, black to brownish in colour. It has fractures of sheeting and columnar joints due to the mass unloading and cooling processes. Laharic breccias consist of andesite fragments planted in volcanic sands, tuff lithic, and tuff crystal. It comes in water-dominant flowing mechanisms.

The first regional hydrogeology condition was introduced by IWACO – WASECO (1989). According to the author, regional aquifer system of Mount Ciremai area is divided into three systems: Surficial Alluvium, Quaternary Volcanic (Young Volcanic), and Tertiary Sediment system.

More detail study was conducted by Puradimaja et al. (2003). Puradimaja found three main aquifer units: pyroclastic breccias, lava, and laharic breccias. All of the observed-aquifers are unconfined aquifers. They feed water to spring zone encircling Ciremai. The spring zone is interpreted to be controlled by slope morphology. However, the morphology forms two slope breaks: at 750 masl (4° of slope difference) and at 1350 masl (19° of slope difference).

Irawan and Puradimaja (2006a) attained three factors control the spring emergence. First factor is the change of rock distribution from lava to laharic breccias. Morphological features in the form of ridges and valleys also contribute to control groundwater flow pattern. Second factor is fracture system in lava flows and continuous conduits in laharic breccias. Third factor is the intensive weathering processes in the study area. The process produces thick residual soil and high final infiltration rate. The residual soil is very potential in storing and transmitting water.

Infiltration tests (according to Chow, 1964; Miyazaki, 1993) was carried out to verify the final infiltration rate of residual soils. Residual soil from lahars shows the largest values of 1.26–2.53 cm/min, followed by residual soil from pyroclastic breccias 1.5 cm/min, and from lava flow 0.5–1.2 cm/min. High final infiltration rate (Linsley and Franzini, 1992) indicates the high capacity of residual soil to be infiltrated by rain water and surface water.

There were three thermal groups of spring, based on 23 spring observations, consisting of: hypothermic, mesothermic, and hyperthermic (Fig. 4). The thermal classifications are based on interaction between groundwater temperature and environmental temperature. The hypothermic group indicates the closed system of groundwater. Groundwater temperature does not relate to surface environmental temperature. Mesothermic group shows interaction between groundwater and surface temperature. Hyperthermic groups are characterized by interaction between groundwater temperatures with specific subsurface heat source. (Hem, 19703; Matthess, 1982). Different groundwater flow

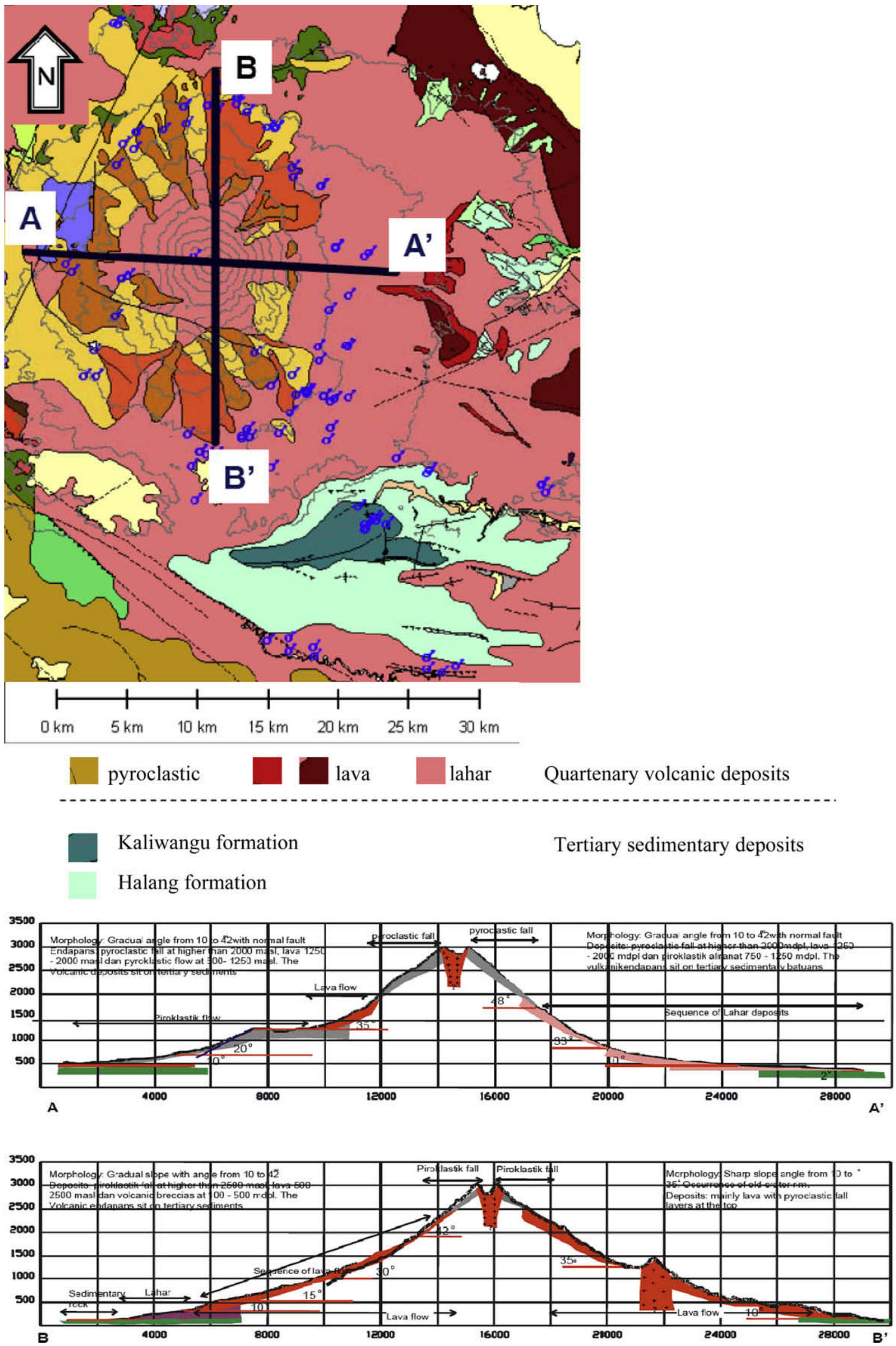

Fig. 3. Geological map of Mount Ciremai and simplified sections (from Situmorang).

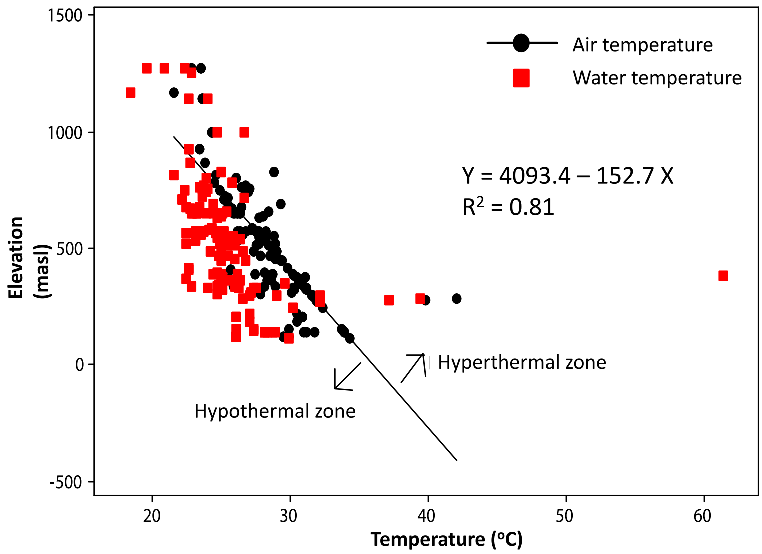

Fig. 4. Chart of thermal gradient of groundwater at Ciremai (Puradimaja et al., 2003).

systems are reflected by chemical characteristics as the characteristics shift from meteoric-dominated waters to formation-dominated waters (Irawan and Puradimaja, 2006b) .

Subsequently, in 2002, Bapeda Kuningan Regency has mapped 161 springs with total of 8285.2 l/sec. The result is five classes of spring discharge magnitude (Meinzer 1923, op.cit Todd, 1980): six springs of Class II (4%), 44 springs of Class III (27%), 15 springs of Class IV (9%), 40 springs of Class V (25%), and 56 springs of Class VI (35%). The preceding study have not analysed the control of geological setting to groundwater springs.

Cluster analysis

Multivariate statistical analysis has been successfully applied in a number of hydrogeochemical studies. Many techniques have been used as summarized by Smith (2002) (Table 1). One of the techniques, cluster analysis, is an unsupervised-multivariate statistical method identifying the similar hierarchical structure of large number observations into smaller groups. Thus, that the objects within a group are very similar and objects from different groups are significantly different in their characteristics (Smith, 2002). Thyne et al. (2004) stated that multivariate statistical methods have been employed to extract critical information from hydrochemical datasets in complex systems. These techniques can help resolve the hydrological factors such as aquifer boundaries, ground water flow paths, or hydrochemical components, identify the control of rock chemistry to water composition, and separate anomalies such as anthropogenic impacts from the background.

There are three steps in cluster analysis (Yang, 2004).

Step 1: Select cluster variables and distance measures. How many and which variables are to be selected will affect the analysis results. In cluster analysis, it is implicitly assumed that every variable is equally important.

Step 2: Select cluster algorithm. Cluster algorithm is the procedure to determine "clusters," or "groups." There are two categories of cluster algorithms, hierarchical and non-hierarchical. In this paper, we are going to use hierarchical algorithms.

Table 1
Various techniques of multivariate analyses (Smith, 2002).

Method	Cations used	Anions used	Other parameters	Input data and plotting units
Cluster analysis (HCA and KMC)	All major, minor and trace elements	All major, minor and trace elements	All applicable parameters Yes (1) or no (0) statements, discrete variables	Input: *z*-scores of the log-transformed data Output: distance matrix (KMC) and dendogram (HCA)
Principal components analysis (PCA)	All major, minor and trace elements	All major, minor and trace elements	All applicable parameters Yes (1) or no (0) statements, discrete variables	Input, *z*-scores of the log-transformed data Output: PCA scores
Fuzzy k-means Clustering (FKM)	All major, minor and trace elements	All major, minor and trace elements	Same as above	Input: same as above matrix Output: membership
Piper diagram	Na + K, Ca, and Mg	Cl, SO_4 and $HCO_3 + CO_3$	n/a	Relative %meq L^{-1}
Collins bar diagram	Na + K, Ca, and Mg	Cl, SO_4 and HCO_3 CO_3(or $HCO_3 + CO_3$)	n/a	Relative %meq L^{-1} or meq L^{-1}
Pie diagram	Na + K, Ca, and Mg	Cl SO_4 and HCO_3	na	Relative %meq L^{-1}
Stiff pattern diagram	Na (or Na + K), Ca, and MgFe (optional)	Cl,SO4 and HCO_3 CO_3 (optional)	n/a	meq L^{-1}
Schoeller semi logarithmic diagram	Na + K, Ca, and Mg	Cl, SO_4 and HCO_3	n/a	meq L^{-1} in log-scale
Chenoff faces	Up to 20 parameters can be plotted		n/a	meq L^{-1} or mg L^{-1} Other parameters, in their respective units

Step 3: Perform cluster analysis. Cluster analysis will determine the cluster structure-specifically, which objects form a cluster, how many clusters, the features of clusters, etc.
Step 4: Interpretation. We need to explain what these clusters mean and how should we name and make sense of these clusters. The interpretation is based on geological facts.

According to Yang (2004), in cluster analysis, "distance" is used to represent how close each pair of objects is. The most common distance measurement is Euclidean distance (Fig. 5). The Euclidean distance between any two objects, that is, the distance between object i and object k (d_{ik}), is Eq. (1)

$$d_{ik} = \sqrt{\sum_{j=1}^{N} (x_{ij} - x_{kj})^2} \quad (1)$$

In cluster analysis, it is desirable that the distances between objects within a cluster (group) are small and the distances between different clusters are large, as illustrated in Fig. 5. The definition of the distance between clusters depends on the methods to determined relationship between clusters, called linkage. There are several different linkage methods which we will discuss as follows. In single linkage method, the distance between two clusters is defined to be the distance of the nearest neighbours (Fig. 5). The distances between clusters and the joining process are well described in a dendogram. Costello and Osborne (2005) proposed that cluster analyst usually wants to form more than a cluster in further analysis. As we discussed earlier, a good clustering should be as follows:

1. The objects within a cluster should be similar one another, in other words, the distances between the objects within a cluster should be small.
2. The objects from different clusters should be dissimilar, significantly, or the distances between them should be large.

Methodology

The delineation of groundwater system is important to recognize the hydrogeological boundaries enclosing the system and the mechanisms of recharge–discharge, along with the groundwater flow path (Mandel and Shiftan, 1981). In this paper, existing regional-scale maps at scales of 1:50,000 or smaller were used. Analysis of the hydrochemistry and geological features was performed to determine which sets of geological features control the groundwater system.

In order to map the hydrogeological boundaries and recharge – discharge mechanism, this research used two main approaches: map and section analysis and hydrochemical analysis of major element concentration. A methodological objective of the study was also to assess the applicability cluster analysis in achieving the scientific objective. Finally, as an aid to management and future development of groundwater resources in the region, these

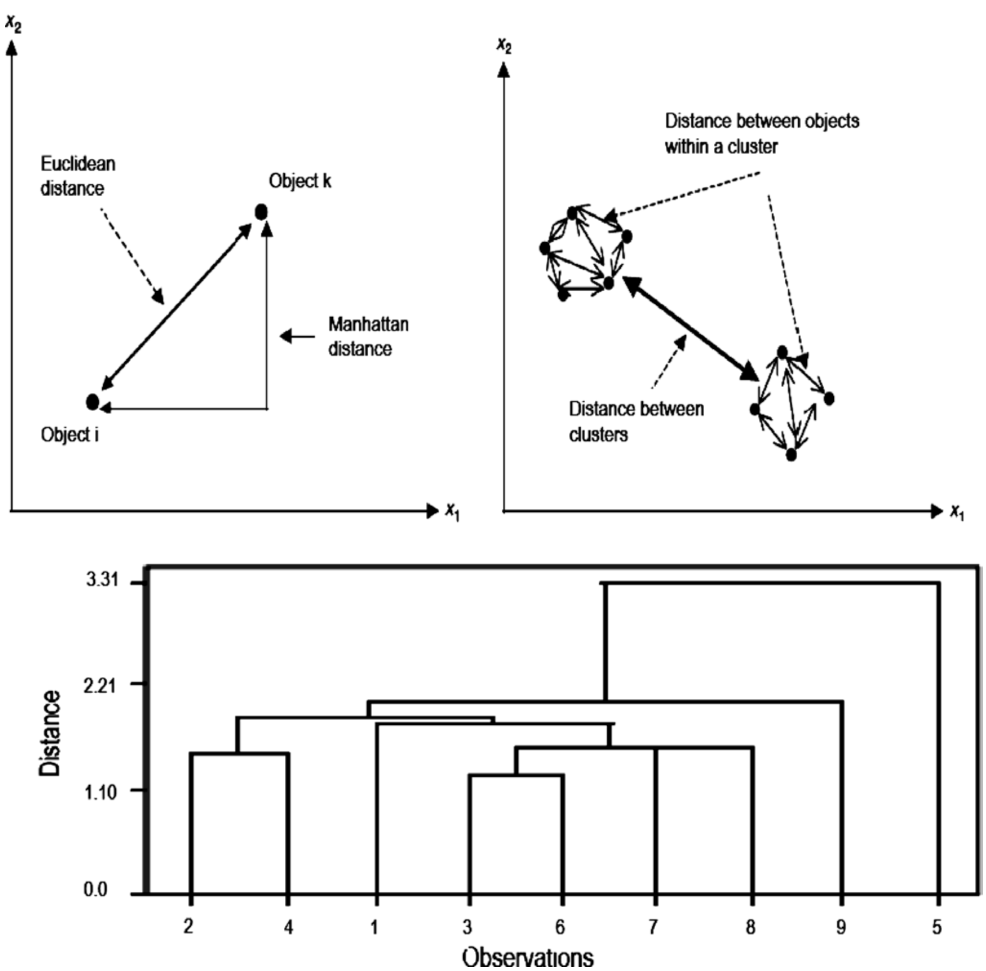

Fig. 5. The schematic of Euclidean distance in cluster analysis.

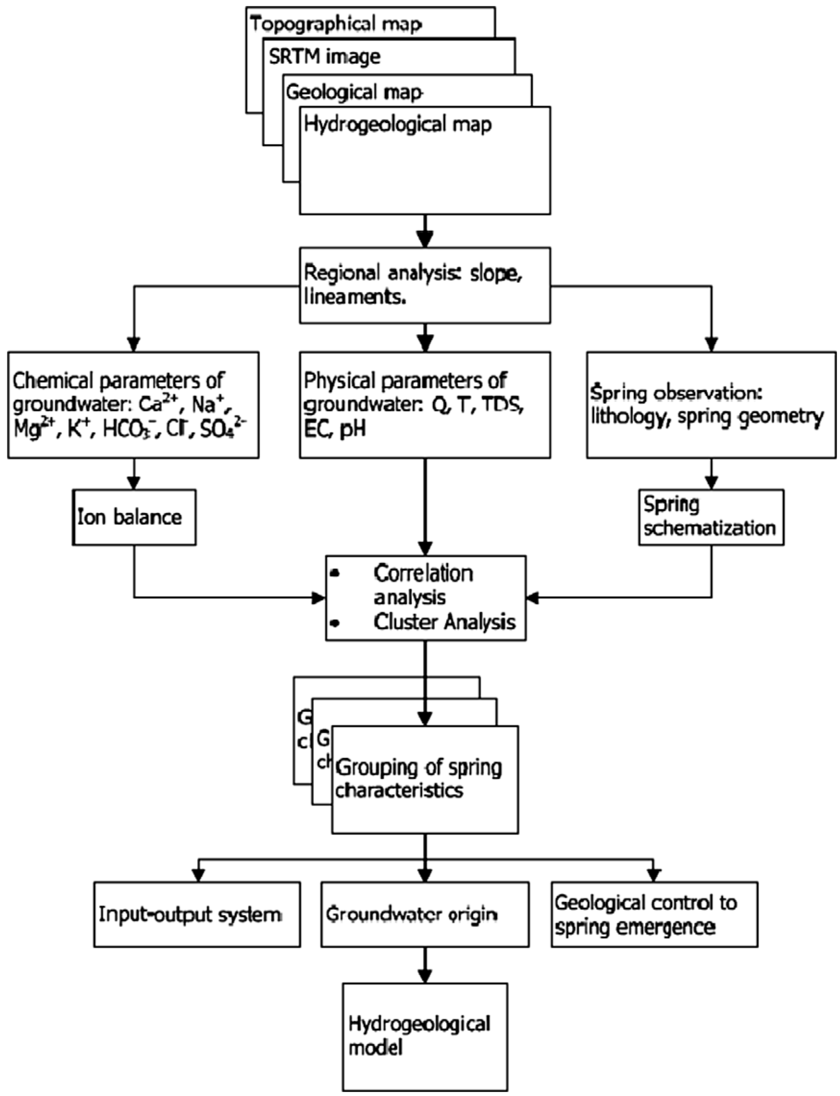

Fig. 6. The methodology of the research.

approaches were also applied to divide the territory in areas with distinct groundwater quality. The detailed work describes as follows (see Fig. 6).

(1) *Map and section analysis*: Ihe desk study consisted of plotting groundwater spring locations based on geological map. Geological sections were drawn across the spring belt. The sections were checked with field observation at each spring location. Field observations also measured the coordinates, physical and chemical parameters of groundwater quality parameters. Physical parameters taken on the field comprised of: air temperature, water temperature, Electric Conductivity (EC), Total Dissolved Solids (TDS), and pH, using portable equipments. The discharge was measured using current meter for large discharge (more than 5 L/s) springs and volumetric method with a 10 L bucket and stopwatch for small discharge (less than 5 L/s).

(2) *Hydrochemical analyses*: For laboratory analyses, the spring water was sampled using 2 L plastic bottles. Duplets analysis was carried out comprised of the calculation of major elements concentrations using Standard Method for the Examination of Water and Wastewater (SMEWW) forhardness, calcium, magnesium, chloride, sodium, sulphate, and potassium measurements, and Standard National Indonesia (SNI) or Indonesian National Standards for bicarbonate measurements , as listed in Table 2. Chemical test results then was validated using ion balance equation (see Eq. (2)), before further analyses. We determined 20% error balances as permitted limit. Samples have higher than 20% of error balance will be re-tested while samples have lower than 20% error will be analyzed.

Table 2
Laboratory methods for major element measurements.

No	Parameters	Units	Methods
1	Hardness ($CaCO_3$)	mg/L	SMEWW 2340-C
2	Calcium (Ca^{2+})	mg/L	SMEWW 3500-Ca
3	Magnesium (Mg^{2+})	mg/L	SMEWW 3500-Mg
4	Chloride (Cl^{-})	mg/L	SMEWW 4500-Cl
5	Sodium (Na^{+})	mg/L	SMEWW 4500-Na
6	Sulphate (SO_4^{2-})	mg/L	SMEWW4500-SO_4
7	Potassium (K^{+})	mg/L	SMEWW 3500-K
8	Bicarbonate (HCO_3)	mg/L	SNI 06–2420

$$\left[\left(\sum \text{cations} - \sum \text{anions}\right) \Big/ \left(\sum \text{cations} + \sum \text{anions}\right)\right] \times 100\% \tag{2}$$

Table 3
Raw data.

ID	Spring name	ELV (masl)	Q (L/s)	TDS (ppm)	EC (μS/cm)	pH	Water temp, (°C)	Air temp, (°C)	Na (meq/L)	K (meq/L)	Ca (meq/L	Mg (meq/L)	Cl (meq/L)	HCO_3 (meq/L)	SO_4 (meq/L)	Charge Balance	Spring Type	Lithology
1	Cicurug i	573	19.49	88.00	176.00	6.70	23.70	26.70	0.36	0.15	0.65	0.68	0.27	1.54	0.19	−4.39	Fracture spring	Lava
2	Cicurug ii	573	18.81	90.00	190.00	6.80	23.10	26.12	0.38	0.12	0.73	0.54	0.28	1.36	0.26	−3.32	Fracture spring	Lava
3	Sindangparna	565	21.00	72.00	144.00	7.60	24.60	27.58	0.48	0.09	0.74	0.68	0.19	1.84	0.12	−3.79	Fracture spring	Lava
4	Pereng	577	28.42	91.00	182.00	6.70	24.10	27.09	0.43	0.09	0.53	0.40	0.10	1.16	0.10	3.44	Fracture spring	Lava
5	Cikamalayan	137	36.40	142.00	284.00	7.80	28.90	31.78	0.44	0.09	0.90	0.76	0.08	2.05	0.06	0.26	Fracture spring	Lahar
6	Leles	550	29.69	98.00	196.00	6.80	25.80	28.75	0.48	0.08	0.82	0.82	0.18	2.06	0.16	−4.15	Fracture spring	Lahar
7	Cipari	667	17.83	89.00	178.00	7.00	22.70	25.73	0.55	0.12	0.95	0.70	0.47	1.68	0.33	−3.14	Fracture spring	Lava
8	Cipicung Kubur	554	18.19	94.00	188.00	6.90	25.00	27.97	0.52	0.18	0.79	0.68	0.18	2.07	0.10	−4.01	Fracture spring	Lava
9	Palutungan	1165	5.53	107.00	214.00	8.10	18.40	21.53	0.97	1.15	1.01	0.92	0.60	2.80	1.03	−4.47	Fracture spring	Pyroclastic
10	Pereng	134	30.55	123.00	246.00	7.40	28.10	31.00	0.77	0.15	1.19	0.66	0.37	2.27	0.24	−1.88	Fracture spring	Lahar
11	Talaga Remis	310	25.24	62.50	125.0	7.70	27.10	30.02	0.57	0.11	0.65	0.76	0.30	1.63	0.28	−2.90	Fracture spring	Lava
12	Balong Kagungan Cilimus	560	18.77	64.00	128.00	7.00	23.50	26.51	0.52	0.12	0.51	0.40	0.15	1.22	0.10	2.54	Fracture spring	Lahar
13	Cibulan	544	17.00	109.00	218.00	7.90	24.70	27.68	0.65	0.13	0.85	0.96	0.37	2.02	0.39	−3.50	Fracture spring	Lahar
14	Dangdeur	330	11.57	111.00	222.00	7.60	27.30	30.22	0.62	1.08	1.21	0.88	0.16	3.48	0.10	0.61	Depression spring	Lahar
15	Cicerem	332	23.40	61.00	122.00	6.85	22.80	25.83	0.51	0.12	0.48	0.36	0.16	1.20	0.18	−2.19	Fracture spring	Lahar
16	Kebon Balong	466	21.65	84.00	168.00	7.20	25.50	28.46	0.56	0.14	0.81	0.44	0.19	1.81	0.05	−2.53	Fracture spring	Pyroclastic
17	Sangkanhurip	462	32.21	1200.00	2400.00	6.80	24.80	27.78	0.57	0.14	0.77	0.48	0.22	0.12	1.70	−2.00	Fracture spring	Lahar
18	Balong Dalem	571	29.54	94.00	188.00	6.70	24.70	27.68	0.43	0.14	0.89	0.40	0.19	1.45	0.17	1.21	Fracture spring	Lahar
19	Balong Kagungan (Kramat Mulya)	638	20.54	172.00	344.00	7.80	25.00	7.80	0.87	1.20	1.54	0.56	0.93	2.72	0.92	−4.63	Fracture spring	Lahar
20	Cikajayaan	408	15.58	72.00	144.00	6.80	22.60	25.63	0.57	0.13	0.69	0.44	0.11	1.71	0.05	−1.04	Fracture spring	Lahar
21	Citengah	135	29.78	132.50	265.00	7.40	28.30	31.19	0.65	0.14	1.15	0.36	0.15	1.86	0.12	3.93	Fracture spring	Lahar
22	Cicerem	320	13.43	63.00	126.00	6.48	25.00	30.30	0.48	0.13	0.69	3.45	0.11	4.59	0.07	−0.21	Fracture spring	Lahar
23	Silinggonom	568	17.94	69.00	138.00	7.20	23.30	26.31	0.53	0.10	0.69	0.36	0.14	1.38	0.07	2.52	Fracture spring	Lahar
24	Situsari	705	19.93	72.50	145.00	7.10	22.10	25.14	0.45	0.10	0.69	0.44	0.16	1.50	0.16	−4.28	Fracture spring	Lava
25	Cibitung	743	16.46	83.00	166.00	7.00	23.90	26.90	0.28	0.06	0.98	0.72	0.19	1.83	0.16	−3.30	Fracture spring	Lava
26	Cibewok	570	27.85	199.00	398.00	7.90	25.20	28.17	0.77	0.17	1.54	1.45	0.93	2.08	1.03	−1.47	Fracture spring	Lahar
27	Cibulakan	530	31.56	45.00	90.00	7.35	23.10	26.12	0.58	0.11	1.17	0.68	0.18	2.15	0.18	0.91	Fracture spring	Pyroclastic
28	Cikole	335	20.45	97.00	194.00	6.60	25.90	28.85	0.52	0.09	0.89	0.52	0.18	1.82	0.13	−2.61	Depression spring	Lahar
29	Ciuyah Desa	278	2.45	12000.00	24000.00	7.30	39.40	42.03	2.90	3.20	2.20	04.80	4.80	2.70	1.20	2.79	Fracture spring	Klw
30	Cigugur	678	9.66	107.00	214.00	6.90	22.40	25.43	0.25	0.10	1.40	0.36	0.11	2.06	0.15	−4.75	Fracture spring	Lava
31	Ciputri	815	6.43	98.00	196.00	7.10	21.50	24.56	0.42	0.11	0.85	0.74	0.41	1.61	0.24	−3.26	Fracture spring	Pyroclastic
32	Cibinuang	762	15.81	81.00	162.00	7.25	23.40	26.41	0.50	0.09	0.77	0.52	0.15	1.68	0.16	−3.00	Fracture spring	Lava
33	Cibulakan	650	19.00	108.00	216.00	7.00	22.80	25.83	0.32	0.09	0.73	0.48	0.15	1.50	0.12	−4.45	Fracture spring	Lahar
34	Citambak	658	16.86	123.00	246.00	7.70	25.40	28.36	0.48	0.10	1.89	0.76	0.18	2.63	0.42	0.12	Fracture spring	Lava
35	Cibuluh	389	20.00	54.00	108.00	7.00	24.40	27.39	0.50	0.13	0.85	0.85	0.58	1.10	0.79	−2.95	Fracture spring	Lahar
36	Citengah	519	27.33	41.00	82.00	7.00	22.40	25.43	0.39	0.12	0.62	0.20	0.16	1.17	0.12	−4.42	Fracture spring	Lava
37	Cikupa	770	9.55	109.00	218.00	6.15	23.70	26.70	0.54	0.12	0.67	0.32	0.16	1.20	0.16	4.11	Depression spring	Pyroclastic
38	Cipanas II	367	15.85	126.00	252.00	9.00	22.40	25.43	4.64	0.06	0.61	0.12	1.20	3.70	1.02	−4.35	Fracture spring	Lahar
39	Citiis	629	25.89	110.00	220.00	7.90	24.70	27.68	0.61	0.17	0.85	0.81	0.40	1.65	0.55	−3.27	Fracture spring	Pyroclastic
40	Cikabuyutan	361	19.30	156.00	312.00	8.00	25.60	28.56	0.71	0.08	1.63	1.27	0.15	3.14	0.11	4.07	Fracture spring	Lahar
41	Cibulakan	672	10.33	110.00	220.00	7.20	23.40	26.41	0.38	0.10	1.52	0.20	0.12	1.69	0.27	2.55	Fracture spring	Lava
42	Cipetey	534	20.72	45.00	90.00	7.10	23.10	26.12	0.38	0.10	0.50	0.32	0.15	1.11	0.09	−1.57	Fracture spring	Lahar
43	Cihanyir	517	19.71	165.00	330.00	7.20	25.90	28.85	0.36	0.14	0.60	0.16	0.16	1.10	0.11	−4.56	Fracture spring	Lava
44	Citambak Girang	651	23.00	116.50	233.00	6.90	22.90	25.92	0.50	1.10	1.09	0.56	0.47	2.09	0.44	4.20	Fracture spring	Lava
45	Balong Beunteur	751	14.69	77.00	154.00	6.90	24.00	27.00	0.42	0.12	0.95	0.26	0.15	1.59	0.12	−3.02	Fracture spring	Lahar
46	Bandorasa	453	21.05	86.00	172.00	6.70	25.90	28.85	0.42	0.10	1.01	0.70	0.21	1.78	0.15	1.95	Fracture spring	Lahar
47	Puncak Lapang	754	11.06	76.00	152.00	76.0	23.60	26.61	0.42	0.11	0.93	0.39	0.27	1.50	0.26	−4.85	Depression spring	Lava
48	Liang Panas	275	3.86	1000.00	2000.00	6.70	37.10	39.79	2.28	2.25	1.14	0.60	3.50	2.20	1.15	−4.42	Fracture spring	Klw
49	Cibayuning	535	21.41	123.00	246.00	7.10	25.90	28.03	0.39	0.13	0.65	0.25	0.16	1.25	0.14	−4.51	Fracture spring	Lava
50	Cibulakan Cilimus	571	20.32	69.00	138.00	7.10	23.70	27.50	0.52	0.10	0.65	0.66	0.20	1.71	0.12	−2.53	Fracture spring	Lava
51	Cibulakan 1	484	11.02	63.00	126.00	6.40	26.50	29.00	0.35	0.10	0.80	0.90	0.18	1.78	0.10	2.01	Fracture spring	Lahar
52	Cibulakan tarik	925	4.72	93.00	186.00	6.92	22.60	23.40	0.61	0.20	1.00	0.66	0.31	1.93	0.23	0.03	Fracture spring	Lava

(*continued on next page*)

Table 3 (*continued*)

ID	Spring name	ELV (masl)	Q (L/s)	TDS (ppm)	EC (μS/cm)	pH	Water temp, (°C)	Air temp, (°C)	Na (meq/L)	K (meq/L)	Ca (meq/L	Mg (meq/L)	Cl (meq/L)	HCO_3 (meq/L)	SO_4 (meq/L)	Charge Balance	Spring Type	Lithology
53	Cicalung	483	13.07	211.00	422.00	7.02	25.00	28.70	0.35	0.10	0.75	0.82	0.18	1.87	0.17	−4.64	Fracture spring	Lahar
54	Cigasong	215	31.85	143.00	286.00	6.77	27.00	30.50	0.68	0.15	2.80	2.35	0.38	4.70	0.42	4.21	Fracture spring	Lahar
55	Cigempur	413	28.60	39.00	78.00	7.20	22.60	29.82	0.30	0.06	0.80	0.25	0.18	1.23	0.10	−3.52	Fracture spring	Lava
56	Cigirang	292	3.06	2000.00	4000.00	7.80	37.10	31.60	3.10	3.26	2.10	0.80	1.20	3.50	3.90	3.70	Fracture spring	Lahar
57	Cigobang	355	30.78	96.00	192.00	7.50	26.00	30.67	0.61	0.08	1.60	1.07	0.17	2.78	0.17	3.64	Fracture spring	Lahar
58	Cigorowong	561	26.87	36.00	72.00	7.15	22.40	27.64	0.52	0.10	0.80	0.74	0.18	1.98	0.16	−3.51	Fracture spring	Lava
59	Cigugula	320	14.87	42.00	84.00	7.40	25.00	31.19	0.39	0.13	0.60	3.29	0.08	4.51	0.08	−2.99	Fracture spring	Lahar
60	Ciguludung	486	11.40	64.00	128.00	7.29	24.20	27.30	0.35	0.06	0.61	07.29	0.18	1.12	0.11	−3.88	Fracture spring	Lava
61	Ciguranteng	778	14.30	120.00	240.00	7.40	25.70	24.45	0.52	0.10	0.80	0.58	0.17	1.78	0.16	−2.61	Fracture spring	Lava
62	Cihiuem	324	12.46	112.00	224.00	8.50	24.00	31.13	0.52	1.08	1.12	0.66	0.11	2.90	0.08	4.39	Depression spring	Lahar
63	Cijambar	649	14.08	101.00	202.00	6.90	24.40	26.35	0.48	0.10	0.60	0.49	0.15	1.54	0.14	−4.48	Fracture spring	Lava
64	Cijambu	443	20.00	252.00	504.00	7.70	26.70	29.38	0.39	0.20	0.90	0.49	0.20	1.50	0.15	3.90	Fracture spring	Lahar
65	Cikalamayan	382	1.28	424.00	848.00	8.80	61.40	30.28	0.52	0.10	0.80	0.74	0.51	1.27	0.52	−3.03	Fracture spring	Lahar
66	Cikamalayan	652	9.78	123.00	246.00	6.90	23.90	26.31	0.57	0.18	1.20	0.66	0.28	2.12	0.22	−0.26	Depression spring	Lava
67	Cikaracak	349	32.00	562.00	1124.00	7.90	29.60	30.76	0.61	0.08	1.50	0.99	0.14	2.92	0.17	−0.91	Contact spring	Lahar
68	Cikidang	363	18.44	169.00	338.00	7.90	26.30	30.55	0.48	0.13	2.00	0.82	0.34	2.60	0.21	4.23	Depression spring	Lahar
69	Cikuda	508	10.87	55.00	110.00	6.75	25.50	27.50	0.30	0.05	1.40	0.33	0.08	1.76	0.36	−2.74	Fracture spring	Lava
70	Cikuya	371	19.83	250.00	500.00	8.00	25.00	30.44	0.44	0.05	0.75	0.41	0.48	0.65	0.48	1.16	Fracture spring	Lahar
71	Cilegog	342	12.20	28.00	56.00	6.50	24.80	30.86	0.91	0.20	1.20	0.74	0.48	1.67	0.77	2.29	Depression spring	Lahar
72	Cileles	582	11.83	39.00	78.00	6.50	24.30	27.20	0.44	0.10	1.55	0.41	0.1	2.11	0.12	3.11	Contact spring	Lava
73	Cimalaka	330	15.33	105.00	210.00	7.40	27.50	31.04	0.44	0.10	0.40	0.25	0.17	0.98	0.13	−3.90	Fracture spring	Lahar
74	Cimampira	1139	3.20	81.00	162.00	7.05	23.90	23.60	0.200	0.20	0.80	0.80	0.19	1.97	0.14	4.29	Fracture spring	Lava
75	Cinyusu	650	22.09	110.00	220.00	7.00	25.10	26.34	0.48	0.15	1.70	0.58	0.31	2.01	0.36	4.07	Fracture spring	Lava
76	Cipago	278	23.32	475.00	950.00	26.50	26.50	31.80	0.70	0.20	2.89	2.47	0.56	4.90	0.30	4.10	Depression spring	Lahar
77	Cipanas(Argalingga)	1273	3.68	23.00	46.00	7.38	19.60	22.80	0.61	0.23	1.00	0.49	0.25	1.83	0.21	0.92	Contact spring	Lava
78	Cipulus	712	18.66	146.00	292.00	7.10	26.60	25.42	0.48	0.08	0.50	0.49	0.17	1.33	0.16	−3.48	Fracture spring	Lava
79	Ciruyug	537	21.66	84.00	168.00	6.40	26.30	28.00	0.44	0.15	0.50	0.25	0.18	1.12	0.17	−4.84	Fracture spring	Lava
80	Cisarai	748	9.17	16.00	32.00	6.80	22.30	24.89	0.44	0.08	1.84	0.33	0.42	1.75	0.32	3.67	Depression spring	Pyroclastic
81	Citembong	320	14.87	101.00	202.00	7.30	25.10	31.19	0.44	1.05	1.00	0.58	0.18	2.74	0.14	−0.03	Fracture spring	Lahar
82	Citimbang	722	10.00	95.00	190.00	7.10	23.60	25.28	0.52	0.10	0.70	0.58	0.17	1.76	0.06	−2.43	Fracture spring	Lava
83	Citutupan	650	11.12	30.00	60.00	7.07	23.20	26.10	0.52	0.18	0.90	0.41	0.34	1.44	0.37	−3.42	Fracture spring	Lava
84	Ciuyah Kasim	242	4.60	12000.00	24000.00	7.20	30.20	32.33	3.20	2.60	2.60	1.10	4.90	2.60	1.50	2.70	Fracture spring	Klw
85	Ciuyah Pago	275	3.41	12000.00	24000.00	7.00	32.10	31.85	2.80	3.10	2.10	1.10	4.50	2.30	1.50	4.60	Fracture spring	Klw
86	Ciuyah Seugeuh	271	4.53	12000.00	24000.00	7.00	32.10	31.91	2.30	3.80	1.80	0.90	4.60	2.40	1.08	4.27	Fracture spring	Klw
87	Ciwetan	135	37.63	123.00	246.00	7.40	28.70	33.91	0.39	0.08	0.85	0.66	0.14	1.38	0.28	4.52	Depression spring	Lahar
88	Dusun Manis	389	22.24	192.00	384.00	8.40	26.10	30.17	0.48	0.10	0.75	0.66	0.11	1.78	0.06	0.91	Depression spring	Lahar
89	Gn Herang Tonggoh	797	5.49	95.00	190.00	7.21	23.90	26.00	0.57	0.13	0.75	0.58	0.14	1.82	0.10	−1.07	Fracture spring	Lava
90	Janawi	517	12.20	131.00	262.00	6.36	24.90	27.70	0.35	0.15	0.80	0.16	0.17	1.23	0.11	−1.54	Fracture spring	Lava
91	Jingkang	823	10.47	67.00	134.00	7.37	25.00	28.80	0.70	0.10	0.90	0.49	0.23	1.86	0.17	−1.45	Fracture spring	Lava
92	Kalapa Gunung	572	15.56	186.00	372.00	7.70	24.70	27.48	0.57	0.13	0.70	0.74	0.23	1.70	0.15	1.54	Fracture spring	Lava
93	Kebon Seureuh	111	40.33	139.00	278.00	8.00	29.90	34.26	0.52	0.08	1.90	0.25	0.34	1.84	0.39	3.39	Depression spring	Lahar
94	Leles	135	16.63	149.50	299.00	8.40	28.10	33.91	0.42	0.13	1.20	0.25	0.18	1.57	0.10	3.64	Depression spring	Lahar
95	Leles	336	14.45	51.00	102.00	6.99	24.70	28.10	0.91	0.20	1.15	0.66	0.45	1.80	0.75	−1.29	Fracture spring	Lahar
96	MCK	330	18.30	84.00	168.00	7.20	26.20	31.04	0.57	1.08	1.15	0.74	0.17	3.33	0.16	−1.78	Fracture spring	Lahar
97	Mencut(Bp. Jamahi)	119	17.83	85.00	170.00	6.99	26.00	29.50	0.65	1.10	0.90	0.49	0.32	2.37	0.21	4.05	Contact spring	Lahar
98	Mencut(Bp. Suheri)	118	32.21	97.00	194.00	6.48	26.00	29.90	0.57	0.08	1.85	0.33	0.29	2.15	0.19	3.47	Contact spring	Lahar
99	Pakuan	511	11.30	118.00	236.00	6.80	25.90	28.38	0.30	0.05	0.80	0.33	0.18	1.32	0.12	−4.28	Depression spring	Lava
100	Paniis	293	20.85	160.50	321.00	6.90	27.00	31.58	0.44	0.10	0.50	1.64	0.18	2.54	0.14	−3.24	Fracture spring	Lahar
101	Panten Kaler	1270	6.93	29.00	58.00	7.72	20.80	23.50	0.55	0.10	0.80	0.41	0.25	1.29	0.21	3.21	Fracture spring	Pyroclastic
102	Pasawahan	360	14.72	34.00	68.00	7.05	25.00	28.30	0.65	0.08	1.50	0.82	0.14	2.60	0.19	2.01	Fracture spring	Lahar
103	Pasawahan(Bujangga)	448	9.72	65.00	130.00	6.42	25.00	29.30	0.35	0.06	0.40	0.29	0.17	0.93	0.10	−4.63	Contact spring	Lava
104	Pasawahan(Tespong)	387	11.77	38.00	76.00	8.28	25.00	28.70	0.44	0.10	0.85	0.82	0.54	1.24	0.62	−4.17	Fracture spring	Lahar
105	PDAM Paniis	347	31.49	199.00	398.00	6.64	26.00	30.70	0.87	0.23	1.25	0.82	0.51	2.13	0.79	−3.91	Fracture spring	Lahar
106	Rambatan	295	24.84	910.00	1820.00	8.80	29.00	31.55	0.44	0.10	0.55	2.88	0.18	3.93	0.06	−2.57	Fracture spring	Lahar
107	Rancakesik	149	10.07	134.00	268.00	7.60	27.30	33.70	0.26	0.08	0.75	0.49	0.06	1.56	0.10	−4.27	Fracture spring	Lahar
108	Situ Sangiang	998	4.61	85.00	170.00	8.53	26.60	24.30	0.65	0.18	0.90	0.74	0.39	1.97	0.25	−2.75	Fracture spring	Lava

109	Sugih Pamalengan	866	5.89	93.00	186.00	6.67	22.70	23.80	0.57	0.15	0.95	0.58	0.28	1.89	0.21	−3.02	Fracture spring	Lava
110	Talaga Deleg	204	14.67	63.00	126.00	6.65	763.00	30.90	0.30	0.08	0.80	0.41	0.08	1.39	0.12	−0.27	Fracture spring	Lahar
111	Tarikolot	145	34.07	116.00	232.00	7.30	07.30	33.76	0.22	0.05	0.70	0.33	0.08	0.90	0.22	3.66	Fracture spring	Lahar
112	Telaga Pancar(dekatAlun2)	373	13.58	73.00	146.00	6.57	25.10	31.10	0.48	0.08	0.80	0.66	0.48	1.21	0.50	−4.22	Fracture spring	Lahar
128	Talaga Deleg. Kaduela. Pasawahan. and Kuningan	204	30.40	63.00	126.00	6.65	26.00	30.90	0.33	0.09	0.78	0.35	0.10	1.45	0.12	−4.00	Fracture spring	Lahar
129	Cicerem. Kaduela. and Pasawahan	320	14.87	63.00	126.00	6.48	25.00	30.30	0.52	0.15	0.65	0.74	0.28	1.67	0.31	−4.62	Fracture spring	Lava
130	PDAM Paniis. Pasawahan. and Kuningan	347	16.12	199.00	398.00	6.64	26.00	30.70	0.99	0.26	1.15	0.94	0.56	1.78	0.89	1.68	Fracture spring	Lahar
131	Cigimpul. Cingkup. and Pasawahan	360	16.73	34.00	68.00	7.05	25.00	28.30	0.57	0.13	0.75	0.82	0.31	1.84	0.29	−3.77	Fracture spring	Lava
132	Telaga Pancar. Pasawahan (dekat Alun2)	373	21.25	73.00	146.00	6.57	25.10	31.10	0.52	0.13	0.60	0.74	0.25	1.66	0.27	−4.69	Fracture spring	Lava
133	Bujangga, Padabeunghar, Pasawahan	448	20.82	65.00	130.00	6.42	25.00	29.30	0.44	0.15	0.95	0.58	0.20	1.91	0.17	−3.73	Contact spring	Lahar
134	Tespong, Padabeunghar, and Pasawahan	387	14.99	38.00	76.00	8.28	25.00	28.70	0.29	0.06	1.41	0.25	0.10	1.61	0.16	3.59	Fracture spring	Lava
220	Rt 5, Rw 1, Blok Sang Raja, and Cigasong	185	13.41	143.00	286.00	6.77	27.00	30.50	0.44	1.07	2.15	1.19	0.19	4.08	0.18	4.18	Fracture spring	Lahar
221	Tirta Wening/Balong Gede, Paniis, and Maja	542	12.92	146.00	292.00	6.65	25.50	28.20	0.55	0.07	2.72	0.59	0.26	3.04	0.39	3.31	Fracture spring	Lahar
222	Jero Kaso, Sada Sari, and Maja	687	10.23	93.00	186.00	6.76	24.40	29.30	0.41	0.04	0.82	0.79	0.16	1.76	0.15	0.03	Fracture spring	Pyroclastic
223	Gn Herang Tonggoh, Sada Ari, and Argapura	797	10.02	95.00	190.00	7.21	23.90	26.00	0.35	0.05	0.85	0.74	0.16	1.48	0.24	2.90	Depression spring	Pyroclastic
224	Jingkang, Sukadana, and Argapura	823	10.55	67.00	134.00	7.37	67.00	28.80	0.38	0.05	0.80	0.74	0.15	1.47	0.24	2.93	Depression spring	Pyroclastic
225	Rt 1/Rw2,Kerta mukti, Cicalung, and Maja	483	12.67	211.00	422.00	7.02	25.00	28.70	0.28	0.08	1.05	0.41	0.17	1.70	0.13	−4.78	Depression spring	Lahar
226	Mencut, Rajawangi, Leuwi Munding (Bp, Suheri)	150	14.58	137.30	274.60	6.48	26.00	29.90	1.86	1.13	1.48	1.44	0.08	6.28	0.08	−4.27	Depression spring	Pyroclastic
227	Mencut, Rajawangi, Leuwi Munding (Bp, Jamahi)	119	14.00	124.50	249.00	6.99	26.00	29.50	0.89	0.16	0.55	0.40	0.11	1.78	0.17	−1.49	Contact spring	Lahar
235	Talaga Herang, Lengkong Kulon, and Sindangwangi	303	13.75	53.00	106.00	6.57	24.70	27.80	0.30	0.07	1.62	0.27	0.12	1.96	0.16	0.22	Fracture spring	Lahar
236	Leles, Padaherang, and Sindangwangi	395	12.24	51.00	102.00	6.99	24.70	28.10	0.26	0.86	0.89	0.29	0.15	1.76	0.28	2.41	Depression spring	Lahar
237	Cikuda, Padaherang, and SindangWangi	508	11.00	115.30	230.60	6.75	25.50	27.50	0.26	0.07	1.45	0.13	0.07	1.54	0.16	3.80	Fracture spring	Lava
238	Cibulakan, Bantar Agung, and Sindangwangi	484	11.66	176.60	353.20	6.40	26.50	29.00	0.24	0.19	1.70	0.45	0.10	2.29	0.10	1.80	Fracture spring	Lahar
239	Citutupan, Teja, and Sindangwangi	650	9.76	11.10	22.20	7.07	23.20	26.10	0.32	0.07	1.45	0.15	0.14	1.57	0.16	3.43	Fracture spring	Lava
240	Cileles, Teja, and Rajagaluh	582	10.98	39.00	78.00	6.50	24.30	27.20	0.44	0.08	2.69	0.58	0.17	3.61	0.33	−4.18	Contact spring	Lahar
241	Janawi, Payung, and Rajagaluh	517	10.29	131.00	262.00	6.36	24.90	27.70	0.28	0.06	1.45	0.15	0.17	1.50	0.14	3.50	Fracture spring	Lava
242	Ciguludung, Payung, and Rajagaluh	486	11.33	64.00	128.00	7.29	24.20	27.30	0.30	0.07	1.40	0.16	0.16	1.57	0.14	1.85	Fracture spring	Lava

(*continued on next page*)

Table 3 (*continued*)

ID	Spring name	ELV (masl)	Q (L/s)	TDS (ppm)	EC (µS/cm)	pH	Water temp. (°C)	Air temp. (°C)	Na (meq/L)	K (meq/L)	Ca (meq/L	Mg (meq/L)	Cl (meq/L)	HCO_3 (meq/L)	SO_4 (meq/L)	Charge Balance	Spring Type	Lithology
243	Panten Kaler. Aegalingga, and Argapura	1270	6.24	29.00	58.00	7.72	22.32	23.50	0.13	0.06	1.40	0.10	0.28	1.21	0.22	−0.91	Depression spring	Pyroclastic
244	Cipanas. Argalingga, and Argapura	1254	5.98	38.20	76.40	7.38	22.83	22.80	0.16	0.06	1.45	0.07	0.12	1.29	0.23	3.08	Fracture spring	Pyroclastic
245	Cimampira, Tejamulya	1139	6.54	81.00	162.00	7.05	24.02	23.60	0.15	0.38	0.72	0.51	0.16	1.19	0.26	4.30	Fracture spring	Pyroclastic
246	Cibulakan tarik, Sunia Lama, and Banjaran	925	7.20	16.30	32.60	6.92	22.60	23.40	0.38	0.05	0.44	0.68	0.14	1.42	0.15	−4.62	Fracture spring	Lava
247	Stu Sangiang, Sangiang, and Talaga	998	6.39	32.10	64.20	8.53	24.67	24.30	0.04	0.02	1.70	0.11	0.10	1.58	0.12	2.15	Fracture spring	Pyroclastic

(3) *Statistical analysis*: The hydrochemical parameters and the result from field observations were analyzed using basic statistical analysis and cluster analysis to assist the hydrogeological analysis, by using Minitab version 14 (trial version) by Minitab Inc.

(4) *Interpretation*: The interpretation aims to schematization of hydrogeological system based on cluster analysis of hydrogeochemistry parameters. Interpretation of hydrogeochemistry is underlined by several assumptions as listed: (1) natural water chemistry is a result of rock-water reactions such as dissolution/precipitation, reactions on aquifer surfaces, and biological reactions. (2) Distinctive chemical signatures are related to specific sets of reactions. (3) Dissolved concentrations generally increase along the subsurface flow path until major components reach maximum values dictated by mineral equilibrium. (4) Hydrochemical facies are directly related to the dominant processes (Thyne et al., 2004).

Analysis and interpretations

The survey was conducted in period of May until June 2006, in dry season, with less than 50 mm of precipitation per month. As much as 119 springs from east slope. At each spring, there were 14 variables measurements (see Table 3): elevation (Elev) in masl, spring discharge (Q) in L/s, Total Dissolved Solids (TDS) in ppm, electro conductivity (EC) in µS/cm, acidity (pH), water temperature (W.temp) (°C), air temperature (A.temp) in °C, major elements concentration (mg/L): calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), sodium (Na^+), sulfate (SO_4^{2-}), potassium (K^+), and bicarbonate (HCO_3^-). Large deviations as shown by seven variables: elevation, TDS, EC, hardness, chloride, sodium, and bicarbonate (Table 4). This deviation should affect the cluster arrangements. Observations with maximum value of those variables should separate relatively from the other observations with normal value. In this section, we are going to discuss the separation of groundwater samples based on Piper diagram and cluster analysis.

Piper diagram

Piper diagram has successfully extracted three major groundwater facies: calcium bicarbonate, magnesium bicarbonate, and sodium–potassium–chloride type. The highly concentrated and possibly more mature chloride groundwaters are separated from the more dilute bicarbonate waters using this method. Groundwa-

Table 4
Descriptive analysis of the variables. Large deviations as shown by several variables: TDS EC, hardness, chloride, sodium, and bicarbonate should affect the clustering processes. Observations with maximum value of those variables should separated relatively from the other observations with normal value.

Variable	Mean	StDev	Minimum	Maximum
Elevation (Masl)	491.6	**237**	111	1273
Discharge (Q) (1/s)	17.522	8.6	1.3	40.3
TDS (ppm)	159.6	**221.7**	16	1001
EC (mS/cm)	130.3	**102.8**	16.3	515.5
PH	1221	0.6	6.2	9
W.temp	25.635	4.4	18.4	61.4
A.temp	28.581	3.1	21.5	42
Hardness ($CaCO_3$)	144.4	**331.7**	28.2	2488.8
Calcium (Ca^{2+})	26.07	39.5	8	283.4
Magnesium (Mg^{2+})	2187	61 5	1.4	432
Chloride (Cl)	564	**2536**	2	13,100
Sodium (Na^+)	426	**1916**	5	10,000
Sulfate (SO_4^{2-})	14.34	23	0	120
Potassium (K^+)	.3.96	41	2	210
Bicarbonate (HCO_3^-)	.81.9	**409.5**	12	2098.4

ter flows through aquifers composed dominantly of volcanic rocks are characterized by normal water temperature and bicarbonate enrichment, whereas those associated with deeper aquifer dominated by marine-based sediments exhibit elevated temperature and chloride enrichment.

The evolution of groundwater chemistry starts from no dominant ions type, then differentiated into three systems from high elevation to lower elevation respectively, as shown in Fig. 7. The first groundwater flow system is undergone calcium enrichment from intensive interaction with plagioclase-rich rocks. The second flow system is influenced by magnesium enrichment from sedimentary rocks with high magnesium, possibly from dolomite layers, which are intercalated in the sedimentary formations underneath the volcanic deposits. The third flow system is influenced by sodium–potassium–chloride from saline waters of sedimentary rocks.

Cluster analysis

Cluster analysis, with Minitab has successfully extracted three clusters. Cluster 1 consists of 112 observations, cluster 2 comprises of five observations, cluster 3 consists of two observations (see Table 5 Fig. 8).

Cluster 1 has small average distance from centroid of 1.99 and large maximum distance from centroid (9.23). Cluster 2 has small average distance from centroid of 1.55 and closer maximum distance from centroid of 3.05. Cluster 3 does not have the two distance measurements since they only consist of two observations.

Cluster 1 with large members (112 spring points) is occupied by spring data from heterogeneous rocks, pyroclastic breccias, lava flows, and laharic breccias. The heterogeneous lithology also gives various chemical characteristics as shown by maximum distance from centroid. Based on the same parameter, cluster 2 shows more homogeneous data characteristics as shown by closer distance from centroid. Cluster 3 cannot be analysed with only two members.

Centroid distance between cluster 1 and cluster 3 is 15.68. This is the longest distance, affected by entirely different spring characteristics of the two clusters. Cluster 1 and cluster 2 have 13.97 of Euclidean distance, while cluster 2 and cluster 3 has the closest distance of 9.28. This value indicates that cluster 2 and cluster 3 have rather similar characteristics. They both have high temperature, TDS, and EC, but different concentration of chloride.

Outlining hydrogeological systems

Every hydrochemical area can be distinguished by the geological formations, hydrogeological contexts, hydraulic gradients, groundwater clusters. The outline of hydrogeological system is

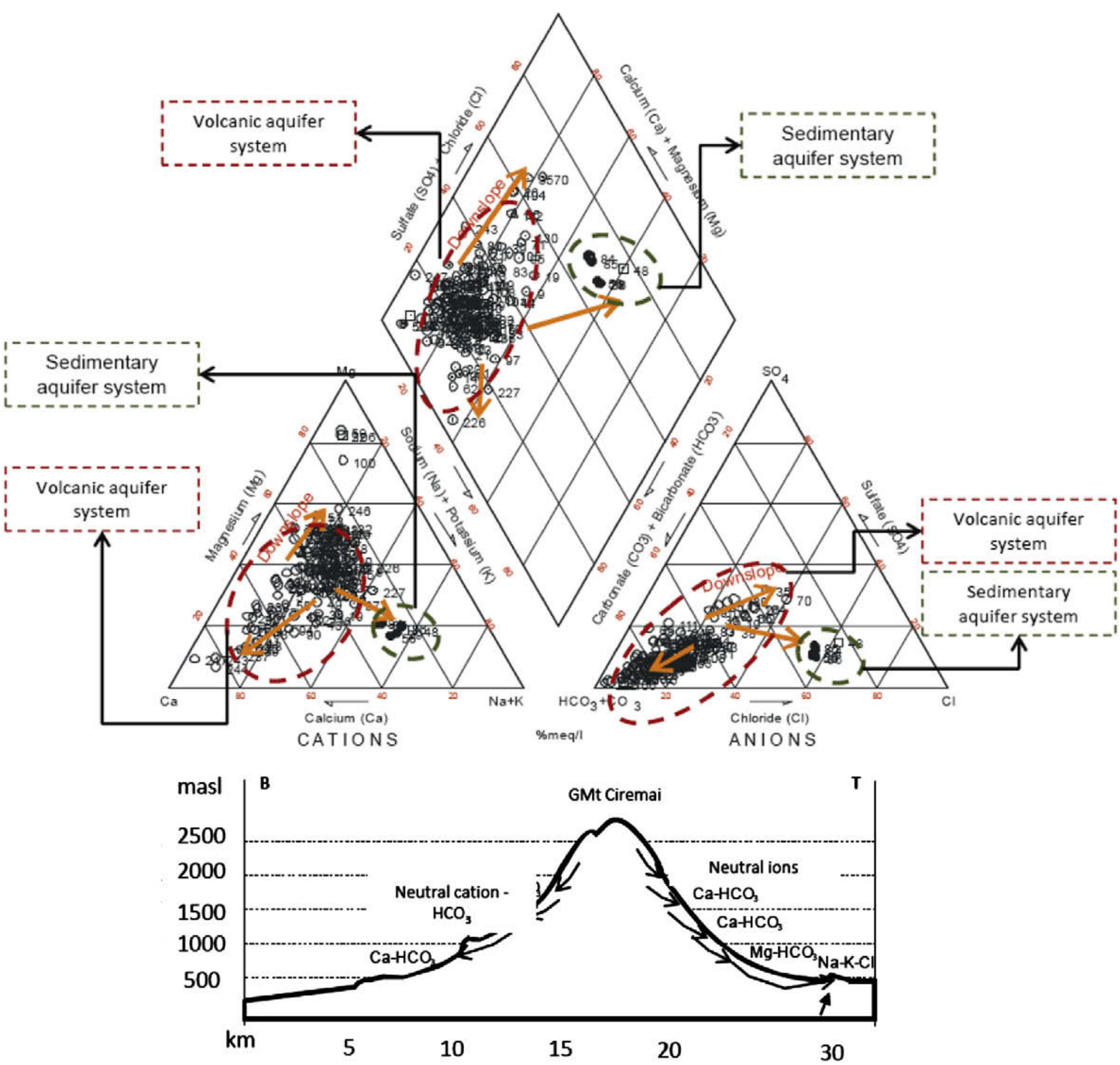

Fig. 7. The Piper diagram of major element concentrations in groundwater samples.

Table 5
Cluster analysis results (Minitab trial version). Centroid is the focal point of cluster. Maximum distance of observation from centroid is measured on each cluster. Cluster 1 shows more variation as shown by the large maximum distance from centroid (9.23), relatively to cluster 2 (3.05).

Cluster basics description	Number of observations	Average distance from centroid	Maximum distance from centroid
Cluster 1	112	1.99	9.23
Cluster 2	5	1.55	3.05
Cluster 3	2	0	0
Centroid distance			
	Cluster 1	Cluster 2	Cluster 3
Cluster 1	0	13.97	15.68
Cluster 2	13.97	0	9.28
Cluster 3	15.68	9.28	0

based on schematization of the three clusters. The interpretations lead to three hydrogeological systems (HS) (Fig. 9).

HS1 related to cluster 1, HS2 related to cluster 2, and HS3 related to cluster 3. HS1 consists of 112 observations is characterized by large variations of data with normal water temperature, TDS, EC, high loadings of calcium, magnesium, and bicarbonate. This condition is due to the many chemical influences as the groundwater flow from recharge area to discharge area in unconfined aquifer system of three lithological type (from up to down): pyroclastic breccias, lava, and laharic breccias. The groundwater characteristic is still dominated by meteoric water. Based on triangular plot from Herdianita and Priadi (2008), HS1 data points are classified as immature waters.

HS2 with five observations is characterized by moderately loadings of sodium, chloride, and bicarbonate is related to groundwater mixing with more saline hot water of volcanic origin. It suggest the dominant of volcanic rock dissolution in high temperature environment. This also lead to the moderately TDS and conductivity.

HS3 with two observations is separated by two other clusters due to the homogeneous characters (spring number 65 and 100) with deeper flow system, compared to HS2. The two springs, Cikalamayan (65) and Liang Panas (100) are differentiated from the other samples by high loadings of potassium, and chloride, in high water temperature. This indicates the dissolution of marine-based sediments with marine clay aquitard of Kaliwangu and Halang Formations. Layers of sand and clay in the formation below Ciremai's volcanic deposits, contribute to the high chloride content in the groundwater samples. Both HS2 and HS3 data points are classified as mature waters in the triangular plot from Herdianita and Priadi (2008). Another point from Uliana and Sharp (2001), Geochemical data from samples along the hypothesized regional flow path indicate a trend of increasing dissolved solids and Cl–HCO_3 ratios and decreasing Na–Cl ratios. These are consistent with evolution of groundwater in an unconfined regional system dominated by carbonates and evaporates. In the bicarbonate facies, the waters represent recent recharge modified by mineral dissolution and cation exchange. In the sulfate zones, the hydrochemical facies are controlled by gypsum, anhydrite, and halite dissolution, cation exchange, and mixing with Na–Cl waters. In the chloride zones, the hydrochemical facies are controlled by halite dissolution and irrigation return flow.

The first system showed high loading on bicarbonate and magnesium, and this factor was interpreted due to influence of the chemical interaction between water and volcanic rocks. The second system showed moderately loading on chloride and sodium, and it was assumed to be an influence of saline water from deeper aquifer. The third system showed high loading on chloride and sodium.

Thus, the following factors were recognized as influencing the evolution of groundwater identified in every cluster. The first factor is volcanic rock composition, which is different than sedimentary rock. This should give major differentiation to groundwater chemistry.The second factor is high hydraulic conductivity of volcanic aquifer system. It drives the high discharge of volcanic groundwater springs. Fractures makes this possible. Conversely, such low hydraulic conductivity of sedimentary rock gives the

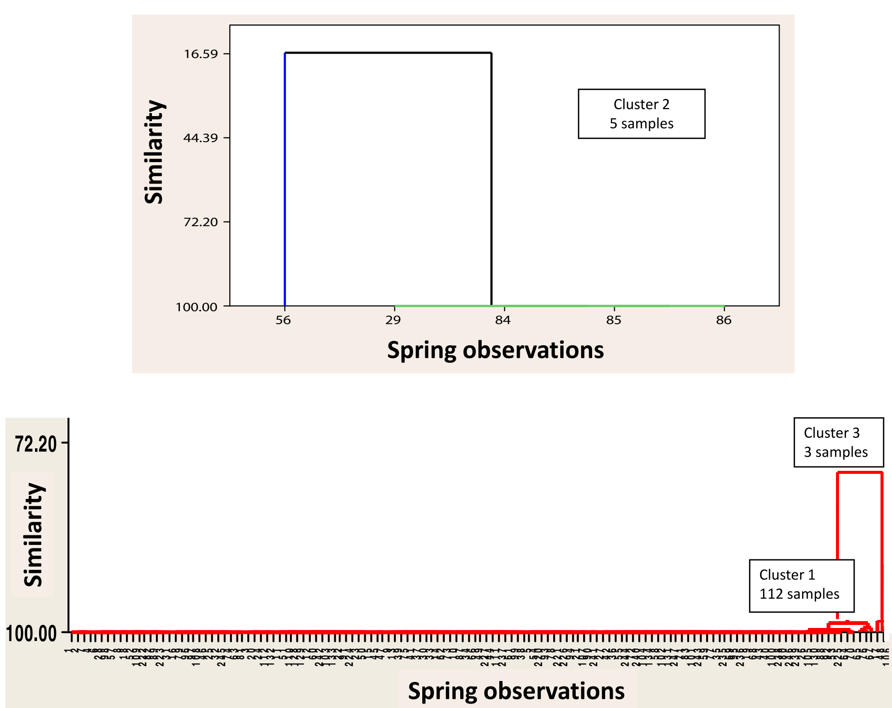

Fig. 8. Dendogram of cluster analysis (Minitab trial version). The lower dendogram is the continuation of the upper dendograrn. There are three clusters: cluster 1 (112 observations), cluster 2 (five observations), and cluster 3 (two observations).

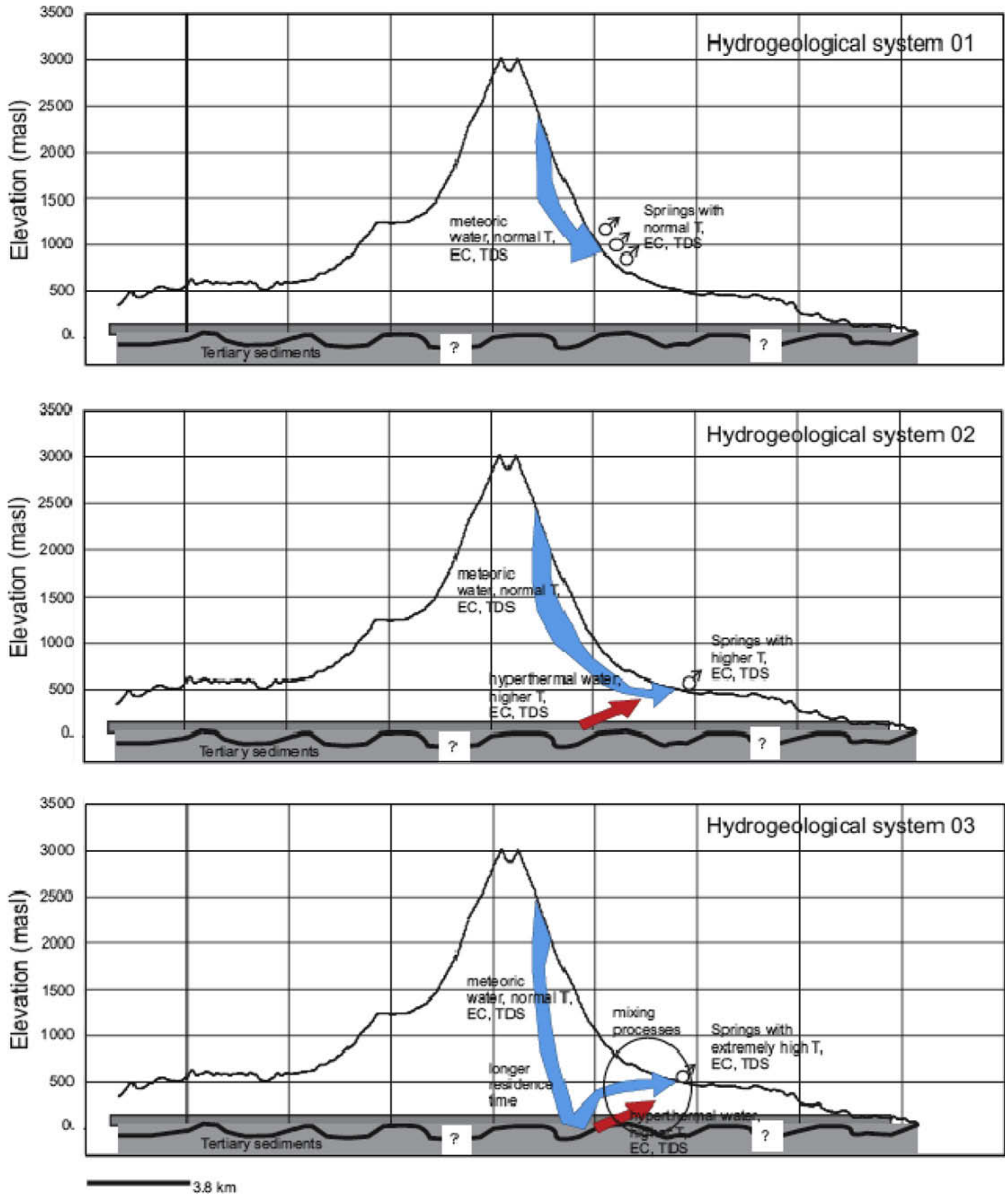

Fig. 9. The schematization of three hydrogeological systems. The schematization is based on interpretations of three clusters, lead to three hydrogeological systems: Hgl 1 (above), Hgl 2 (middle), and Hgl 3 (below). Hgl 1 is volcanic-meteoric lyfe ground wilier (cluster 1), Hgl 2 is volcanic-transition type ground wilier (cluster 2), and Hgl 3 is sediTnenliiTV-formation type ground water (cluster 3).

extremely limited discharge springs. The third factor is heat source with the possibility of two heat sources. The first is related with volcanic activity. The same hot springs with similar hydrochemical composition are also emerge at Kromong area, north from Ciremai. The second is related with geothermal gradient. Some portions of groundwater are able to reach deep formation and gain high temperature before come up to surface.

Conclusions

Cluster analysis has successfully extracted three clusters: cluster 1 (112 observations), cluster 2 (five observations), cluster 3 (two observations). The highly concentrated and possibly more mature groundwaters are separated from the more dilute waters using this method. It describes differences in the chemistry of the groundwaters resulting from the different aquifer materials through which they have flowed. Groundwaters flowing through aquifers composed dominantly of volcanic rocks are characterized by normal water temperature and bicarbonate enrichment, whereas those associated with deeper aquifer dominated by marine-based sediments exhibit elevated temperature and chloride enrichment.

The hydrogeological schematization has been made based on interpretations of three clusters. There are three hydrogeological systems (HS). HS1 with 112 springs is characterized by: heterogeneous data, normal water temperature, TDS, EC, and major elements concentrations. This condition is due to the many chemical influences as the groundwater flow from recharge area to discharge area in unconfined aquifer system. HS2 with five springs is characterized by: homogeneous data, high water temperature, TDS, and EC. The groundwater is interpreted as the result of interaction between normal meteoric water and hot water of volcanic origin. HS3 with two springs is characterized by: homogeneous characters with deeper flow system. High concentrations of chloride along with high water temperature are interpreted to be the effect of interaction between hot water with sedimentary layers of Fm. Kaliwangu, which deposited in marine environment.

The understanding and the particularities of the hydrochemistry of volcanic aquifer system represent further opportunities to apply multivariate statistical analysis. This method gives more quantitative approach in groundwater samples classification, to study correlate between chemical variables, and to evaluate the correspondence between groundwater sample observations. This paper has demonstrated the usefulness of the approach in hydrogeochemical investigations when considering the geological and hydrogeological knowledge of the aquifer.

This hydrogeochemical study fetches independent pieces of information that improved our knowledge of the volcanic aquifer system. Therefore, better understandings of the groundwater flow system could come out from hydraulic and geochemical modelling interaction. The regional understanding of the Ciremai aquifer system can be used to elaborate the steps of resources management and to estimate the impact of future development on the groundwater resources.

Acknowledgements

The authors would like to thank Directorate General of Higher Education for funding this research through Graduate Program Grant. Also, we highly appreciate contributions from The Board for Regional Planning of Kuningan Regency for water resources data and Director of PDAM Kuningan Regency for access to spring site. We also would like to thank our base camp owner and our team of undergraduate students that gave their time and effort to help us surveying spring data and gathering the first level analysis.

References

Bapeda Kuningan, 2002. Inventarisasi Mataair Kab. Kuningan, Bapeda Kuningan.

Chow, 1964. Soil Water. Prentice Hall.

Costello, A.B., Osborne, J.W., 2005. Best practices in exploratory factor analysis: four recommendations for getting the most from your analysis. Practical Assessment Research and Evaluation 10 (7), 20.

Dept. Pertambangan dan Energi, 1979. Data Dasar Gunungapi Indonesia, Dept. Pertambangan dan Energi.

Hem. J.D., 1973. Study and interpretation of natural water. USGS Water Supply Paper.

Herdianita, N.R., Priadi, B., 2008. Arsenic and mercury concentrations at several geothermal systems in West Java, Indonesia. ITB Journal of Science 40A(1), 1–14.

Irawan, D.E., Puradimaja, D.J., 2006a. The hydrogeology of the volcanic spring belt, east slope of Gunung Ciremai. In: Proceeding of IAEG Conference. West Java, Indonesia.

Irawan, D.E., Puradimaja, D.J., 2006b. The differentiation of hyperthermal groundwater origin by using multivariate statistics on water chemistry. Journal Geoaplika 1 (2).

IWACO – WASECO, 1989. Kuningan Regency Provincial Water Supply Report, Dept. of Public Works.

Linsley, R.K., Franzini, J.B., Freyberg, D.L., Tchobanoglus, G., 1992. Water Resources Engineering. New York, McGraw-Hill.

Mandel, Shiftan, 1981. Groundwater Resources: Investigation and Development. Academic Press.

Matthess, G., 1982. Properties of Groundwater. McGraw-Hill.

Miyazaki, T., 1993. Groundwater Basin Management. Tokai University Press.

Puradimaja, D.E., Sukarno, I., Abidin, Z., Irawan, D.E., 2002. Sistem Pengembangan dan Pengusahaan Air Bersih di Jawa Barat. Potensi dan Pola Bisnis Air Bersih serta Air Minum, Dipresentasikan pada acara Seminar Pemanfaatan dan Pengelolaan Air Bersih Guna Meningkatkan Kesehatan Masyarakat Jawa Barat Menuju Era Globalisasi, Aula Barat ITB, 22 Nopember 2002.

Puradimaja, D.J., Irawan, D.E., Hutasoit, L.M., 2003. The influence of hydrogeological factors on variations of volcanic spring distribution, spring discharge, and groundwater flow pattern. Bulletin of Geology 35 (1/2003), 15–23. ISSN: 0126-3498.

Situmorang, 1995, Peta Geologi Gunung Ciremai, Direktorat Vulkanologi.

Smith, L.I., 2002. A Tutorial on Cluster Analysis. <http://www.cs.montana.edu>.

Thyne, G., Güler, C., Poeter, E., 2004. Sequential analysis of hydrochemical data for watershed characterization, ground water. Dublin 42(5), 711, 13 pgs.

Uliana, M.M., Sharp, J.M., 2001. Tracing regional flow paths to major springs in trans-pecos Texas using geochemical data and geochemical models. Journal of Chemical Geology (179), 53–72.

Yang, K. (Ed.), 2004. Multivariate Statistical Methods and Quality, Downloaded from Digital Engineering Library @ McGraw-Hill. (<http://www.digitalengineeringlibrary.com>).