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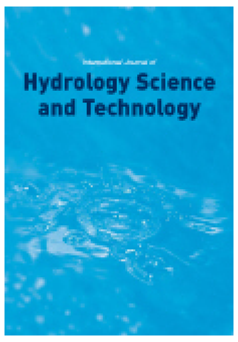

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Numerical study of shallow-water equations using three explicit schemes - application to dam break flood wave

Tahar Ikni Ali Berreksi Mohamed Belhocine

Vol. 12, No. 2, pp 101–115 • July 1, 2021

https://doi.org/10.1504/IJHST.2021.116662

Abstract & Keywords

The numerical method to solve dam break problem on regular bathymetry was developed. Two cases of dam break wave propagation on wet and dry bottoms were selected to verify the numerical model elaborated. Three numerical schemes of Lax-Friedrichs, Adams-...

Keywords

dam break | explicit schemes | artificial viscosity | Lax-Friedrichs | Adams-Bashforth | Adams-Moulton

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The implication of tectonic structures compartment in the hydrochemical distribution in the Merapi unconfined aquifer system

Herry Riswandi Emi Sukiyah Boy Yoseph C.S.S. Syah Alam Mohamad Sapari Dwi Hadian

Vol. 12, No. 2, pp 116–141 • July 1, 2021

https://doi.org/10.1504/IJHST.2021.116665

Abstract & Keywords

This study focuses on the tectonic structures compartment. Furthermore, it controls the hydrochemical and piezometric groundwater distribution in the Merapi unconfined aquifer system. The investigation methods are proposing morphotectonic, statistical, ...

Keywords

hydrochemical | morphotectonic | hierarchical cluster | piezometric | groundwater | tectonic

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Modelling the hydrological processes of Koupendri catchment Northwest, Benin

Chukwuebuka Vincent Azuka Attanda Muinou Igué Bernd Diekkrüger

Vol. 12, No. 2, pp 142–163 • July 1, 2021

https://doi.org/10.1504/IJHST.2021.116663

Abstract & Keywords

This study calibrated and validated rainfall-runoff model (WaSiM) to aid decisions on sustainable management of scarce water resources in Koupendri catchment. The model was successfully calibrated (NSE = 0.61; R^2 = 0.61, RMSE = 0.63) and validated (NSE = ...

Keywords

surface runoff | rainfall-runoff | water resources | hydroclimate | hydrological

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Most efficient channel section with multiple slender obstructions in flow path

Sabita Madhvi Singh Pabitra Ranjan Maiti

Vol. 12, No. 2, pp 164–175 • July 1, 2021

https://doi.org/10.1504/IJHST.2021.116685

Abstract & Keywords

An open channel is to be considered most efficient when it can pass maximum discharge for a given cross-sectional area, bottom slope and resistance of flow in the side walls. In the present work, the efficiency of channel section is determined ...

Keywords

slender structure | multiple barriers | flow path | economic depth

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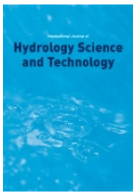

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Assessing impacts of climate change on hydrology in data-scarce Volta River Basin using downscaled reanalysis data

Sulemana Abubakari

Vol. 12, No. 2, pp 176–201 • July 1, 2021

https://doi.org/10.1504/IJHST.2021.116667

Abstract & Keywords

This study uses high resolution (0.3°~3 km) climate forecast system reanalysis (CFSR), SWAT and statistically downscaled A1B emission scenario to assess impacts of climate change on hydrology in data scarce Volta River Basin of West Africa. SWAT was ...

Keywords

Volta River Basin | climate change | SWAT | IPCC | scenario | NCEP climate forecast system reanalysis | CFSR

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Cloud classification: principles and applications

Seema Mahajan Bhavin Fataniya

Vol. 12, No. 2, pp 202–213 • July 1, 2021

https://doi.org/10.1504/IJHST.2021.116669

Abstract & Keywords

Clouds classification is essentially required in weather forecasting and climate related study. Detection, removal and classification of cloud are the major challenges to deal with in satellite-based images. In this paper, literature survey on cloud ...

Keywords

cloud detection | classification | classifier | machine learning | statistical classifiers | artificial intelligence

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Comparison and evaluating reaction factor and drainage water quality with respect to direction of surface irrigation

Zeinab Mirzaie Rohallah Fatahi Saeid Eslamian Azarakhsh Azizi

Vol. 12, No. 2, pp 214–222 • July 1, 2021

https://doi.org/10.1504/IJHST.2021.116684

Abstract & Keywords

This research was carried out to compare the performance of subsurface drainage laterals for four units including two laterals parallel to irrigation direction which are called LP and two laterals perpendicular to irrigation direction which are called LV. ...

Keywords

subsurface drainage | irrigation direction | reaction factor | drainage water salinity | water quality

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The implication of tectonic structures compartment in the hydrochemical distribution in the merapi unconfined aquifer system

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Abstract: This study focuses on the tectonic structures compartment. Furthermore, it controls the hydrochemical and piezometric groundwater distribution in the Merapi unconfined aquifer system. The investigation methods are proposing morphotectonic, statistical, and a hierarchical cluster of hydrochemical analysis. Thus, the methods are to characterise the multi-element of the structure's spatial pattern on the structural compartment. The aim is the cross-correlation of the hydrochemical population on the compartment. The morphotectonic studies showed structures lineament created by active tectonics, and it controls the groundwater flow system. The statistical analysis represents a relation between structure lineament controlling flow pattern and groundwater piezometric. It is related to the hydrochemical characteristics in the concentration of the ion analysis and the value of total dissolved solids. The analysis results are depicted on the digitised map for each compartment compared with the groundwater distribution flow and trends of piezometric. From there, the hydrogeochemical spatial distribution allowed us to characterise the unconfined aquifer system.

Keywords: hydrochemical; morphotectonic; hierarchical cluster; piezometric; groundwater; tectonic.

Reference to this paper should be made as follows: Riswandi, H., Sukiyah, E., Syah Alam, B.Y.C.S.S. and Hadian, M.S.D. (2021) 'The implication of tectonic structures compartment in the hydrochemical distribution in the merapi unconfined aquifer system', *Int. J. Hydrology Science and Technology*, Vol. 12, No. 2, pp.116–141.

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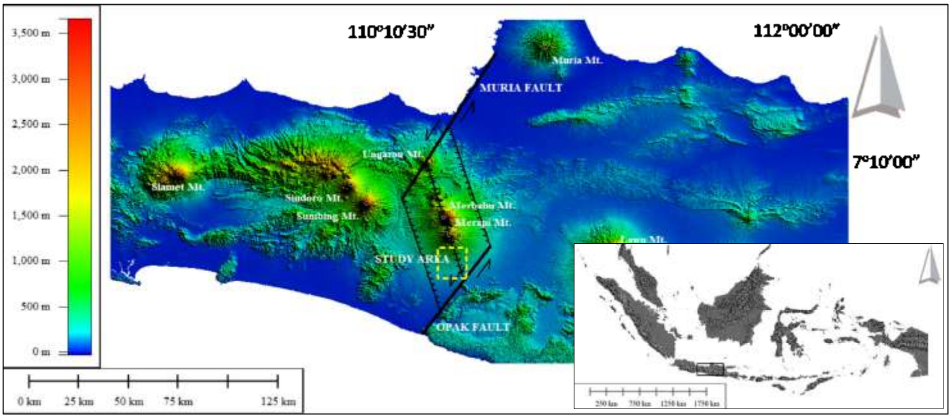
1 Background

Regionally, the need for clean water in the Southeast Asian region is highly dependent on the availability of groundwater. In developing countries such as Indonesia, where people still lack access to safely managed water. The gap in knowledge by the population about groundwater development is because groundwater is more accessible, considering that users can directly exploit it. Groundwater is the critical source of fresh water, and the recharge zone as the key to the availability of groundwater, and it must be protected and monitored. The study area located in the preserve recharge zone with a complex aquifer system (Hendrayana and Vicente, 2013) on the southern part of the volcanic slope Merapi Mountain of Yogyakarta, Indonesia. This potential area has to avoid the disrupted threat to maintaining the evolution of quality and quantity of the groundwater sources and to protects the significant water-level declines in the Yogyakarta Basin (Hendrayana et al., 2016). Base on the study will evaluate the spatial variability of the hydrochemical element with a structured compartment, where the tectonic activity in this volcanic area intended. Tectonic activity strongly influences the pattern or lineament of the rivers on the landscape of morphology, and it is easy to be recognised with digital elevation models (Sukiyah, 2017; Shi and Xue, 2016). Morphometry characteristic is part of the evaluation of differences. And structures involvement for flow patterns and hydrochemical of groundwater. Structure change on the river morphology visualises the variation of groundwater flow pattern, which is affected by lithology variations and the value of the hydrochemical element (Bali et al., 2016). Structure potential on the hydrochemical of groundwater effect when the fault of the structure have displacement with a different type of lithology and reservoir character, as a result of groundwater hydrochemical can change every side of the fault compartment (Chihi et al., 2015; Daly et al., 1980). This study aims to investigate the structure pattern and hydrochemical groundwater distribution, delineate groundwater compartment, and to interpret spatial variability of hydrochemical related to groundwater flow and geological structure. This study workable delineate the structural, spatial trend into three different zones, analysing hydrochemical data to modify the different of the hydrochemical compartment, and making a map of piezometric and hydrochemical spatial distribution. The unconfined aquifer system in the southern slope of Merapi Mountain is the specific case of volcanic lithology with different structural patterns and limited hydrochemical data and the result of data analysis and data interpretation that can contribute to groundwater management.

2 Geological

The location study area is located on the southern slope Merapi volcanic mountain in the upper reaches of the main river (Gendol River and Opak River) with a dominated dendritic drainage pattern. It is located between latitudes 110° 22’ 00 to 110° 29’ 30 N and longitudes 7° 35’ 0 to 7° 46’ 30 E, and it has a total catchments area 244 km^2 (Figure 1). There are two seasons alternately every year, rainy season and dry season. Rock unit in the southern slope of the Merapi Mountain is composed of Quaternary rock formations (Paripurno, 2009; Charbonnier et al., 2013) and composed of Young Merapi volcano deposits composed of tuff, ash, breccias, agglomerates, lava, deposits of avalanches (Gertisser et al., 2012). Old Merapi volcano deposit composed of breccia, agglomerates, andesite lava, and olivine basalt. Merapi Mt. located between Northern Serayu Mountains with Southern Serayu Mountains, separated by a young volcanic deposit from Merapi. Merapi Mt. placed in the center of depression zone in Central Java, and grow it in the middle of a joint point between lineament of volcanic Ungaran-Telomoyo-Merbabu-Merapi and Lawu-Merapi-Sumbing-Sindoro-Slamet. Also, Mt. Merapi, located in the big meeting fault of Semarang, directed North-South, and Solo Fault direct West-East (Van Bemmelen, 1949). Merapi volcanic activity in 1961 to 1994 directed tend to West and Southwest, but in 1994 Merapi debris flow start to change direction to the South in the upper stream of Boyong River (Paripurno, 2009). In 2006, the pyroclastic flow changed direction to the southeast in the upstream of the Gendol river.

Figure 1 The study area located on the southern slope of Merapi Mountain active volcanic in Java Island, Indonesia (see online version for colours)



Note: Merapi-Merbabu Mountain is related to the pull-apart basin of the active tectonic structure with the NW-SE direction.

3 Methods

Geological data were analysed to determine the tectonic structure role, hydrogeology data analysing to determine piezometric, physic, and hydrochemical groundwater character. Groundwater evolution can identify by the statistical relation between hydrochemical groundwater with a pattern of lineament structure, and from spatial distribution hydrochemical map with the piezometric map.

Table 1 Statistical variable characteristic of hydrochemical data from 87 samples

Variable (mg/L)	*Minimum*	*Maximum*	*Mean*	*Standard deviation*	*Variance*	*Coeficient of variation*
K^{+}	2	36	12.2	4.9	24.8	0.41
Na^{+}	4	163	40.5	34.2	1,166.7	0.82
Ca^{++}	6.4	61.4	24.8	9.2	84.7	0.36
Mg^{++}	1.5	22.5	9.4	3.1	9.8	0.32
Cl^{-}	0.6	38.5	10.5	6.6	43.7	0.70
HCO3^{-}	19.8	255.1	106.3	37.9	1,433.3	0.35
SO4^{--}	6	238	34.4	36.8	1353.3	1.00
SiO$_2$	3.5	51.3	27.2	6.4	4,1.1	0.22
EC (µS/cm)	60	554	279.1	79.9	6,359.5	0.28
TDS	30	274	141.5	41.9	1,762.9	0.30

Table 2 Hierarchical analysis for hydrochemical parameter values divided into six clusters

Cluster	*Well monitoring*		*Cation (mg/L)*				*Anion (mg/L)*			*µS/cm*	*mg/L*
			K^+	*Na^+*	*Ca^{++}*	*Mg^{++}*	*Cl^-*	*HCO_3^-*	*SO_4^{--}*	*EC*	*TDS*
A	339, 340, 341, 342, 343, 344, 345, 346, 347, 348, 349, 350, 351	Min	8	85	16.7	4.8	5.5	112	6	220	110
		Max	16	163	25.5	9.2	16.5	255.1	18	282	147
B1	353, 361, 365, 377, 378, 381, 391, 396, 404, 429, 430, 452, 458	Min	12	13	22.5	9.8	4.5	42.7	21.5	220	110
		Max	36	39	61.4	22.5	51.5	170.8	238	550	274
B2	366, 368, 373, 376, 380, 386, 390, 400, 409, 413, 433, 436, 438, 444, 451, 457, 464	Min	2	21	23.3	6.4	6	24.4	16	221	111
		Max	18	40	38.6	18.9	28	146.4	115	463	272
B3	354, 364, 367, 370, 371, 372, 374, 379, 382, 383, 384, 385, 393, 398, 414, 416, 425, 427, 463	Min	10	22	16.1	7.3	5	73.2	13	200	115
		Max	19	36	31.4	11.3	14.5	164.7	59	554	269
C1	362, 394, 397, 408, 432, 440, 455	Min	2	4	6.4	1.5	0.6	19.8	6	154	77
		Max	18	28	22.3	6.8	9.5	103.7	16	294	147
C2	363, 387, 388, 392, 395, 399, 400, 401, 402, 403, 403, 405, 406, 407, 412, 417, 418, 431, 437, 465	Min	7	12	15.3	6.4	2.5	61	6	60	30
		Max	14	27	27.3	10.8	11	115.9	53	301	172

Data management of geology, hydrology, and hydrochemical systematically arranged and aligned into a geographic information system (GIS), and it can export to computer-aided design (CAD) to different interpretation data of geological and hydrochemical. GIS data from geological and hydrochemical constructed to specific information on morphology (slope, curvature, aspect, hillshade), structure (lineament, fault, fracture). Stratigraphy (lithology, profile), hydrogeology (piezometric, resistivity, conductivity, transmissivity), hydrochemical (anion, cation, TDS, EC, pH, Temperature). Structure analysis researching the intersection of the structures system influencing groundwater flow in a different segment of lithology, and it changes the character of the aquifer. Lithology profile in VES methods are used to prepare the geological subsurface data for structure intersection systems (Greswell et al., 1998), and the correlation between geological section and fault interpret in small scale.

The hydrochemical study was using geostatistical to interpret the hydrochemical spatial distribution, also the influence of groundwater flow and the structure. Groundwater samples collected are not all input parameters measured, and only 87 hydrochemical samples are selected based on the complete measured input parameters. This research using 87 hydrochemical data sample analysis from each observation site, collected irregularly for three weeks, and analysis in the laboratory for eight weeks. Every groundwater sample is asses in the hydrochemical study, and it takes all sampling at once.

Hydrochemical data analysed according to ion balance less than five percent, statistical analysis (for the minimum, maximum, mean, and variance data), hydrochemical in Piper and Stiff diagram (Lee et al., 2004), and spatial sample distribution in every compartment.

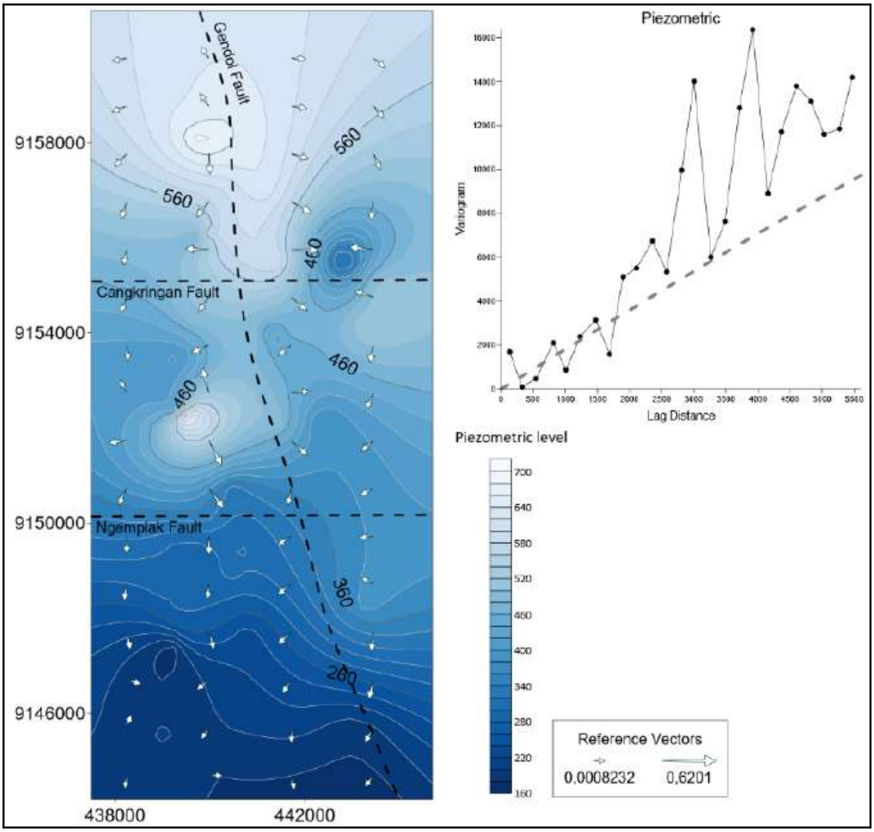
Hierarchical cluster analysis from hydrochemical elements focuses on K^+, Na^+, Ca^{++}, Mg^{++}, Cl^- HCO_3^{--}, SO_4^{--}, and TDS-EC (Table 1 and Table 2) using for statistically hydrochemical classification to investigate the groundwater hydrochemical along with the flow path.

Several studies have used hierarchical cluster analysis technique to classify hydrochemical evolution (Helstrup et al., 2007; Monjerezi et al., 2011; Matos and Alves, 2016; Daughne et al., 2012; Tay et al., 2015; Samani and Moghaddam, 2015).

In this paper, the relation between hydrochemical in the tectonic compartment and the flow permeability of the fault are using the hierarchical cluster analysis. Euclidean distance (space of straight-line calculation from two-point between angle and distance) used for same distance measurements (Steve et al., 2012; Mao et al., 2012). Ward's method for clustering classification, base on the missing information because of object merging to cluster and its measuring use total of square deviation on the mean cluster (Vega et al., 1998; Lin and Chen, 2006). The SPSS (Statistical Package for the Social Sciences) Statistics software that we were used to analysing hydrochemical samples (Usunoff and Guzman-Guzman, 1989; Demlie et al., 2008). The spatial hydrochemical distribution was analysed with geostatistic methods to help to represent the characteristic of hydrochemical data and piezometric of the groundwater flow. Hydrochemical and piezometric data mapped by kriging gridding method with Surfer software using a non-directional variogram estimator type. Experimental variograms of hydrochemical parameters show a sharp curve and linear with a spherical variogram component model

(Figure 2). All the data collected along with the general directions of the regional groundwater flow direction and the data do not tightly cover the entire study area, particularly in the North of a compartment where the data are too rare close to the top of the volcano. Even the computational technique used for closing the weak data area; there is no other way to make estimating maps for hydrochemistry parameters. The interpretation of interpolation every computed method compares with realising errors from counting. A comparison of the generated hydrochemical map was evaluated in statistical (maximum, minimum, mean, and variance) to every sample value. They are merging quantitative data such as piezometric, TDS-EC, and major ion in concentration with qualitative data such as preliminary geologic studies. All this method were enforced to a geostatistical framework to explain the hydrochemical characteristic of the structural compartmentalisation.

Figure 2 Piezometric map with the groundwater flow (→) in fault compartment (see online version for colours)



Note: Piezometric variogram level with directional of (---) experimental and (–•–•–) modelled.

4 Result and analysis

Geology and structural analysis

The structural geometry was implementing by morphotectonic quantitative to locate the tectonic compartments and mapping the structural system that effects the different unconfined aquifer units.

4.1 Morphotectonic analysis

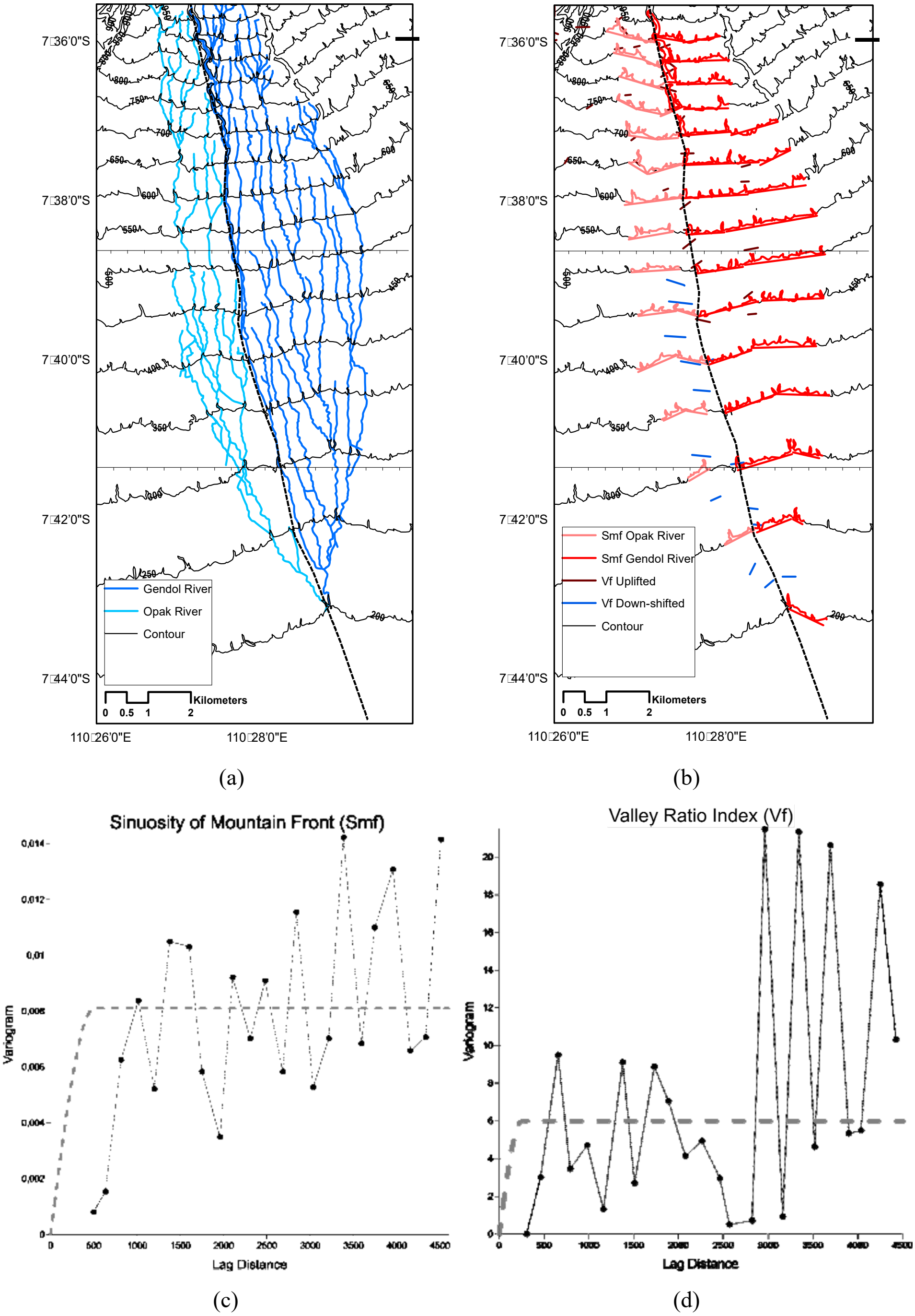
Quantitatively calculate the valley ratio index (Vf) to determine of tectonic activity level (Keller and Pinter, 1996; Bull and McFadden, 1977) and sinuosity of mountain front (Smf) to determine the uplift classification (Doornkamp, 1986; Sukiyah et al., 2018) variables (Table 3) that crossed the lineament from DEM to raster the detailed of structure pattern with GIS software (Figure 3). With the result that reveals and verifies the lineament is the implication of tectonic activity. There are two NW-SE directions of structure lines that are Gendol faults with Quarternary volcanic deposits. These faults signify the extension of Opak faults from the southern path NE-SW direction of Opak-Prambanan faults with Miosen sediment deposited. Merapi-Merbabu Volcanic area is in the pull-apart basin as interpretation base on the active Opak-Prambanan faults (Nurwidyanto et al., 2014) and Muria faults (Moody and Hill, 1956; Wilcox et al., 1973) with NE-SW lineament direction (Figure 1). In the study area, the NW-SE direction of Gendol fault was an intersection with the East-West direction of Cangkringan and Ngemplak faults. These updated fault lines develop the structural compartment along with different of hydrochemical classification (Figure 6).

Table 3 The sinuosity of mountain front (Smf) to determine the class of tectonic activity, and valley ratio index (Vf) to determine the uplifted classification

No.	*Smf*	*Tectonic*	*Vf*	*Uplift*	*No.*	*Smf*	*Tectonic*	*Vf*	*Uplift*
1	0.506	Active	0.021	High	16	0.369	Active	5.556	Low
2	0.514	Active	0.034	High	17	0.728	Active	5	Low
3	0.514	Active	0.06	High	18	0.547	Active	1.333	Low
4	0.526	Active	0.012	High	19	0.616	Active	3.509	Low
5	0.448	Active	0.092	High	20	0.484	Active	2.151	Low
6	0.531	Active	0.036	High	21	0.482	Active	6.667	Low
7	0.553	Active	0.032	High	22	0.526	Active	0.8	Medium
8	0.523	Active	0.001	High	23	0.397	Active	0.429	High
9	0.550	Active	0.008	High	24	0.533	Active	1.923	Low
10	0.540	Active	0.02	High	25	0.402	Active	1.075	Low
11	0.473	Active	0.061	High	26	0.540	Active	0.533	Medium
12	0.468	Active	10	Low	27	0.523	Active	7.142	Low
13	0.294	Active	2.581	Low	28	0.408	Active	4	Low
14	0.336	Active	0.75	Medium	29	0.476	Active	5.714	Low
15	0.312	Active	0.711	Medium					

Notes: Colour of compartment zone of upper-stream ☐, middle-stream ▒, and down-stream ▓.

Figure 3 (a) River pattern flow NW to SW direction (b) Sinuosity of mountain front (Smf) to determine the class of tectonic activity level and valley ratio index (Vf) to determine the uplift class (c) Variogram of Smf (d) Variogram of Vf (see online version for colours)



(a) (b)

(c) (d)

Comparing with the results of previous researchers' tectonic evolution research, it shows that the tectonic evolution study proved that the renewed pulses of extensional fault movements intensified the number of fault displacements along with the affected areas throughout geologic times (Chihi et al., 2013).

4.2 Vertical electric sounding analysis

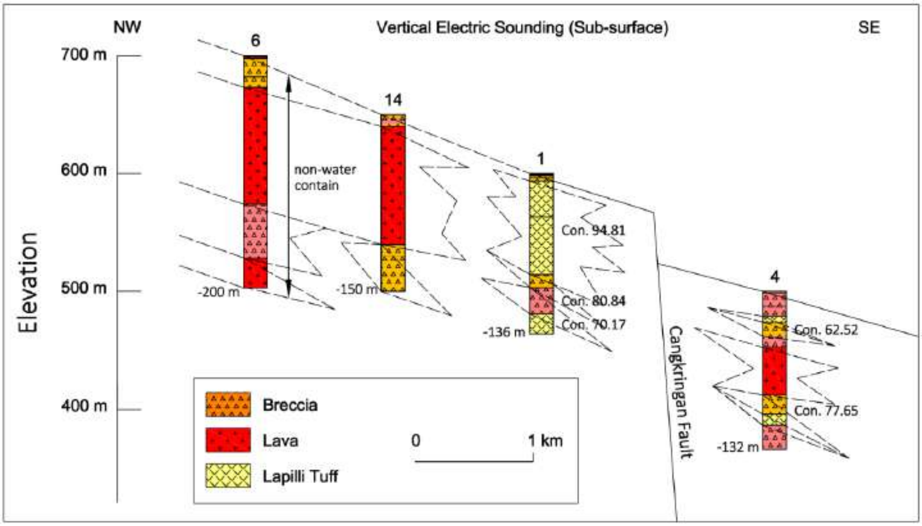
Interpreting profile from vertical electric sounding (VES) to evaluate the lithostratigraphic layer, the existence of groundwater depth in the unconfined aquifer layer. VES data obtained from resistivity (Niwas and Singhal, 1981) value, which then compute the conductivity (Shevnin et al., 2006) and transmissivity (Zohdy, 1989; Henriet, 1976) value. Conductivity value shows that water from the surface has quick absorption to infiltrate down following the depth because of the rock porosity (Table 4, Figure 4 and Figure 5).

Table 4 The result of vertical electric sounding to get resistivity, conductivity, and transmissivity

Site[1]	*Depth*[2]	*Res.*[3]	*Con.*[4]	*Trans.*[5]	*Site*[1]	*Depth*[2]	*Res.*[3]	*Con.*[4]	*Trans.*[5]
1	36.65	83.9	94.81	2,873.60	10	56.05	63.34	2,688.63	56.05
	85.51	71.54	80.84	3,949.85		50.28	56.82	2,829.46	50.28
	135.89	62.1	70.17	1,178.20	11	51.35	58.03	118.37	51.35
2	21.14	24.66	27.87	339.41		66.52	75.17	236.78	66.52
	120.05	51.03	57.66	2,700.98		89.02	100.59	440.60	89.02
3	4.61	71.12	80.37	145.46		42.66	48.21	164.38	42.66
	82.43	96.65	109.21	1,123.82		43.51	49.17	259.60	43.51
	105.95	68.54	77.45	1,821.63		98.93	111.79	1,029.59	98.93
4	25.91	55.33	62.52	311.99	12	103.58	117.05	344.11	103.58
	113.32	68.19	77.05	729.71		71.46	80.75	368.22	71.46
5	1.06	76.54	86.49	83.03		114.47	129.35	1,565.15	114.47
	11.83	32.05	36.22	362.53	16	86.706	97.98	244.94	86.706
	47.7	35.55	40.17	724.29		88.705	100.24	1,002.37	88.705
7	18.94	95.06	107.42	1,394.28		58.1	65.65	656.53	58.1
	128.93	53.2	60.12	1,808.29	17	75.65	85.48	1,709.69	75.65
8	1.69	69.32	78.33	39.17	18	325.17	367.44	3,490.70	325.17
	23.2	99.6	112.55	1,996.60		95.62	108.05	540.25	95.62
	37.19	21.15	23.90	334.35		80.59	91.07	910.67	80.59
	164.56	65.72	74.26	2,782.66	19	65.835	74.39	1,487.87	65.835
9	132.25	21.35	24.13	1,656.22					

Notes: [1]Vertical electric sounding site, [2]Reservoar depth (m), [3]Resistivity (Ωm), [4]Conductivity (m/s), [5]Transmissivity (m^2/s).

Figure 4 VES data in site six and section 14 are non-water contain in lava and breccia, with zero transmissivity value (see online version for colours)



4.3 *Lithostratigraphy correlation*

Lithostratigraphy correlation was analysed from fieldwork profile with VES cross-section to check the fault system in the quarternary volcanic deposit is expressed in the filed. Volcanic deposits sediment with NW-SE direction and down-tilted gradually; the layers were multiple variations and thinning upward (Figure 6). From this correlation (Figure 5), the volcanic stratigraphy in the study area actively controls by tectonic deformation.

Figure 5 Rock profile on the surface used to describe relationships in the surface and sub-surface lithology (see online version for colours)

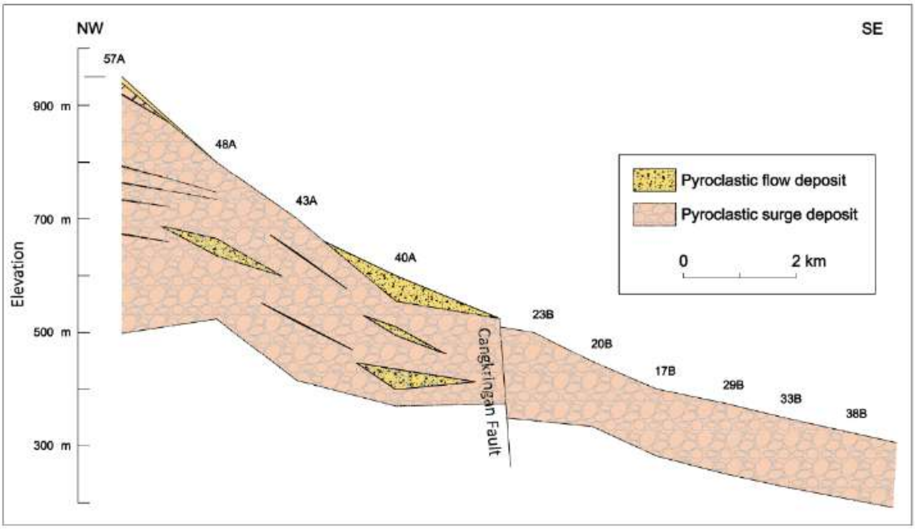
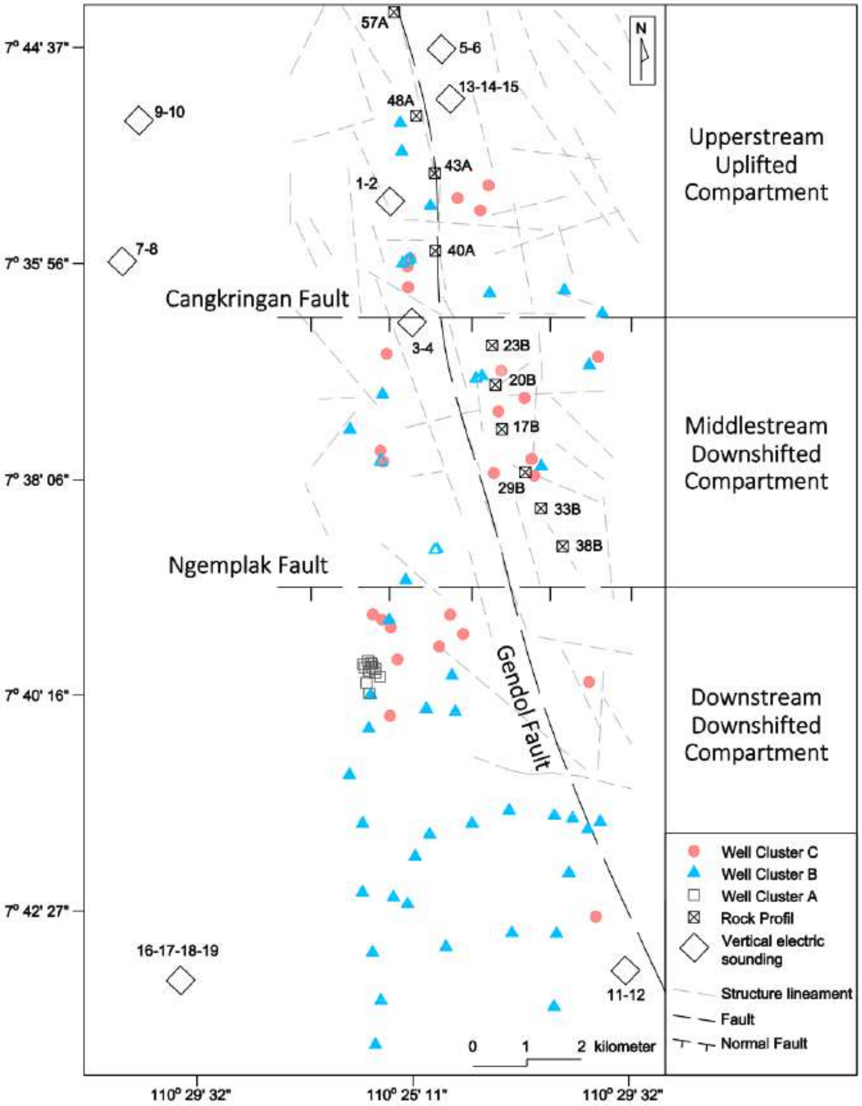


Figure 6 The study area divided into the network structure lineament and three fault compartments with data location (see online version for colours)



4.4 Structural compartment

Structure compartment system in the study area built from NW-SE (Gendol fault) and E-W (Cangkringan and Ngemplak fault) major faults, uplifted and downshifted structure with down-sifted-tilted to the south direction. Researcher validating about structure as preferential infiltration, and processes that impact the permeability of fault zones in different rock types (Bense et al., 2013). The Cangkringan fault is separating the ‘upstream unconfined aquifer’ with an uplifted domain from “mid-stream unconfined aquifer” with the downshifted domain. The Ngemplak fault is separating the “middle stream unconfined aquifer" from "downstream unconfined aquifer" with the downshifted domain (Figure 6).

Three geological compartments characterise the study area. In the upper stream, NE uplifted compartment composed with young Merapi deposited mainly lava, breccia, and lava debris, and downshifted in the middle downstream SW compartment filled with old Merapi deposits consist of breccia, lava debris, coarse sand and alluvial river deposits (Figure 5).

5 Groundwater chemical analysis

The groundwater flow in the recharge area depends on the fault barrier and volcano lithostratigraphy for the continuity, and the implication of tectonic structure in the hydrochemical distribution of the unconfined aquifer using multivariate statistic and geostatistical methods.

5.1 Statistic analysis

Statistical analysis used to identify the characteristics of hydrochemistry to show the quality of groundwater in the southern slope of the Merapi area, and it compared with electrical conductivity and total dissolved solids (TDS-EC) concentration (Table 1). All hydrochemical sample does not exceed the WHO (World-Health-Organization, 2006) standard recommendation maximum limits for drinking water, that is Na^{++} 200 mg/L, Ca^{++} 75 mg/L, Mg^{++} 50, Cl^{-} 200 mg/L and SO_4^{--} 500 mg/L. The maximum concentration value order of cations was

1 $Ca^{++} > Na^{+} > K^{+} > Mg^{++}$ for the upper and middle stream area (A and B zone)

2 $Na^{+} > Ca^{++} > K^{+} > Mg^{++}$ for the downstream area (C zone).

The order of the maximum concentration value of anions was

1 $SO_4^{--} > HCO_3^{--} > Cl^{-}$ for the upper stream area (A zone)

2 $HCO_3^{--} > SO_4^{--} > Cl^{-}$ for the middle and downstream area (C and D zone).

The statistical data (Figure 7 and Table 2) show that the quality of groundwater locally implies by specific components:

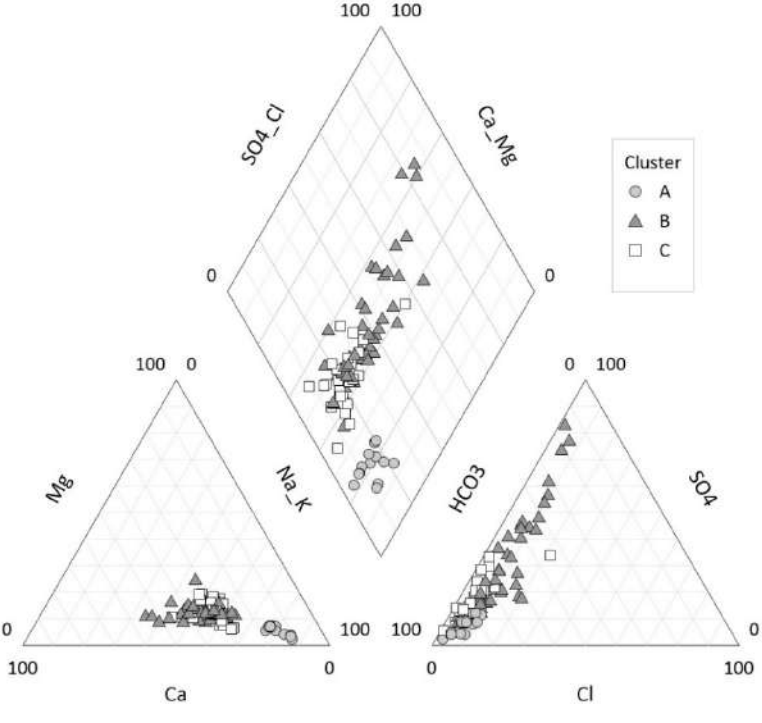
1 The upper stream unconfined aquifer zone with 15 samples of hydrochemical (362, 425, 427, 429, 430, 431,432, 433, 436, 440, 451, 452, 455, 458, 465) generally high sulphate and bicarbonate concentration, the order of maximum concentration is $SO_4^{--} > HCO_3^{--}$.

2 The middle stream unconfined aquifer zone with 21 samples of hydrochemical (406–409, 412, 413, 414, 416, 417, 418, 437, 444, 463, 390, 391, 392–395, 398, 400). Generally, high bicarbonate and sulphate concentration, the order of maximum concentration are $HCO_3^{--} > SO_4^{--}$.

3 The downstream unconfined aquifer zone with 43 samples of hydrochemical (339–351, 387, 388, 396, 397, 399–405, 353, 354, 361, 363–368, 370–373, 374, 376, 377, 380–385, 386, 403, 438, 457, 464) generally high bicarbonate, sodium and sulphate concentration, the order of maximum concentration is $HCO_3^{--} > SO_4^{--}$.

The hydrochemical concentration in the study area is showing the value of the difference in the statistical analysis. The implication from various structural and stratigraphic conditions relatively make differences in groundwater competition. The piper diagram (Figure 7) shows the anion diagram mark on the volcanic aquifer system, is similar to the volcanic aquifer system in Mount Ciremei, West Java, Indonesia (Irawan et al., 2009).

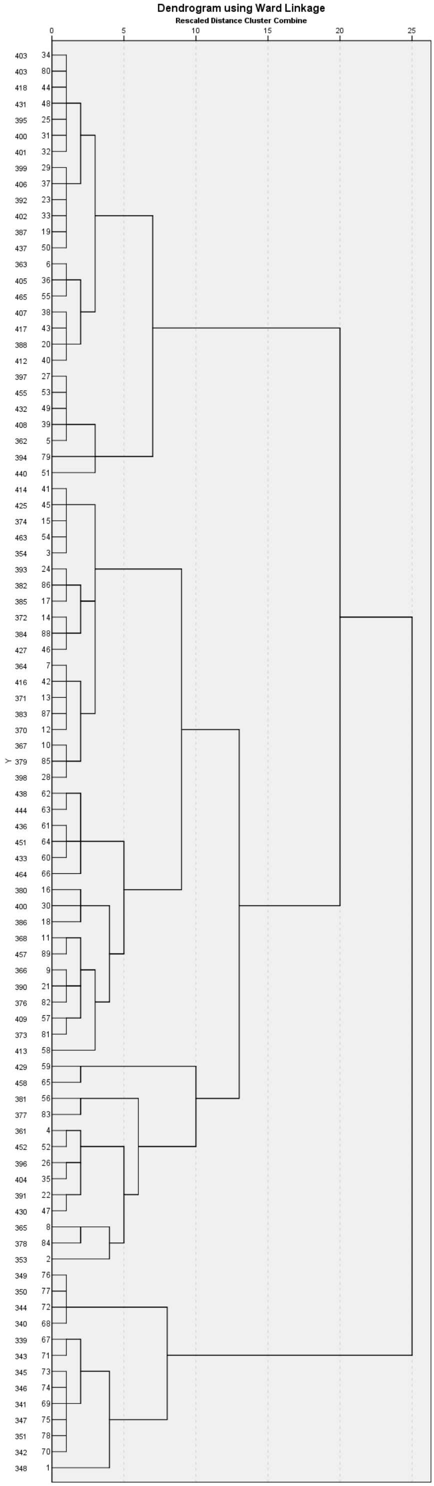
Figure 7 Piper class diagram is showing hydrochemical classification



5.2 Hydrochemical cluster analysis

The cluster analysis used to confirm the statistical clustering of the hydrochemical characteristic in statistical analysis, which is discussing in the following section. Hierarchical Cluster Analysis generates the dendrogram for the 87 samples (Figure 8). The dendrogram shows six groups (cluster A, B1, B2, B3, C1, and C2) base on three class of cluster analysis with 7, 9, 10, 20, and 25 linkage distance to evaluate the sample of hydrochemical classification. The cluster analysis for every hydrochemical sample concluded into maximum-minimum ranges, mean, standard deviation, and a variance value. The coefficient variations of the rest parameters in the table are less than 1, showing a smaller spatial variation (Table 1 and Table 2).

Figure 8 Dendrogram of a hydrochemical cluster generated by hierarchical cluster analysis



The dendrogram showed two clusters (B and C class) distributary at the 20 linkage distance level (Figure 8). Every cluster consists of a sample variable of hydrochemical elements. Cluster B consist of 49 samples with TDS-EC higher than in cluster C (Table 2), and the concentration of HCO_3^{--} and SO_4^{--} are higher than Mg^{++} and Ca^{++}. Cluster C consists of 27 samples with TDS-EC lower than in cluster B (Table 2), and the concentration of HCO_3^{--} and SO_4^{--} are higher than Mg^{++}. Cluster B is subdividing at nine and ten levels into B1, B2, and B3, and cluster C is subdividing at seven-level into C1 and C2. All these samples characterised by a difference in relative's anion and cation value.

Comparing with the results of previous researchers' tectonic evolution research, it shows that cluster analysis has successfully extracted three clusters volcanic hydrogeological system of Mount Ciremai, West Java, Indonesia. It describes differences in the chemistry of the groundwaters resulting from the different aquifer materials through which they have flowed. Groundwaters dominantly influence by volcanic rocks characterised by average water temperature and bicarbonate enrichment. In contrast, those associated with deeper aquifer dominated by marine-based sediments exhibit elevated temperature and chloride enrichment (Irawan et al., 2009).

5.3 Hydrochemical and structural compartment

The hydrochemical grouping (Table 2 and Figure 8) identified by the morphographic, lithostratigraphic and structural lineament, TDS-EC, and piezometric analysis. The hydrochemical cluster indicates compartmentalised derived from well-water sample data in the Merapi slop recharge area, because of the structural influencing the flow path and the down-dip flow. The hydrochemical composition can change along with the compartment of the groundwater flow path with different mineral contact. The potential of the hydrochemical compartment of the unconfined aquifer (structural compartment) in each location in the small scale in the upstream, midstream, and downstream of an unconfined aquifer (Figure 6 and Table 2).

Hydrochemical data based on the composition value, and its group into a compartment that the groundwater has few influences from different lithology in the unconfined aquifer layer. The hydrochemical data group characterises in the cluster analysis section from the wells in the upstream, midstream, and downstream.

1. The upstream compartment with two clusters (B and C) are very similar to those of Cluster B (Figure 8). The groundwater from this compartment has higher bicarbonate and sulphate, and this assumed the groundwater mixing with the higher bicarbonate and sulphate content. The upper stream compartment located in the North of Opak and Gendol River, where the surface water comes from the top of the volcanic rocks and the groundwater, is contaminating by the infiltration of the surface water that high concentration of bicarbonate and sulphate.
2. The mid-stream compartment mixture two clusters (B and C) has higher bicarbonate concentration, and this zone suggests the groundwater mixing with higher bicarbonate content and lithologic unit in the same unconfined aquifer compartment, with the upstream may receive water by leakage.

3 The downstream compartment has their water comes from the mid-stream compartment. The specific show that is consists of Cluster A, B, and C is representing this compartment's unconfined aquifer system down-sifted.

The result generates from the cluster analysis obtained an efficient system to analyse the limited data (Swanson et al., 2001; Reghunath et al., 2002; Lambrakis et al., 2014).

5.3.1 Analysis of groundwater flow with a piezometric map in the recharge zone

Piezometric analysis's purpose is to estimate the groundwater flow in the kriging map projection (Chenini and Mammou, 2010; Diamantopoulou and Voudouris, 2008; Ahmadi and Sedghamiz, 2007). The Merapi unconfined aquifer system in the southern slope receives water from the surface by rainwater in the runoff of Opak, and Gendol Rivers, these both river are recharging from the higher elevation area within the uplifted upper-stream component (Figure 3). This unconfined aquifer also receives groundwater from the west and east side of another aquifer. The combination between the surface and subsurface water take this aquifer to have specific hydrochemical composition. The piezometric map in the study area shows significant water level changes that indicate the groundwater generally flow from northwest to southeast, and revealed the tectonic structure present to control the hydraulic head.

1 The groundwater flow direction is following the down-dip of the topographic slope, higher elevation in the upper stream compartment as a recharge area to the lower elevation as a discharge area.

2 The Cangkringan Fault influences the direction between different compartments, the uplifted compartment, and the down-shifted compartment; it appeared to function as structural discontinuities or structure barrier (Figure 6).

The groundwater counter generally has flow direction from northwest to the southeast, and it is crossing the structure lineament in the Cangkringan and Ngemplak Fault in the uplifted and down-shifted compartment. The direction from east and west turn to southeast when the groundwater closer to the Opak and Gendol Fault in the different lithologies. The flow of groundwater changes because the fault with different lithology becomes combined with the structure barries system.

In the upper stream, the uplifted compartment act as a semipermeable with low hydraulic conductivity value (Figure 5). The layer of the lithology is very thick, deposited by up to several tens of meters. The lithology has resulted in placing the high permeability unit against low permeability (Figure 6). The composition of the Cangkringan Fault acts as a conduit for groundwater flow, and this fault caused different from the lithologies unit confirmed with hydrochemical composition. That showing increasing concentration (Figure 9 and Figure 10). The aquifer system where discharge from the unconfined aquifer system is relatively high.

Figure 9 Schoeller diagram (Schoeller, 1962) showing a cluster of hydrochemical classification (see online version for colours)

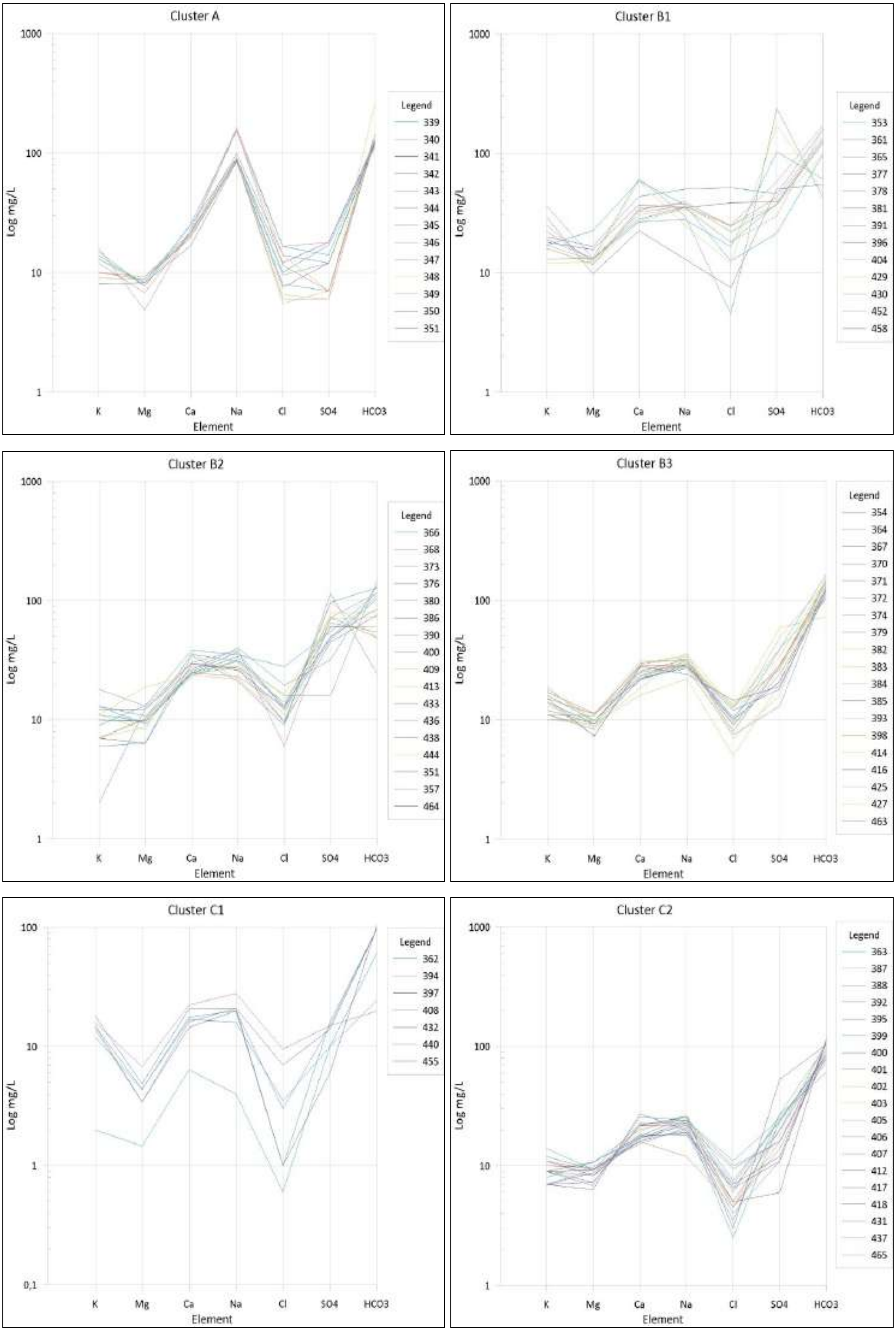
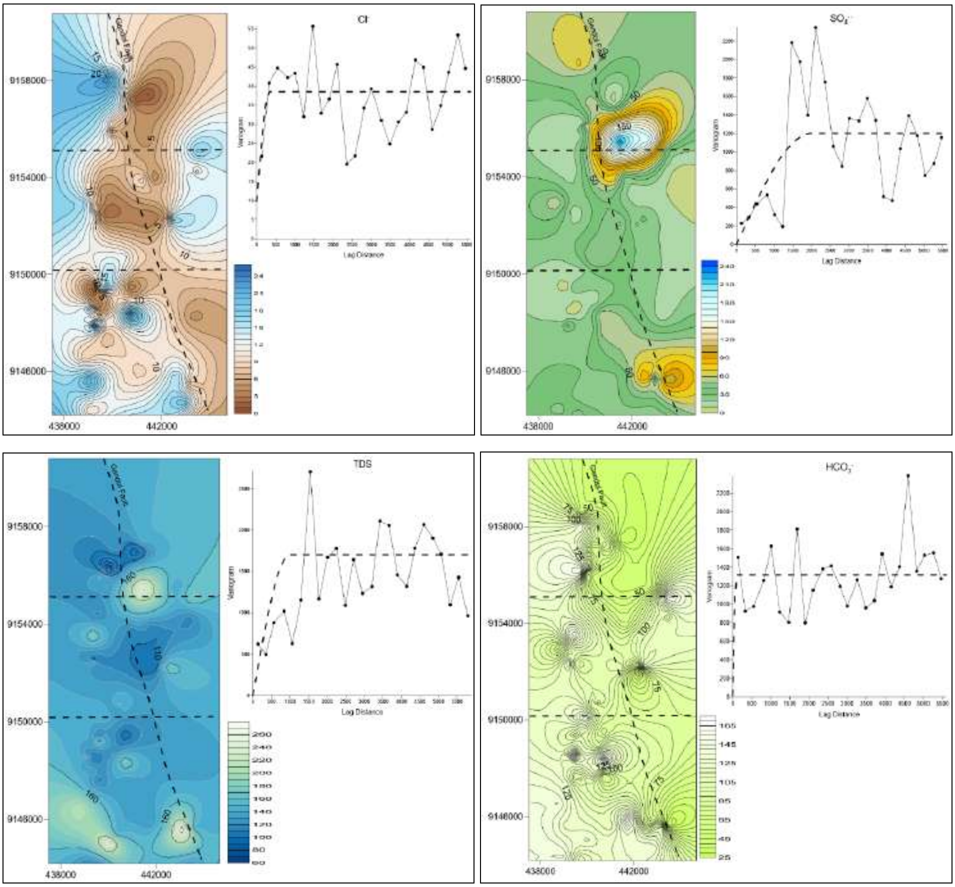


Figure 10 Concentration of TDS, SO_4^{--}, Cl^-, and HCO_3^{--} spatial distribution in fault compartment, with variogram for TDS, SO_4^{--}, Cl^-, and HCO_3^{--} concentration directional (---) experimental and (–•–•–) modelled (see online version for colours)



5.3.2 *Spatial distribution of total dissolved solids and electrical conductivity*

Total dissolved solids (TDS) and electrical conductivity (EC) in the study area are confirming the differences between a hydrochemical cluster and the structure compartment. The Merapi unconfined aquifer from the northwest to the southeast generally more mineralised along with the flow path (Figure 2). The TDS-EC increases from Cluster B to Cluster C and Cluster A (Figure 10, Table 2, and Table 5).

6 Hydrochemical evolution

The spatial analysis used to study the spatial evolution of the hydrochemical composition. All hydrochemical data analyses in the way of geostatistical methods (Figure 9 and Figure 10).

Table 5 Hydrochemical data by structural compartment

Structural compartment	*Cluster*	*Monitoring well*	*Abundance*
Uplifted upper-stream compartment	B1	429, 430, 452, 458	26%
	B2	436, 451, 425	20%
	B3	427, 433	13.4%
	C1	432, 440, 455, 462	26%
	C2	431, 465	13.4%
Down shifted middle-stream compartment	B1	391	4.7%
	B2	400, 390, 444, 409, 413	23.8%
	B3	398, 414, 393, 463, 416	23.8%
	C1	394, 408	9.5%
	C2	437, 395, 418, 406, 407, 412, 417, 392	38%
Down shifted down-stream compartment	A	339, 340, 341, 342, 343, 344, 345, 346, 347, 348, 349, 350, 351	29%
	B1	404, 361, 396, 381, 353, 365, 377	13.7%
	B2	438, 366, 373, 380, 368, 464, 376, 457	15,6%
	B3	364, 386, 370, 385, 372, 371, 367, 354, 374, 382, 383,384	23.5%
	C1	397	1.9%
	C2	402, 400, 388, 405, 401, 399, 387, 403	15.7%

Note: Hydrochemical data by structural compartment, shaded cells indicate the percentage abundance in the cluster.

6.1 Spatial distribution of major-ion concentration

The spatial distribution direction systematically shows that following the path to the South of the Hindia Ocean, and locally this path describes in the major-ion concentration map. The hydrochemical abundance of major-ion and TDS-EC of the water increase from NW uplifted gradient to the SE down-shifted gradient compartment (Figure 6).

The structural compartment related to the distribution of hydrochemical composition. The concentration of a major ion in the NW uplifted compartment is higher than in the down-shifted compartment. HCO_3^{--} and SO_4^{--} concentration in the down-shifted compartment are higher than the uplifted compartment.

The concentration of HCO_3^{--} similar to TDS-EC in the SE down-shifted compartment similar to TDS-EC, which are higher downgradient from Ngemplak Fault. The trend in ion concentration in the SE direction for sodium, chloride, and bicarbonate increases, where sulphate decrease.

The major-ion concentration and TDS-EC are different from one compartment to another; they increase in the downshifted compartment and a decrease in the uplifted compartment. The hydrochemical with high TDS-EC concentration have dominated high sulphate and bicarbonate concentration. The hydrochemical competition show various concentration ranges in the uplifted domain and different variable in the down-shifted.

6.2 Interpretation

The hydrochemical and TDS-EC concentration in Merapi unconfined aquifer influences by rain and river surface run-off water, various of the surface lithology volcanic layer, moves downgradient along to the unconfined aquifer flow.

1. In the upstream compartment, the groundwater has over time contact with the thick layer of lithology, and it caused TDS-EC concentration to be high in the process to recharge the unconfined aquifer.
2. The Quarternary material deposited in the Merapi southern slope (Charbonnier et al., 2013) interacts with groundwater along the flow path. Lava basalt- andesite the most likely source of Na^{+}–K^{+}–Mg^{++}–Ca^{++}, the secondary mineral from multiple intrusion activities such as pyrite and Fe oxides may be a source of SO_4^{--}. HCO_3^{--} may regulate by cation exchange or dissolution of silicate and carbonates from the precipitation surface.
3. The hydrochemical concentration also controls from various another side of the aquifer compartment by mixing the groundwater process interact with various lithology.
4. The structural compartment controls the movement of groundwater from one compartment to another compartment.

Comparing with the results of previous researchers' tectonic evolution research, it shows that gas inputs, rock mineralisation, and the process of the volcanic activity itself influence groundwater in volcanic areas (Armienta et al., 2008).

6.2.1 The upstream uplifted compartment

The composition of unconfined aquifer lithology in the upstream uplifted compartment is Quarternary volcanic deposits (Figure 5) with Opak and Gendol River [Figure 3(a)] in the surface. In this area, meteoric water from surface infiltrate directly to the ground and have limited exposure to evapotranspiration.

The recharge water from the surface have limited water interaction to settle, and ion sifted exchange in the unconfined aquifer, because of the porosity and impermeable deposited. These conditions make the cation is lower than other compartment and the TDS-EC concentration generally between 30–270 mg/L and 60–420 Ms/cm, and show SO_4^{--} and HCO_3^{--} dominant ion in the group Na^{+}–K^{+}–Ca^{++}–Mg^{++} (Figure 7 and Figure 9).

6.2.2 The middle stream downshifted compartment

The middle stream compartment has TDS-EC concentration 101–160 mg/L and 202–310 µS/cm, and the water types are dominantly Na^{+}–K^{+}. The lithology layer in this area is the Quarternary volcanic deposit (Figure 5) and firmly beneath the Opak dan Gendol River on the surface. This area indicates sodium is releasing by volcanic deposits and infiltrate into the unconfined aquifer, and this aquifer more shallow than the upstream compartment because of water interaction and ion-exchange higher concentration than in the upstream compartment.

6.2.3 The downstream downshifted compartment

The downstream compartment with the downshifted flow to the SE direction has increased all ion concentration and TDS-EC concentration 220–256 mg/L and 112–130 µS/cm. In this compartment, the unconfined aquifer has a lithology layer older volcanic deposit from the overhead compartment, which is a various and thinner layer. Groundwater is gathering mostly from above this compartment (Figure 5). The unconfined reservoir flow to downer and show level of depth is very much shallow. The highest ion concentration in this compartment is bicarbonate and sodium. It related to the time of lithology contact longer and has time to the groundwater to restore. Naturally, discharge spring brings the water to come out from the unconfined aquifer through the structure zone (Figure 3).

7 Conclusions and recommendations

The characteristics of the structure compartment in Merapi unconfined aquifer system need a method that is combining tectonic, geophysical with statistical analysis. The methodology describes the faulted aquifer system with the statistical analysis to the modeling of piezometric, electrical conductivity and total dissolved solids, and major ion concentration. The hierarchical cluster analysis method has defined the interpretation of the spatial dependence between the properties of hydrochemical differences.

The multivariate statistical analysis is a useful approach to determine a characteristic of the hydrochemical of the structural compartment. From this, it can identify as hydrochemical and structural in three compartments.

The relationship between structural groundwater compartment and hydrochemical process show it up in the frigid maps of piezometric, TDS-EC, and major ion concentration that control the hydrochemical distribution. The aquifer system in this area is influenced by the hydrochemical process and the time of the groundwater flow path with ion exchange and its spatial distribution.

The aquifer system describes the hydrochemical process and the time of the groundwater flow path into structural compartment NW-SE and N-E fault, and the thickness of Quarternary lithology also has contributed to control the hydrochemical in the different compartment. The methods used in this study are hydrochemical spatial analysis and hydrochemical properties, and the methods can apply to other aquifer spatial issues.

The hydrochemical compartment in Merapi's unconfined aquifer system can provide clean water supply control, provide the conceptual groundwater model, and control the influences of mineralisation for human activity water supply. The result of data analysis for collected data along the direction of regional groundwater flow and interpretation of lithostratigraphy and hydrochemical correlation provides evidence of lateral compartmentalisation in Merapi southern slope unconfined aquifer.

This study can show that compartmentalisation in aquifer systems controlled by fault structures that divide groundwater flow. An understanding of the function of an aquifer system needs to be improved, especially in terms of more detailed characterisation of the different heterogeneity in each aquifer compartment, which requires closer sampling distances with higher resolution. The results of this study can be used as a reference for new sampling because the current excavations of new wells can be found, especially on the western side of the NW and SE compartments.

8 Summary

The results of structural compartments using analysis of variogram and ordinary kriging show topographic deformation on the surface affect the occurrence of variations in the depth and hydrochemical variation of groundwater and indicate the higher elevation. The groundwater density gets more in-depth, and the smaller the concentration of hydrochemical elements.

The hydrochemical concentrations clusters distributed in the three compartments of the structure, and the results of the analysis show an abundance of specific cluster percentages in each compartment. Cluster compartment in the upstream compartment, there are clusters B1 and C1. In the mid-stream compartment, there are clusters B2, B3, and C2. In the downstream compartment, there are clusters A and B3. Analysis based on the comparison of cation and anion values with the number of hydrochemical elements, shows that cluster A with elements K^{++} Na^+ rises to cation values, cluster B with elements Ca^{2++} Mg^{2+} rises to cation and HCO_3^-, $Cl^- + SO_4^2$ increases with the anion value.

Based on hierarchical cluster analysis, the hydrochemical element variable divided into six clusters, namely cluster A, B1, B2, B3, C1, and C2. Based on the Piper diagram, the dominant groundwater type is alkaline with the addition of bicarbonate (Na^+–HCO_3^-), groundwater flow originates from, or is of the same quality as groundwater in distressed aquifers. Based on the Schoeller diagram, all clusters in the Scatter line show the highest concentration of Na^+–HCO_3^-, and the lowest K^+–Cl^- concentration. The concentration of HCO_3^{--} SO_4^{2-}, TDS-DHL value in the derivative area is higher than the lifting area in the northern part. Hydrochemical and TDS-DHL concentrations are affected by rain and surface water runoff, lithology variations, and fault structures.

In the upstream compartment, meteoric water infiltrates directly into the soil and has limited time to interact on the surface and unconfined aquifer layer. The low value of TDS-DHL also indicates this. In the mid-stream compartment, meteoric water mixed with water collected in unconfined aquifers. In the downstream compartment, more meteoric water percolates into the aquifer layer, so it stores much groundwater and has much time to interact with aquifer lithology.

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