TRACING THE ORIGIN OF SPRING WATER BY USING ENVIRONMENTAL ISOTOPES IN THE SOUTHERN SLOPE OF MOUNT MERAPI, INDONESIA

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Abstract

The first and most fundamental question to conserve a springs is where the boundaries of springs' recharge zone. Research in determining recharge zone of Wadon springs (631 m.asl) which located at the southern slope of mount Merapi has been conducted. Topography and hydro-geological data used to find out the locations of groundwater sampling or recharge zone hypothetic, meanwhile the isotopic compositions (H, O, and C) utilized to determine the origin of groundwater. The isotopic compositions in groundwater samples were collected from wells, springs, and boreholes at southern slope of mount Merapi. Merapi meteoric water line (MMWL) describing the relationship between isotopic compositions and elevation [6] was used as a reference of isotopic compositions of water samples to find out the origin of groundwater. Based on the δ^2H and δ^{18}O values and MMWL, it can be concluded that the recharge zone of Wadon springs is ranging from the elevation of 650 m.asl (Pagerjurang) to 1260 m.asl (Plawangan). The δ^{13}C value as well as tritium supports the conclusion; mostly δ^{13}C in recharge zone and Wadon springs comes from the same source of carbon; that is -17.74±0.27‰ to -10.96±0.66‰ Pee Dee Belemnite (PDB); this holds for δ^{13}C in the range of groundwater Dissolved Inorganic Carbon (DIC). Based on the tritium concentration decreasing from ≥ 4.20 TU to <4.20 TU exhibits that groundwater also comes from recharge zone to Wadon springs. By referring to the recharge elevation and topography maps, it can be estimated that the area of recharge zone is 8.033 km^2.

Keywords: Environmental isotopes, Groundwater origin, Isotopic compositions, MMWL, Recharge zone, Wadon springs.

Introduction

Umbul Wadon springs located at the southern slope of mount Merapi, Yogyakarta Special Region, Indonesia is strategic clean water resources for the community of Sleman and Bantul regencies, as well as Yogyakarta City. It was reported that after Merapi eruption in 2010, Umbul Wadon is the one of the springs in the slope of mount Merapi which stills "sustainable", meanwhile hundreds of other springs have declined, whilst some others have dried out [1]. Recently the growths of population, urban and business activities in the recharge zone hypothetic have developed rapidly. Because of it transformation of this area for housing community and business center are growing fast. As a result, it also needs supporting water supply. Groundwater resources are susceptible to over exploitation to fulfill the increasing of clean water demand. Exploitation of groundwater intensively without conserve catchment area faces degradation problems of groundwater balance, both of quality and quantity aspects from time to time [2, 3]. Therefore, the development and management of groundwater must be based on the area of recharge zone and amount of replenish-able resource [2, 3]. Unfortunately the boundaries of spring recharge zone have not been defined in detail yet. Hence, the most of the recharge zone (hypothetical) in the southern slope of mount Merapi used for agriculture and forestry has been converted to be a new settlements and residential zones which cause the recharging of groundwater decreases significantly. Accordingly, groundwater table has declined more than 0.5 m/year and the springs discharge has decreased from 500-550 liters per second in 2002 to 265-300 liters per second in 2010, just before mount Merapi eruption [1]. Therefore, research in determining the boundary of springs' recharge zone is important and urgent.

Determination of recharge zone boundaries by integrating topographic, hydrogeology and geologic approach has been performed by researchers [2, 3, 5], but this approach cannot be assured the origin of the groundwater. This method is difficult to ascertain the origin of groundwater because it does not trace the patterns of the groundwater flow but based on the analysis of the aquifer characteristics. Due to origin of the groundwater unknown, the border of recharge zone cannot be located, as consequence the conservation in recharge zone is unable to be carried out effectively and efficiently [2].

The stable isotope ratios of oxygen ($^{18}O/^{16}O$) and hydrogen ($^{2}H/^{1}H$ or D/H) show systematic variations in hydrologic systems that can be used to trace the origin and transport pathways of different water masses [2, 4, 5]. Water molecules are partitioned between the vapor (cloud) and liquid (rainfall) according to differences in mass. Molecules containing heavy isotopes tend to go into the liquid phase, in the other hand tend to remain in the vapor. This process is referred to as isotopic fractionation [2, 5, 6].

Generally, when a saturated air mass lifting over an orographic barrier such as a mountain slope and experiencing low temperature, the $\delta^{18}O$ and δD values in rainfall will decrease with increasing of altitude [2, 5, 6, 7]. Otherwise evaporation processes also fractionate the oxygen and hydrogen isotopes ratios in water, where evaporation progressively enriches the remaining water in heavy isotopes. These isotopic fingerprints will remain unchanged until the infiltration of rainfall in to the saturated zone in the soil [2, 5, 7, 8].

By analyzing $\delta^{18}O$ and δD values in groundwater samples, the secondary effect of evaporation is easily distinguished from the primary rainfall fingerprint. It is therefore $\delta^{18}O$ and δD values in groundwater have been the most frequently used in hydrological investigations of springs, such as tracing the groundwater origin, the mode of groundwater recharge, the determination of groundwater age, and the springs discharge response to precipitation [2, 5, 8], particularly in zone with significant topographic relief.
The concentration of D, O-16, and C-13 in the natural water are measured using mass spectrometer and are stated as parts per thousand (‰) using δ-notation, where [2, 5, 8]:

$$\delta = \frac{Rs - Rst}{Rst} x1000 \text{‰} \quad \text{...(1)}$$

δ stable isotopic value is stated as $\delta^{18}O$, δD, or $\delta^{13}C$; R_s is ratio $^{18}O/^{16}O$, $D/^{1}H$, or $^{13}C/^{12}C$ of samples; R_{st} is ratio $^{18}O/^{16}O$ or $D/^{1}H$ of standard mean ocean water (SMOW), or $^{13}C/^{12}C$ of standard Pee Dee Belemnite (PDB).

Meanwhile, the tritium concentration in groundwater interpreted by tritium dating methods [5, 8] and expressed by one tritium unit (TU) corresponds to 1 tritium atom (^{3}H) per 10^{18} atoms of ^{1}H. Tritium is the radioactive isotope of hydrogen and decays with a half-life of 12.43 years to the noble gas isotope ^{3}He. The concentration of tritium (^{3}H or T) will be used to determine the flow path and linear velocity of groundwater.

Research Area

Wadon springs located at Umbulharjo village, district of Cangkringan, Sleman regency, Yogyakarta Special Region-Indonesia, with the altitude 631 meters above the sea level (m.asl). The research area boundaries are the northern part borders with the peaks of mount

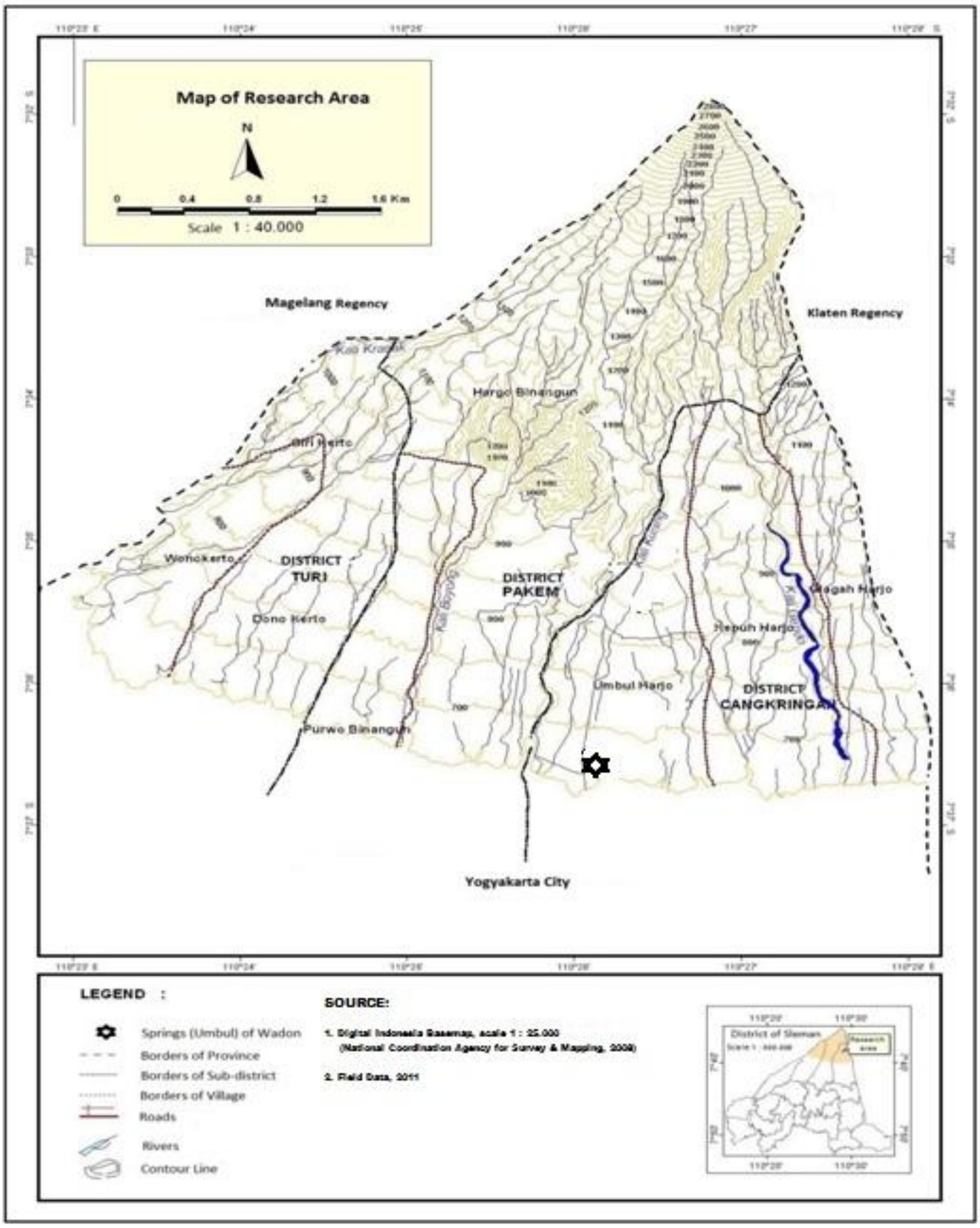

Figure 1. Map of Research Area

Merapi, the western part borders with Magelang regency, the eastern part borders with Klaten regency, and the southern part borders with Yogyakarta city. Geographically, the research area is spread out from $7^0 32' 0''$ until $7^0 37' 0''$ Southern Latitude, and from $110^0 23' 0''$ until $110^0 28' 0''$ Eastern Longitude, with the altitude between 630 until 2800 m.asl, (as shown in Figure 1); Preliminary survey shows that the total area of research is about 17.063 hectares and administratively the main areas of research consist of four districts (districts of Cangkringan, Pakem, Turi, and Ngemplak) Sleman regency, Yogyakarta

Special Region, Indonesia. The research area has total and average population of 154,322 peoples [9] and of about 9.044 peoples per hectares. Table 1 indicates the total area, population, and density of each district. The land utilization can be classified in to three groups which are for community housing 4,364 hectares (25.58%), agriculture land 8,700 hectares (50.99%), and business, industry, etc [9]. This means that almost 50% of the research area is used as community housing and urban activities (as shown in Table 2).

Table 1. Number of Population, Total Area and Population Density in Research Area [9].

No.	Name of District	Population, peoples	Total area, hectares	Population density, peoples/hectares
1.	Cangkringan	28,960	4,799	6.035
2.	Pakem	34,575	4,384	7.887
3.	Turi	35,894	4,309	8.330
4.	Ngemplak	54,893	3,571	15.372
	Total	154,322	17,063	9.044

The growths of community housing and urban activities will definitely need supporting water supply. These all activities tend to transform an open field for housing and business center or to cover open fields, which cause the recharging of groundwater will decrease. Intensive land transformation and groundwater withdrawal without conservation of groundwater recharge zone will degrade groundwater balance. In order to conserve recharge zone, research in determining the boundary of springs' recharge zone is important and urgent

Table 2. Land Utilization Area in Research Area, hectares [9].

No.	Name of District	Wet-land	Dry-land	House Compound	Other	Total
1.	Cangkringan	1,092 (22.75%)	1,187 (24.73%)	1,309 (27.28%)	1,211 (25.23%)	4,799 (100%)
2.	Pakem	1,687 (38.48%)	655 (14.94%)	905 (20.64%)	1,137 (25.94%)	4,384 (100%)
3.	Turi	506 (11.74%)	1,461 (33.91%)	1,128 (26.18%)	1,214 (28.17%)	4,309 (100%)
4.	Ngemplak	1,963 (54.97%)	149 (4.17%)	1,022 (28.62%)	437 (12.24%)	3,571 (100%)
	Total	5,248 (30.76%)	3,452 (20.23%)	4,364 (25.58%)	3,999 (23.44%)	17,063 (100%)

Materials and Methods

Research started by determining the hypothetical recharge zone and the location of sampling. From literature review and desk evaluation of topography profile, geology and hydrogeology data, with emphasized on hydraulics character as a media of groundwater flows, it can be defined the hypothetical recharge zone and the location of sampling. Figure 2 shows the algorithm of research step. The similar method has been conducted to determine the water protection zones in Malang [10], delineation of springs' protection zones in Delhi India [2], as well as to estimate flow patterns and linear velocity of groundwater by using environmental isotopes in Sleman [11]. Locations of water sampling are in the hypothetic recharge zone and determined by purposive sampling. Nineteen groundwater samples were collected between September, 2010 and September, 2011 from wells, springs and boreholes (as indicates in Figure. 3) which geographically situated at different locations. The coordinates of the sampling locations were measured in-situ using Garmin GPS, and checked with the topography maps, scale-1:40,000, as shown in Figure 1. Groundwater sampling was conducted directly at the springs, while groundwater samples were collected from wells by drawing and from boreholes by pumping. Groundwater samples were stored in sealed plastic bottles to avoid evaporation and contact with the air. Isotopic compositions of samples were measured using Liquid-Water Stable Isotope Analyzer LGR DLT-100 at Center for the Application of Isotopes & Radiation Technology Laboratory, National Nuclear Energy Agency (BATAN), Jakarta, Indonesia; Table 3 exhibits the elevation and the average isotopic compositions.

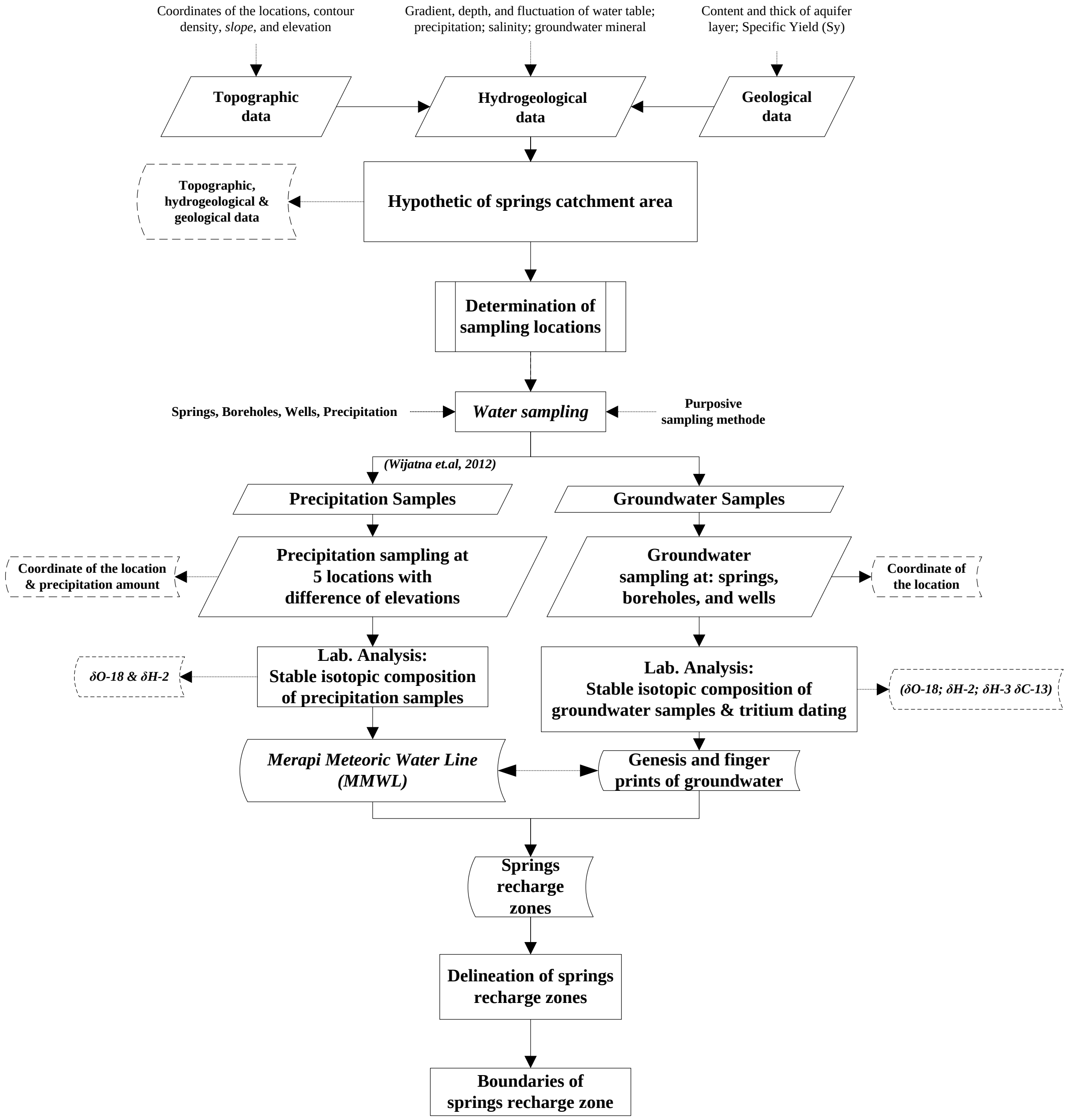

Figure 2. Algorithm of research stage.

Isotopic compositions of groundwater are interpreted based on the theory that the hydrogen and oxygen heavy isotope contents ($\delta^{18}O$ and δD or $\delta^{2}H$) of rainfall decrease with increasing altitude [2, 8]. Therefore $\delta^{18}O$ and δD compositions of recharge waters in a particular environment have a specific isotopic fingerprint which depends on their origin [2, 5, 8]. If $\delta^{18}O$ and δD compositions of groundwater in boreholes, wells or springs more depleted than $\delta^{18}O$ and δD compositions of water collected from rainfall near the boreholes, wells or springs (local rainfall), it can be concluded that the water feeding to the boreholes, wells or springs comes from a higher elevation. However if $\delta^{18}O$ and δD compositions of groundwater in boreholes, wells and springs are similar to local rainfall, it can be concluded that recharge of them comes from local rainfall [5, 7, 8]. In this study, Merapi meteoric water line (MMWL) describing the relationship between isotopic compositions and elevation [6] was used as a reference of isotopic compositions of water samples to find out the origin of groundwater or to evaluate whether the groundwater comes from around local rainfall or higher elevation. Analogously, groundwater was sampled from boreholes, wells, and springs which were situated differently but they have the same isotopic compositions then it can be suspected that they are hydraulically interconnected or the origin of groundwater is from the same recharge zone [2, 5, 8].

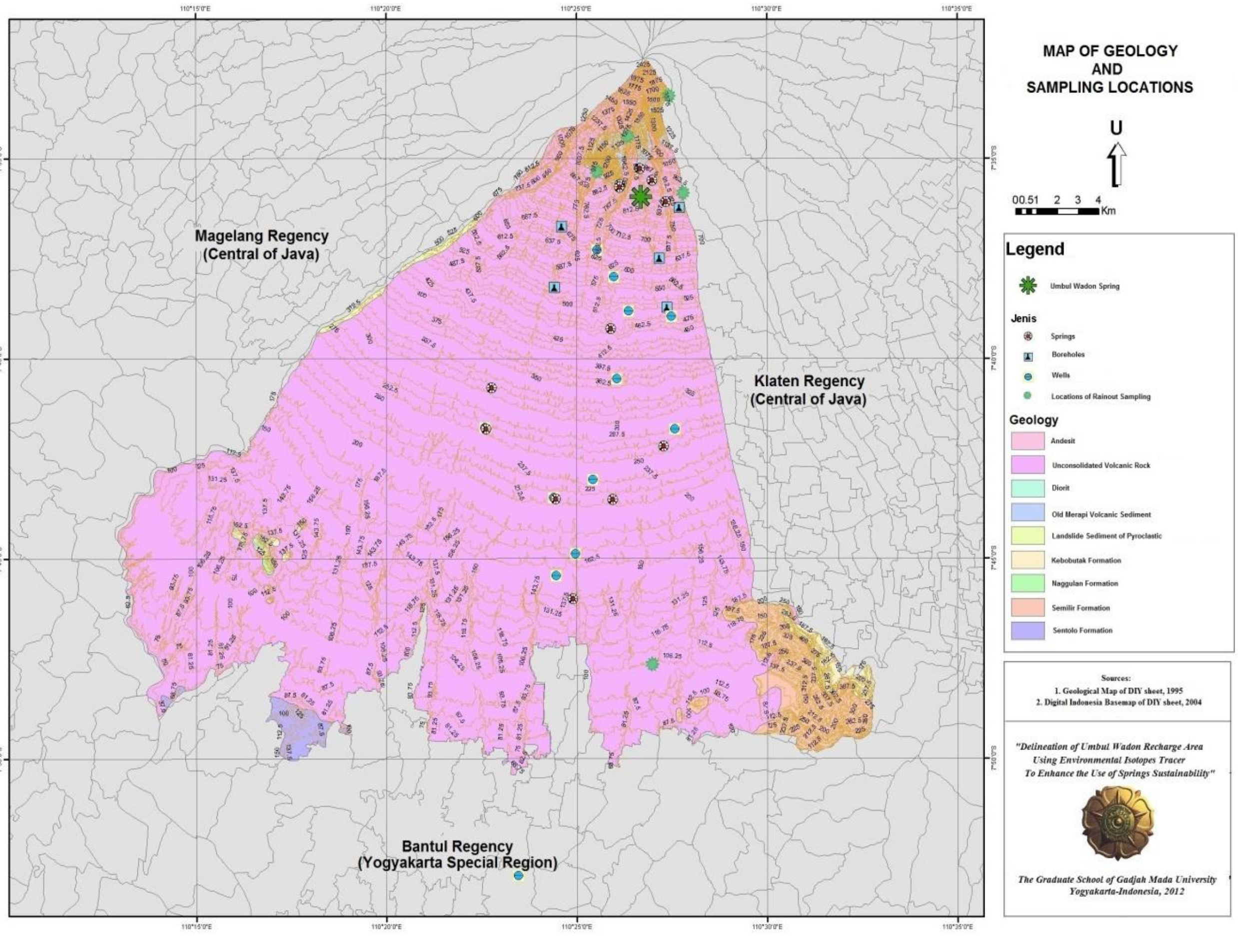

Figure 3. Map of Geology and Sampling Locations

Meanwhile, flow path and linear velocity of groundwater were determined based on tritium concentration. Declining of tritium concentration through the decay process can be used as a guide to find the age, direction, and linear velocity of groundwater. Table 4 shows the concentration of tritium or the age of groundwater samples.

Results and Discussions

Groundwater samples were collected from 8 different springs at the southern slope of mount Merapi, mostly during June-July, 2011, meanwhile 11 groundwater samples from wells and boreholes were collected during May-September 2011. Geographically, all groundwater samples were collected from altitude of 329 to 1196 m.asl; the coordinate of water samplings as shown in Figure 3.

Table 3. Coordinate and altitude of water samplings

No.	Name of Location	UTM Coordinates		Altitude m.asl	WT m.asl
		Easting	Northing		
Shallow groundwater: springs					
S-1	Bebeng	445769	9157711	1196	1196
S-2	Putri	453752	9140246	761	761
S-3	Muncar	448547	9138705	755	755
S-4	Lanang	452211	9149764	634	634
S-5	Wadon	444257	9141126	631	631
S-6	Sempu	446705	9142972	465	465
S-7	Martani	451536	9151115	355	355
S-8	Ngepas	440234	9149536	329	329
Shallow groundwater: wells					
W-1	HargoB.	439929	9148491	671	654
W-2	Umbulharjo	450379	9144296	620	609
W-3	Wukirsari-3	450196	9143989	527	523
W-4	Wukirsari-1	443675	9140849	486	485
W-5	Wukirsari-2	449755	9154952	445	443
W-6	Pakem	444290	9139007	359	357
Deep groundwater: boreholes					
BH-1	Srunen	460572	460572	846	829
BH-2	Pagerjurang	444561	444561	665	650
BH-3	Ngepring	452529	452529	644	625
BH-4	Kuweron	446637	446637	643	624
BH-5	Bubur	450727	450727	544	534

UTM = Universal Transverse Mercator; m.asl = meters above sea level; WT = water table.

The $\delta^{18}O$ and δD values of 19 groundwater samples were measured its isotopic compositions. Variations of isotopic compositions of groundwater samples are used to evaluate the origin of groundwater and transport pathways of different water masses. The measurement results are showed in Table 4; it can been seen that the range of -7.42 to -6.32‰ for $\delta^{18}O$; -46.1 to – 37.1‰ for δD; -17.74 to -10.96‰ for $\delta^{13}C$; 3.0 to 5.64 TU for ^{3}H

Table 4. The isotope values of groundwater samples of $\delta^{18}O$, δD, $\delta^{13}C$, and ^3H.

No.	DR *), $L.sec^{-1}$	$\delta^{13}C$, ‰	δD, ‰	$\delta^{18}O$, ‰	^3H, TU
Springs					
S-1	40	-17.74±0.27	-45.4	-7.42	5.64±0.7
S-2	18	NA	-44.4	-7.38	4.84±0.3
S-3	25	NA	-44.7	-7.35	NA
S-4	215	-16.31±0.74	-45.0	-7.41	3.6±0.8
S-5	265	-16.21±0.54	-46.1	-7.41	3.5±0.2
S-6	15	NA	-37.7	-6.40	NA
S-7	NA	NA	-41.1	-6.69	NA
S-8	15	NA	-40.4	-6.70	NA
Wells					
W-1	-	-16.91±0.24	-43.5	-7.42	4.3±0.1
W-2	-	NA	-38.2	-6.32	NA
W-3	-	NA	-39.9	-6.61	NA
W-4	-	NA	-39.1	-6.55	NA
W-5	-	NA	-37.1	-6.41	NA
W-6	-	NA	-39.8	-6.54	NA
Boreholes					
BH-1	-	-16.96±0.23	-45.4	-7.40	4.96±0.3
BH-2	-	NA	-43.7	-7.41	4.20±0.2
BH-3	-	-10.96±0.66	-44.9	-7.39	3.2±0.4
BH-4	-	NA	-44.1	-7.40	3.0±0.1
BH-5	-	NA	-40.3	-6.57	NA

DR : discharge rate [9]

Table 4 indicates a good correlation between isotopic compositions of springs (S-1 to S-8) and their discharge rates. Theoretically, evaporation of lower discharge springs is greater than evaporation of higher discharge springs; therefore three of the smaller springs (S-6; S-7; and S-8) with discharge rates $\leq 15\ L.sec^{-1}$ have $\delta^{18}O < -7$‰ and $\delta D < 42$‰; this is higher than the springs with discharge $\geq 15\ L.sec^{-1}$ (S-1, S-2, S-3, and S-5), that is $\delta^{18}O \geq -7$‰ and $\delta D \geq 42$‰. This is due to the more water contact with the free air the more it will evaporate.

Table 4 also exhibits that isotopic compositions of groundwater at Bebeng springs (S-1; 1196 m.asl) are -7.42‰ for $\delta^{18}O$ and -45.40‰ for δD; it is similar to isotopic composition of rainfall at Bebeng area (1205 m.asl), that are -7.41‰ for $\delta^{18}O$ and -46.36‰ for δD [6]. This means that water feeding to the Bebeng springs is from local rainfall or from meteoric water.

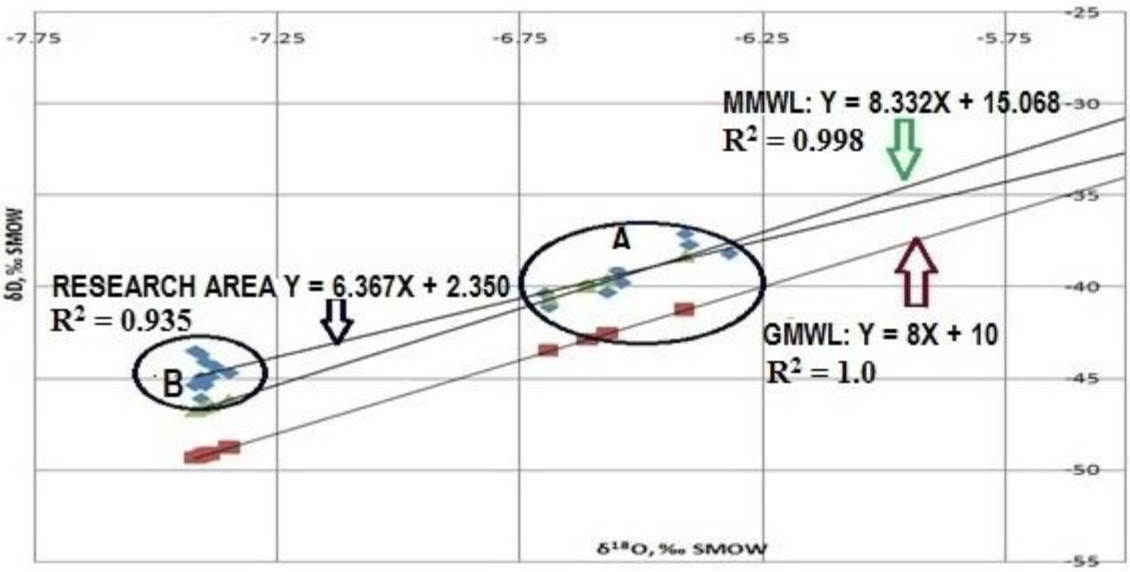

Figure 4. The $\delta^{18}O$ and δD values (‰ SMOW) for groundwater in research area.

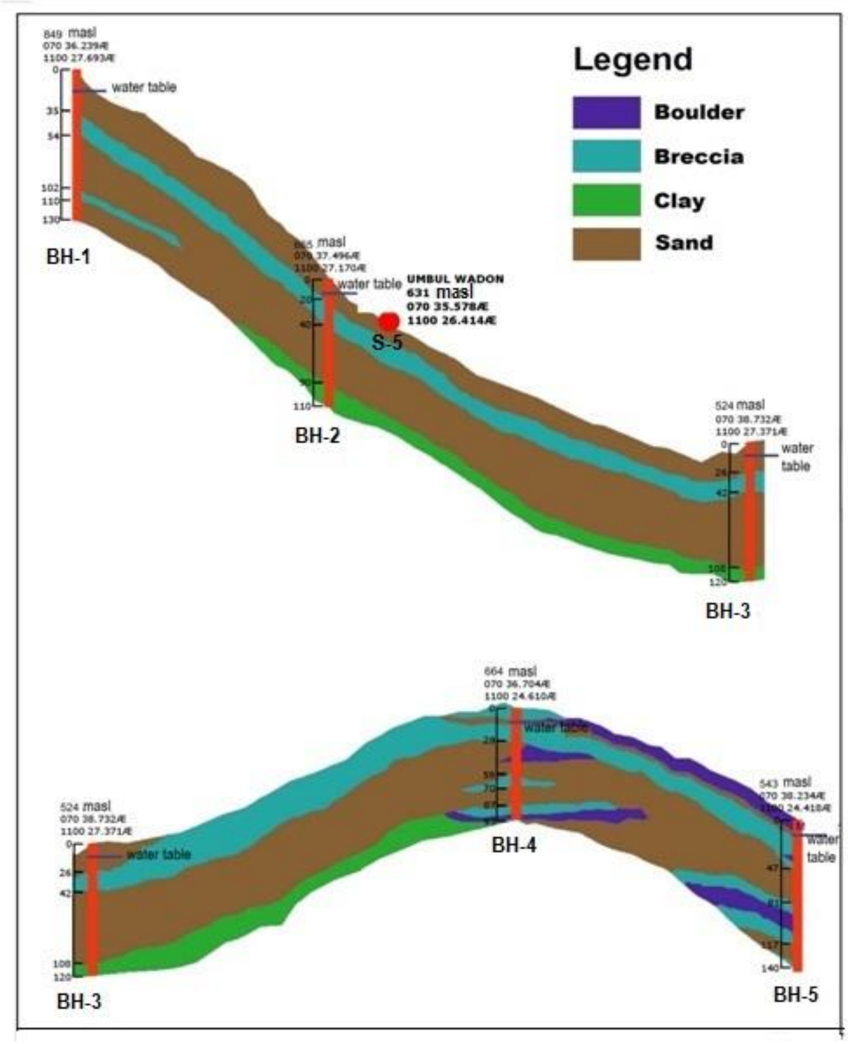

Figure 5. Geology profile around the boreholes and Wadon springs (S-5).

Figure 4 shows plotting values of the $\delta^{18}O$ and δD from Table 4 into the MMWL graph which found from earlier research [6]; if $\delta^{18}O$ and δD values water sample fall along or close to the MMWL, it means that groundwater sample experience minimal fractionation. This is because of rapid infiltration of rainfalls to the water table. This is in a good agreement with the conditions of the research zone hypothetical. It has hilly topography with slope less than 18%. Majority of soil structures of the research zone hypothetical are Young Merapi volcanic sediment, which consists of boulder, volcanic breccia, unconsolidated breccia, sand, and clay [12, 13], as exhibited in Figure 5.

Groundwater of Group-A

Figure 4 indicates that the most isotopic groundwater samples of Group-A (S-6, S-7, S-8, W-2, W-3, W-4, W-5, W-6, and BH-5), which were collected from springs, wells and boreholes at elevation of 329 to 620 m.asl, fall along or close to the MMWL. It means that the origin of groundwater Group-A are local rainfall or meteoric water, and there is no isotopic fractionation or effect of geothermal activities to groundwater.

Groundwater of Group-B

- From Figure 4 it can been seen that groundwater of Group-B (S-1, S-2, S-3, S-4, S-5, W-1, BH-1, BH-2, BH-3, and BH-4) which were collected from elevation of 624 to 761 m.asl have similar isotopic compositions, in the range from -7.42 to -7.35‰ for $\delta^{18}O$ and -46.10 to – 43.5‰ for δD. It can be concluded that the origin of groundwater Group-B comes from the same catchment zone [2, 5, 8], so hydraulically there is no interconnection aquifer between Group-A and Group-B.
- Earlier studies [6] showed that from Kricak area (126 m.asl) to Balerante (940 m.asl), where the groundwater samples of Group-B were collected, isotopic compositions of local rainfall are in the range of -6.76 to -5.85‰ for $\delta^{18}O$ and -41.61 to – 33.52‰ for δD. Thus isotopic compositions of Group-B are more depleted than local rainfall. This means that the water feeding to Group-B does not come from local rainfall; however it comes from a higher elevation.
- Due to the isotopic compositions of Group-B are almost similar to the isotopic composition of rainfall which were collected from Kinahrejo (1136 m.asl) to Plawangan (1260 m.asl), which range from -7.57 to -7.35‰ for $\delta^{18}O$ and -48.02 to -44.4‰ for δD [6]; Therefore, it can be suspected that the origin of groundwater in Group-B comes from the area which is located between Kinahrejo and Plawangan.

To ensure that the groundwater in Group-B flows through the same aquifer, and then water samples from Group-B were measured its $\delta^{13}C$ values. The $\delta^{13}C$ values can trace the carbon sources and reactions for numerous inter-reacting organic and inorganic species. The springs' $\delta^{13}C$ value gives information whether there are interconnections between aquifers or not. The $\delta^{13}C$ values in three groundwater of springs (S-1, S-4 and S-5), one groundwater of well (W-1) and two groundwater of boreholes (BH-1 and BH-3) were examined. It is found that the range of $\delta^{13}C$ values is from -17.74±0.27‰ to -10.96±0.66‰ (as shown in Table 4).

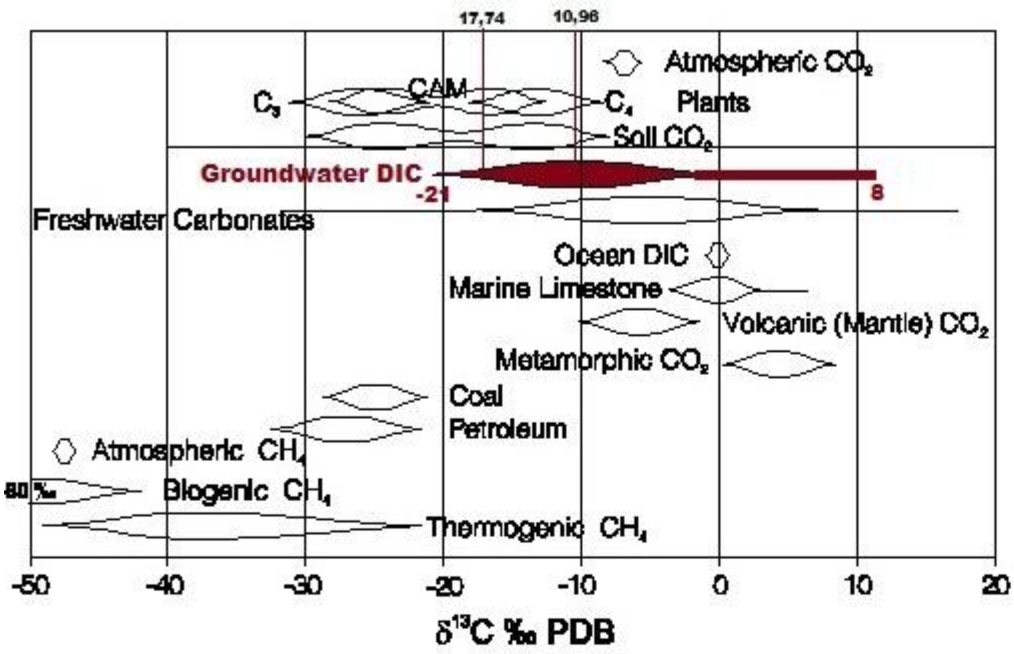

Figure 6 Ranges for δ^{13}C values in selected natural compounds [14].

Plotting data of the δ^{13}C from Table 4 in Figure 6 shows that the values of δ^{13}C ranges from -17.74±0.27‰ to -10.96±0.66‰ PDB and it is still in the range of δ^{13}C values of groundwater Dissolved Inorganic Carbon (DIC), that is -18‰ to 8‰ PDB. Figure 5 indicates that the carbon contained in the groundwater samples comes from groundwater DIC.

Therefore, it is suspected that aquifer of Group-B hydraulically interconnected or the groundwater origin of Group-B is from the same recharge zone. This is in line with the geological profile in the study area, particularly the relationship between Wadon springs with 5 boreholes in the vicinity (as exhibited in Figure 5).

Tritium dating method is utilized evaluate the direction, residence time and the linear velocity of groundwater. In the saturated zone, water is isolated from the atmosphere and the tritium concentration drops due to radioactive decay only. Groundwater recharge occurred from the areas of high tritium flows to the areas of low tritium concentration; therefore the decrease in the concentration of tritium can be used to determine the flow direction of groundwater, resident time, and its linear velocity. The measurement of tritium concentration in the groundwater samples Group-B shows that the concentration of groundwater samples which were collected from elevation 665-1196 was ≥ 4.20 TU, while the groundwater samples which were collected at elevations below was < 4.20 TU. This indicates that groundwater flows from higher to lower elevations.

From δ^{18}0, δD, δ^{13}C values and tritium concentration, it can be concluded that the groundwater between Pagerjurang (650 m.asl) and Plawangan (1260 m.asl) flows to Wadon springs; it is estimated that the area of recharge is 8.033 km^2.

Conclusions

From the study of environmental isotopes tracing to determine the origin of groundwater springs it can be concluded that:

- The origin of groundwater Group-A (S-6, S-7, S-8, W-2, W-3, W-4, W-5, W-6, and BH-5), which located at elevation of 329 to 620 m.asl, are local rainfall or meteoric water, and there is no isotopic fractionation or effect of geothermal activities to groundwater.

- The origin of groundwater Group-B (S-1, S-2, S-3, S-4, S-5, W-1, BH-1, BH-2, BH-3, and BH-4), which located at elevation of 624 to 761 m.asl), comes from the same catchment zone (hydraulically interconnected).
- The water feeding to Group-B does not come from local rainfall; however it comes from a higher elevation.
- Hydraulically there is no interconnection aquifer between Group-A and Group-B.
- Mostly $\delta^{13}C$ in recharge zone and Wadon springs comes from the same source of carbon; that is -17.74±0.27‰ to -10.96±0.66‰ Pee Dee Belemnite (PDB); this holds for $\delta^{13}C$ in the range of groundwater Dissolved Inorganic Carbon (DIC), that is -18‰ to 8‰ PDB.
- The tritium concentration in water samples were collected from elevation 665-1196 m.asl (S-1, S-2, W-1, BH-1, and BH-2,) to elevations below (S-4, S-5, BH-3 and BH-4) decreasing from $\geq$ 4.20 TU to <4.20 TU exhibits that groundwater comes from recharge zone hypothetic to Wadon springs.
- The origin of groundwater in Wadon springs (631 m.asl) comes from the area which located between Pagerjurang (650 m.asl) and Plawangan (1260 m.asl); the area of recharge zone is 8.033 km^2.

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