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Aquifer System Analysis to Identify the Cause of Groundwater Depletion at Umbulan Spring, Indonesia

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Umbulan Spring is an Indonesian groundwater spring with a historically significant discharge up to 3,500 L/s which has significantly declined in recent years, has significantly declined from 5,262 L/s since 1987. In terms of hydrogeology, this declination of discharge indicates a depletion of water resources in the groundwater basin. This study aimed to identify the cause of the depletion in the Umbulan Spring discharge by analysing the aquifer system using an integrated methodology of hydrochemical and geological approaches. Results show that groundwater that discharges via Umbulan Spring is of the same groundwater facies as that of the surrounding artesian wells, having $CaMgHCO_3$-type water with a bicarbonate anion facies and no dominate cation facies. The range of groundwater isotopes from -7.8 to -8.2 ‰ for ^{18}O and -46.2 to -50.5 ‰ for deuterium correspond to the local Bromo Meteoric Water Line (BMWL). Groundwater isotope correlation with the BMWL and the site elevation shows that the recharge area is located on the northern slope of the Bromo-Tengger Volcanic Complex between 1,300 – 2,300 m above sea level. The groundwater source flows through a lapilli tuff aquifer which is covered by impermeable pyroclastic flow deposits. Due to its determination as part of the same aquifer system as the artesian wells, the depletion of the Umbulan Spring discharge is related to the increasing number of artesian wells around the spring.

1. Introduction

Promoting clean water conservation has become a major world issue (Jia et al., 2019). Meanwhile, worldwide water demand increases by 1 % /y due to population growth, changes in the economy, and increasing consumption habits (United Nations Water, 2018). Over 50 % of the world's population are expected to live in water-stressed regions by 2050 (Sa'ad et al., 2021). One location in critical need of better water resources conservation is on the northern slope of the Bromo-Tengger Volcanic Complex in East Java, Indonesia. This active volcano has a caldera at the top filled with pyroclastic deposits (Mulyadi, 1993), referred to as the Bromo-Tengger Caldera. Like other volcanoes in Indonesia, this volcano produces andesitic magma and forms cone-shaped volcanic bodies known as stratocones or stratovolcanoes (Selles et al., 2015), features which are characterised by steep slopes and intersections of lava, pyroclastic and volcaniclastic deposits (Bogie and Mackenzie, 1998). The Bromo-Tengger Volcanic Complex comprises several lava and pyroclastic deposits such as pyroclastic fall, pyroclastic surge, and pyroclastic flow deposits (Van Gerven and Pichler, 1995).

The northern side of the Bromo-Tengger Volcanic Complex has attracted interest for its unique hydrogeological conditions which produce Umbulan Spring, one of the largest freshwater springs in Indonesia. Umbulan Spring, located at 7°45'34.94"S 112°56'3.65"E, discharges 3,500 L/s of freshwater (Toulier et al., 2019). The establishment of hundreds of artesian wells in relatively close proximity to the spring confirm that the adjacent area has enormous groundwater resources potential. The wells range in depth from 20–200 m with a discharge up to 30 L/s flowing for 24 h. Apart from industrial needs, most of these wells are intended for irrigating rice fields and meeting the daily needs of the surrounding residents. The number of established artesian wells has been continuously increasing since 1970 in line with the population growth and development of the industrial areas.

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Even though Umbulan Spring has an enormous groundwater potential, as a resource, this location faces serious challenges. Groundwater depletion in this location has been observed, signalled by a decrease in Umbulan Spring discharge. Historical East Java Water Resource data from Seizarwati et al. (2016) showed that the discharge of Umbulan Spring in 1987 reached 5,262 L/s, yet over the following 32 y decreased by 1,762 L/s. This dramatic decrease is a clear sign of the depletion of groundwater in the basin.
This work aims to determine the cause of depletion in the Umbulan Spring discharge by newly analysing the aquifer system using a combined hydrochemical and geological approach. Several researchers have carried out studies to determine the cause of the spring's depletion but have not previously considered geological data in their analytical methods. Therefore, the primary contribution of this study involves newly identifying geological data, including exceptionally detailed identification of rock types from bore log data and interpretation of their distribution, combined with hydrochemical data analysis. Results of this study are expected to provide a reference for creating regulations in an effort to conserve clean water better.

2. Methodology

Aquifer system identification in this study uses the integration of hydrochemical and geological methods. For the hydrochemical method, eight groundwater samples were collected from the research site, including one water sample at Umbulan Spring. The sampling locations are shown in Figure 1. Hydrofacies analyses were then conducted by determining groundwater groups based on the content of major elements (Ca, Na, K, Mg, Cl, CO_3, HCO_3, and SO_4) using a piper trilinear diagram from the opensource software GW_Chart version 1.30 by Winston (2020).

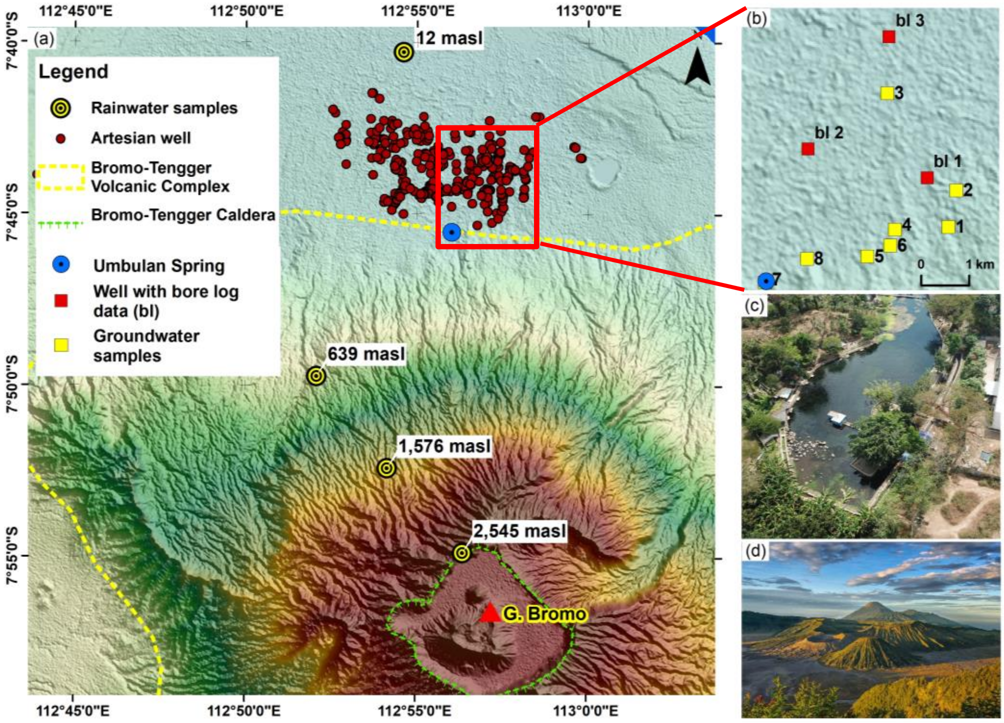

Figure 1:(a) Map of the research site and distribution of data and sample sites. Artesian well location based on Toulier et al. (2019), (b) Map of groundwater sample and bore log data locations, (c) Umbulan Spring viewed from above, (d) Bromo-Tengger Caldera at the top Bromo-Tengger Volcanic Complex

The analysis of the isotopes ^2H (deuterium or D) and ^{18}O, as stable isotopes in water, can be used for groundwater classification by observing the amount of isotope content in groundwater samples and comparing that with the isotope content of rainwater samples at the research site which are representative of the local meteoric water line (Craig, 1961). The isotopic information is reported using the conventional delta notation (‰) as a deviation from the Vienna Standard Mean Ocean Water (VSMOW). Furthermore, D and ^{18}O isotopes can also be used to determine the location of recharge areas for the groundwater (Mazor, 1997). Several previous studies have shown the advantages of using D and ^{18}O isotopes to analyze recharge areas (Bertrand et al., 2010).

In this study, apart from the isotopes of groundwater samples, the isotope content of rainwater from different elevations was also analysed. For that part of the methodology, rainwater samples were taken from four elevations on the slopes of the Bromo-Tengger Volcanic Complex: 12, 639, 1,576, and 2,545 m above sea level (masl) (Figure 1), to obtain the Bromo Meteoric Water Line (BMWL). The BMWL was then compared with the Global Meteoric Water Line (GMWL) (Craig, 1961) and other Local Meteoric Water Lines (LMWLs) from previous research by Seizarwati et al. (2016) and Toulier et al. (2019). This comparison aimed to determine whether the isotopes of rainwater at the study site, or the BMWL, show changes or anomalies compared to the GMWL or LMWLs.

For the geological analysis part of the methods, aquifers were identified based on bore log data and geological surveys. These analyses used stratigraphic bore log data from three drilling wells in close proximity to Umbulan Spring such that the subsurface stratigraphy could be clearly illustrated; specifically, to identify such rocks acting as permeable–impermeable layers and their distribution. The three bore log section correlations were combined with geological survey data collected at the research location to determine the distribution of rocks and aquifer systems. The locations of the three wells with bore log (denoted as bl) data are shown in Figure 1. In the bore log data, apart from showing the lithological composition, data on the presence of confined aquifers from the emergence of self-flowing groundwater is also shown. The bore log depths of bl 1, bl 2, and bl 3 were 69, 82, and 39 m.

3. Results and discussion

3.1 Hydrofacies analysis

The results of the major element contents (Ca, Na, K, Mg, Cl, CO_3, HCO_3, and SO_4) from the eight samples were plotted on a piper trilinear diagram to determine the hydrofacies, equivalent to groundwater facies groups (Figure 2). The hydrofacies results confirm that all eight groundwater samples belong to the same groundwater facies group, showing a bicarbonate type of anion phase with no dominate type of cation facies and overall $CaMgHCO_3$-type water. Since the chemical composition of groundwater is strongly influenced by the water dissolution process of its surrounding host rocks (Mazor, 1997), this indicates that Umbulan Spring and its surrounding artesian wells originated from an aquifer with the same rock type and same residence time of water-rock interaction. As a result, the elements within the sampled groundwater are derived from the dissolution of the surrounding rocks and reflect similar chemistry. In addition, at the time of sample acquisition, measurements of electrical conductivity (EC) and temperature (°C) were also carried out. The EC of groundwater ranged from 204 to 267 µS cm^{-1}, and its temperature ranged from 22-23 °C.

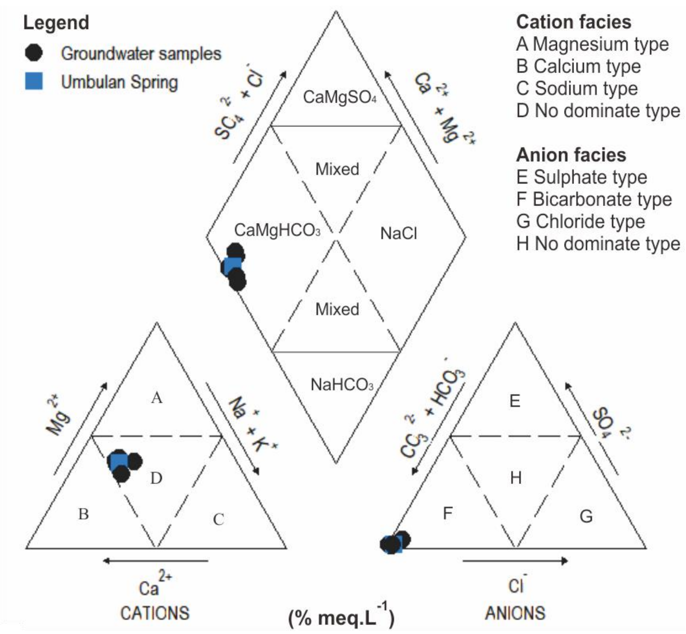

Figure 2: Hydrofacies analysis using the piper trilinear diagram from the software GW_Chart by Winston (2020)

3.2 Hydroisotopic analysis

Results of the δD and $\delta^{18}O$ isotope contents are plotted in Figure 3a on the BMWL. Figure 3a also displays the meteoric water lines of the GMWL (Craig, 1961) and two LMWLs which were previously determined at the same location, LMWL 1 (Seizarwati et al., 2016) and LMWL 2 (Toulier et al., 2019). Figure 3a shows that the BMWL has relatively the same GMWL, LMWL 1, and LMWL 2. The BMWL trend graph is based on Eq (1) as follows:

$$\delta D = 7.58\, \delta^{18}O + 13.06 \quad (1)$$

Isotope tests of the eight groundwater samples showed that the δD content ranged from -46.2 to -50.5 ‰ while the $\delta^{18}O$ content ranged from -7.8 to -8.2 ‰. The isotope test results are plotted in Figure 3a and show that all eight groundwater samples are of the same groundwater group and correspond to the BMWL trend, therefore indicating that the groundwater likely originates from the rainwater system comprised of recharge from the slopes of the Bromo-Tengger Volcanic Complex. Next, the specific location of the recharge area was analysed from groundwater discharging at Umbulan Spring and at the surrounding artesian wells by plotting the number of isotopes with elevation. Rain isotope and acquisition elevation data were crucial for this step.
The two types of data were plotted on the BMWL trendline of $\delta^{18}O$ versus elevation (Figure 3b) and the BMWL trendline of δD versus elevation (Figure 3c). The isotope content of each groundwater sample is plotted on the two graphs such that the origin of the rainwater that supplies groundwater from Umbulan Spring and the artesian wells at the research site can be located. Based on the graph of $\delta^{18}O$ versus elevation in Figure 3b, the water from Umbulan Spring and the artesian wells originates from the infiltration of rainwater falling at elevations of 1,600 – 2,000 masl. The graph of δD versus elevation in Figure 3c shows an indistinctive result located at elevations of 1,600 – 2,050 masl. Considering the correction rate for isotope analysis (± 300 masl) and the uncertainty of the analysis, it can be concluded that the groundwater recharge area which discharges to Umbulan Spring and the artesian wells in the research site is located between the elevations of 1,300 – 2,300 masl.

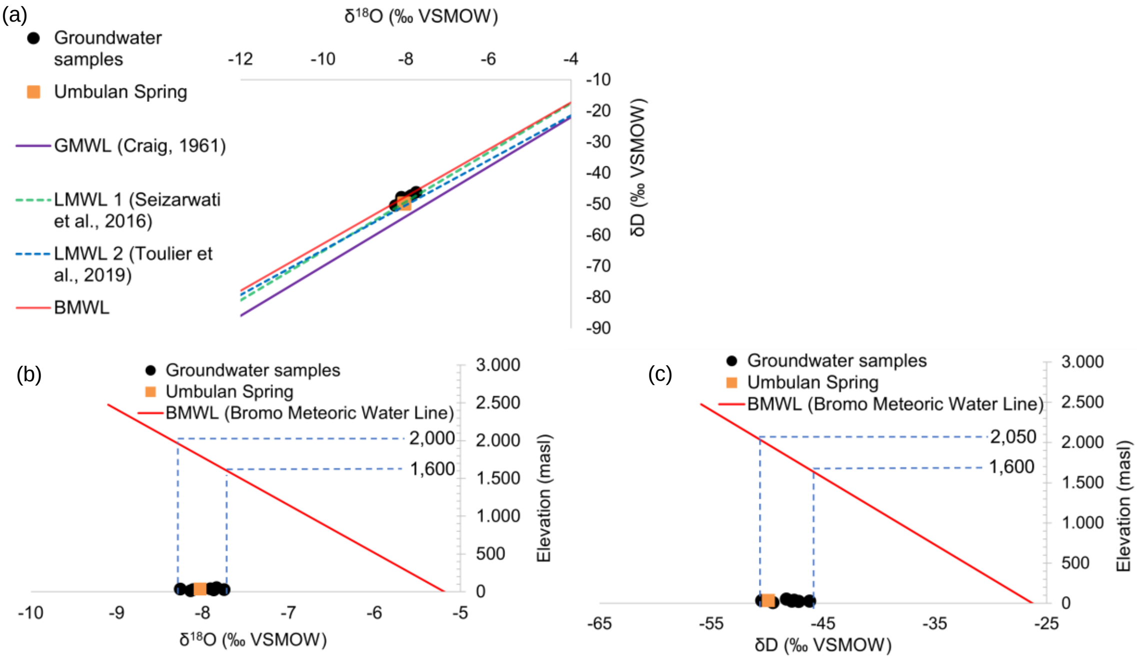

Figure 3: (a) Trendlines of δD versus $\delta^{18}O$ from isotope test data, (b) $\delta^{18}O$ versus elevation, (c) δD versus elevation

3.3 Geological data and aquifer system analysis

In this study, the subsurface conditions were identified through bore log data analysis. These data suggest that the research site comprises tuff lapilli with breccia inserts as the oldest layers, followed by pyroclastic flow deposits intercalated with lapilli tuff, tephra, and soil. The production of artesian wells originates from a layer of lapilli tuff which forms a confined aquifer, and has a hydraulic conductivity of up to 9.5 m/s (Smith and Sharp, 2006). This layer has intercalations of breccia, suggesting that the long-time deposition of lapilli tuff interspersed with lahar deposition produced breccia. Above this aquifer layer, a layer of pyroclastic flow deposits has undergone welding to become consolidated. According to Moyer et al. (1996), this rock has a hydraulic conductivity of 10^{-5} m/s, it is classified as an impermeable layer. Above this layer, at the top, there is tephra with a relatively broad distribution of deposit on the surface of the study site which acts as an unconfined aquifer with wetted soil. Based on the surface geological survey, lava flow deposits and pyroclastic fall deposits (tephra) can be found on top of the pyroclastic flow deposit. Lava flow deposits begin to appear from the break of the slopes to the volcano's peak, while tephra deposits are found at the top surface below weathered soil. The locations of the bore log are shown in Figure 1, and the bore log data is shown in Figure 4.

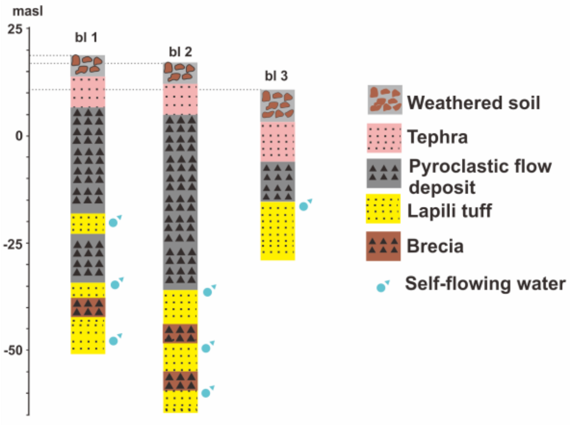

Figure 4: Bore log data at bl 1, bl 2, and bl 3

According to the stratigraphic and aquifer system analysis, the lapilli tuff with breccia insertions was estimated as a permeable layer. However, an impermeable layer overlaps the lapilli tuff layer, namely consolidated pyroclastic flow deposits. The interaction of these two layers forms a confined aquifer, and produces self-flowing water (Figure 4). This aquifer is filled by rainwater infiltration at elevations of 1,300 – 2,300 masl on the slopes of the Bromo-Tengger Volcanic Complex, which includes the Bromo-Tengger Caldera. After infiltration, the rainwater becomes groundwater and flows down the slope towards the discharge zone, where Umbulan Spring and the artesian wells are located. The correlation of the artesian well aquifer system with Umbulan Spring has been proven by the hydrochemical analysis of this study, according to the hydrofacies and hydroisotopic result. Hence, it can be concluded that Umbulan Spring and the artesian wells share the same aquifer system, illustrated in detail in Figure 5. The formation of Umbulan Spring is thought to be due to a natural fracture (Mac Donald, 1995 as cited in Seizarwati et al. 2016). The cause of this natural fracture formation which characterises Umbulan Spring will be an exciting focus of future research directions.

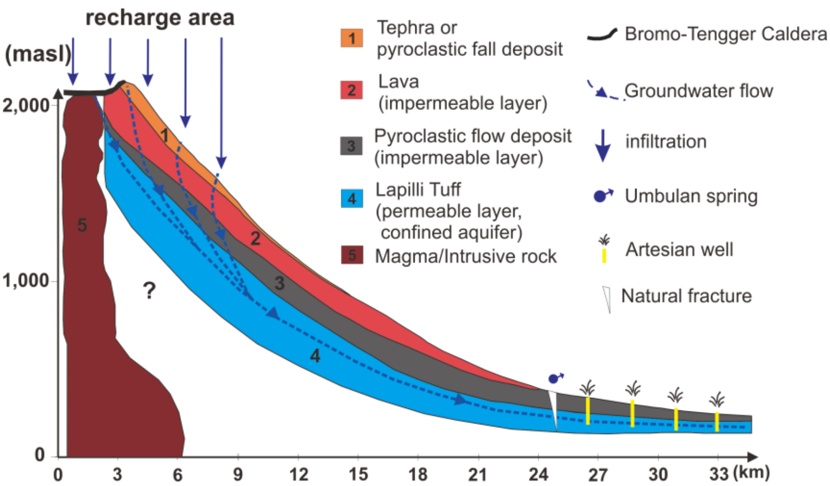

Figure 5: Aquifer system model of Umbulan Spring and the artesian wells on the northern slope of the Bromo-Tengger Volcanic Complex

4. Conclusion

Based on the results of hydrochemical and geological analyses, it has been confirmed that Umbulan Spring and its surrounding artesian wells are part of a single aquifer system based on their identical groundwater hydrofacies as $CaMgHCO_3$-type groundwater, with a bicarbonate type of anion facies, no dominant cation facies, and relatively similar isotopic composition of between -7.8 to -8.2 ‰ for $\delta^{18}O$ and from -46.2 to -50.5 ‰ for δD in line with the BMWL. The groundwater aquifer is characterised as lapilli tuff covered by an impermeable pyroclastic flow deposit. In terms of the hydrogeological process, this aquifer system originates from rainwater infiltration at an elevation of 1,300 - 2,300 masl to form the recharge area, including the Bromo-Tengger Caldera. Due to the spring and the artesian wells being part of the same groundwater system, the declined discharge of Umbulan Spring and overall depleted groundwater resources are affected by the increasing number of artesian wells. The results of this study are necessary to inform clear and structured regulations for future drilling of artesian wells to help conserve the existing groundwater resources of this area.

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