Delineation of Mrutu Spring Protection Zone: An Attempt to Maintain the Sustainability of Groundwater Resources

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Abstract. Lumajang Regency government plans to optimize water resources using Mrutu Spring groundwater as a water source for the Drinking Water Supply System (SPAM). The maintenance of the groundwater quality and quantity sustainability is necessary to delineate the protection zone of Mrutu Spring. Geological, hydrogeological, and land use parameters assessed the spring protection zone. The Mrutu Spring protection zone determination was conducted using manual and analytical solutions and combination hydrogeological methods. This study finds that the protection zone of Mrutu Spring is around Mrutu Spring up to Mrutu Spring groundwater recharge in the northwest. Mrutu Spring protection zone is divided into protection zone I, II, III, and groundwater recharge for the spring protection zone. The geometry of protection zone I is a circle with a radius of 1.64 km and 314 m². Protection zone II is in the fifth circle with a 1.64 km and 2.87 km². Protection zone II has an ellipsoidal shape with a radius of 16.74 km and 67.28 km². The groundwater recharge for the spring protection zone is oval, with a radius of ± 12 km and 57,85 km².

Keywords: Spring Protection Zone, Groundwater, SPAM, Mrutu Spring

1. Research Background

The purpose of delineating a spring protection zone is to determine a spring recharge area (Ministry of Environment and Forestry, 2020). Adam and Foster (1992) stated that the delineation of spring protection zone and proper land application is the key to sustainable drinking water resources. To get a close assumption in the spring, empirical and conservative approaches can delineate the spring protection zone boundaries (Foster et al., 2002).

According to Carey et al. (2009), the delineation of the spring protection zone is carried out using the manual mapping method. Information about spring is limited to the elevation of the spring, and spring is often complicated because it is within a system consisting of a system of several springs. The groundwater protection zone is divided into Zone I (Inner Protection Zone), taking into account the lifetime of fecal pathogens (Taylor et al., 2004). It is assumed to have a radius of 50 meters. Zone II (Outer Protection Zone) considers minimal time to experience delay, dilution, and attenuation of pollutants. Zone III (Catchment Area Protection Zone) protects groundwater for an extended period.

Research on groundwater protection in Indonesia is mainly done for vulnerability assessment and conservation purposes. Widyastuti et al. (2012) examined the vulnerability of groundwater to pollution in Gunung Sewu Karst ponor recharge area; Hendrayana and Ramadhika (2016) zoned conservation areas in Wates Groundwater Basin, and Putranto et al. (2019) conducted research on vulnerability to pollution in Karanganyar-Boyolali Groundwater Basin. The study of Mrutu Spring protected zone aims to maintain the quality and quantity of the spring groundwater for sustainable use.

2. Research Area

Administratively the research area is located in Lumajang Regency, which borders Probolinggo Regency in the north. The research focuses on Bondoyudo Sub-watershed, an area around Mrutu Spring, located between UTM coordinates (WGS 1948) Zone 49N, 719749-746881m and 9100507-9120224m.

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This research area is spread in 5 Guci Alit Sub-districts, Klakah Sub-district, Senduro Sub-district, Kedungjajang Sub-district, and Sukodono Sub-district (Figure 1).

Figure 1. Map of Mrutu Spring research area and its surroundings

3. **Geology of the Research Area**
The research area is under the Lumajang and Probolinggo Geological Map Sheet (Suwarti et al, 1992). The rock formation of the research area composes of Mandalika Formation (Tomrn), Jembangan Volcanic Rock (Qvj), Breakthrough Rock (Qi a,b), Tengger Volcanic Rock (Qvt), Rock Mount Semeru (Qvs), Cemara Tiga Debris Deposits (Qtt), Lamongan Volcanic Rocks (Qvl), and Alluvium (Qa) (Figure...
2). The research area is focused on the Bondoyudo sub-watershed. A geological mapping survey aimed to cross-check the actual conditions, focusing on The Tengger Volcanic Rock formation (Qvt). This formation comprises andesite lava, volcanic tuff and breccia, and Alluvium (Qa), which consists of loose materials from clay, mud, sand, gravel, gravel, and boulders.

![Figure 2. The geological map of the research area is based on the Geological Map of Indonesia Lumajang and Probolinggo sheet (Suwati et al., 1992) with modification.](image1)

![Figure 3. Geological Cross Section](image2)
The dominant lithology found in the field is the result of volcanism such as:

a. gray and brown (weathered) andesite lava with massive structure, porphyroclastic texture with grain size < 1mm-2mm, and with a mineral composition consisting of pyroxene, plagioclase, and mafic minerals as the base mass;

b. brown (weathered) pyroclastic breccia, poor sorting, loose fabric, tuff-lapilli matrix, fragments sizes 64-300 mm in the form of lithic andesite and scoria. Based on its characteristics, the pyroclastic breccia is interpreted as the result of an explosive eruption and deposited by a flow mechanism;

c. gray and dark brown (weathered) tuff characterized with well sorting, structurally layered – finer upwards, composed of ash (fine dust) – lapilli and consolidated andesite lithic fragments. Based on its characteristics, tuff is interpreted as the result of an explosive eruption deposited by a falling mechanism;

d. gray and dark brown agglomerates characterized with poor sorting, open fabric, fragment sizes > 64 mm (almost rounded), and tuff matrix. Based on these characteristics, agglomerates are interpreted as the result of explosive volcanism with andesite material as fragments, then transported and deposited with a tuff matrix until they are lithified into rock; and

e. alluvium deposits, found in river floodplains, composed of unconsolidated material with sizes of block - clays and with normal graded bedding type with coarse to finer grain upwards.

4. Hydrogeology of the Research Area

Based on the Hydrogeological Map of Indonesia, Kediri sheet, compiled by Poespowardoyo et al. (1981) (Figure 4), in general, the potential for groundwater availability and aquifer productivity is found in aquifers – with flow through inter-grain spaces – consisting of gravel, sand, and clay materials of medium to high loose and young volcanic deposits; divided into productive aquifers with a wide distribution, and moderately productive aquifers with a wide distribution.

Aquifers with flow through inter-grain spaces consisting of volcanic sedimentary materials – andesite-basalt lava – are divided into highly productive aquifers, productive aquifers, and local productive aquifers.

Low productive fractured aquifers and areas of scarce groundwater consisting of volcanic deposits are located in valleys. They are divided into minor aquifers with very low drainage and localized groundwater in valleys or rock weathering zones.

A total of 29 springs and 16 dug wells were found in the research area. Springs in the research area were found in various places and conditions (Figure 5), such as on rock fractures, hillsides, landslides, floodplains in rivers, small springs formed due to decay of plant roots, and in the form of seepage. Meanwhile, dug wells were found locally in volcanic rocks and predominantly found in areas that have alluvial deposits.

From 45 groundwater observation points, interpolation was carried out to determine the groundwater level in the study area. The highest groundwater level is 1864 masl, and the lowest is 67 masl. The groundwater level is relatively the same as the ground surface elevation.

The groundwater flow direction is northwest to southeast, and a small portion of the groundwater flows east (Figure 6). The groundwater that flows to the southeast mostly flows towards areas where many dug wells are found, and a small portion moves towards Mrutu Spring. This shows that groundwater flow direction is parallel with the number of groundwater emergences in the dug wells. Dug wells are often found in the southeastern part of the study area with the lithology of alluvial deposits.
Figure 4. Hydrogeological map of the research area, based on Indonesia Hydrogeological Map of Indonesia Kediri sheet (Poespowardoyo, 1981) with modification.

Figure 5. The emergence of groundwater in the research area at Mrutu Spring from andesite lava fractures (A), the emergence of groundwater as a seepage (MA 9, B), the emergence of groundwater in depression springs (MA 6, C), the emergence of groundwater in free springs (MA 11, D), the emergence of groundwater in small tubular springs (MA 15, E) and the emergence of groundwater in dug wells (F).
5. **Methodology**

There were two stages of delineating the Mrutu Spring protection zone: field mapping and data analysis. The field mapping stage aimed to cross-check the lithological conditions, register the emergence of springs, and measure Mrutu Spring discharge. The second stage, data analysis, was to delineate Mrutu Spring protection zone, which is the primary goal of this research.

5.1. **Mrutu Spring Discharge Measurement**

The measurement of the discharge of Mrutu Spring was carried out in February, March, and April to coincide with the rainy season using the floating method. This method was used because it more represented the discharge of Mrutu Spring that emerged through several fractures. This method’s measurement uses two parameters: water flow velocity and cross-sectional area. The cross-sectional area of the spring could be calculated using Equation (1).

\[ A = W_{\text{average}} \times H_{\text{average}} \]  

Where:
- \( A \) = Cross-sectional area (m\(^2\))
- \( W_{\text{average}} \) = Cross-sectional average width (m)
- \( H_{\text{average}} \) = Average depth (m)

The water flow velocity in the spring was obtained from the division of the length of the channel/flow (P) with the average time (T average) of a floated object towards the endpoint of the cross-section. The calculation of the velocity can be seen in Equation (2).

\[ V = \frac{L}{T_{\text{average}}} \]  

Where:
- \( V \) = Velocity (m/sec)
The water discharge was obtained from the multiplication of the cross-sectional area \( A \) of the channel/stream/pond with the velocity of the water flow of the spring \( V \), the calculation of the spring discharge can be seen in Equation (3).

\[
D = A \times V
\]  

Where:
- \( D \): Water discharge (m\(^3\)/sec)
- \( A \): Cross-sectional area (m\(^2\))
- \( V \): Velocity

5.2. Research Area Hydrology Study

The groundwater availability is inseparable from the hydrological system (Davie, 2007); three factors play a role in the hydrology cycle – evaporation, precipitation, and runoff. The hydrological cycle can be mathematically represented to determine the hydrological process. The cycle proceeds within a certain period or is commonly referred to as water balance, as shown in Equation (4).

\[
P = E + \text{runoff} + \text{infiltration} + \Delta SM
\]  

Where:
- \( P \): Precipitation (mm/year)
- \( E \): Evapotranspiration (mm/year)
- Runoff: Surface flow (mm/year)
- Infiltration: The entry of water from the ground surface to subsurface (mm/year)
- \( \Delta SM \): Soil moisture

The amount of evapotranspiration can be calculated using the Thornthwaite method (1948) in Davie (2007), which can be seen in Equation (5-7).

\[
ET = 1,62 \left( \frac{10^T}{1} \right)^a
\]  

Where:
- \( ET \): Evapotranspiration (cm/year)
- \( T \): Average monthly temperature \(^\circ\)C

with

\[
I = \sum_{j=1}^{12} \left( \frac{2}{j} \right)^{1.5j}
\]  

\[
a = 67.5 \times 10^{-8}I^3 - 77.1 \times 10^{-6}I^2 + 0.0179I + 0.49
\]

The amount of infiltration is calculated using the soil water balance method by calculating the infiltration and outflow (seepage and evaporation). This method estimates the amount of water entering the groundwater saturation zone.

5.3. Mrutu Spring Protection Zone

The delineation of the spring protection zone aims to determine the natural boundary of Mrutu Spring recharge area. The classification of the protected zone is determined using the hydrogeological mapping method – manual and analytical – that has been developed by Carey et al. (2009).

5.3.1. Hydrogeological Mapping Method.

The boundary of the protected zone is based on the hydrogeological mapping method and the geology conditions. The parameters are used to consider the delineation and limitation of the catchment area. Groundwater usually divides border groundwater catchment areas.
5.3.2. Manual Method.

Zone determination using the manual method can only be used as a reference because this method does not represent local hydrogeological conditions. This method assumes that the piezometric surface is horizontal; the catchment area to the abstraction source is considered to be circular, and the radius can be calculated (Figure 8). Although this condition is rarely encountered in the real world, this method can be useful without data on hydraulic gradients and groundwater flow directions. The area and radius of the catchment protection zone using the manual procedure are calculated using Equation (8-9).

\[ A_R = \frac{Q}{U} \]  
\[ r = \sqrt{\frac{A_R}{\pi}} \]  

Where:
- \( Q \): Groundwater pumping rate (m\(^3\)/year)
- \( U \): Annual recharge (m/year)
- \( r \): Radius from catchment zone to source (m)

The area and radius of the 50 and 400-day protection zones can be calculated using Equation (10-11).

\[ A_d = \frac{Q \times t_d}{b \times n} \]  
\[ r_d = \sqrt{\frac{Q \times t_d}{b \times n \times \pi}} \]  

Where:
- \( t_d \): Groundwater travel time
- \( b \): Aquifer thickness (m)
- \( n \): Effective porosity

5.3.3. Analytical Method.

The analytical method more represents local hydrogeological conditions and is semi-quantitative than the manual method. Analytical methods can be used when local hydrogeological conditions such as groundwater flow maps, aquifer thickness, and hydraulic conductivity are known. The zone generated using the analytical method is ellipsoidal. Calculations using the analytical method are based on aquifer characteristics and manual calculations of the catchment area, which can be done using Equation (12).

\[ X_L = \frac{q}{2 \times \pi \times K \times b \times i_0} = \frac{q}{2 \times \pi \times T \times i_0} \]  

The maximum width of the catchment zone perpendicular to the flow line can be calculated using Equation (13).

\[ Y_L = \frac{q}{K \times b \times i} = \frac{q}{T \times i_0} \]  

The value of the hydraulic gradient can be calculated using Equation (14).

\[ i_0 = \frac{\Delta h}{l} \]  

Where:
- \( Q \): Groundwater discharge (m\(^3\)/sec)
- \( T \): Transmissivity aquifer (m\(^2\)/sec)
- \( K \): Hydraulic conductivity (m/day)
- \( b \): Aquifer thickness (m)
- \( i_0 \): Hydraulic gradient before pumping
- \( \Delta h \): Differences in groundwater levels (m)
- \( l \): Distance (m)

The location of the maximum width from the zero point towards the upstream (\( D_{wr} \)) can be calculated using Equation (15).

\[ D_{wr} = \frac{X_u^2 + \left(\frac{b}{2}\right)^2}{2 \times X_u} \]
The boundaries of zone I (50 days) and zone II (400 days) in the form of a radius from the zero point can be calculated using Equation (16-17).

\[ r_{50} = \sqrt{\frac{Q \times t_{50}}{\pi \times b \times n_e}} + \frac{K \times I_0}{n_e} \times t_{50} \]  \hspace{1cm} (16)

\[ r_{400} = 8 \times r_{50} \]  \hspace{1cm} (17)

Where:
- \( r_{50} \): Radius of zona I
- \( r_{400} \): Radius of zona II
- \( n_e \): Aquifer effective porosity

Determining protection zone boundaries for springs is more complex than determining the protection zone for production wells; manual calculation is not suitable for springs (Hendrayana & Putra, 2008). The determination of zone III in springs can be done by combining the results of hydrogeological research on the boundaries of the spring system. A rough estimation of spring recharge areas can use a nomogram (Todd, 1980 in Hendrayana and Putra, 2008) obtained from the relationship between spring discharge and annual average groundwater recharge.

6. Discussion

6.1. Mrutu Spring Discharge

The measurements of Mrutu Spring discharge carried out in February, March, and April using the floating method showed relatively consistent results. On average, the discharge is 0.98 m³/second or 980 liters/second from the measurements.

| Measurement Date       | Length of track (m) | Cross-sectional area (m²) | Water flow velocity (m/sec) | Spring discharge (m³/sec) |
|------------------------|---------------------|---------------------------|----------------------------|--------------------------|
| February 1, 2021       | 10                  | 7.45                      | 0.133                      | 1.013                    |
| March 2, 2021          | 10                  | 6.83                      | 0.136                      | 0.93                     |
| April 3, 2021          | 10                  | 7.61                      | 0.134                      | 1.02                     |
| Average                |                     |                           |                           | 0.98                     |

6.2. Mrutu Spring Recharge

Mrutu Spring recharge was calculated using the soil water balance method, showing the lowest recharge rate was 123.12 mm/year in 2015 and 299.28 mm/year in 2018. From the data analysis using data from 2011 to 2020, the average recharge rate of Mrutu Spring is 203.27 mm/year. The results of the recharge rate calculation are shown in Table 2.

| Year | Recharge (mm/year) |
|------|--------------------|
| 2011 | 218.68             |
| 2012 | 170.41             |
| 2013 | 211.05             |
| 2014 | 176.16             |
| 2015 | 123.12             |
| 2016 | 190.48             |
| 2017 | 290.25             |
| 2018 | 299.28             |
| 2019 | 189.11             |
| 2020 | 164.22             |
| Average | 203.27         |

The Mrutu Spring recharge area is known by using the relationship between Mrutu Spring discharge and annual recharge using the Todd (1980) nomogram. The discharge of Mrutu Spring has an average
of 0.98 m³/second, and the average recharge of the research area is 203.27 mm/year. Based on the plot on the nomogram (Figure 7), the width of the recharge area of Mrutu Spring is ± 125 km².

**Figure 7.** Nomogram of the relationship of Mrutu Spring recharge area with Mrutu Spring discharge and the average annual recharge area of the research area.

6.3. **Mrutu Spring Protection Zone**

The protection zone of Mrutu Spring was determined using the hydrogeological method, manual method, and analytical method. The three methods were then combined to obtain Mrutu Spring protection zone. Protection zone I of Mrutu Spring, is determined with a radius of 10 m and 314 m². Manual and analytical methods were used to determine the radius and the area of protection zone II based on the survival time of fecal coliform bacteria that can survive in groundwater for 60 days (Feachem, 1983). Meanwhile, protection zone III of Mrutu Spring is an upstream/above zone II area.

To determine Mrutu Spring protection zone, this research uses the approach method used for unconfined aquifers. Carey et al. (2009) created the method of determining groundwater protection is used to protect groundwater extracted using wells and unconfined aquifers. In springs, meanwhile, this method has several limitations in delineating the spring protection zone. The determination of the downstream part of springs is at the point of the spring towards the upstream/recharge. The determination of the width and the area of the protection zone of Mrutu Spring was not purely using the results of mathematical calculations; the width and the area of the protection zone, bordered by the recharge of Mrutu Spring determined using the hydrogeological method. The length of the stagnation point (Xl), the width (Yl), and the maximum width of the stagnation point (Dwr) in the analytical method were not used in describing the protection zone of Mrutu Spring, because these aspects are used for wells.
6.3.1. **Hydrogeological Method.**
The determination of the protection zone using the hydrogeological method considers the direction of groundwater flow and the extent of recharge. The results of this method only determined the protection zone of Mrutu Spring recharge area. The recharge area of Mrutu Spring has an area of ± 125 km² with a length of ± 28 km and a width of ± 6 km and has an oval geometry (Figure 8). The hydrogeological method needs to be combined with other more detailed methods. In its application, the hydrogeological method resulted in the determination of a recharge protection zone.

6.3.2. **Manual Method.**
The determination of protection zone using manual method uses spring discharge, annual groundwater recharge, aquifer thickness, and effective porosity parameters. As a result of the manual method, the Protection zone is divided into protection zone I, a defined area with a radius of 10 m and 314 m². The protection zone II, generated from the calculation, has a radius of 1.64 km with a size of 2.87 km² and a width adjusted to the width of the recharge area, and the recharge protection zone above zone II with zone II an area of 122.24 km² (Figure 9).

6.3.3. **Analytical Method.**
The determination of the protection zone of Mrutu Spring using the analytical method and considering hydrogeology characteristics such as spring discharge, transmissivity, aquifer thickness, and hydraulic conductivity. The protection zone of Mrutu Spring is divided into protection zone I, a defined area with a radius of 10 meters and 314 m². Protection zone II, resulting from mathematical calculations, having a radius of 16.74 km with an area of 67.28 km²; and the recharge protection zone, all areas above the protection zone II towards the upstream, which is a recharge area of Mrutu spring that has an area of 57.85 km² (Figure 10).

6.3.4. **Combination Method.**
The protection zone of Mrutu Spring is determined using a combination of hydrogeological, manual, and analytical methods by considering the direction of groundwater flow and the extent of the recharge area to determine the direction and shape of the protection zone. Protection zone I is an area decided to have a radius of 10 m and an area of 314 m². Protection zone II, resulting from the calculation, has a radius of 1.64 km from zone I and has an area of 2.87 km². Protection zone III has a radius of 16.74 km from zone II with 67.28 km². The recharge protection zone has an oval shape with a direction to the upstream and a radius of ± 12 km from zone III with an area of 57.85 km² (Figure 11). Protection zone I is determined to protect Mrutu Spring from direct pollution and to assess conservation areas for Mrutu Spring. Protection zone II is intended to preserve Mrutu Spring from pathogenic contaminants such as fecal coliform bacteria. Protection zone III is intended to protect groundwater in Mrutu Spring from biological and chemical pollution so that it does not change and suffer damage. The recharge protection zone is designed to protect and maintain the quality and quantity of groundwater flowing in and out of Mrutu Spring.
Figure 8. Map of Mrutu Spring Protection Zone Using Hydrogeological Method.

Figure 9. Map of Mrutu Spring Protection Zone Using Manual Method.

Figure 10. Map of Mrutu Spring Protection Zone Using Analytical Method.

Figure 11. Map of Mrutu Spring Protection Zone Using Combination Method.
Conclusion
The main purpose of this research is to determine the protection zone of Mrutu Spring to protect the quantity and quality of Mrutu Spring groundwater from being used sustainably.

1. The emergence of groundwater in Mrutu Spring comes from vertically and horizontally fractures in andesite lava. It can be interpreted that Mrutu spring is an artesian spring.
2. The delineation of the Mrutu Spring protection zone aims to protect the Mrutu Spring recharge area divided into four zones: protection zone I, protection zone II, protection zone III, and recharge protection zone.
3. The recharge area of Mrutu Spring has an oval geometry with an area of ±125 km$^2$ with a length of ±28 km and a width of ±6 km.
4. Protection zone I of Mrutu Spring has a radius of 10 m and an area of 314 m$^2$, intended to protect Mrutu Spring from direct impacts of pollution and human activities and make a conservation area for Mrutu Spring.
5. Protection zone II of Mrutu Spring has a radius of 1.64 km from zone I with an area of 2.87 km$^2$, intended to protect Mrutu Spring from pathogenic contaminants, especially fecal coliform bacteria.
6. Protection zone III of Mrutu Spring has a radius of 16.74 km from zone II with an area of 67.28 km$^2$, intended to protect Mrutu Spring from biological and chemical contamination.
7. The Mrutu Spring recharge protection zone has a radius of ±12 km from zone III with an area of 57.85 km$^2$, intended to protect and maintain the quality and quantity of Mrutu Spring groundwater.

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References
[1] Adams B, Foster S D, 1992 Land-surfaces zoning for the groundwater protection Journal of the Institution of Water and Environmental Management pp 312-320
[2] Carey M, Hayes P, and Renner A, 2009 Groundwater Source Protection Zone-Review of Methods (Bristol: Environment Agency) pp 5-56
[3] Davie T, 2007 Fundamental of Hydrology (New York: Routledge Fundamental of Physical Geography) pp 11-46
[4] Feachem R G, Bradley D J, Garelick H, and Mara D D, 1983 Sanitation and Disease – Health Aspect of Excreta and Wastewater Management (New York: Jhon Wiley and Sons) p 60
[5] Foster S, Hirata R, Gomes D, D’Elia M, and Paris M, 2002 Groundwater Quality Protection (Washington DC: The World Bank) pp 31-52
[6] Heath R C, 1983 Basic Ground-Water Hydrology (Virginia: U.S. Geological Survey) p 84
[7] Hendrayana H, 2013 Hidrogeologi Mata Air – Spring Hydrogeology DOI:10.13140/RG.2.1.4304.6884
[8] Hendrayana H, and Putra D P E, 2008 Pengendalian Airtanah “Sebuah Pemikiran” – Groundwater Control “A Thought”DOI:10.13140/RG.2.1.1760.4009
[9] Kresic N, Stevanovic Z, 2010 Groundwater Hydrology of Springs (Virginia: Elsevier) pp 306-334
[10] Pitts M W, Alfaro C, 2001 Springs And Bottled Water of the World (New York: Springer) pp33-69
[11] Putranto T T, Ali R K, Putro A B, 2019 Studi Kerentanan Airtanah Terhadap Pencemaran dengan Menggunakan Metode DRASTIC pada Cekungan Air Tanah (CAT) Karanganyar-Boyolali Provinsi Jawa Tengah - Study of Groundwater Vulnerability to Pollution Using DRASTIC Method in Karanganyar-Boyolali Groundwater Basin, Central Java Province, J. Ilmu Lingkungan. 17(1):159
[12] Ramadhika R, Hendrayana H, Proc. Seminar Nasional Kebumian ke-9 Penentuan Zona Konservasi Cekungan Air Tanah Wates, Kabupaten Kulon Progo, Daerah Istimewa Yogyakarta – Determination of the Conservation Zone for Wates Groundwater Basin, Kulon Progo Regency, Special Region of Yogyakarta (Yogyakarta: Universitas Gadjah Mada) p 20
[13] Taylor R, Cronin A, Pedley S, Barker J and Atkinson T, 2004 The implications of groundwater velocity on microbial transport and wellhead protection – review of field evidence (London: Elsevier) p 17-26
[14] Todd D K, 1980 Groundwater Hydrology second edition (New York: Jhon Wiley & Sons) p 49
[15] Widyastuti M, Sudarmadji, Sutikno, Hendrayana H, 2012 Kerentanan Airtanah Terhadap Pencemaran Daerah Imbuhan Ponor di Karst Gunung Sewu (Studi di Daerah Aliran Sungai Bawah Tanah Bribin) – Groundwater Vulnerability to Pollution in Ponor Recharge Area in Gunung Sewu Karst (Study in Bribin Underground Watershed), J. Manusia dan Lingkungan doi:10.22146/jml.18529
[16] Woessner W W, Poeter E P, 2020 Hydrogeologic Properties of The Earth Material and Principles of Groundwater Flow (Ontario: The Groundwater Project) p 11-14