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Original Research

Groundwater Aquifer Vulnerability Index (AVI) of Purwokerto Area, Indonesia

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Abstract

The rapid development and growth of Purwokerto requires greater groundwater resources. Research on groundwater vulnerability in Purwokerto is important in order to maintain groundwater resources, sustainability and development of the city. The approach or methods used in this research were: groundwater level measurement, geoelectric survey, and infiltration rate measurement to calculate the aquifer vulnerability index or AVI. This research uses soil infiltration rate data from the surface to a certain depth and the hydraulic conductivity of the lithologies located below the soil. The application of soil infiltration rate data and lithological hydraulic conductivity located below the soil provides a more continuous AVI level without any level voids than solely using lithological hydraulic conductivity data in the previous study. The AVI level of Purwokerto area ranges from low, moderate, high to extremely high. The level of AVI vulnerability in the lithology of the Slamet Volcano Lahar Deposits and Alluvium or its weathered soil is more varied than the lithology of the Tapak Formation and its weathered soil. This is thought to be related to variations in the composition of the components that make up each lithology which causes variations in weathering and AVI levels.

Keywords: aquifer vulnerability index, groundwater, geoelectric, infiltration rate

Introduction

Population growth and city development require greater natural resources. One of these natural resources is groundwater. The availability of existing groundwater, if not managed properly, will reduce the quality and quantity required for those needs. On the one hand, a large population and development in all fields will lead to higher groundwater pollution. The existence of shallow groundwater is susceptible to contaminants left over from human and industrial activities on the surface. Sources of contaminants from groundwater pollution can be various, including: daily household waste, agriculture, small and medium scale industries around Purwokerto, or geothermal energy power plants in the northwest of Purwokerto.

The increasing demand for and consumption of groundwater in recent and forthcoming years puts very strong pressure on those responsible for groundwater management. Information on groundwater vulnerability

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and knowledge of hydrogeological management are very important for certain areas, especially on a more detailed local scale, to manage groundwater resources efficiently and effectively [1]. Several studies on groundwater around the research location have been carried out, including the contamination of groundwater by pollutants in the Kaliori landfill, Purwokerto [2-4]. River sediments and water bodies also indicate contamination from the Kaliori TPA waste on the surface [3]. The total population in four sub-districts in Purwokerto continues to increase from 163,432 people in 2010 to 179,323 people in 2018 [5]. The growing population will also trigger an increase in human activities and environmental changes that will affect the quality of groundwater in Purwokerto. The conditions mentioned above need to be observed to obtain information on the level of groundwater vulnerability in Purwokerto for more accurate regional management policy making.

Regionally, the research location occupies the Quaternary Volcanic Physiography [6] (Fig. 1). In the latest regional geological map, the Purwokerto area and its surroundings are composed of lithologies of tertiary-aged sedimentary rocks (Tapak Formation), volcanic rocks of Slamet Volcano and alluvium of quaternary ages. The Tapak Formation is the oldest rock and is composed mainly of coarse-grained sandstone. Above the Tapak Formation, there is Lahar Deposit from the eruption material of Slamet Volcano. On top of the lahar deposits, the youngest alluvium was deposited [7]. Purwokerto is included in the Purwokerto-Purbalingga Groundwater Basin which was determined based on geological and hydrological considerations with an area of 1,318 square kilometers [8]. This location has moderate aquifer productivity with wide distribution. The aquifer system is the space between grains with a discharge of less than 5 liters/second [9].

Methods

Research Sites

The research location was located in Purwokerto, Banyumas Regency, Central Java, with the UTM coordinates (WGS_1984_UTM_Zone_49S) of 300595, 9184133 to 309564, 9172667. Measurement points were determined based on small grids of locations or grids. These measurement points were known and recorded using GPS. The research site was divided into 42 grids

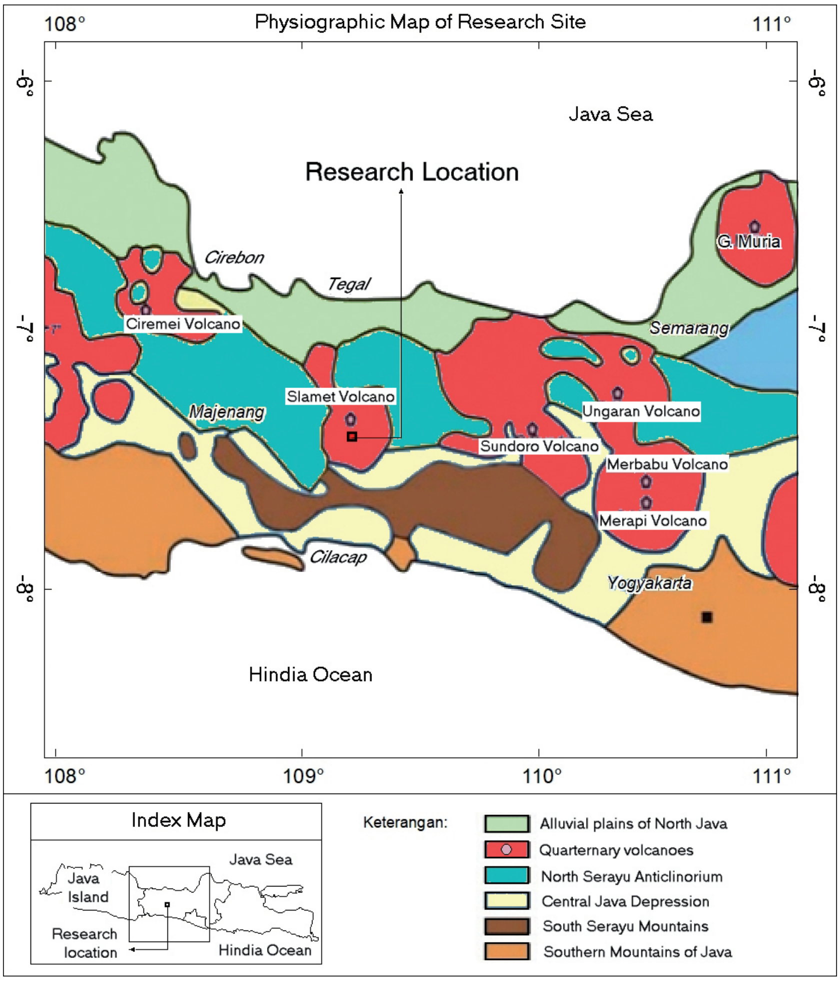

Fig. 1. Physiography of the research site [6].

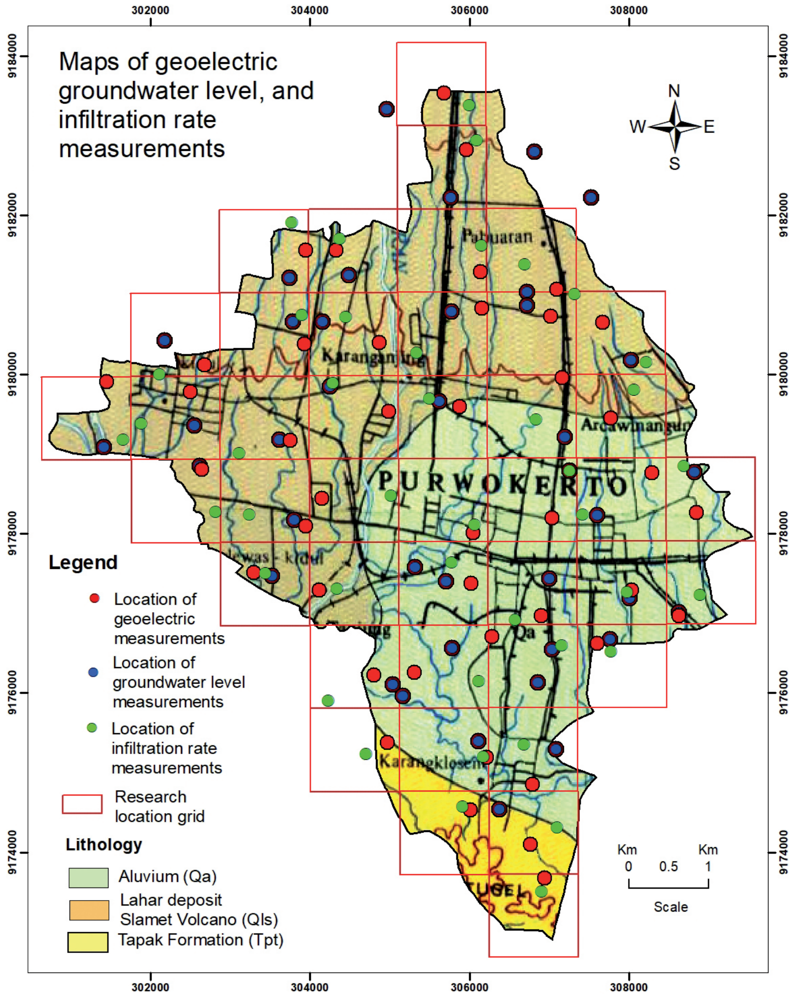

Fig. 2. Geological and location maps of groundwater level, geoelectric and infiltration rate measurements of Purwokerto.

with a size of 1.2 square kilometers each. For each grid box, measurements of ground water level, geoelectric and infiltration rate were conducted. The purpose of these measurements was to obtain information on the parameters for calculating the level of groundwater vulnerability using the AVI method, which included hydraulic conductivity and the thickness of the unsaturated zone of each rock layer (Fig. 2).

Groundwater Level Measurements

In the shallow groundwater areas, the response to rainfall is fast [10]. The variation in groundwater depth is greater when there are dry conditions during the day and rain in the afternoon or evening in the pre-monsoon season than when there is no rain on the same day [11]. Thus, the measurements in this study were carried out in the dry season as there are only season in Indonesia, the dry or hot and the rainy seasons. The depth of the groundwater table was carried out at forty-one (41) resident wells in Purwokerto. Measurements were carried out in August 2021. These measurements are needed to obtain the value of the thickness of the unsaturated zone located above the groundwater table (d), for aquifer vulnerability index (AVI) calculations.

Geoelectric Measurement and Analyses

The purpose of measuring the resistivity of the lithology using the geoelectric method is to obtain information on the subsurface geology of the research location in the form of resistivity values. Geoelectric analysis is mainly used for the analysis of lithological types. The results of the lithological analysis are then used to estimate the depth of the groundwater aquifer. In addition, geoelectric analysis can also be used to analyse the hydraulic conductivity of groundwater aquifers [12]. Of the various methods or configurations, the Schlumberger method identifies subsurface information vertically better than other methods [13]. Geoelectric measurements were carried out at forty-two (42) location points in Purwokerto (Fig. 2). Measurements were made in August 2021. The results of these geoelectric measurements are used for lithology type interpretation and its depth. Geoelectric measurements using the Schlumberger method by expanding the electric current cable by

100 meters to the left and right. Further analysis and interpretation of lithology using the Progress v.3.0 software. This interpretation is used for hydraulic conductivity values of the rock below soil (K) which required for AVI level calculations.

Infiltration Rate Measurement and Estimated Hydraulic Conductivity Values

Infiltration rate is the velocity or speed at which water seeps into the soil, or how deep the water can infiltrate into the soil in a given unit of time. Usually, the infiltration rate is measured by the depth (in mm) of water that can enter the soil in one hour. An infiltration rate of 15 mm/hour means that in one hour water can seep into the soil to a depth of 15 mm. In dry soil, water infiltrates fast as more water replaces the air in the soil pores. Furthermore, the water infiltrates slowly and eventually reaches a steady level which is called the basic infiltration rate [14]. The application of the ring infiltrometer method is commonly used to measure the infiltration rate of the soil to the unsaturated zone boundary above the shallow groundwater table and land cover [15, 16].

Measurement of the ground surface infiltration rate was carried out at 42 location points in Purwokerto (Fig. 2). This infiltration test uses the double ring infiltrometer method. This measurement method is suitable for land that has permeability at intervals of 10^{-5} to 10^{-2} m/sec [17]. The infiltration rate has a large value at the beginning of the measurement (this stage still indicates the conditioning of the infiltrating water rate), then decreases over time until it is close to stable condition which is close to the actual infiltration value in the field. Calculation of K (hydraulic conductivity) was carried out using surface infiltration measurement data for soil and previous research estimates for lithology other than soil [18]. The unit of K value used is in accordance with the calculation of the AVI vulnerability level, which is meters per day (m/day).

Aquifer Vulnerability Index (AVI) Analyses

The AVI calculation considers two parameters associated with the unsaturated zones, they are: (1) thickness (d) of each sediment layer in the unsaturated zones, and (2) estimated hydraulic conductivity (K) of this sedimentary layer [18, 19]. The hydraulic conductivity (K) of the soil was interpreted from the results of the infiltration rate measurements in the soil at 42 locations. The thickness of the soil is interpreted from lithology resistivity measurement of the geoelectric. The value of the hydraulic conductivity (K) and the thickness of the lithology under soil are interpreted from lithological resistivity values. Then the level of AVI is calculated based on the value of hydraulic resistance (c). The AVI level is the logarithmic value of c as shown in Table 1 [18, 20].

Table 1. Relationship between AVI and hydraulic resistance [4, 18].

Hydraulic Resistance (c)	Log (c)	AVI
0-10	<1	Extremely high
10-100	1-2	High
100-1,000	2-3	Moderate/Medium
1,000-10,000	3-4	Low
>10,000	>4	Extremely low

$$c = \sum d / K$$

c: hydraulic resistance, K: hydraulic conductivity, d: thickness of each rock layer.

The AVI values obtained from the calculations were plotted on a map to produce an AVI map. Interpolated AVI map analysis and root mean square error (RMSE) tests were performed on the AVI calculation points to determine the best interpolation method to use (IDW, kriging, natural neighbor, and spline). In addition, validation was carried out between the actual AVI calculation data and the AVI data resulting from interpolation predictions from these methods. The results of the RMSE analysis and calculations are presented in the Results and Discussion section.

Results and Discussion

Groundwater Level

The groundwater level data collection at the research location was conducted in June 2021. In addition to the groundwater level measured from the ground surface, the groundwater level depth calculation from sea level was also performed. This information (depth of the groundwater table from the surface) is required for the estimation of the unsaturated zone for the calculation of the level of groundwater vulnerability. From the measurements and calculations of the groundwater level, the depth of the groundwater level measured from the ground and sea level ranges from 0.3-7.0 meters and 57.0-183.4 meters (Figs 2 and 3). Based on the groundwater level as measured from sea level, in general, the groundwater level increases in the northern part of the study area. On the other hand, the groundwater level decreases in the southern part of the study area, except around Tugel area.

In general, the groundwater level in the study area is relatively low to moderate (less than 2.5 m and between 2.5-5.0 m) from surface. Some locations have relatively deep groundwater levels (>5 m) in all lithologies of the study site (Slamet Volcanic Lahar Deposits, Alluvium and sedimentary rocks of the Tapak Formation or their soils). The depth of the groundwater table in the lahar lithology of Slamet Volcano is relatively more varied than the depth of the groundwater table in other lithologies. In the lahar lithology, the groundwater level is relatively low (less than 2.5 m), moderate (2.5-5 m), to high (5-7 m) (Table 2).

Geoelectrical Analysis

Geoelectric measurements were conducted in August 2021. The locations are scattered around Purwokerto,

Table 2. Groundwater data, resistivity values, interpretation of subsurface lithology from geoelectric data, infiltration rates, estimated values of hydraulic conductivity (K), hydraulic resistance (c) and AVI levels.

Location	Lithology	Thick (m)	GL	K	c	c total	Log c	AVI
1	Soil	4.65	4.65	2.160	2.15	2.15	< 1	E. high
2	Soil	1.27	4.14	1.949	0.65	2,870.65	3.5	Low
	Sandstone	0.54		0.001	540.00			
	Breccia	2.33		0.001	2,330.00			
3	Soil	0.38	0.87	3.629	0.10	490.10	2.7	Moderate
	Sandstone	0.49		0.001	490.00			
4	Soil	0.59	4.93	4.579	0.13	4,340.13	3.6	Low
	Claystone	0.14		0.001	140.00			
	Breccia	3.22		0.001	3,220.00			
	Claystone	0.98		0.001	980.00			
5	Soil	0.40	5.00	7.488	0.05	4,600.05	3.7	Low
	Breccia	3.35		0.001	3,350.00			
	Sandstone	1.25		0.001	1,250.00			
6	Soil	0.92	4.75	9.878	0.09	3,830.09	3.6	Low
	Breccia	2.88		0.001	2,880.00			
	Sandstone	0.95		0.001	950.00			
7	Soil	0.07	2.65	14.170	0.00	2,580.00	3.4	Low
	Breccia	2.58		0.001	2,580.00			
8	Soil	0.66	0.66	1.901	0.35	0.35	< 1	E. high
9	Soil	0.34	5.03	3.005	0.11	4,690.11	3.7	Low
	Breccia	1.92		0.001	1,920.00			
	Sandstone	2.77		0.001	2,770.00			
10	Soil	0.71	0.78	10.051	0.07	70.07	1.8	High
	Breccia	0.07		0.001	70.00			
11	Soil	1.87	1.87	2.726	0.69	0.69	< 1	E. high
12	Soil	0.44	6.10	9.504	0.05	5,660.05	3.8	Low
	Breccia	5.66		0.001	5,660.00			
13	Soil	0.09	0.26	2.419	0.04	170.04	2.2	Moderate
	Breccia	0.17		0.001	170.00			
14	Soil	1.14	2.52	16.214	0.07	1,380.07	3.1	Low
	Sandstone	1.38		0.001	1,380.00			
15	Soil	1.16	1.58	0.778	1.49	421.49	2.6	Moderate
	Claystone	0.42		0.001	420.00			
16	Soil	1.09	2.30	6.307	0.17	1,210.17	3.1	Low
	Sandstone	0.88		0.001	880.00			

Table 2. Continued.

	Claystone	0.33		0.001	330.00			
17	Soil	0.16	2.62	1.123	0.14	2,460.14	3.4	Low
	Sandstone	1.68		0.001	1,680.00			
	Breccia	0.78		0.001	780.00			
18	Soil	0.57	0.57	4.694	0.12	0.12	< 1	E. high
19	Soil	0.72	6.95	7.382	0.10	6,230.10	3.8	Low
	Breccia	0.95		0.001	950.00			
	Sandstone	5.28		0.001	5,280.00			
20	Soil	0.84	0.84	10.282	0.08	0.08	< 1	E. high
21	Soil	0.21	3.44	6.696	0.03	3,230.03	3.5	Low
	Breccia	3.23		0.001	3,230.00			
22	Soil	0.90	1.00	1.210	0.74	100.74	2	High
	Breccia	0.10		0.001	100.00			
23	Soil	0.19	2.38	15.034	0.01	2,190.01	3.3	Low
	Sandstone	2.19		0.001	2,190.00			
24	Soil	1.01	1.45	4.051	0.25	440.25	2.6	Moderate
	Claystone	0.34		0.001	340.00			
	Breccia	0.10		0.001	100.00			
25	Soil	0.37	0.77	1.018	1.02	401.02	2.6	Moderate
	Sandstone	0.40		0.001	400.00			
26	Soil	1.57	6.58	1.382	1.14	5,011.14	3.7	Low
	Breccia	1.16		0.001	1,160.00			
	Sandstone	2.93		0.001	2,930.00			
	Breccia	0.92		0.001	920.00			
27	Soil	0.40	6.63	9.792	0.04	6,230.04	3.8	Low
	Sandstone	2.10		0.001	2,100.00			
	Breccia	4.13		0.001	4,130.00			
28	Soil	0.60	2.84	2.592	0.23	2,240.23	3.4	Low
	Claystone	2.24		0.001	2,240.00			
29	Soil	0.10	1.30	9.302	0.01	1,200.01	3.1	Low
	Sandstone	1.20		0.001	1,200.00			
30	Soil	0.30	1.02	7.171	0.04	720.04	2.9	Moderate
	Claystone	0.30		0.001	300.00			
	Sandstone	0.42		0.001	420.00			
31	Soil	1.99	1.99	8.986	0.22	0.22	< 1	E. high
32	Soil	1.60	1.64	4.781	0.33	40.33	1.6	High
	Claystone	0.04		0.001	40.00			
33	Soil	1.20	4.40	0.651	1.84	3,201.84	3.5	Low
	Sandstone	3.20		0.001	3,200.00			
34	Soil	0.40	2.77	5.098	0.08	2,370.08	3.4	Low
	Claystone	0.40		0.001	400.00			

Table 2. Continued.

	Sandstone	1.97		0.001	1,970.00			
35	Soil	0.60	2.45	5.443	0.11	1,850.11	3.3	Low
	Claystone	1.85		0.001	1,850.00			
36	Soil	0.60	4.57	13.306	0.05	3,970.05	3.6	Low
	Claystone	1.20		0.001	1,200.00			
	Sandstone	2.77		0.001	2,770.00			
37	Soil	1.00	4.71	1.152	0.87	3,710.87	3.6	Low
	Claystone	1.70		0.001	1,700.00			
	Breccia	2.01		0.001	2,010.00			
38	Soil	1.00	1.16	5.011	0.20	160.20	2.2	Moderate
	Breccia	0.16		0.001	160.00			
39	Soil	0.30	4.38	1.469	0.20	4,080.20	3.6	Low
	Breccia	2.40		0.001	2,400.00			
	Claystone	1.68		0.001	1,680.00			
40	Soil	0.90	6.10	0.769	1.17	5,201.17	3.7	Low
	Sandstone	4.10		0.001	4,100.00			
	Claystone	1.10		0.001	1,100.00			
41	Soil	0.30	1.02	4.982	0.06	720.06	2.9	Low
	Sandstone	0.72		0.001	720.00			
42	Soil			8.064	0.10	13,700.10	2.9*	Low*
	Claystone			0.001	5,400.00			
	Sandstone			0.001	8,300.00			

Note:
Litho: lithology above groundwater level
GL: Groundwater level from surface or unsaturated zone (m)
K: infiltration rate for soil or hydraulic conductivity for lithology (meter/day)
c: hydraulic resistance
AVI: aquifer vulnerabilty index
*: there is no ground water level measurement data, log c and AVI levels are obtained from interpolation with other nearest location calculations

covering three regional rock formations, namely the Tapak Formation, Alluvium and Slamet Volcano Lahar Deposits. Land use is dominated by residential and agricultural areas. The lithological resistivity values of geoelectrical measurements ranged from 1.4-640.5 ohm.m. The type of lithology is interpreted based on the resistivity value at each depth. Resistivity with a range of values between 1.4-384.7; 0.8-65.6; 10.2-37.3; and 33.2-764.7 ohm.m is interpreted as soil, claystone, sandstone, and breccia. The lithology resistivity value intervals are as shown in Table 3.

The upper and lower limits of the resistivity value of each particular lithology are not necessarily the same. Lithological changes above and below it are based on significant changes in resistivity values. From direct field observations, the topmost part of all locations was identified as soil. Soil resistivity values and other lithologies in all locations vary, depending on several factors. The results of the interpretation of lithological types from this geoelectric data will be used to estimate the hydraulic conductivity parameters in calculating

Table 3. Summary of the lithological resistivity value interval of the study site.

No.	Lithology	Resistivity (ohm.m)	
		Lowest	Highest
1	Soil	1.4	384.7
2	Claystone	0.8	10
3	Sandstone	10.19	37.3
4	Breccia	33.19	764.7

the groundwater vulnerability level using the AVI method, as shown in Table 2 and Fig. 6.

Groundwater Infiltration Rate

On the surface, almost all of the measurement locations are soil that is the result of weathering of previous lithology. Infiltration rate measurements were carried out on 13 June - 24 August 2021. In general, the research locations are residential, gardens and agricultural land. Measurements were made at locations where lithology conditions were still natural. Measurement of infiltration until it reaches a constant rate between 90-240 minutes with an average measurement time of 131 minutes.

The infiltration rate at the study site ranges from 0.8-18.8 x 10^{-5} meters/second (or 0.7-16.2 meters/day), with an average of 6.6 x 10^{-5} meters/second or 5.7 meters/day. Those interval and average values of the infiltration rate are slow infiltration rate type [21]. The infiltration rate in the northern part is composed of soil lithology resulting from weathering of lahars and alluvium of 0.9-18.8 and 1.2-17.4 x 10^{-5} meters/second. The soil from weathering Tertiary sedimentary rocks in the southern part has an infiltration rate of 0.8-9.3 x 10^{-5} meters/second. The rate of soil infiltration in all research locations is slightly higher (0.8-18.8 x 10^{-5} meters/second) than the rate of soil infiltration at several other research locations previously, ranging between 0.06-5.2 x 10^{-5} meters/second [22-24]. The infiltration rate in the soil from weathering of the Tertiary sedimentary rocks of the Tapak Formation is lower than the infiltration rate in the soil from the Quaternary lithology of Slamet Volcanic Lahar Deposits and Alluvium. This soil infiltration rate or lithological hydraulic conductivity will be used as the K value (or hydraulic conductivity) in the calculation of the AVI level (Table 2). Meanwhile, the K value for lithology located under the soil uses the K value based on previous studies, as shown in Table 4 [18].

Aquifer Vulnerability Index (AVI)

The DEM (digital elevation model) map shows that the elevation of the research site is generally a plain, the further North the elevation is higher (Geospatial Information Agency, 2020). The lowest point is located in the center (68 m) and the highest point is in the North (162 m) of the study site. Resistivity data and lithological interpretation from 42 measurement points are presented in Table 2. The depth of the groundwater table (results from measurements of resident wells in the field) and the thickness of the unsaturated zone at each measurement location (d) are shown in Table 2. The value of hydraulic conductivity (K) calculated from soil infiltration rate measurement data and interpretation of lithological types from geoelectric data is presented in Table 2.

The AVI method is one of the popular methods for assessing groundwater vulnerability in an area in addition to other methods [25]. The Aquifer Vulnerability Index (AVI) of the study sites varied from low, moderate, high to extremely high (Table 2). Several locations are acquired to have extremely high AVI values (or log c less than 1), at locations 1, 8, 11, 18, 20 and 31. In the field, these locations are in the areas of North, East and West of Purwokerto. It is known that these locations (which have extremely high groundwater vulnerability of AVI) have a relatively low to moderate depth of groundwater table from the surface (less than 5 meters) (Fig. 3).

The AVI values were interpolated using several methods to obtain the best AVI map. The AVI map resulting from the interpolation of the kriging and spline methods did not match the data obtained from the AVI calculation. Meanwhile, the map resulting from the interpolation of the natural neighbor method did not cover several locations. The RMSE values of the IDW, kriging, natural neighbor, and spline interpolation methods were 0.003, 0.577, 0.071, and 0.039 m, respectively. Thus, the IDW interpolation method was used to generate the AVI map (Fig. 6). Several previous

Table 4. Values of hydraulic conductivity of some sediments [18].

Sediment type	Hydraulic conductivity (m/d)
Gravel	1,000
Sand	10
Silty sand	1
Silt	0.1
Fractured till, clay or shale (0-5 m from ground surface)	0.001
Fractured till, clay or shale (5-10 m from ground surface)	0.0001
Fractured till, clay or shale (10 m from ground surface, but weather based on colour, brown or yellow)	0.0001
Sand-silt-clay (massive or mixed)	0.00001
Massive till or mixed sand-silt-clay	0.000001

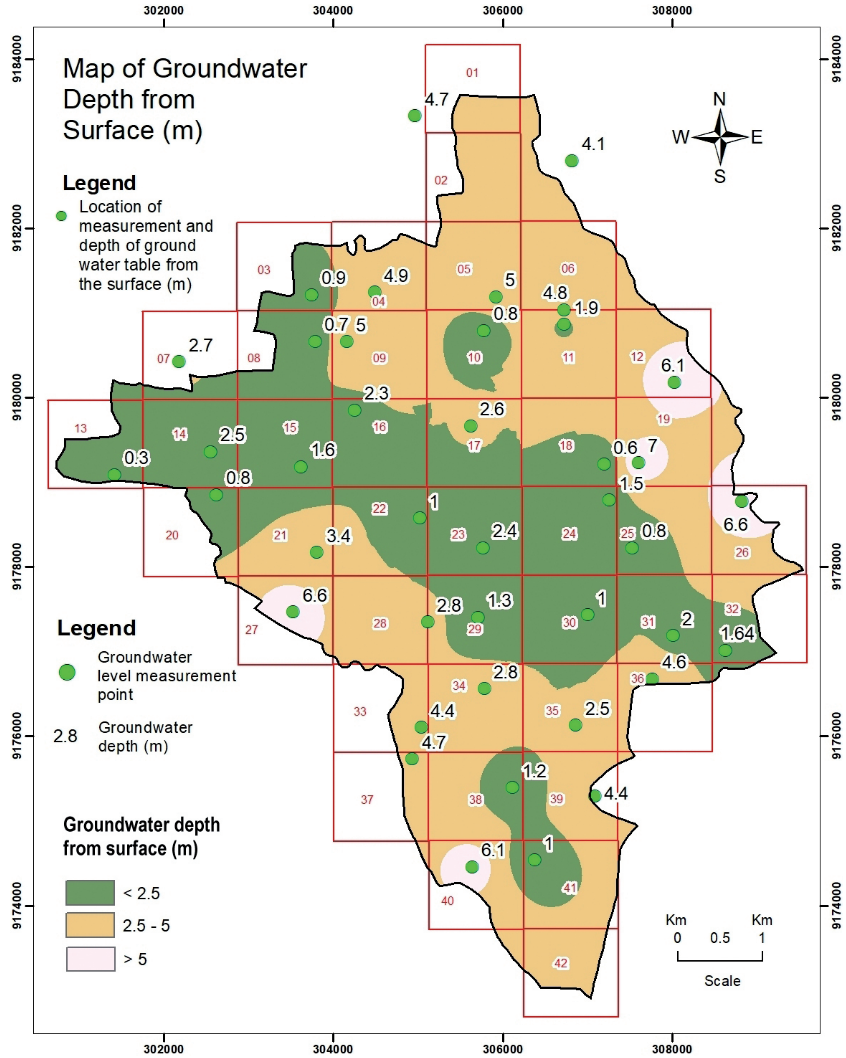

Fig. 3. Groundwater table map which measured from the ground surface (m).

studies have shown that the IDW method is better than other interpolation methods [26, 27].

Location 1 has a relatively moderate groundwater table level (4.7 meters) and has a high soil infiltration rate (Fig. 3). Calculation of AVI was calculated using the parameters of the unsaturated zone, the thickness of each layer of sediment above the groundwater table (d) and the estimated value of the hydraulic conductivity of each layer (c). These parameters were compiled and calculated from measurements of infiltration rate, groundwater level and geoelectric surveys. Each parameter values and the calculations of the AVI level are presented in Table 2.

Maps of groundwater table depth, infiltration rate, and AVI (Figs 3, 5, and 6) do not show a distribution pattern that is similar and consistent with the geological map (Fig. 2). This is because the measurement of these parameters (groundwater table depth, infiltration rate, and AVI level) is carried out on the soil resulting from the weathering of previous rocks, not just rock formations based on the geological map. While the geological map describes the distribution of rocks, the soil characteristics resulting from weathering of bedrock can be different from the bedrock itself. The area of Indonesia which has a tropical climate, with high rainfall and sunshine all the time allows high levels of weathering and soil formation.

The weathering rate tends to be high on the surface of the Earth. The deeper the rock formation, the lower weathering rate hence it has similar characteristics to the original lithology or bedrock. Weathered lithology will have different characteristics than the original character of the original or fresh rock before weathering occurs, including porosity and infiltration rate. The two systems (soil and rock) will have different hydraulic conductivity characters or infiltration rates. Thus, allowing the formation of shallow aquifers in the weathering zone in the form of soil due to the greater lithological or soil porosity than the original rock.

The northern part of Purwokerto which is composed of volcanic rock lithology of lahar deposits at several points has various infiltration rates and AVI level, ranging from low to extremely high. This is possible

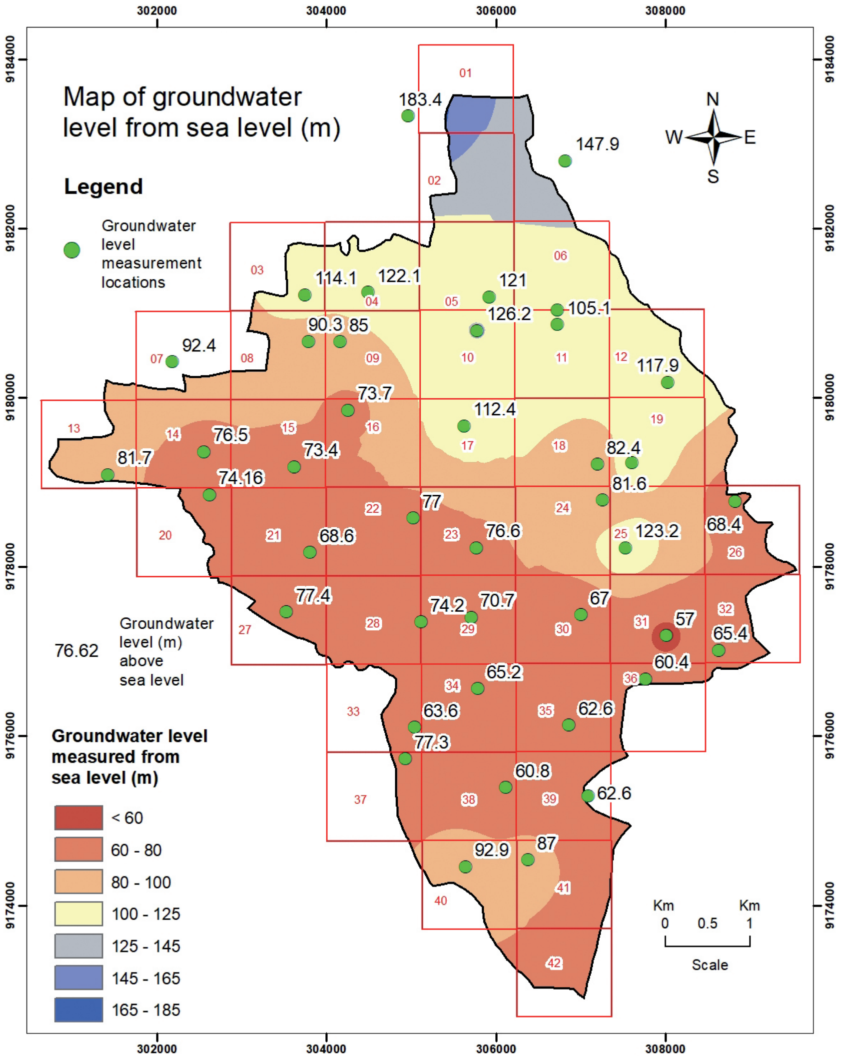

Fig. 4. Groundwater table map which measured from sea level (m).

because the lahar lithology has varying components, so is the level of weathering. A high weathering rate in the lahar matrix will result in a high infiltration rate and vice versa. A Low level of weathering in the lahar fragments will result in a low infiltration rate. To the East of Purwokerto, almost the same as AVI level that occurs in lithology or soils resulting from weathering of lahars, in alluvium lithology or soils resulting from weathering of alluvium also has AVI levels that vary from low to extremely high. The proportion of areas in alluvial lithology that have a extremely high level of AVI is smaller than that in lahar lithology or weathered soils (Figs 2 and 6). Alluvium lithology and weathered soil Alluvium which is composed of various components and is heterogeneous with varying degrees of weathering, and allow the various levels of AVI as well. This condition was not found in locations of the Tertiary sedimentary rock (Tapak Formation) and soil

Table 5. Comparison of soil infiltration rate values in several studies [22-24].

No.	Infiltration rates	Infiltration rates (meter/second) $*10^{-5}$	References
1	0.05-30 m/day	0.058 - 34.7	(Kirkham, 2005) [22]
2	2.4 - 3.4 m/day	2.78 - 4.0	(Bagarello et al, 2017) [23]
3	4.48 - 3.31 m/day	3.83 - 5.19	(Fu et al, 2021) [24]
4	0.7 - 16.2 m/day	0.8 - 18.8	(Purwokerto, 2022, in this study)

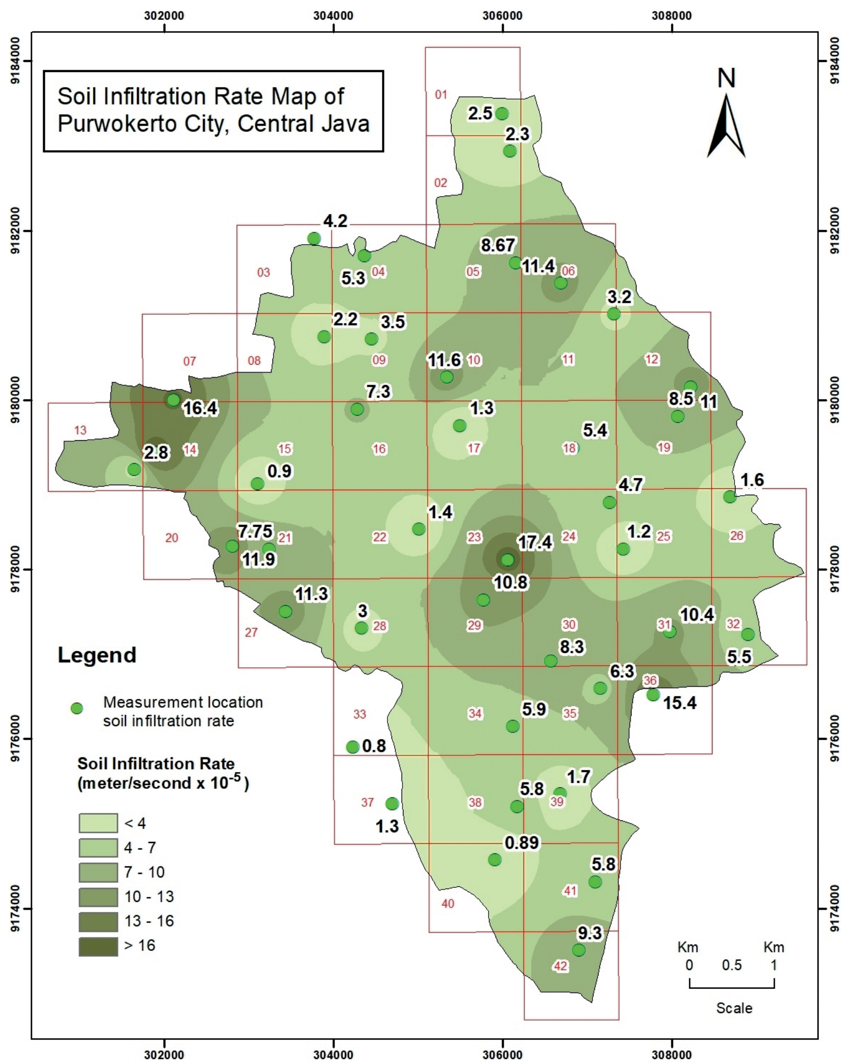

Fig. 5. Infiltration rates map of 42 measurement sites.

resulting from weathering of the lithology which is more homogeneous.

The study on the vulnerability of groundwater aquifers have been carried out in Semarang, Indonesia [4]. In that study the hydraulic conductivity parameter used value obtained from previous studies as shown in Table 4. This study uses the value of the soil infiltration rate measured from the soil surface to the depth of the soil base. While the value of the hydraulic conductivity of the underground lithology below soil using the values of previous studies [18]. The hydraulic conductivity values in several studies and the results of measurements of soil infiltration rates in Purwokerto have small variations [22-24] (Table 5). The higher the hydraulic conductivity value or the infiltration rate, the greater the vulnerability level of the groundwater aquifer, and the easier it is for contaminants to enter the groundwater aquifer, hence the groundwater aquifer is more vulnerable. Calculation of AVI levels using soil infiltration rate and lithological hydraulic conductivity in this study provides continuous AVI level intervals and does not have an AVI level gap as happened in previous studies [4].

Locations with high to extremely high AVI degrees are the concerns for many parties. During the dry season, groundwater quality is even worse than during the rainy season. Better groundwater quality exists in the rainy season due to dilution of contaminants by rainwater [28].

Conclusions

Aquifer vulnerability index (AVI) of Purwokerto ranges from low to extremely high and is controlled by the soil from weathering of the original rock. The level of vulnerability of AVI on the lithology of the Slamet Volcano Lahar Deposits and Alluvium or soil resulting from weathering of these lithologies are higher and more variable than the lithologies of the Tapak Formation sedimentary rock or its weathered soil. The variation in the level of AVI on the soil resulting from weathering of the Slamet Volcanic Lahar Deposits and Alluvium is believed due to the variations in the components that make up the lithology consisting

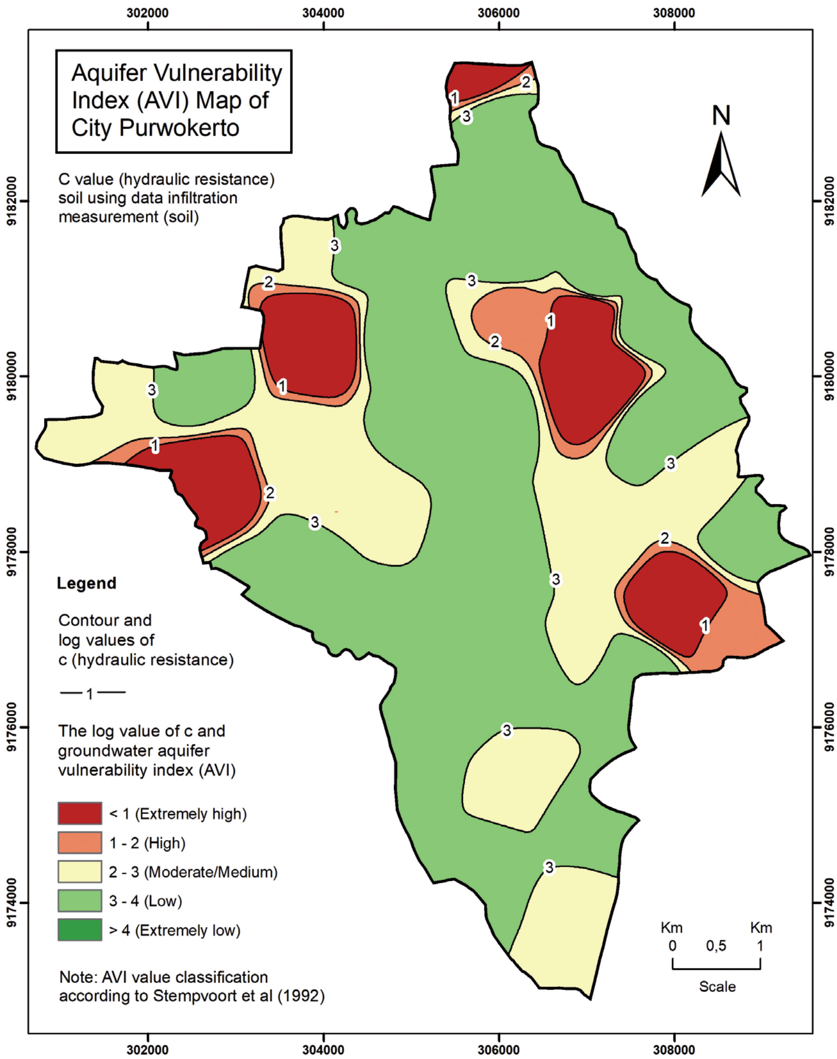

Fig. 6. Aquifer vulnerability index (AVI) map of Purwokerto.

of matrix and fragments (highly heterogeneous) than other lithology (Tapak Formation sedimentary rock) that are more homogeneous. Variations in lithological components cause variations in the level of weathering which causes variations in the level of vulnerability of AVI. As the components of the lithology become more diverse, so does the degree of weathering and AVI level.

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Conflict of Interest

The authors solemnly declare that they have no conflict of interest.

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