Groundwater Vulnerability Assessment Using Simple Vertical Vulnerability Method

in Wonosari, Gunungkidul, Yogyakarta, Indonesia

Moch Hasmannoor Rachman[1,2] Wahyu Wilopo[1,2*] Doni Prakasa Eka Putra[1,2]

[1] *Departement of Geological Engineering, Faculty of Engineering, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia*
[2] *Center for Disaster Mitigation and Technological Innovation (GAMA-InaTEK) Universitas Gadjah Mada, Yogyakarta, Indonesia*
**Corresponding author. Email: wilopo_w@ugm.ac.id*

ABSTRACT

Research on groundwater vulnerability using the simple vertical vulnerability (SVV) method in Wonosari district, Gunungkidul, Yogyakarta was conducted to identify groundwater vulnerability zones that require careful management in the research area. It is very important to know the extent of existing environmental and geological conditions in protecting groundwater from the potential pollution that may arise. In addition, this study also wants to prove the accuracy of the SVV method when carried out in limestone lithology conditions. The method used is the SVV method concerning three intrinsic parameters, namely the type of lithology based on the value of each specific retention of the soil or rock, the thickness of the unsaturated zone, the amount of groundwater recharge, and verified by land use. The nitrate content test in water samples at the research site was conducted to validate the research results. The study results found that two lithology types compose the research area, namely crystalline limestones, which are generally scattered in the southern part, and calcarenite limestones distribution in the central and northern parts. The depth of the unsaturated zone in the study area varies from 0 to more than 40 m, with the groundwater recharge being 438.68 mm/year. The land use of the research area varies from urban regions and rice fields to community plantation areas. The existing parameter overlay results are divided into three groundwater vulnerability zones: medium, high, and very high. The potential sources of pollutions zone are divided into four zones: low zone, medium zone, high zone, and very high zone. Based on the validation results carried out by comparing the nitrate content of groundwater samples taken in the research area, a correlation was found between the potential sources of pollutants and nitrate concentration. Therefore, the research results using the SVV method are considered accurate enough to represent nature's ability to protect groundwater quality in the research area. The result of the groundwater vulnerability zone by the SVV method is considered accurate enough to represent nature's ability to protect groundwater quality in the research area.

Keywords: *Groundwater vulnerability, SVV, Simple Vertical Vulnerability, Gunungkidul, Wonosari.*

1. INTRODUCTION

The Wonosari district community is very dependent on the availability of groundwater, and this is due to the geological condition of the area, which is mainly composed of limestone [1,2]. It is easily dissolved, where surface water will quickly seep into the underground water system or aquifer due to small, medium, or large cracks [3].

Wonosari district is an area that has the highest population density in Gunungkidul Regency [4]. The more densely populated a site is, the groundwater quality tends to be less suitable for drinking water needs because there is a great chance of increasing sources of pollution that can pollute the groundwater quality in that location [5,6,7]. Therefore, it is necessary to protect groundwater in the research area. The first step that can be taken to protect groundwater is by mapping the vulnerability of shallow groundwater based on pollution in the research area. The results of the map can be used as a reference for handling groundwater pollution prevention in the future.

Techniques for testing groundwater susceptibility are generally based on the physiographic factors of the test area, the quantity and quality of the data, and the research

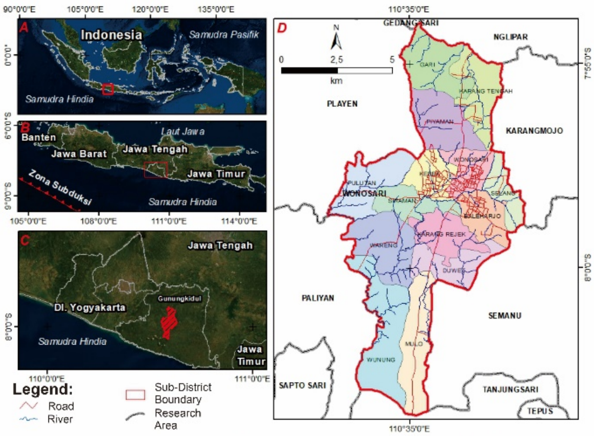
A. D. Saputro et al. (Eds.): ICOSEAT 2022, ABSR 26, pp. 632–642, 2023.
https://doi.org/10.2991/978-94-6463-086-2_84

objectives. The groundwater vulnerability testing technique comprises three primary groups: the hydrogeological complex and setting (HCS) method, the parametric method, and the analog and numerical relationship model method [7].

The SVV method was developed in 2007 and is designed to examine groundwater's vulnerability to quaternary shallow site groundwater conditions, especially in regions where there is a lack of measurement and data of soil/rock properties (e.g., field capacity, specific retention) [6]. According to this method, the degree of vulnerability is expressed as the protective effectiveness (the ability of the overlaying layers above an aquifer to protect the groundwater) in terms of advective transport time [6]. In this study, the method used is the SVV method which applies a parametric approach [6]. The SVV method was chosen to test the application of this method in the rock, especially limestone.

2. RESEARCH AREA AND DATASET

The research location is in Wonosari district, one of the districts in Gunungkidul Regency, Yogyakarta Special Region Province, Indonesia. Consists of 14 villages namely Baleharjo, Duwet, Gari, Karang Rejek, Karang Tengah, Kepek, Mulo, Piyaman, Pulutan, Selang, Siraman, Wareng, Wonosari, and Wunung [4,8,9]. Geographically, the research area is located at coordinates 110°33'0" E to 110°38'0" E and 7°54'0" S to 8°03'30" S, with an area of approximately 75.51 km² [4,8,9] (Figure 1).



Source: Rupa Bumi Indonesia (RBI) Map and Contour Map, Scale 1: 25.000 Badan Informasi Geospasial (BIG) and Google Earth, Wonosari district in Google Earth. https://earth.google.com/web/ (2020)

Figure 1 Research location

2.1. Land Use

The land use map of the research area was created with ArcGIS and is based on Peta Rupa Bumi Indonesia (RBI) and updated using ESRI ArcGIS Imagery satellite images and field observation. It consists mainly of rice fields and Urban areas with a small area of plantation. The land cover comprises five different units and can be divided into three major groups based on potential pollution from land use [8,9,10].

First, urban and settlement areas are used for industrial and commercial use. These areas are located primarily in the middle and north parts of the research area. It covers an area of 33 km². The second group contains rice fields and farms with 40.5 km². The third group enfolds an area of 2 km² consisting of plantation areas and pastures. In conclusion, the general land use of the research area is presented in Figure 2.

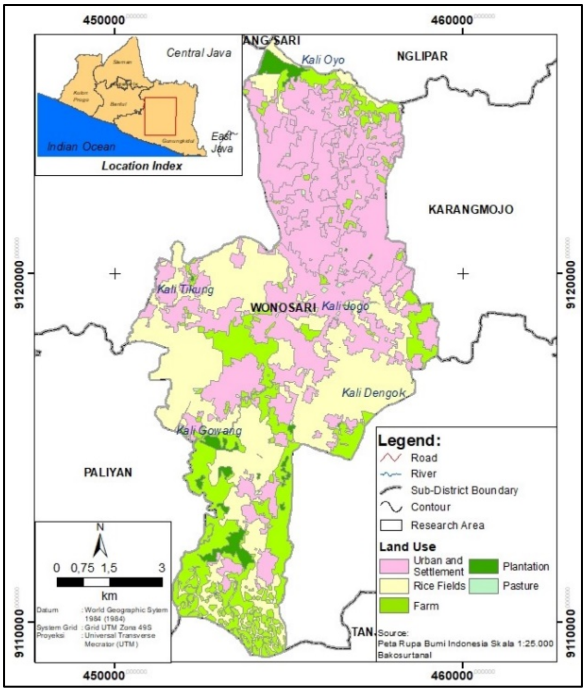


Figure 2 Land use map based on RBI and updated using ESRI ArcGIS Imagery satellite images in the research area.

2.2. Climate

The research areas are located in the tropical zone. Its climate is characterized by a warm monsoon climate with an average temperature of 10 years (2011-2020) is 26.6 °C [4]. The average annual rainfall value from 2011 to 2020 in the research area was recorded at 2,295.7 mm/year, and the average monthly rainfall was 191.3 mm/year [11]. The real evapotranspiration value can be calculated using the formula based on Turc (1964) [6]

$$ET_r = \frac{P}{(0,9 + P^2/(300 + 25(T_m) + 0.05(T_m{}^3))^2)^{0,5}} \quad (1)$$

Where **ET$_r$** = real evapotranspiration (mm/year), **P** = the average annual rainfall (mm/year), and **T** = the average annual temperature (°C) [6]. The results of calculations based on existing data, obtained a real evapotranspiration value of 1497,52 mm/year.

2.3. Geology And Geomorphology

According to the regional geological context, the research area is included in the physiography of the western part Southern Mountains Zone of East Java [12]. It consists of 3 formations with the Kepek formation in the middle, the Wonosari Formation in the south, and the Oyo formation in the north of the research area [1,2,12,13]. These three formations are limestone and carbonate rocks with various characteristics [1,2,12,13]. It belongs to the Wonosari subzone and slightly in the Gunungsewu subzone [12].

Geological observations were carried out to determine the lithological distribution and conditions around the research area. The overall geology of the research area is shown in Figure 3. Based on field observations and the Grabau classification [14], the lithology of the research area was simplified into two lithological units, namely calcarenite limestone and crystalline limestone. Calcarenite limestone unit has grain sizes between 63 μm and 2 mm, and crystalline limestone units with a massive texture in the form of crystals and has a very small porosity [3,14]. Vertically the rock layer consists of weathered soil with a certain depth then, followed by the base rock in the form of limestone. The base rock can be crystalline limestone or calcarenite limestone. The majority of calcarenite limestones are found in the central and northern parts of the research area, while crystalline limestones are mostly found on the south side and a little on the north side of the research area.

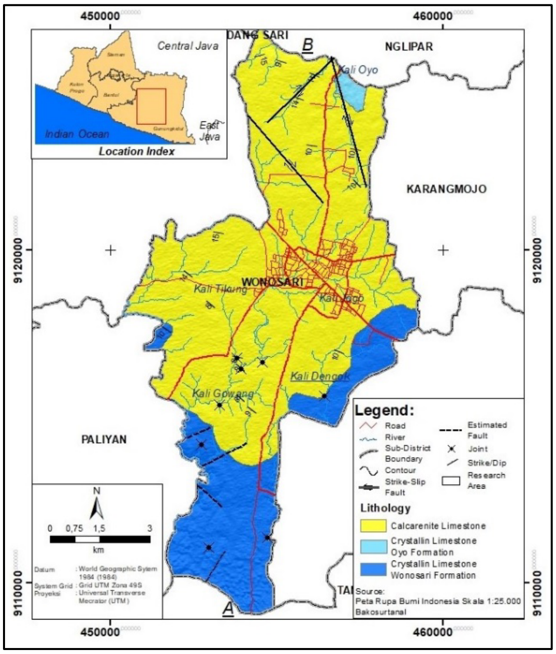


Figure 3 Geology map of Wonosari.

The geomorphology in the research area is divided into three units based on morphography and morphogenesis, namely the Karst Plain in the middle, Moderately Sloped Karst Hill in the south, and Isolated Karst Hill in the north. In conclusion, the overall geomorphology of the research area is pictured in Figure 4.

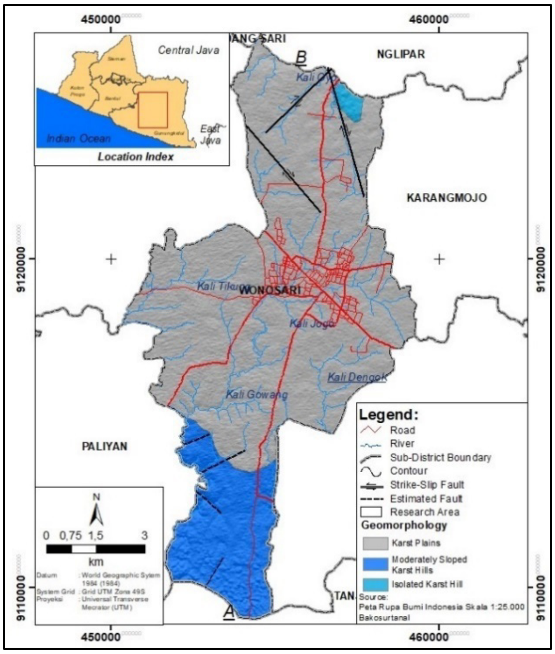


Figure 4 Geomorphology map of Wonosari.

The nine samples of soil and rock were taken from 6 locations (Figure 5) to carry out total organic carbon (TOC) testing, grain size distribution tests, and hydrometer tests to determine the characteristics of the rock layers in the research area, such as the percentage of each grain size and organic content in soil and rock. The results of the test are presented in Table 1.

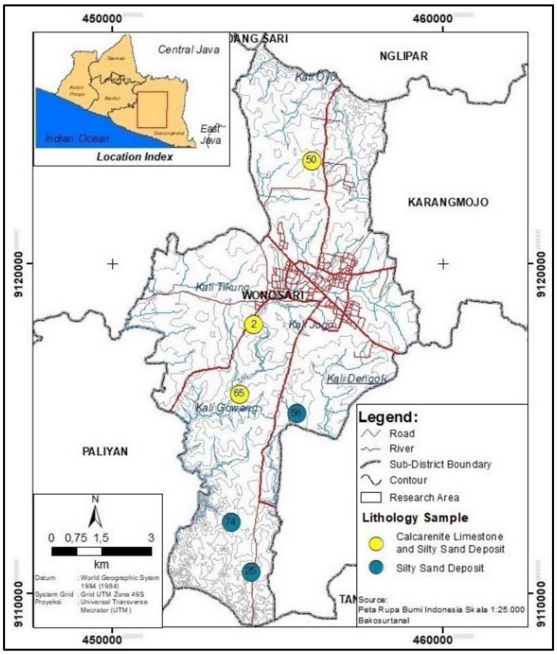


Figure 5. Lithology sampling location map of Wonosari

Table 1. Percentage of TOC, grain size, and hydrometer test results on lithological samples of the research area

No	Sample Name	% Gravel	% Sand	% Silt	% Clay	% TOC	ρb (g/cm³)
1	Silty Sand Deposit (STA 74)	0	73.23	25.049	1.721	18.46	1.92
2	Silty Sand Deposit (STA 56)	0	69.6	28.625	1.775	8.29	1.92
3	Silty Sand Deposit (STA 25)	0	70.53	27.701	1.769	15.35	1.92
4	Silty Sand Deposit (STA 02)	0.36	73.72	24.149	1.771	21.27	1.92
5	Silty Sand Deposit (STA 50)	2.46	63.35	32.44	1.75	16.16	1.92
6	Silty Sand Deposit (STA 65)	0	68.47	29.783	1.747	14.52	1.92
7	Calcarenite Limestone (STA 02)	5.34	71.98	21.095	1.585	19.7	2.55
8	Calcarenite Limestone (STA 50)	2.44	63.82	31.52	2.22	23.78	2.55
9	Calcarenite Limestone (STA 65)	0	73.83	23.994	2.176	18.14	2.55

The majority of soil found based on the results of laboratory tests falls into the class of silty sandy deposits with a percentage of sand of more than 50% and a portion of silt of more than 25 % (Table 1) [15]. Bulk density is obtained based on the average density value of each rock from Telford et al. (1990). The average bulk density value for soil is 1.92 g/cm³ and for limestone is 2.55 g/cm³ [16].

There has to be mentioned that the characteristics of crystalline limestone are very fine grain size and have low porosity, so the percentage of sand, silt, and clay cannot be known. In addition, in the southern part of the research area, the crystalline limestones have more significant secondary porosity due to the intensity of the structure. Therefore, the water flow tends to pass through it [3].

2.4. Hydrogeology

The groundwater recharge in the study areas is mainly by infiltration of precipitation. The infiltration value can be calculated using the formula based on Putra [6].

$$U = P - ET_r - Ro_N \qquad (2)$$

Where ET_r = real evapotranspiration (mm/year), P = the average annual rainfall (mm/year), and Ro_N = runoff in the research area (mm/year) [6]. Runoff can be calculated using the formula based on Sharma (1990) in Putra [6].

$$Ro_N = \frac{1.511(P^{(1.44)})}{T_m^{(1.34)}(A^{(0.0613)})} \qquad (3)$$

Where Ro_N = runoff in the research area (mm/year), P = the average annual rainfall (mm/year), T = the average annual temperature (°C), and A = area (km²) [6]. The calculations based on existing data obtained a runoff value of 359,5 mm/year. At the same time, the recharge of groundwater value is 438.68 mm/year.

Measurement data in the field shows that the groundwater level in the research area varies from 0 meters in the form of a spring to more than 40 meters, as shown in Figure 6.

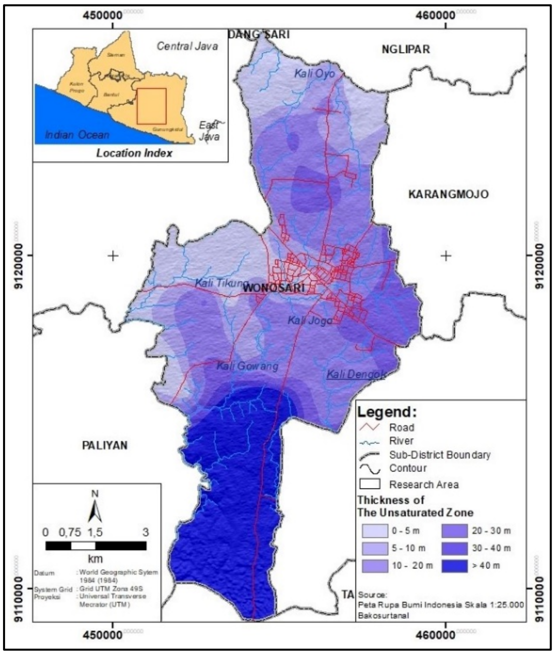


Figure 6. Groundwater level depth in Wonosari district.

The area with a groundwater level depth of fewer than 5 meters is mainly located in the west and north areas of the Wonosari district. South areas of Wonosari have the deepest groundwater level reaching more than 40 meters. The groundwater flow direction is from the west to the south, but some parts split towards the north, as shown in Figure 7.

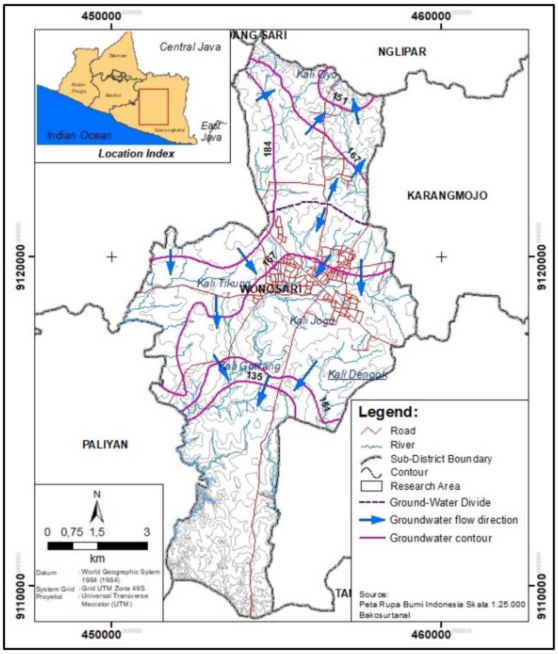


Figure 7 Groundwater flow direction in the Wonosari district.

Groundwater pollution analysis in the Wonosari district was conducted by determining nitrate concentration using an IC (Ion Chromatography on 35 groundwater samples in the field (Figure 8). The average groundwater temperature in the study area is 29°C, with an average pH of 6.9. Total dissolved solids (TDS) range from 120 mg/L to 450 mg/L, and electrical conductivity ranges from 260 µS/cm to 920 µS/cm. The highest electrical conductivity values and total dissolved solids (TDS) are in the western part of the Wonosari district, while the smallest values are in the southeast and northeastern parts.

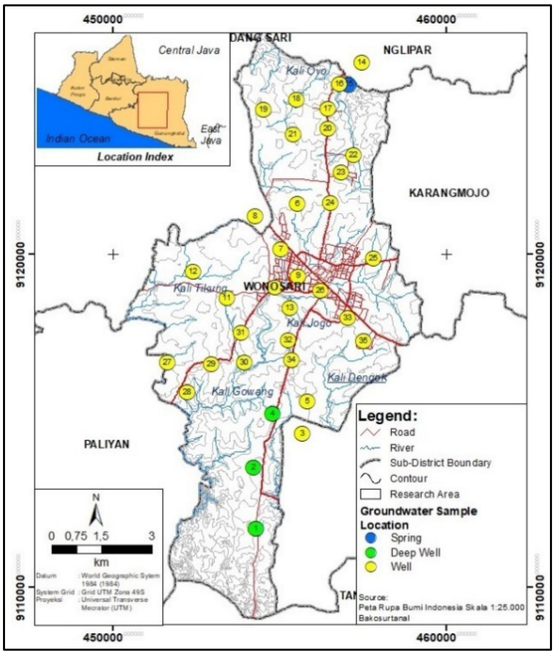


Figure 8 Groundwater sampling location map of Wonosari

Nitrate is used because it is considered persistent and easy to move in groundwater. Besides, that nitrate is present in groundwater with high concentrations compared to other contaminants and can come from various sources such as agricultural fertilizers and fecal sources [17]. The results of the nitrate concentration test can be seen in Table 2.

Table 2. Nitrate concentration in groundwater samples in Wonosari district

Station	Sample Name	Nitrate concentration (mg/L)
1	MHR 01	12.477
2	MHR 02	10.216
3	MHR 03	10.412
4	MHR 04	24.573
5	MHR 05	23.904
6	MHR 06	12.853
7	MHR 07	7.891
8	MHR 08	0.07
9	MHR 09	22.898
10	MHR 10	11.532
11	MHR 11	0.116
12	MHR 12	8.282
13	MHR 13	28.027
14	MHR 14	21.01
15	MHR 15	14.999
16	MHR 16	12.995
17	MHR 17	46.422
18	MHR 18	1.51
19	MHR 19	34.314
20	MHR 20	24.66
21	MHR 21	35.979
22	MHR 22	9.017
23	MHR 23	41.684
24	MHR 24	20.577
25	MHR 25	20.658
26	MHR 26	37.508
27	MHR 27	2.842
28	MHR 28	1.77
29	MHR 29	32.385
30	MHR 30	21.694
31	MHR 31	28.792
32	MHR 32	39.065
33	MHR 33	20.985
34	MHR 34	28.047
35	MHR 35	14

The results of laboratory tests from groundwater samples, the nitrate content ranged from 0.07 to 46.422

mg/L. Based on drinking water quality standards, the research area has a high content of nitrate contaminants because it is above the maximum permissible level of nitrate for drinking water, which is 10 mg/L [18].

3. METHODOLOGY

In this study, the method used is the SVV method. This method uses three variables: the thickness of the unsaturated zone, the rate of groundwater recharge or percolation, and the type of layering material for the unsaturated zone [6]. According to this method, the degree of vulnerability is expressed as the protective effectiveness (the ability of the overlaying layers above an aquifer to protect the groundwater) in terms of advective transport time [6].

Each variable was assessed and scored accordingly to its effect on the level of groundwater vulnerability. The thickness of the unsaturated zone score is based on the depth of the groundwater table in meters. The deeper the depth of the groundwater table, the higher the score given, and the smaller the vulnerability of the groundwater [6] (Table 3).

Table 3. SVV Score for Specific Value Factor of Unsaturated Zone Thickness

Depth of Groundwater Table (m)	Thickened Unsaturated Zone
1	1
2	2
3	3
4	4

Source: Putra [6]

The specific score of recharge rate was determined non-linearly according to the normalized value of the transport velocity of percolating water through similar thicknesses and materials in different scenarios of recharge value [6] (Table 4).

Table 4. SVV for percolation rate factor according to the class of recharge rate

Recharge Rate (mm/year)	The Score of Percolation Rate
<50	14
50-100	10
100-200	8
200-300	6
300-400	5
400-500	4
500-600	3
>600	2

Source: Putra [6]

The specific score of the unsaturated materials was assigned non-linearly according to the field capacity or specific retention value of soils/unconsolidated rock [6]. Scores for overlaying material factors according to soil and rock type can be seen in Table 5. Specific retention is the volume of water that remains in the rock pores after the water leaves the rock pores due to gravity [19]. The greater the specific retention of a layer of rock or soil, the greater the volume of water retained in the rock, and the less likely the flow of water can pass through the rock or soil [5].

In Table 5, the score for the limestone in the research area has not been determined, so a specific retention calculation needs to be carried out. In this study, specific retention was determined based on the formula developed by Twarakavi et al. (2009) [20]. This formula used pedotransfer function relationships to estimate the van Genuchten parameter and the field capacity or specific retention [20]. Pedotransfer functions relate soil-hydraulic parameters to measured soil properties such as bulk density and proportions of clay, silt, sand, and organic matter (carbon) [20]. The Van Genuchten parameter is based on the model van Genuchten (1980) carried out from the analytical approximation of pressure head, water content, and saturated hydraulic conductivity relations [20]. The formula developed by Twarakavi et al. (2009) can be seen as follows [20]:

$$\theta fc = \theta^{*} fc(\theta vG - \theta r) + \theta r \tag{4}$$

$$\theta^{*} fc = n^{(-0.60.[2+Log_{10}(K_h)])} \tag{5}$$

$$\theta r = 0,015 + 0,005(Clay) + 0,014(C) \tag{6}$$

$$\theta vG = 0,810 - 0,283(\rho b) + 0,001(Clay) \tag{7}$$

$$\begin{aligned} n = exp(0,053 - 0,009(Sand) - 0,013(Clay) \\ +0,00015(Sand^{2}) \end{aligned} \tag{8}$$

$$\begin{aligned} K_h = 1,1574(10^{(-5)}) - exp[20,6 - 0,96ln(Clay) \\ -0,66ln(Sand) - 0,046ln(C) - 8,43(\rho b)] \end{aligned} \tag{9}$$

Where Θfc = Field capacity (Specific retention), ΘvG = Van Genuchten porosity parameter, Θr = Residual water content, n = Van Genuchten exponent, K_h = Saturated hydraulic conductivity (cm/s), C = Organic Carbon Content (%), Clay = Clay fraction (%), Sand = Sand fraction (%), ρb = bulk density (g/cm^3) [20].

The final numerical scores of the SVV method are calculated using the following formula [6]:

$$P_T = \frac{(L_1 + L_2 + ...L_n)}{n} + Z + W_u \tag{10}$$

Where P_T = final score of protective effects of the unsaturated zone, L_n = average points of soil/rock cover, Z = points of the thickness of unsaturated zone, W_u = points of the recharge rate, and n = number of the overlying layers [6]. The classes of the final numerical scores and the corresponding residence time are given in Table 6.

Table 5. SVV for overlaying material factor according to soil/unconsolidated rock type

No.	Soil/Rocks Textural Class	Code of Soil/Rocks Texture (AG Boden, 1996)	Scores of Overlaying Material Factor
1	*Gravelly sand –sandy gravel).*	Gs, SG	8
2	*Medium sand*	mS, mSgs	11
3	*Medium – fine sand, fine-medium sand, coarser – fine sand, slightly silty sand.*	mSfs, fSms, Su’	16
4	*Loamy sand, slightly clayey sand, fine sand.*	Su, St, Us	24
5	*Silty sand), clayey sand, sandy silt.*	Su, St, Us	29
6	*Sandy loam, silty loamy sand, sandy loamy silt.*	Ls, Slu, Uls	32
7	*Silty loam, silt, clayey silt.*	Lu, Uu, Ut	36
8	*Clayey loam, sandy clayey loam.*	Lt, Lts	42
9	*Silty clay.*	Tu	49
10	*Loamy clay.*	Tl	51
11	*Clay.*	Tt	56

*T/t – clay; U/u – silt; L/l – loam; S/s – sand; G/g – gravel

Source: Putra [6]

Table 6. The final rating of the SVV method and its classification of groundwater vulnerability.

Interval of Final Rating	Protective Effectiveness of Overlaying Layers	Intrinsic Groundwater Vulnerability	Relative Residence Time in Unsaturated Zone
>70	Very High	Very Low	> 25 years
>65-70	High	Low	10 – 25 years
>35-65	Moderate	Moderate	3 – 10 years
>24-35	Low	High	Several months – to 3 years
≤24	Very Low	Very High	A few days – 1 year

Source: Putra, 2007

The groundwater vulnerability map will be overlaid with a land-use map to produce a map of the potential pollution of the research area. In addition to the three variables above, intrinsic elements and specific parameters are also needed in the mapping to obtain more accurate data [7]. A specific parameter used is land use, which has the potential to be a source of pollution or population data where the denser the population in a place, the more pollution will occur [5,6,7].

4. RESULTS AND DISCUSSION

4.1. Groundwater Vulnerability

The research area has a depth that varies from 0 to more than 40 meters based on the data obtained. The rate of recharge in the study area is 438.68 mm/year. The specific retention value for silt sand deposits in weathered soil on limestone is 26.5 and for calcarenite is 9.1.

It should be mentioned that the SVV method cannot be applied to the southern part of the Wonosari district. This is because the specific retention of limestone in the area cannot be determined through the laboratory testing method conducted by the researcher. In addition, crystalline limestones in this area tend to form secondary porosity so that scoring with the system matrix cannot represent the state of existing groundwater vulnerability.

By observing the morphology or surface conditions of the karst area and the type of flow in the aquifer, the southern part of the study area has a high intensity of fault and joint structures, and the presence of a sinkhole was found. Groundwater flow in the area has a type of fracture and conduit. In this type of flow, groundwater flow will move faster and resemble river flow so that the travel time for groundwater flow to reach the groundwater table will be faster [3]. From this approach, it can be concluded that the southern part has a very high groundwater vulnerability value [3,6].

Groundwater vulnerability in the central and northern parts of the research area was carried out using the SVV method. The index values of the three parameters are added up based on calculations using equations and classified based on the final value interval according to the classification table for the class division of the SVV method (Table 6) [6]. The vulnerability level obtained is dominated by a moderate vulnerability in the east and a high vulnerability in the west and north of the study area. The distribution of groundwater vulnerability can be seen in Figure 9.

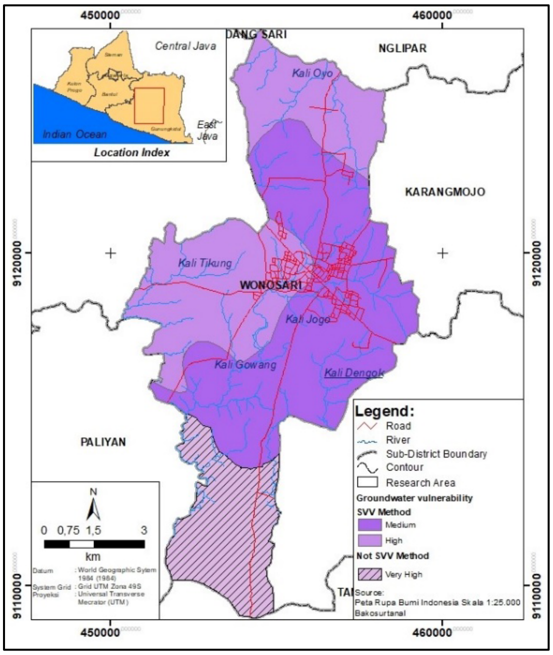


Figure 9 Groundwater vulnerability in Wonosari District using SVV method

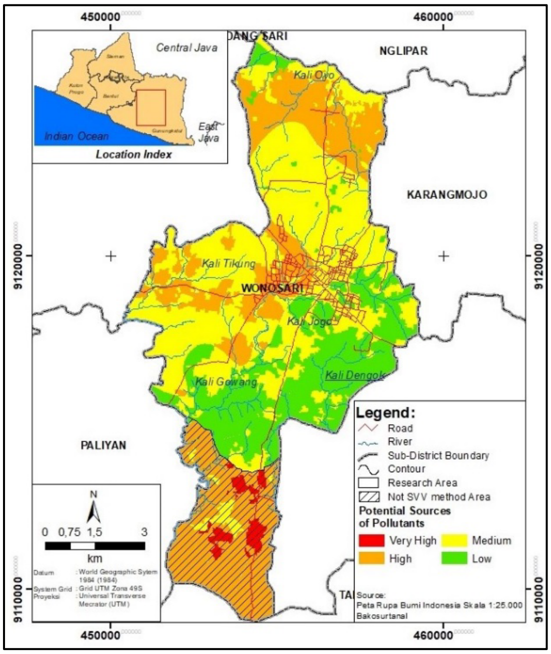


Figure 10 Potential sources of pollutants in Wonosari District.

Potential sources of pollutants in the Wonosari district are obtained by overlaying the distribution of groundwater vulnerability with land use in the research area. There are four types of distribution areas of potential sources of pollution in the research area, namely low, medium, high, and very high pollutant source potentials. The very high possible area is generally located in the southern part of the Wonosari district. In contrast, areas with high and medium potential are located in the northern part, and the central part spreads to the west. Areas with low potential are generally found in the eastern part. The distribution of potential sources of pollution can be seen in Figure 10.

4.2. Validation

Data validation of the level of groundwater vulnerability was carried out to determine the relationship between the Potential sources of pollutants and the actual groundwater pollution of the research area. Validation was carried out using the nitrate element as a pollutant which could be identified through laboratory tests on groundwater samples. The non-parametric statistical analysis was applied to find the correlation between groundwater vulnerability and nitrate concentration. 30 of the 35 water samples that have been analyzed are used in this statistical calculation (Table 2). For interpretations Spearman's rho correlation coefficient base on Akoglu (2018) [21,22,23]. Correlation is considered strong if the correlation coefficient has a value of more than 0.51, sufficient if it has a value of 0.26 - 0.50, and weak if it has a value of 0.0 - 0.25 [21,22,23].

The result shows (Table 7) that a correlation was found between the potential sources of pollutants and nitrate concentration. Therefore, the results of research using the SVV method are considered accurate enough to represent nature's ability to protect groundwater quality in the research area [21,22,23].

Table 7. Spearman rho correlation analyzed with JASP software

		Potential sources of pollutants	Nitrate (mg/L)
Potential sources of pollutants	Spearman's rho	-	
	p-value	-	
	N	-	
Nitrate (mg/L)	Spearman's rho	0.313	-
	p-value	0.092	-
	N	30	-

*p < .50, ** p < .01, *** p < .001

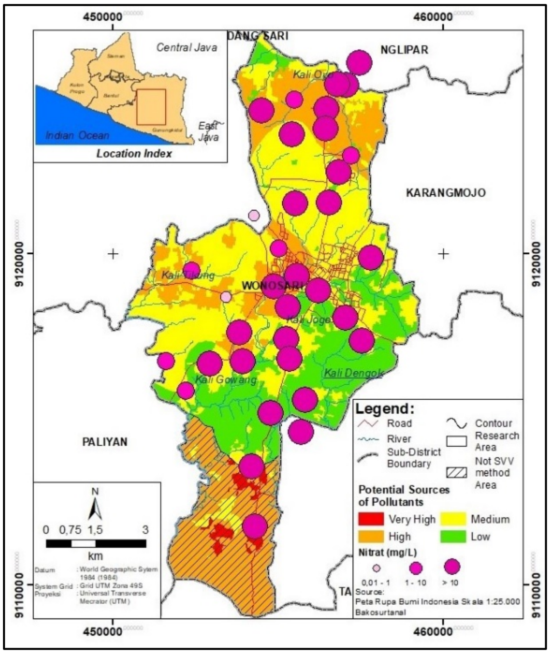


Figure 11. Potential sources of pollutants and nitrate concentration in Wonosari District.

CONCLUSIONS

This study applied the SVV method for vulnerability assessment in the karst aquifer. Additionally, the SVV method has been validated using non-parametric statistical analysis. It was complimented for a potential source of pollutants assessment. Results revealed three classes of groundwater vulnerability in the Wonosari district. The high vulnerability class is located in the west and north, the medium vulnerability class is in the west, and the very high vulnerability class is in the southern part. There are four classes of the potential source of pollutants in the Wonosari district, namely very high in the southern part, then high and medium, which are evenly distributed in the northern, western, and southern parts of the research area, and low in the western part of the research area. Based on the study results, the SVV method can be applied to clastic karst lithology types with the non-dominant influence of fault and joint structures. It cannot be applied to lithology with high secondary porosity, which significantly contributes to the specific retention value. A correlation between the potential sources of pollutants and nitrate concentration has Spearman's rho 0.313 (sufficient). Therefore, the results of groundwater vulnerability assessment using the SVV method are considered accurate enough to represent nature's ability to protect groundwater quality in the research area.

AUTHORS' CONTRIBUTIONS

Moch Hasmannnor Rachman, Wahyu Wilopo, and Doni Prakasa Eka Putra participated in the conceived and designed analysis.

Moch Hasmannoor Rachman participated in collecting the data, performing the analysis, and preparing the manuscript.

Wahyu Wilopo and Doni Prakasa Eka Putra supervise and check the manuscript.

All authors read and approved the final manuscript.

ACKNOWLEDGMENTS

We would like to thank the Department of Geological Engineering and Department of Civil and Environmental Engineering for their support during laboratory work.

REFERENCES

[1] Surono, Toha, B., and Sudarno, I. *Peta Geologi Lembar Surakarta-Giritontro, Jawa (Skala 1:100.000)*, Pusat Penelitian dan Pengembangan Geologi, Bandung, 1992.

[2] Surono. *Litostratigrafi Pegunungan Selatan Bagian Timur Daerah Istimewa Yogyakarta dan Jawa Tengah. In Publikasi Khusus Geologi Pegunungan Selatan Bagian Timur*. Kementrian Energi dan Sumber Daya Mineral, Badan Geologi, Pusat Survei Geologi. Bandung, 2009.

[3] Ford, D. C., dan Williams, P. W., *Karst Geomorphology and Hydrology*, Jhon Wiley and Sons Ltd, Chichester, 2007, pp. 39-265.

[4] Badan Pusat Statistik, *Kecamatan Wonosari Dalam Angka 2020*, Gunungkidul: Badan Pusat Statistik Kabupaten Gunungkidul, 2020, pp. 1-66.

[5] Appleyard, S., The Impact of Urban Development on Recharge and Groundwater Quality on Coastal Aquifer Near Perth, Western Australia, *Hydrogeology Journal*, 3(2), Springer-Verlag,1995, DOI: https://doi.org/10.1007/s100400050072.

[6] Putra, D. P. E., *The Impact of Urbanization in Groundwater Quality : A Case Study in Yogyakarta City*. Indonesia: Aachen, 2007, pp. 1-120.

[7] Vrba, J., and Zoporozec, A., *Guidebook on Mapping Groundwater Vulnerability*. Vol 16, International Association of Hydrogeologists, Verlag Heinz Heise, Hannover, 1994, pp. 1-131.

[8] Anonim, Peta Rupa Bumi Indonesia (RBI) dan Peta Kontur. Badan Informasi Geospasial (BIG). Bogor, 2016.

[9] Google Earth, Wonosari district in Google Earth. The website of Google Earth *is available at* https://earth.google.com/web/. (2020).

[10] Todd, D. K., *Groundwater Hydrology.* 2nd Edition. New York: John Wiley and Sons, 1980, pp. 359-409.

[11] *Jaxa Global Rainfall Watch System*, GSMap Climate in Wonosari District from 2011 to 2020. The website of the *Jaxa Global Rainfall Watch System is available at https://sharaku.eorc.jaxa.jp/GSMaP/.* (2021).

[12] Bemmelen, R. W., *The Geology of Indonesia Vol. IA*. Amsterdam: Government Printing Office, The Hauge, 1949, pp. 554-558.

[13] Barianto, D. H., Margono, U., Husain,S., Novian, M.I. dan Permana, A.K., *Peta Geologi Lembar Wonosari*, Pusat Survei Geologi Badan Geologi Kementrian ESDM, Bandung, 2017.

[14] Grabau, A.W., On the Classification of Sedimentary Rocks. *American Geologist*, 1904, **33**.

[15] ASTM (American Society for Testing and Material) D 2487, *Standard Practice for Classification of Soils for Engineering Purposes* (Unified Soil Classification System), U.S. pp. 1-8.

[16] Telford, W. M., Geldart, L. P., Sheriff, R. E., *Applied Geophysics*. 2nd Edition. London: Cambridge University Press, 1990, pp. 16.

[17] Putra, D. P. E., *Project final report: Integrated water resources management in Merapi-Yogyakarta basin* (Project SEED-Net No. UGM 0104), Universitas Gadjah Mada, Yogyakarta, 2003.

[18] Peraturan Pemerintah Nomor 22 Tahun 2021 tentang Penyelenggaraan Perlindungan dan Pengelolaan Lingkungan Hidup (Lembaran Negara Republik Indonesia Tahun 2021 Nomor 32), 2021.

[19] Meinzer, O. E, The Occurrence of Ground Water in the United States, *Geological Survey Water-Supply Paper*: the United States, 1923, pp. 28-29, DOI: https://doi.org/10.3133/wsp494.

[20] Dingman, S. Lawrence., *Physical Hydrology: Third Edition*. Waveland Press: Illonis, 2015, pp. 335-355.

[21] Dancey, C. D., and Reidy, J., Statistics Without Maths for Psychology [electronic resource]: 2020, pp.636.

[22] The jamovi project. *jamovi*. (Version 2.3) [Computer Software]. Retrieved from https://www.jamovi.org. (2022).

[23] R Core Team (2021). *R: A Language and environment for statistical computing*. (Version 4.1) [Computer software]. Retrieved from https://cran.r-project.org. (R packages retrieved from MRAN snapshot 2022-01-01).