Groundwater vulnerability assessment and mapping in shallow groundwater

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Abstract. The increasing population density can contaminate groundwater. So far, groundwater is still the primary source to fulﬁl clean water and drinking water in Muntilan, Salam, and Ngluwar Sub-District. Studies on groundwater vulnerability are essential to minimize the contamination risks as a piece of basic information for land use planning. This research aims to assess groundwater vulnerability in Muntilan, Salam, and Ngluwar Sub-District. The simple vertical vulnerability (SVV) method with GIS was selected to develop a groundwater vulnerability map. The parameters of this method consist of the type of soil/rock, the thickness of the water-unsaturated zone, and the recharge value. The results show that the research area can be divided into three vulnerability classes: very low, moderate, and high groundwater vulnerability. Very low groundwater vulnerability has a value of more than 70 with very high protection effectiveness. The class is distributed in Muntilan and Salam Sub-Districts. Moderate groundwater vulnerability has a value less than 35 to 65 with moderate protection effectiveness, and high groundwater vulnerability has a value ranging from 24 to 35 with low protection effectiveness. Both of the class is evenly distributed in Muntilan, Ngluwar and Salam Sub-Districts.

1. Introduction

Groundwater is still an essential resource for people in Muntilan, Salam, and Ngluwar Sub-District Central Java. Many people still use dug wells obtained from shallow groundwater. Shallow groundwater is groundwater located in shallow aquifers with less than 30 m depth and primarily located in the unconfined aquifer [1, 2]. The role of groundwater is vital which most people in the world depend on groundwater for their drinking water consumption. In addition, most of the irrigated agriculture in the world still depends on groundwater. In the future, groundwater still becomes essential for economic growth and increasing water supply demand in many aspects [3]. It thus plays an essential but often little-appreciated role in human well-being, as well as that of some aquatic and terrestrial ecosystems [4]. Contaminants in groundwater have always been a concern of researchers because of their negative impact on health [5]. Nitrate and other nutrients are common problems in groundwater contamination, primarily generated from anthropogenic activities such as onsite wastewater treatment, agricultural and
livestock [6-7]. The map of groundwater vulnerability can be used to protect and conserve groundwater resources [8]. Many groundwater vulnerabilities assessing and mapping methodologies have been developed, such as the GOD, The Irish approach, AVI, DRASTIC, SINTACS, EPIK [9]. Groundwater vulnerability assessment and mapping in Muntilan, Salam, and Ngulwar Sub-Districts use the simple vertical vulnerability (SVV) method with spatial analysis in ArcGIS.

The research area is located in the Muntilan sub-district, Salam sub-district, and Ngulwar sub-district, a part of Magelang Regency, Central Java Province. The study area is approximately 82.68 Km² area. It can be shown in Figure 1.

![Figure 1. Research Location](image)

2. Method

The SVV method is the self-develop mapping approach of groundwater vulnerability aimed at quaternary shallow site groundwater conditions, especially in the region lacking measurement and soil/rock properties [10]. The SVV method is used depth to the groundwater below 20 m [11]. Three aspects in the SVV method: (1) the thickness of the unsaturated zone, (2) recharge or percolation rate, and (3) type of overlying layers material [10]. The formula of calculation using the following Equation 1.

\[ PT = L_a + Z + W_u \]  

Where \( PT \): the final score of the unsaturated zone protective effectiveness; \( L_a \) = average score of the rock/soil cover; \( L_a = (L_1 + L_2 + ... + L_n)/n \); \( Z \) = unsaturated zone thickness scores; \( W_u \) = recharge rate scores; \( n \) = the overlying layers number and the final rating of SVV method can be shown in Table 1.

| Interval of a class | Protective effectiveness of overlying layers | Intrinsic groundwater vulnerability | Relative residence time on 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 – 3 years                 |
| <24                 | Very low                                    | Very high                         | A few days – 1 year                      |
3. Results and Discussion

3.1. Unsaturated zone thickness (Z)

The first vulnerability parameter in the SVV method is the unsaturated zone thickness. The closer groundwater is to the land surface; therefore, the quicker dissolved contaminants can reach the groundwater surface. The data was obtained from measurements of the groundwater table depth in 94 wells spread across Muntilan, Salam, and Ngluwar sub-districts. The depth range of the groundwater table is 0.4 – 10 m and is divided into ten classes based on depth, while for the other four classifications located on the hill, it is done by calculating the contour with the nearest well. The classification can be seen in Figure 2 (a).

3.2. Recharge or percolation (Wu)

The second parameter is percolation. A higher percolation factor value indicates a more effective level of groundwater protection. The effectiveness of automatic protection minimizes the level of groundwater vulnerability. On the other hand, a small percolation value means a higher level of groundwater vulnerability. Percolation rate is calculated from evapotranspiration, rainfall, and runoff. Rainfall data were collected from the Departement of Public Works of Magelang Regency and Yogyakarta Special Province, and The Central Bureau of Statistics (BPS). The percolation map can be seen in Figure 2 (b).

![Figure 2](a) Groundwater depth map; (b) Net recharge map

3.3. Average Point of Soil/Rock Textures (La)

The third parameter to assess the level of vulnerability is the lithological factor of the unsaturated zone. Lithological data were obtained from field mapping and secondary data in the research area’s geoelectric results and geological maps. The average point of soil/rock can be divided into three classes, as shown in Table 2 and Figure 3 (a).

Rock layers identification was obtained from field mapping and secondary data such as drilling logs and geoelectrical data, as shown in Table 2. Identification of layer one was obtained by sieving analysis.
of 34 topsoil samples. Layer one (L1) is the topsoil divided into two textures, sand and sandy loam. The second layer (L2) is divided into two different rocks, breccia, and andesite. The third layer (L3) was found in the hilly area consist of breccia. According to regional geology, this area is covered by old volcanic deposits of Merapi volcano consisting of lava flows, breccia, agglomerate, and young volcanic deposits consisting of undifferentiated tuff breccia, ash, agglomerate, and lava flows [12].

| Table 2. Points of overlying material factor |
|--------------------------------------------|
| Layer 1 (L1) | Layer 2 (L2) | Layer 3 (L3) | Point of L1 | Point of L2 | Point of L3 | Average (L1+L2+L3)/n |
|-------------|-------------|-------------|-------------|-------------|-------------|---------------------|
| Sand        | Breccia     | -           | 24          | 32          | -           | 28                  |
| Sandy Loam  | Breccia     | -           | 32          | 32          | -           | 32                  |
| Sand        | Andesite    | Breccia     | 24          | 56          | 32          | 37.3                |

3.4. **Groundwater Vulnerability Map**

The result of groundwater vulnerability by the SVV method is shown in Figure 3 (b). The interval rating classification in this study area is divided into three classes. A very low vulnerability has a value >75 with very high protection effectiveness. A moderate vulnerability has a value from 35 to 65 with moderate protection effectiveness. A high vulnerability has a value from 24 to 35 with low protection effectiveness. The moderate and a high vulnerability class is evenly distributed in Muntilan, Ngluwar, and Salam Sub-Districts. Low vulnerability distributed in Muntilan and Salam Sub-Districts.

![Figure 3.](image)

(a) Average point of soil/rock textures; (b) Groundwater vulnerability map by SVV method.

3.5. **Validation Groundwater Vulnerability with Nitrate Concentration**

Comparing the results of vulnerability mapping with the contamination that occurred is one of the best ways to gain confidence and trust in vulnerability mapping [13]. In this study, nitrate contaminants are comparing with the SVV result. The distribution of nitrate concentrations for the research area is shown
The concentrations of NO$_3^-$ are divided into two ranks: 0 mg/L to 10 mg/L and 10 mg/L to 20 mg/L. There are similarities between the nitrate value and the SVV vulnerability value. Nitrate with a value of 10 to 20 mg/L is located mostly in the high vulnerability zone. The average nitrate concentration in the high groundwater vulnerability is 5.7 mg/L, wherein the moderate vulnerability is 3.4 mg/L.

Figure 4. Nitrate concentration and final score of SVV method

4. Conclusion
The results of groundwater vulnerability by the SVV method in the Muntilan sub-district, Salam sub-district, and Ngluwar sub-district can be divided into very low, moderate, and high vulnerability. The low groundwater vulnerability has a value of more than 70 with very high protection effectiveness. The class is distributed in Muntilan and Salam Sub-Districts. Moderate groundwater vulnerability has a value between 35 to 65 with moderate protection effectiveness, and high groundwater vulnerability ranges from 24 to 35 with low protection effectiveness. Both of the class is evenly distributed in Muntilan, Ngluwar and Salam Sub-Districts. Relative residence time on the unsaturated zone from contaminant for very low vulnerability is more than 25 years, moderate vulnerability is three to ten years, and high vulnerability is several months until three years. The result of the SVV method has a positive correlation with nitrate concentration. The high vulnerability area zone has a higher average nitrate concentration of 5.7 mg/L, while the moderate vulnerability zone has a lower value of 3.4 mg/L. Good groundwater management can help to keep high vulnerability zones being polluted from human activities.

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