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RESEARCH ARTICLE

Groundwater Vulnerability Comparison Using DRASTIC and GOD Methods in Surakarta City

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Abstract Demographic growth, urbanization, economic development, agriculture, and consumption per capita have increased the demand for water resources. The population density of Surakarta affects the city's ability to fulfil its residents' clean water requirements. As an urban region, Surakarta may be impacted by development activities that degrade the quality and quantity of groundwater. This growing demand should be balanced against effective management of water source regions. This research aims to investigate groundwater vulnerability in Surakarta City. We employed the DRASTIC and GOD methods and compared both results. These methods used the overlay and indexing approaches using GIS based on field data and secondary data such as drill, rainfall, and topographic data. The results of DRASTIC show three types of vulnerability: high (0.21%; 9.87 ha), moderate (94.22%; 4,355.98 ha), and low (5.56%; 257.25 ha), while GOD method results in high (7.03%; 324.96 ha), moderate (52.90%; 2,445.84 ha), low (38.69%; 1,788.81 ha), and negligible (1.37%; 63.49 ha). Based on both methods, we identified Banjarsari district as a location with high groundwater vulnerability. The correlation coefficient between the two methods is 0.511. This value shows that the correlation criteria are acceptable and comparable. This research can be used by local authorities and policymakers to manage groundwater resources.

1. Introduction

The presence of water in the environment is essential to all forms of life. Demographic expansion, urbanization, economic activity, agriculture, and rising consumption per capita have all contributed to a growing demand for water resources (Aschonitis et al., 2016). Surakarta is one of the big cities in Central Java province, Indonesia, and is a densely populated urban region. The population density affects the city's ability to fulfil its residents' clean water requirements. According to Perdana (2019), the population requires 18.62 billion liters of water annually. Free groundwater reserves during the transition season comprise of 1.34 billion liters. As an urban region, Surakarta may be impacted by development activities that degrade the quality and quantity of groundwater. Furthermore, Edisar (2013) states that when water catchment regions are not appropriately managed, groundwater quantity and quality will become increasingly scarce in certain places. As a result, the growing demand for water resources should be balanced against effectively managing water source regions.

Vulnerability in hydrogeological context refers to the extent to which an aquifer is susceptible to contamination that may adversely affect groundwater quality. Two terms are utilized to describe groundwater vulnerability: intrinsic and specific. Intrinsic vulnerability reflects the inherent susceptibility based on environmental physical characteristics, while specific vulnerability involves the calculation of contaminant transport properties through the subsurface. Intrinsic characteristics determine the sensitivity of water to contaminants, with contaminant transport generally resulted from advection, hydrodynamic dispersion, and retardation processes. Advection involves the movement of water-carrying contaminants, hydrodynamic dispersion occurs through contaminant diffusion, and retardation is due to reactions between contaminants and soil media hindering their movement (Ligget and Talwar, 2009; Notodarmojo, 2005).

The DRASTIC method is widely employed for assessing intrinsic vulnerability to various potential contaminants. This overlay and index model generates vulnerability scores by combining multiple thematic maps. The acronym DRASTIC represents the key factors in hydrogeology that control groundwater pollution. Another suitable parametric system for analyzing groundwater vulnerability is the GOD method, an acronym for its parameters (Linggasari et al., 2020). This method utilizes GIS-based mapping to determine aquifer vulnerability based on the vertical percolation of pollutants through the unsaturated zone. The DRASTIC method is designed for large areas, and as the analysis area expands, the mapping of vulnerability becomes more detailed. In contrast, the GOD method can be applied to map vulnerability within aquifers at a small to medium scale. Both DRASTIC and GOD methods provide vulnerability levels based on geological, hydrological, and hydrogeological characteristics in a region.

In Indonesia which has tropical climate, Surakarta presents geological and climatic conditions different from the United States and Europe, where DRASTIC and GOD were developed. DRASTIC, with parameters such as groundwater depth and net recharge, is relevant for Surakarta's susceptibility to intense rainfall and complex geological formations. Although GOD, focusing on aquifer types and lithology, was developed in Europe, its simplicity allows for adaptation to tropical climates, as in Surakarta. The application of DRASTIC and GOD in Indonesia, including Surakarta, requires consideration of local geological and climatic conditions. There is only a few of study comparing both methods in Indonesia, for instance by Koesuma et al. (2022) who applied these methods in a small area of a village in Karanganyar regency. Several other studies were conducted by Sunarti et al. (2017) in Yogyakarta using DRASTIC method, while Sejati and Saputra (2022) analyzed groundwater pollution in Bantul regency using GOD.

The DRASTIC and GOD methods are ideal for identifying groundwater vulnerability, but require many data to calculate the index. We used the results of geoelectric surveys as input data for DRASTIC and GOD so that the lack of data for input data for DRASTIC and GOD could be fulfilled. This is very useful for areas that do not have geological or hydrogeological data and are densely populated. The results of this research can be used as a reference by local authorities in determining land use policies, especially for residential locations, rice fields and industries based on groundwater vulnerability maps.

2. Methods

2.1 Description of Research Area

The research area was Surakarta city, located between 110^0 45' 15" E - 110^0 45' 35" E and 7^0 36' 00" S - 7^0 56' 00" S, as illustrated in Figure 1. The city has an area of 44,04 km^2 divided into five districts: Jebres, Banjarsari, Serengan, Laweyan, and Pasar Kliwon (Disdukcapil, 2018). The city is covered by quaternary sediment, which is mostly alluvium. The stratigraphic sequence follows the metamorphic rock consisting of schist, marble, altered volcanic, and sedimentary rock, the oldest formation in this area (Koesuma et al., 2017).

The geological condition of Surakarta city based on the Geological Map Sheet Surakarta-Giritontro is composed of three rock structures: Alluvium (Qa), Old Alluvium (Qt), and Young Merapi volcano alluvium (Qvm) (Krisna H, Revina, and Soegiarto, 2017). Figure 1 depicts a geological map of Surakarta.

Surakarta generally has diverse types of aquifers, including volcanic deposits and basalt rock formations that play a crucial role in groundwater circulation. The Karanganyar-Boyolali basin in Surakarta is a geological area rich in potential groundwater resources. Located in the southern part of Surakarta City, Central Java, Indonesia, this basin is known for its diverse forms and lithology types, significantly influencing regional hydrogeology. The aquifers within this basin involve various types, including alluvial deposits, sedimentary rocks, and volcanic formations. The circulation of groundwater within the basin is also influenced by rivers and surface water flows that traverse the area. This diversity makes the Karanganyar-Boyolali basin a crucial groundwater resource to be carefully managed. Further research and continuous monitoring of the hydrogeological conditions in this basin are essential for understanding and maintaining the sustainable use of groundwater resources in the Surakarta region.

The presence of groundwater basins (Karanganyar-Boyolali basin) and river flows around the city also influence its hydrogeological conditions. These factors significantly impact the management of groundwater resources in Surakarta.

2.2 DRASTIC Method

The DRASTIC method is the most frequently used groundwater vulnerability analysis applied in various studies (Wachniew et al., 2016). This method was developed by

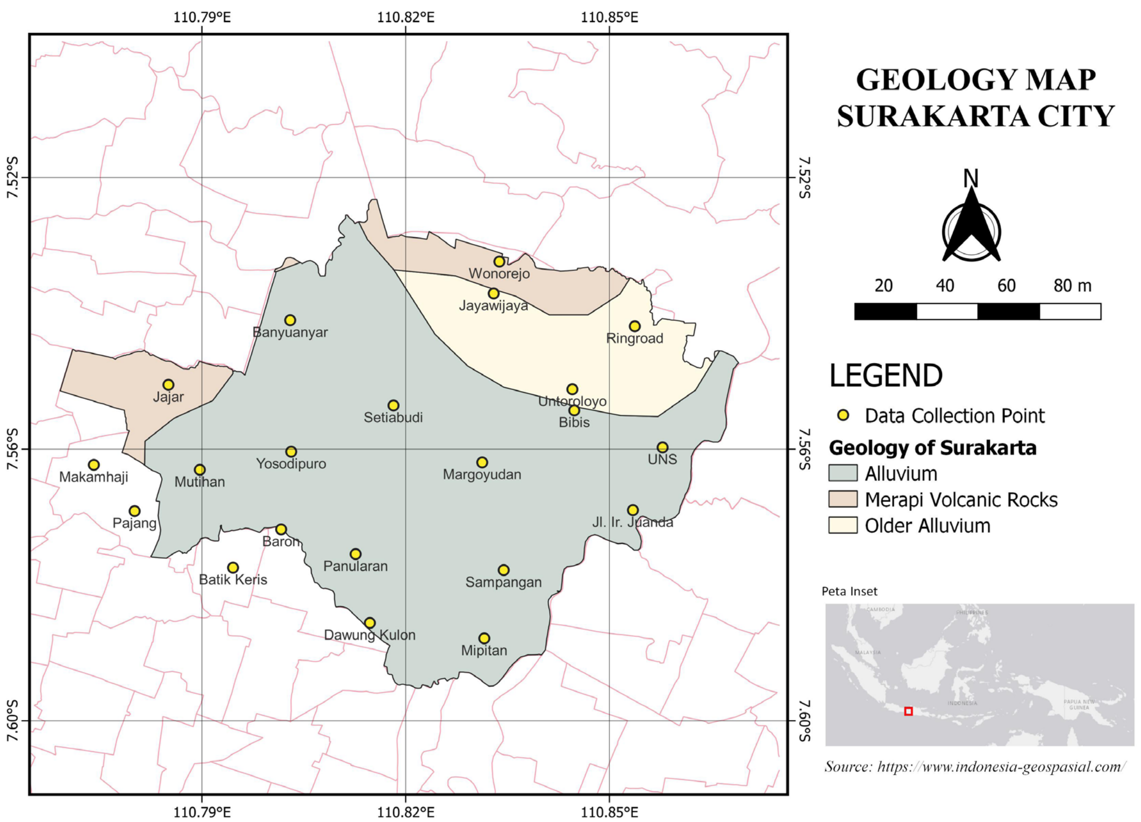


Figure 1. Geological map of Surakarta city, the solid yellow dot is geoelectric survey locations (modified from Koesuma et al., 2017)

Aller et al. in 1987 for the US Environmental Protection Agency (Putranto et al., 2016). Assessment of groundwater vulnerability uses seven hydrogeological parameters, including depth of water table (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I), and hydraulic conductivity (C) (Wachniew et al., 2016). The name of the DRASTIC method comes from the first letter of each parameter or the letter of its variable.

The main data utilized in this research was obtained from the results of geoelectric survey data of 21 sites, as shown in Figure 1. Based on the results of geoelectric data, it was obtained the data of depth of water table (D), aquifer media (A), soil media (S), impact of vadose zone (I), and hydraulic conductivity (C). While the net recharge (R) data was derived from the rainfall data of the Meteorological Climatological and Geophysical Agency (BMKG). The Topography data (T) were extracted from topographic map data. We also used logging data from the Ministry of Public Works and Public Housing (PUPR) to validate the result of the geoelectric interpretation. Table 1 shows the site of the geoelectric survey, while Figure 2 shows the inversion layer model of lithology in Mutihan site. The right side of Figure 2 shows the depth and resistivity value of each layer. A detailed layer interpretation can be found in Koesuma et al. (2019) and Koesuma et al. (2021). Hastuti et al. (2016) also used geoelectrical and hydrogeological data to input the GOD method to obtain groundwater vulnerability in Semarang, but their research did not compare it to the DRASTIC method.

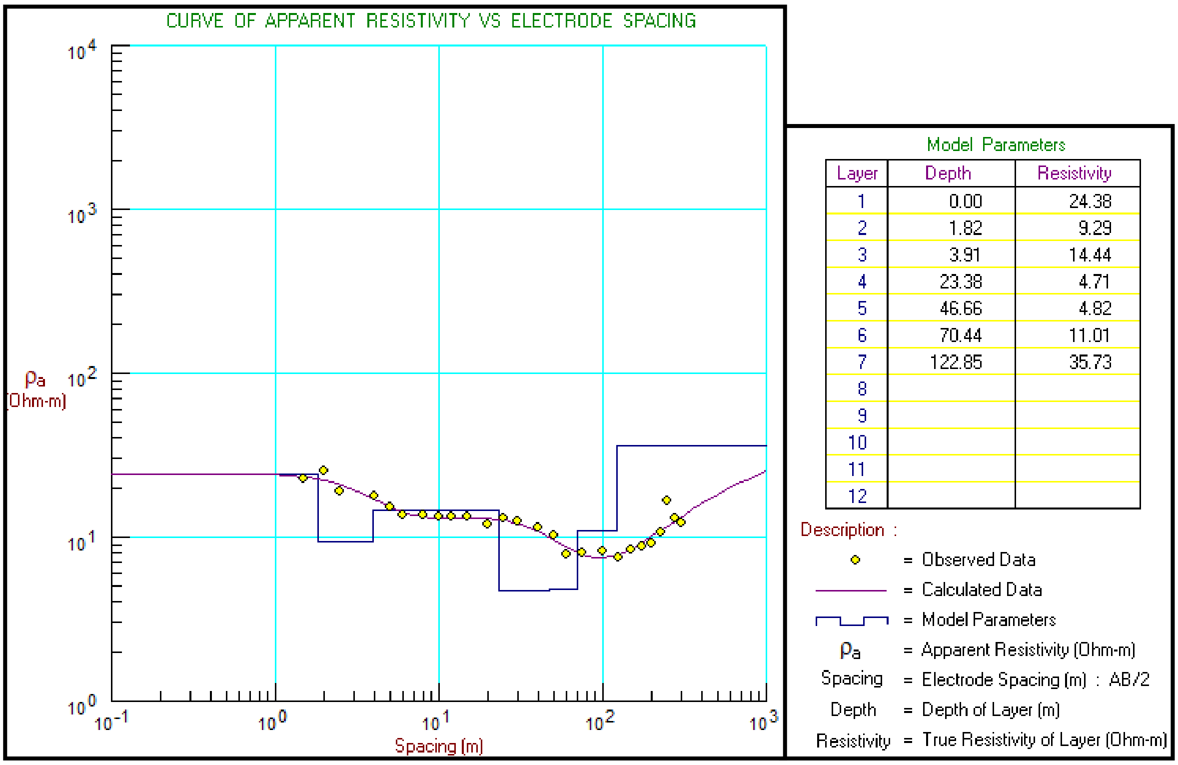


Figure 2. Results of geoelectric survey in Mutihan site, Jebres district. The table on the right side shows the inversion results (depth and resistivity value). (modified from Koesuma et al., 2021)

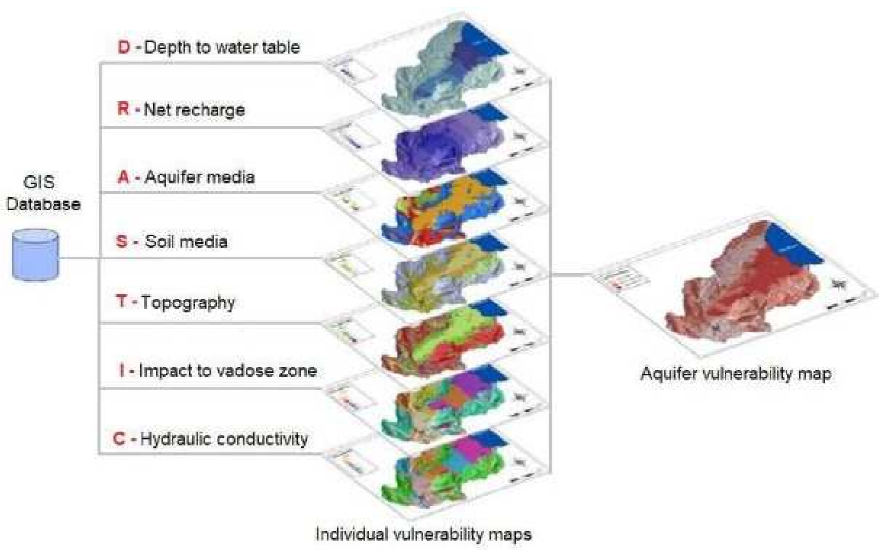


Figure 3. Flowchart of mapping vulnerability method using DRASTIC (Barbulescu, 2020).

Table 1. Weight of Groundwater Vulnerability Parameters (Widyastuti et al., 2006)

	Parameter	Weight
D	Groundwater Depth	5
R	Net Recharge	4
A	Aquifer Media	3
S	Soil Media	2
T	Topography	1
I	Impact of Vadose Zone	5
C	Hydraulic Conductivity	4

Table 2. Criteria for vulnerability levels (Corniello et al., 1997)

Vulnerability Level	DRASTIC Index
<80	Very Low
80-120	Low
120-160	Moderate
160-200	High
>200	Extreme

DRASTIC vulnerability index is calculated based on a ranking system that contains weights, ranges, and ratings for each parameter (Voutchkova et al., 2021). Calculation of the weight is carried out to generate relative importance. Each parameter has its weight with a given range of 1 to 5. Meanwhile, the ratings for each DRASTIC parameter range are from 1 to 10 (Ahirwar & Shukla, 2018). The index value is determined using Equation 1, which is defined by Aller et al. (1987) in (Ghazavi & Ebrahimi, 2015), as follows:

$$DRASTIC\ INDEX\ (DI) = \sum_{i=1}^{i=7} r_i \times w_i \quad (1)$$

DI is the vulnerability index of the DRASTIC method, *r* belongs to the rating of each parameter, *w* is the weight of each parameter, and *i* represents the seven hydrogeological parameters of the method.

2.3 GOD Method

The GOD method determining groundwater vulnerability was developed by Foster in 1987 and 1998 (Mohammad, 2017). This method utilizes GIS-based cartography, first developed in the United Kingdom (Putranto et al., 2016). The naming comes from the three parameters of Groundwater occurrence (G), Overlying lithology (O), and the Depth of the groundwater table (D) (Hastuti et al., 2016). Firstly, an assessment is conducted on the aquifer type (C_A) to identify the water flow characteristics and the sustainability of groundwater resources. Secondly, the lithology of the aquifer (C_L) is evaluated to comprehend its physical and chemical properties. Last, the depth of the groundwater table (C_D) is measured as a crucial indicator in assessing the extent to which groundwater resources may be influenced by external factors. All those three parameters are obtained from the results of the geoelectric survey.

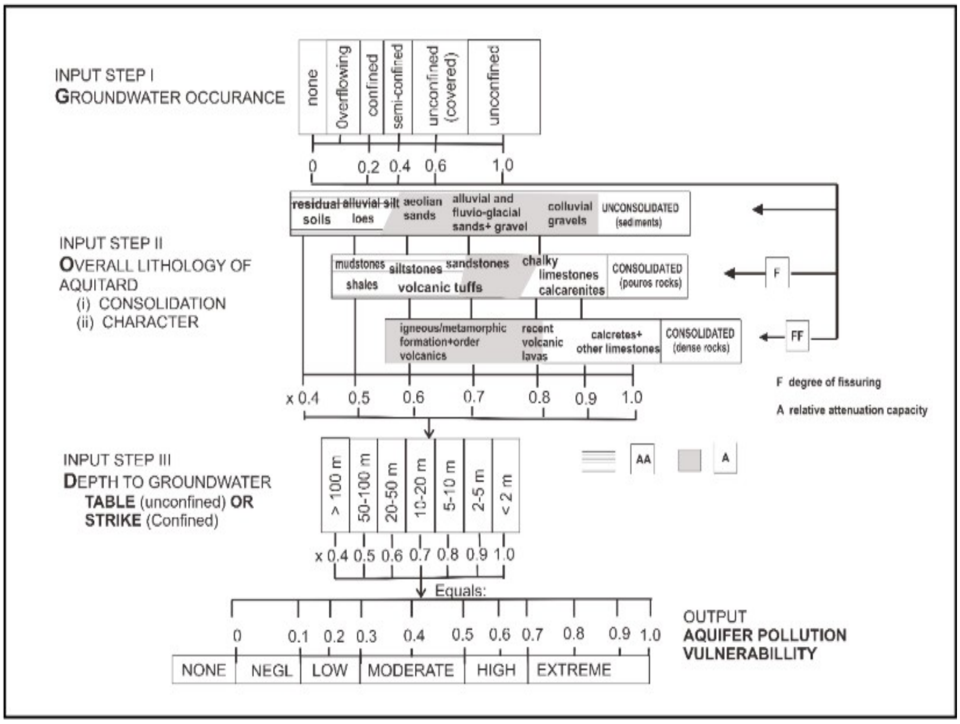


Figure 3. GOD parameter assessment method (Hastuti et al., 2016)

Table 3. Criteria for groundwater vulnerability levels based on the GOD index (Putranto et al., 2019)

GOD Index	Vulnerability Level	Definition
0 – 0.1	Not vulnerable	Limited to places without significant vertical groundwater flow (leaks).
0.1 – 0.3	Low	Susceptible to conservative contaminants that are removed extensively and continuously over the long term
0.3 – 0.5	Moderate	Susceptible to several types of contaminants that are continuously discharged
0.5 – 0.7	High	Susceptible to all pollutants, except contaminants that require high absorption capacity, easily change over time and in various pollution scenarios
0.7 – 1.0	Extreme	Susceptible to most water pollutants with rapid impact in various pollution scenarios

Table 4. Calculation of DRASTIC-GOD index and its vulnerability level

No.	District	Sites	DRASTIC Index	Vulnerability Level	GOD Index	Vulnerability Level
1	Jebres	UNS	136	Moderate	0.196	Low
2		Jayawijaya	116	Low	0.084	Negligible
3		Untoroloyo	129	Moderate	0.168	Low
4		Ringroad	121	Moderate	0.168	Low
5		Bibis	145	Moderate	0.630	High
6		Ir Juanda	101	Low	0.072	Negligible
7		Margoyudan	112	Low	0.400	Moderate
8	Banjarsari	Setiabudi	132	Moderate	0.540	High
9		Wonorejo	120	Moderate	0.084	Negligible
10		Yosodipuro	161	High	0.450	Moderate
11		Banyuanyar	155	Moderate	0.540	High
12	Laweyan	Jajar	114	Low	0.168	Low
13		Mutihan	130	Moderate	0.540	High
14		Baron	146	Moderate	0.480	Moderate
15		Panularan	142	Moderate	0.400	Moderate
16		Pajang	142	Moderate	0.630	High
17		Makam Haji	158	Moderate	0.450	Moderate
18	Pasar Kliwon	Sampangan	148	Moderate	0.140	Low
19		Mipitan	136	Moderate	0.168	Low
20	Serengan	Dawung Kulon	130	Moderate	0.540	High
21		Batik Keris	118	Low	0.450	Moderate

Each parameter has a different contribution to the results of the GOD vulnerability level (Djoudi et al., 2019), with its criteria (Sugianti et al., 2017). GOD vulnerability assessment was conducted by calculating the index for the region, according to equation 2 (Rukmana et al., 2020).

$$GOD\ INDEX\ (GI) = C_A \times C_L \times C_D \quad (2)$$

GI is the vulnerability index using the GOD method, C_A belongs to the aquifer type parameter rating, C_L is the aquifer lithology parameter rating, and C_D is the groundwater table parameter rating.

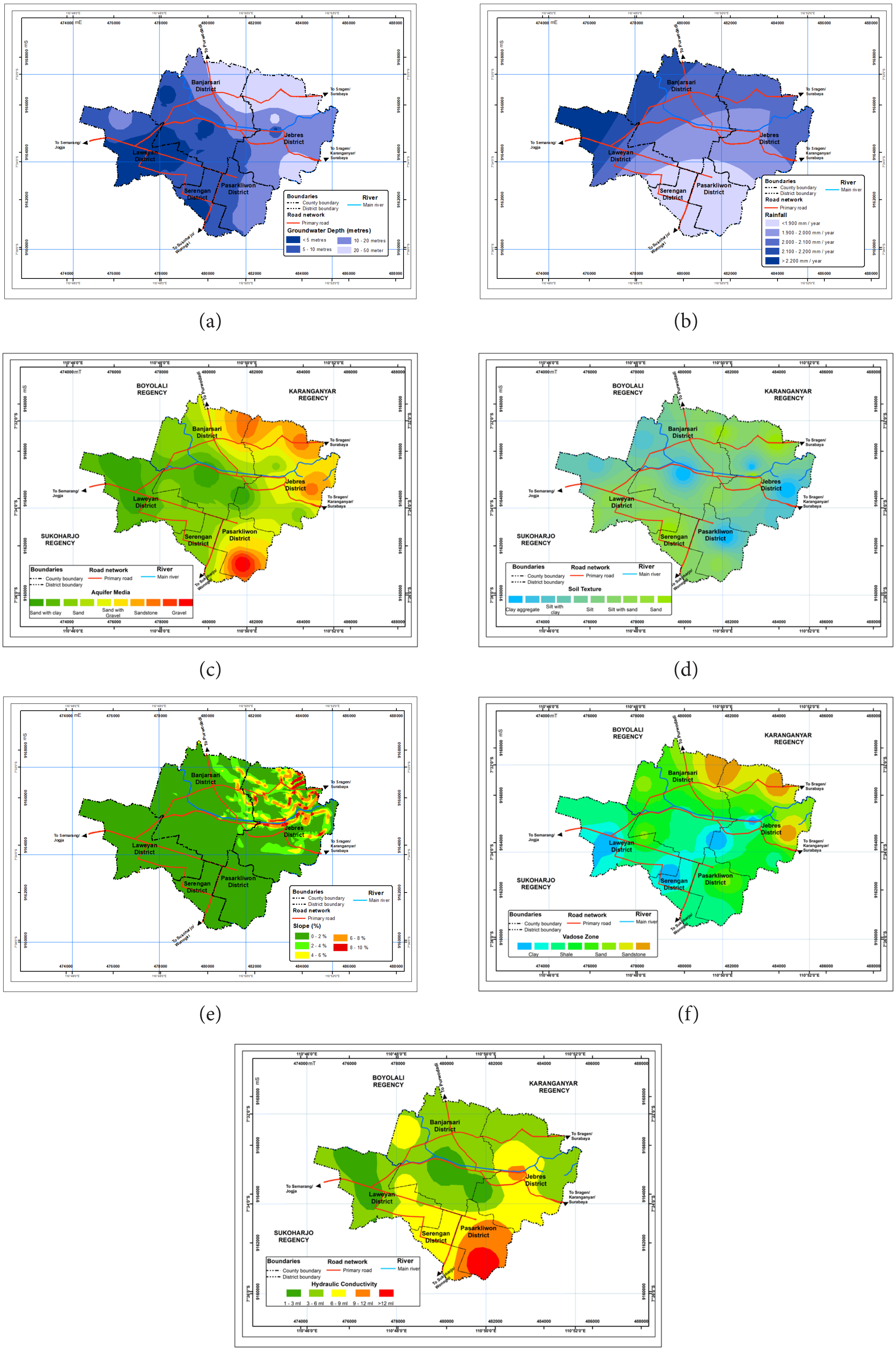
2.4 Data Processing

Data processing and analysis were conducted using ArcGIS software. The DRASTIC and GOD methods generate the results of the groundwater vulnerability level map from the Inverse Distance Weighted (IDW) interpolation map from the index values. The DRASTIC and GOD vulnerability maps were then compared according to the vulnerability class. Subsequently, the correlation coefficient between the two created maps was also obtained. The GOD method was selected concurrently with the DRASTIC method because the parameters used were environmental factors that control the aquifer contamination processes (Mfonka et al., 2018). Mfonka et al. (2018) explained that the application of the GOD method alongside the DRASTIC method can result in a strong correlation between the two. This has been demonstrated by numerous researchers, for instance Ghazavi and Ebrahimi (2015), Djoudi et al. (2019) and Mohammad (2017).

3. Results and Discussion

3.1 Vulnerability Map Using the DRASTIC Method

The DRASTIC method has seven parameters with predetermined weights and ratings. Each DRASTIC parameter has a different contribution level in assessing groundwater vulnerability, and various conditions influencing the level. Figure 4 shows the values of each groundwater vulnerability parameter. Figure 4a shows the depth of the groundwater table, which represents the vertical distance between the ground surface and the water table. Figure 4b shows the intensity of rain as a medium for transporting contaminants vertically to the water surface and spreading horizontally in the aquifer. Figure 4c shows the distribution of the constituent media of the aquifer, while 4d shows the distribution of soil texture that affects infiltration from the soil surface. Furthermore, Figure 4e shows the topography of Surakarta area, indicating whether contaminants will run off or be retained on the soil surface to infiltrate. Figure 4f shows the impact of the vadose zone



(a) (b) (c) (d) (e) (f) (g)

Figure 4. Maps of each parameter of the DRASTIC method (a) Depth to water (b) Net recharge (c) Aquifer media (d) Soil media (e) Topography (f) Vadose zone (g) Hydraulic Conductivity

that determines whether or not contaminants move into the aquifer. Finally, Figure 4g shows the hydraulic conductivity of the aquifer media to transmit water through the pore spaces.

The calculation of the DRASTIC index in Surakarta City is known ranged from 101 to 161, and the vulnerability map is presented in Figure 5. According to the results, Surakarta has low, moderate, and high levels of vulnerability. The classification of vulnerability classes was carried out by calculating the ratings and weights of the seven DRASTIC parameters. Based on Figure 5, about 6.66% or 307,416 Ha of the area of Surakarta City was identified to have a low level of groundwater vulnerability. Meanwhile, 93.33% or 0.214% of the area was identified as having moderate and high levels of groundwater vulnerability.

High vulnerability class was identified in Banjarsari district with a point location in Yosodipuro. The sand was recognized as the aquifer media and vadose zone with loamy soil. Additionally, areas with a high level of vulnerability were identified as having low groundwater with a depth of 4.4 m. Therefore, the high value of water permeability in the aquifer, soil, and vadose zone, as well as the low value of the depth of the groundwater table, result in the high vulnerability of the DRASTIC index in the area.

Low vulnerability classes were identified in Jebres, Laweyan, and Serengan districts. These locations have aquifer and soil media in the form of loamy sand, while the vadose zone is shale to clay. In comparison to sandstone, clay has a lower hydraulic conductivity coefficient value.

3.2 Vulnerability Map Using the GOD Method

Each GOD parameter has a different level of contribution in assessing groundwater vulnerability. This can be determined by classifying and assigning values according to the GOD method. Based on the results of geoelectric and hydrogeology data, we found three types of aquifers, as shown in Figure 6a. Two confined aquifers were found in the north and a small area in the east of Surakarta city. Confined aquifer is an aquifer that has a limiting layer with very low permeability, and the pressure is higher than atmospheric pressure. Semi-confined aquifers have boundary layers whose permeability is higher than confined aquifers (Anna, 2016). Semi-confined aquifers were found in the eastern part of Surakarta, while unconfined aquifers were dominant in the western part of the city. Figure 6b shows three kinds lithology in the upper layer of aquifer, i.e. clay, sandy clay, and sand or sandstone. Most of the upper layer of aquifer is dominated by sandy clay. Figure 6c shows the depth of water map, which was divided into 4 categories, i.e. less than 5 meters, 5–10 meters, 10–20 meters, and 20–50 meters. This water depth map also correlates with topography, where the north part is higher than the south part.

The GOD vulnerability map was generated from the overlap of the parameter as illustrated in Figure 6. The results show that about 8%, 57%, 42%, and 1% of areas in Surakarta have high, moderate, low, and negligible levels of vulnerability, respectively, as presented in Figure 7.

Based on the GOD index calculation, six research points were identified as having high vulnerability. The points were spread over Jebres, Banjarsari, Laweyan, and Serengan districts. The free aquifer types were found in locations with a high level of vulnerability. However, the lithology type in the upper layer has a high hydraulic conductivity value. This area has a relatively low groundwater depth, ranging from 2 to 4.25 meters.

Areas with a low level of vulnerability were in the eastern part from north to south, containing semi-confined aquifers. The low value of water permeability in the layer above the aquifer and the high value of the depth of the groundwater table resulted in the low vulnerability values. The GOD assessment findings showed the locations with a negligible level of vulnerability. This area was represented by three research points spread across Juanda, Jayawijaya, and Wonorejo sites. Meanwhile, the type of aquifer and the relatively high of the depth value cause the low vulnerability in this area.

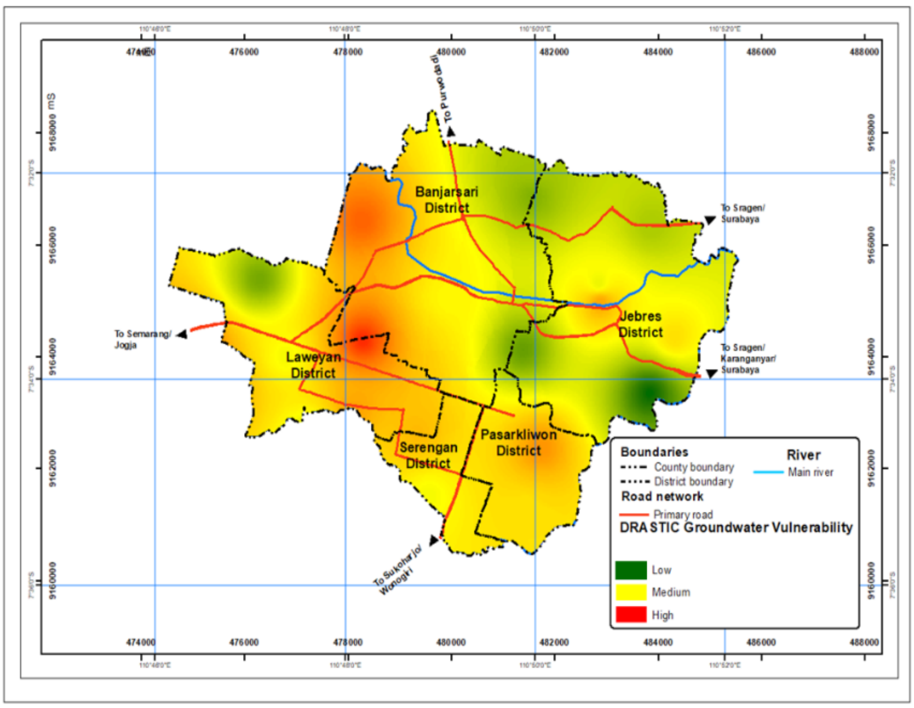


Figure 5. Groundwater vulnerability map in Surakarta City using the DRASTIC method

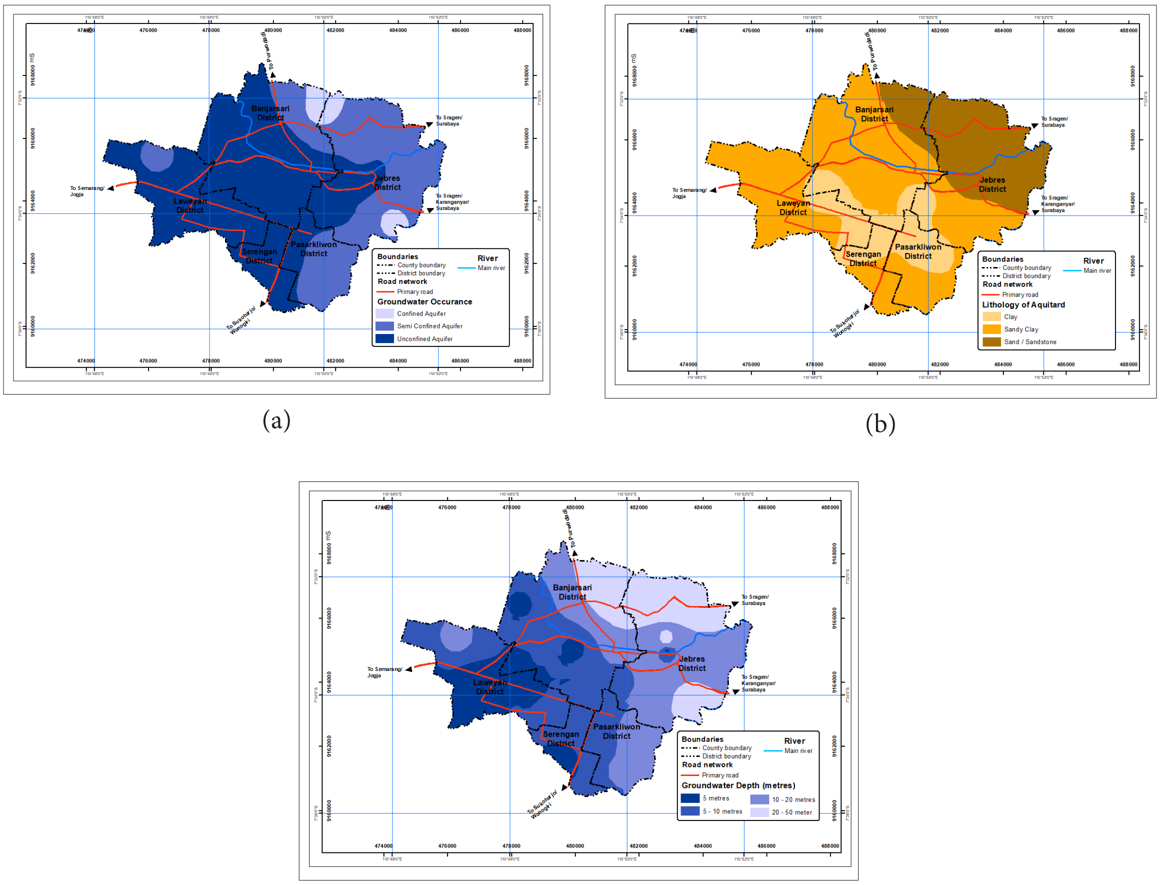

(a) (b) (c)

Figure 6. Map of each parameter of the GOD method (a) aquifer type (b) overlying lithology of aquitard (c) depth to water

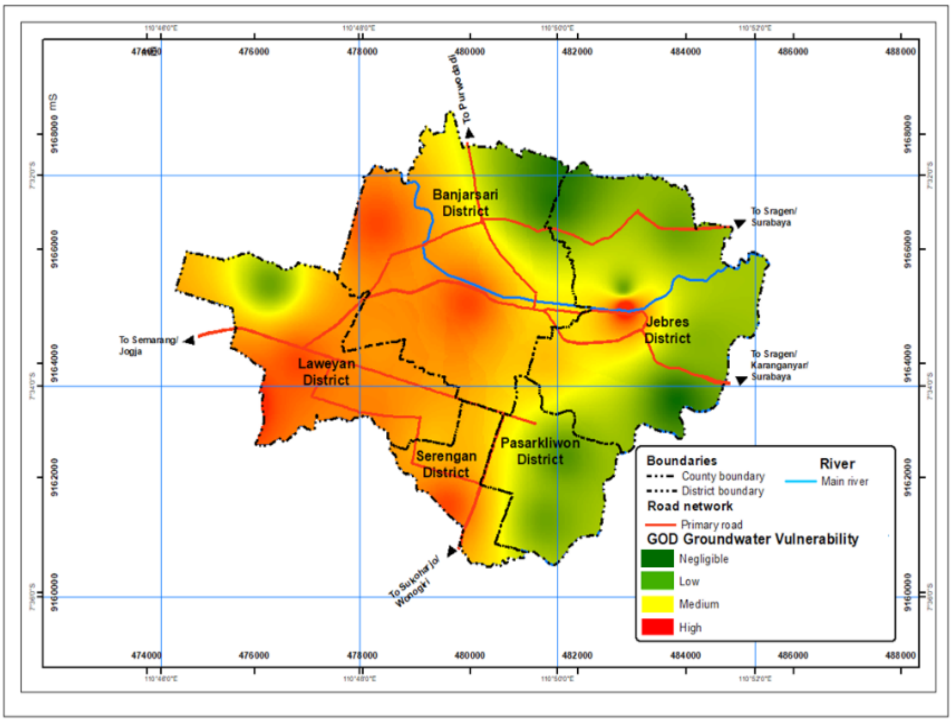


Figure 7. Groundwater vulnerability map in Surakarta using the GOD method

3.3 Comparison Results

Groundwater vulnerability maps obtained using the DRASTIC and GOD methods showed three and four classes with considerable resemblance. The results showed that the DRASTIC and GOD methods obtained 94.44% and 59.93% vulnerability in the moderate and high classes, respectively. The DRASTIC method is more sensitive to variables, given different weights and the number of parameters required. The GOD method is simple, easy to perform, and produces a closely related map to the aquifer-type parameters. The results

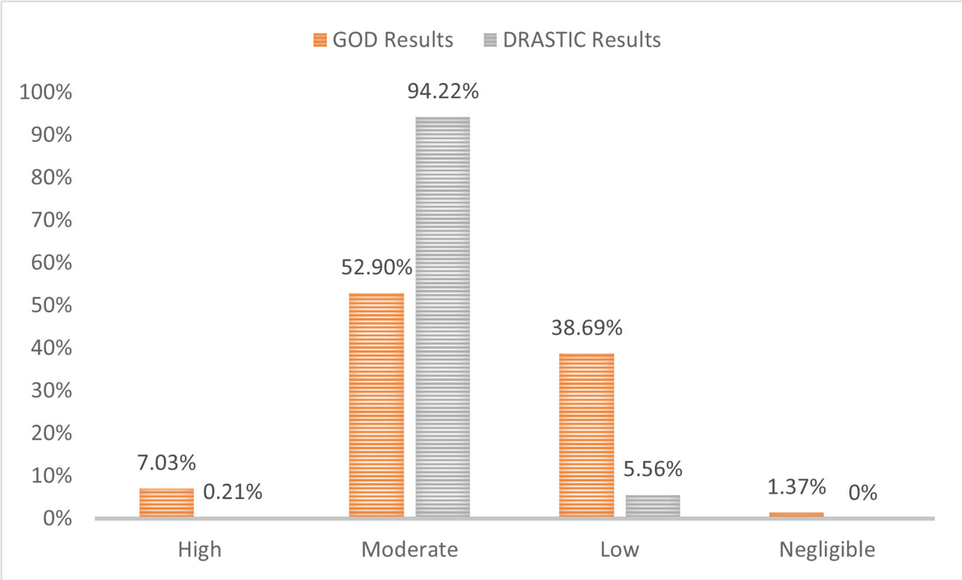


Figure 8 . Comparison of the results area of vulnerability class between DRASTIC and GOD methods

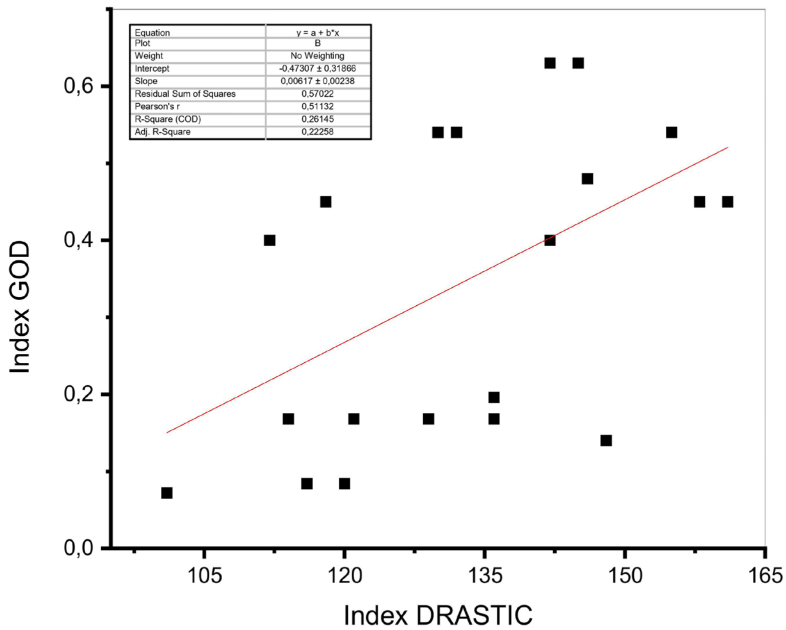


Figure 9. Linear regression of the DRASTIC and GOD index

positively correlate with aquifer-type parameters, and the free type primarily causes the high vulnerability area for GOD results. Table 1 compares the areas of vulnerability classes generated from the two methods.

The map represents the same class of vulnerabilities in the expressive area. Both methods produce the same classes and areas in the moderate and low vulnerability classes. Therefore, it shows that there is a relationship between the two methods. Linear regression analysis determines the correlation and coherence between the DRASTIC and GOD methods. The results showed a sufficient correlation with a coefficient value of 0.511. This indicates a relationship between the results of the DRASTIC and GOD methods. Based on the map, these two methods complement each other. The low-class and negligible areas in GOD method represent the moderate and low-class areas in DRASTIC method. Additionally, high class in GOD method is part of the area in DRASTIC model as well as the moderate class.

4. Conclusion

According to the DRASTIC method, high vulnerability areas comprise a percentage of 0.21%, or equivalent to 9.87 hectares, while medium vulnerability areas dominating the city of Surakarta, constitute of 94.22% or 4,355.98 hectares. Areas with low vulnerability cover 5.56%, or equivalent to 257.25 hectares. On the other hand, based on the GOD method, high vulnerability areas account for 7.03%, or equivalent to 324.96 hectares, while medium vulnerability covers 52.90%, with a total of 2,445.84 hectares. Low vulnerability areas make up 38.69%, or equivalent to 1,788.81 hectares. The vulnerability value that can be ignored is 1.37%, or 63.49 hectares. The two results of the vulnerability methods produce a correlation coefficient of 0.511, and based on the results map, these two methods complement each other. The GOD method tends to be simpler and more cost-effective regarding field survey expenses. This is because GOD focuses on groundwater depth and the presence of groundwater, requiring simpler and easier accessible data. However, if a deeper and more comprehensive analysis is required, especially in complex hydrogeological conditions, DRASTIC method may provide a more accurate depiction, but at a higher cost and requires more data (rainfall and topography).

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