Groundwater Vulnerability Assessment Using Total Organic Carbon and Heavy Metals in Bantul, Yogyakarta, Indonesia

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ABSTRACT

Groundwater vulnerability mapping in the Bantul area, Yogyakarta was carried out to highlight water resources at risk and to identify vulnerable zones that require careful management in the area. In order to meet these objectives, an investigation using statistical approach was suggested to inquire the relationship between contaminants concentration (total organic carbon and heavy metals) in groundwater, land use and the intrinsic vulnerability of groundwater. The object of study of this analysis is 30 water samples from 30 shallow wells in the area. This study is generated from the analysis of a well-established Geographic Information System combined with the GOD method (groundwater occurrence, overall aquifer class, depth to groundwater). The results of the GOD parameters calculation produce a range of vulnerability index values from 0.084 to 0.7. In general, the intrinsic groundwater vulnerability of the study area was divided into four classes viz. very low, low, moderate and high. Most of the study areas (84.64%) located in high intrinsic groundwater vulnerability index while the other 15.36% of the study area especially the eastern part are located in very low to moderate vulnerability. The high groundwater vulnerability area is characterized by unconfined aquifers with shallow groundwater depth (0.15 - 10.7 meter below ground surface) and overlying lithology such as grainstone, marl and alluvium. Despite being dominated by high vulnerability index, statistical analysis shows the correlation between contaminant load, land use and intrinsic groundwater vulnerability are not significant. The most recent data indicated the groundwater vulnerability index in the study area is more influenced by geogenic factors thananthropogenic factors. This approach may facilitate the regular evaluation needed to determine the impact of dynamic anthropogenic activities, regardless of the future groundwater abstraction strategy.

Keywords: *Groundwater vulnerability, GOD, Heavy metals, Total Organic Carbon, Yogyakarta, Indonesia.*

1. INTRODUCTION

Bantul is a regency that located in the south of Yogyakarta city. Yogyakarta is a rapidly growing city hence its development has now crossed the city's administrative boundaries including Sleman and Bantul regency which are currently known as the Yogyakarta Urban Agglomeration Area [1]. Over time, the city of Yogyakarta and its agglomeration areas grew into a bustling city, marked by an annual population growth rate of 1.23 – 1.56% per year since 2000 up to the present time [2].

The population growth from year to year in this area is also in parallel with an increase in waste disposal and an increase in sources of pollution of local water resources. An example of this has occurred in the central city of Yogyakarta where aquifers supporting domestic, industrial and agricultural needs have been affected by various sources of pollution, especially nitrogen compounds [3]. Nitrate is a well-known major problem in Yogyakarta city aquifers and according to a previous study [4], the nitrate level in Yogyakarta has exceeded the human-affected value of 13 mg/L [5], [6] and in

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some places it has even exceeded the maximum acceptance level of 50 mg/L [3]. Thus, providing updated groundwater vulnerability assessments is important for the Bantul regency mainly on the effective water management for the future and to maintain the community health.

The vulnerability concept concentrates on the sensitivity of an aquifer adversely affected at any given point by an imposed contaminant load from the land surface [7]. The aquifer vulnerability assessment and mapping are increasing acknowledged and suggested as an instrument for hydrogeological characterization ofgroundwater systems [8]. Many methods and approaches for vulnerability assessment have been developed over the last few years, ranging from complex models involving many parameters such as physical processes, biological chemistry in the unsaturated zone, to simpler methods using weighting criteria.

Details and conceptual variations of exemplary well established Geographical Information System (GIS) based methods such as DRASTIC and SVV methods have been widely used for cases in the city of Yogyakarta [3]. While many recent studies highlight promising results from the relatively complex DRASTIC and SVV methods, in this study an approach to the GOD method and statistical analysis is employed, which may, respectively, provide a useful simple tool in lacking data conditions and has partially led to comparable result quality. Overall, the current GOD vulnerability assessment study is expected to be a future contribution to local aquifer risk assessment in Bantul.

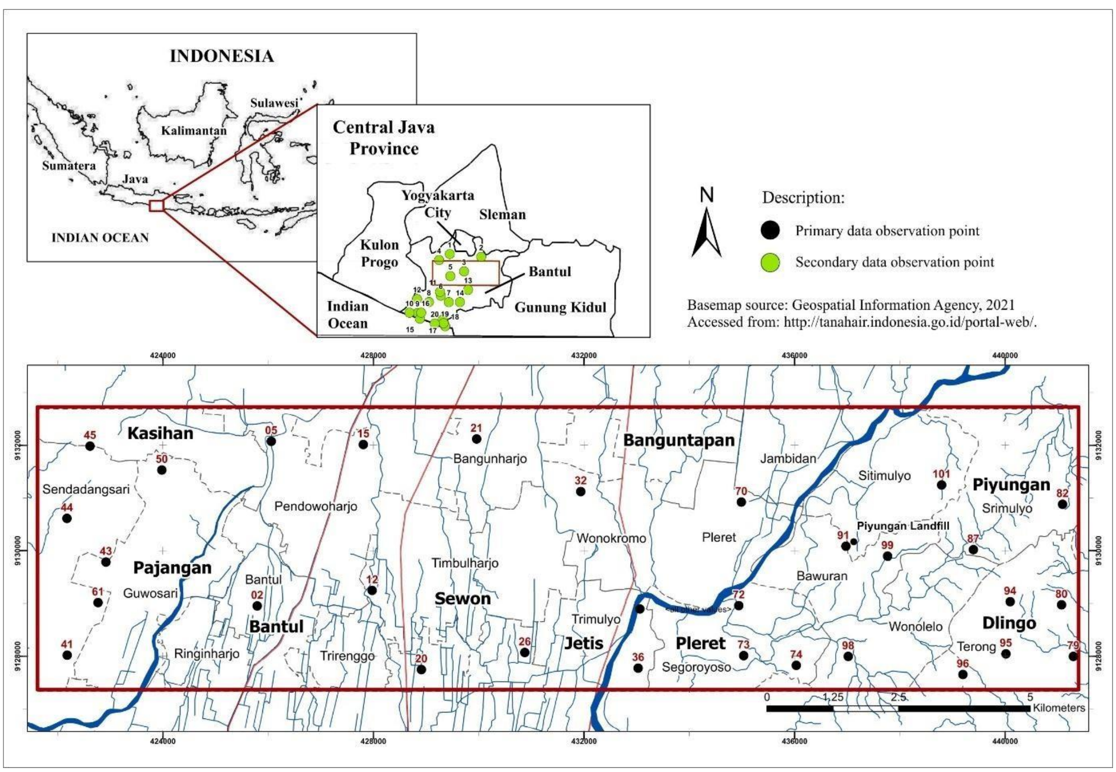

Figure 1 Location of the Bantul-study area in Yogyakarta-Indonesia.

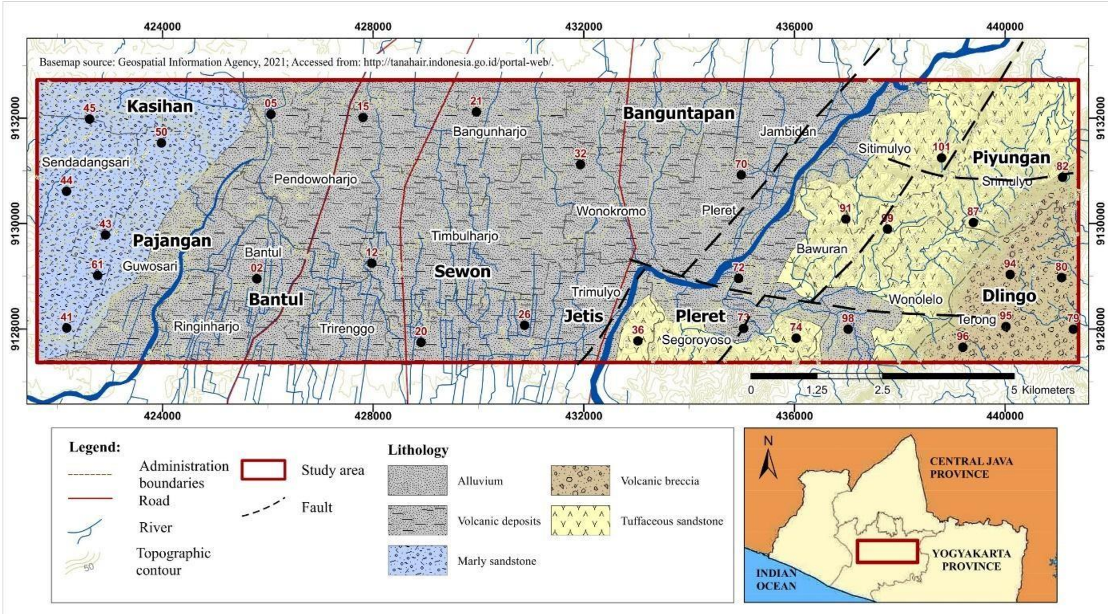

Figure 2 Geological map of the study area, adapted from [12].

2. STUDY AREA

The study area is located in Bantul Regency, Yogyakarta Province covering approximately 100 km^2 extending from west to east (Figure 1). Bantul generally has a tropical monsoon climate with an average annual rainfall of 1,075.2 mm^3 with relatively consistent temperatures throughout the year at an average of 30°C. In 2010, Bantul had a population density of 1,797 per km^2 [9], and continued to increase over time until 2021 data showed a population density of 1,945 per km^2 [10]. The increase in population is caused by urbanization which transformed rural dwellings to become urban settlements.

3. HYDROGEOLOGY

Figure 2 shows the aquifer beneath the study area which can be differentiated into two main aquifers: the productive aquifer that covers the center area (64.32%), and the groundwater scarce area located on the west and east (35.68%). The lithology of the productive aquifers consists of young volcanic deposits (interbedded middle to coarse sands, gravels, and silts), the western part of the groundwater scarce area is composed of carbonate rocks (marl, limestone), while the eastern part is composed of sedimentary rocks (breccia, tuffaceous sandstone) [11,12].

4. METHODOLOGY

One of the simple approaches to groundwater vulnerability with a weighting system based on a Geographic Information System is GOD [13]. To calculate the GOD index (groundwater occurrence, overall aquifer class, depth to groundwater table) the following parameters are needed:

- Groundwater occurrence (G)

This parameter reflects the identification of the aquifer type according to the degree of confinement. Identification of the type of aquifer can be done by analyzing the geological and hydrogeological cross-section data of the research area.

- Overall acquifer class (O)

This parameter reflects the degree of consolidation, porosity, and permeability of the material covering the aquifer. Overall aquifer class data can be collected from observations of lithological profiles in the field as well as geophysical data [14].

- Depth to groundwater table (D)

This parameter represents the thickness of the material through which water passes before it reaches the aquifer saturated zone. The depth of the groundwater table affects the load of contaminants that enter the groundwater. The risk of groundwater contamination increases as the depth of the groundwater table become more shallow [15]. Groundwater depth data is obtained from the results of measurements in the field which are then interpolated.

The GOD parameters mentioned above are then rated for each parameter class as shown in Table 1. The calculation of the GOD index to determine the vulnerability value is carried out by multiplying the three parameters as in the following equation:

$$GOD\ Index = G \times O \times D \quad (1)$$

Overall, the vulnerability index (Vulnerability index/VI) has a value range of 0-1. The groundwater vulnerability index from the calculation of the GOD method can be seen in the following Table 2:

Table 2. Aquifer Vulnerability Index

Vulnerability Index	**0 – 0.1**	**0.1 – 0.3**	**0.3 – 0.5**	**0.5 – 0.7**	**0.7 – 1**
Vulnerability class	Very low	Low	Moderate	High	Very high

Zwahlen [16] describes several methods regarding the validation of groundwater vulnerability. One of these methods is performed by using data on nitrate concentration, metal concentration, and total organic carbon (TOC) as parameters used to validate the assessment of groundwater contamination. Distribution of nitrate concentration, metal contamination, and TOC by area were then mapped. Land use data is also involved concerning possible sources of surface pollutants. Nitrate concentration, metal concentration, TOC, and land use data will reflect the correlation between groundwater vulnerability index and source of contamination.

Table 1. GOD parameter classes and values

Aquifer Class, *G*	**Value**	**Depth, *D* (m)**	**Value**	**Lithology, *O***	**Value**
Non-aquifer	0	< 2	1	Residual soil	0.4
Artesian	0.1	2 – 5	0.9	Limon alluvial; loess; shale, fine limestone	0.5
Confined	0.2	5 – 10	0.8	Eolian sand; siltite; tuff; Igneous rock	0.6
Semi-confined	0.3	10 – 20	0.7	Sand and gravel; sandstone; tuff	0.7
Unconfined with cover	0.4 – 0.6	20 – 50	0.6	Gravel	0.8
Unconfined	0.7 - 1	50 – 100	0.5	Limestone	0.9
-		> 100	0.4	*Fractured* or *karstic limestone*	1

Statistical tests using the logistic regression method were conducted to help determine the relationship between land use conditions, the presence of contamination (Nitrate, TOC, and Metals), and groundwater vulnerability conditions. The dependent variable used is the concentration of groundwater pollutants (Nitrate, TOC, and Metals) which will be defined as binary data. The binary data will show a value of 1 if contaminated and 0 if no contamination occurs. The independent variable data is used in the form of nominal data which includes variables of land use type and groundwater vulnerability index. Each independent variable will be given weight in each class.

This nominal data is then converted into numerical data for another weighting process. This weighting is carried out by considering the relationship of each class on the variable to the presence of contamination based on the theoretical basis. The highest score will be given to the class that has a major influence on the presence of contamination. After that, the dependent variable and the independent variable were digitized so that they could be processed using a machine learning technique. Variable data that has been changed in the form of class codes were then analyzed in SPSS software for logistic regression analysis.

5. RESULT AND DISCUSSION

GOD analysis was established from combining the primary data in the form of field data collection and the secondary data from previous studies by Santosa & Adji [17] and Amalina [18]. The following paragraphs will go into the detail of the results of GOD analysis that was enacted in the research area.

5.1. Aquifer Type Classification

The research location, which is still located in the Sleman-Yogyakarta Groundwater Basin, is generally dominated by the unconfined aquifer type [11]. Unconfined aquifers have the characteristics of a relatively shallow with an unconfined groundwater table. This unconfined aquifer is found mainly in the central part of the study area (Bantul, Sewon, and Banguntapan) and is composed of silt-sand units.

Referring to the scoring by Foster (1987) [19], the determination of the aquifer type score in the study area is divided into three with a score ranging from 0.2 to 1.0. A score of 1 in the aquifer type grouping indicates a higher probability of experiencing contamination than a lower score. The aquifer type score map in the study area can be seen in Figure 3.

The middle part of the area consists of a silt-sand unit (loose sediment), therefore it is given the highest score of 1.0. Based on existing drill data, the western part (marl unit) and eastern part (tuffaceous sandstone unit) fall into the unconfined aquifer category type where most of the rock has been lithified, given a score of 0.8. Whereas the easternmost part of the study area (volcanic breccia units) falls into the confined aquifer category which is given a score of 0.2. The ascertainment of the confined aquifer in the easternmost location of the study area was made by considering the emergence of springs at the geological unit boundary and the presence of artesian wells in the area.

5.2. Lithological Classification

The determination of lithology types in the study area was carried out based on field observations supported by regional data by Rahardjo, et al. [20] and drilling data. Based on the data, it is known that in the western and eastern parts of the study area, the upper part of the aquifer is covered by a thin layer ofalluvial soil/deposit (0.3 – 1meter thickness level).

Referring to the classification of Foster [19], limestone and marl lithology (marl units) were given a score of 0.9, the tuffaceous sandstone unit and the silt-sand unit were given a score of 0.7, while the volcanic breccia unit was given a score of 0.6. The lithology score map of the study area can be seen in Figure 4.

A relatively high score in the marl unit indicates a vulnerable rock characteristic in the event of groundwater contamination. The low score value indicates the characteristic of breccia rocks which tend to be more difficult to channel contamination in groundwater because of a fairly low porosity it has and its tendency to be impermeable.

Foster classification [19] additionally shows that generally, aquifers covered by limestone or loose sand lithology will be easier to pollute and contaminate rather than aquifers with hard rock cover lithology. This is caused due to the soluble characteristic of limestone and the permeable characteristic of sand, making groundwater pass more easily in those materials instead of hard rock materials. Thus, making those materials possess a higher level of vulnerability.

5.3. Groundwater Depth Classification

Ranging from 0 to 13.5 meters, the depth of the groundwater table in the study area was obtained from direct measurements in the field at dug wells and springs widespread in the study area.

Based on Foster [19], the classification of groundwater depth in the study area can be grouped into 4 categories. The first is groundwater depth of less than 2 meters which has a score of 1, the second has a depth of 2 - 5 meters which given a score of 0.9, the third one with a depth of 5 - 10 meters and given a score of 0.8, and lastly depths of more than 10 meters were scored as 0.7 (Figure 5).

The shallower groundwater table depths on the groundwater depth score map may indicate that the area has a higher likelihood of experiencing contamination. On the other hand, the deeper the groundwater, the more difficult it is for contaminants from the surface to enter the groundwater.

5.4. Intrinsic Groundwater Vulnerability Map

The groundwater vulnerability map was generated from the overlay of existing parameter maps, namely the groundwater depth score map, aquifer score map and cover lithology score map. Data processing was carried out by weighting based on geographic information systems. The assessment of each GOD parameter in the research area can be seen in Table 3.

Calculation of the GOD index to determine the vulnerability value was conducted by multiplying the three-parameter scores in Table 3. Calculations were carried out at grid points at 50-meter intervals. The results of the calculation of the GOD value at each grid point are interpolated using the Inverse Distance Weighting method to produce a map of the groundwater vulnerability class of the research area.

Table 3. The value of the GOD parameter in the study area

Aquifer Class, G	Score	Depth, D (m)	Score	Lithology, O	Score
Confined	0.2	< 2	1	Volcanic breccia	0.6
Unconfined (tuffaceous sandstone)	0.8	2 – 5	0.9	Tuffaceous sandstone; sand-silt	0.7
Unconfined (sand-silt)	0.1	5 – 10	0.8	Marl; Limestone	0.9
		10 – 20	0.7		

The results the GOD parameters calculation value produce a range of vulnerability index values from 0.084 to 0.7. Derived from those values, groundwater vulnerability in the study area is then divided into 4 classes, namely very low (GOD index = 0 – 0.1), low (GOD index = 0.1 – 0.3), moderate (GOD index = 0.3 – 0.5), and high (GOD index = 0.5 – 0.7).

Very low groundwater vulnerability area is locatedin the Terong area, Dlingo District with a distribution area of 2.64 km^2 or 2.5% of the study area. A very low vulnerability area is composed of confined aquifer, where the cover lithology is volcanic breccia. The groundwater depth in this vulnerability class ranges from 8.4 – 13.5 m below the surface level.

Low groundwater vulnerability area is sited in the Muntuk and Terong areas, Dlingo District with a distribution area of 4.41 km^2 or 4.16% of the study area. This area is composed of confined aquifers, where the cover lithology is in the form of volcanic breccias. The groundwater depth in this vulnerability class ranges from 4.3 – 12.3 m below the surface level.

Moderate groundwater vulnerability area is located in the Wonolelo, Bawuran, Segoroyoso, Pleret and Srimulyo areas, Piyungan districts with a distribution area of 9.21 km^2 or 8.70% of the total research area. The area of moderate groundwater vulnerability is composed of unconfined aquifers, where the main constituent lithology is tuffaceous sandstone. The groundwater depth in this vulnerability class ranges from 0.9 – 10.25 m below the surface level.

High groundwater vulnerability area covers a fairly large area, that is the Pajangan District, Bantul District, Sewon District, Banguntapan District, Partly Pleret District, and Partly Piyungan District with a distribution area of 89.7 km^2 or 84.65% of the total research area. The high vulnerability area is composed of unconfined aquifers, where the lithology is comprised of limestone, marl, sand deposits, and local sandstones. Groundwater depth in this vulnerability class ranges from 0.15 – 10.7 m below the surface level.

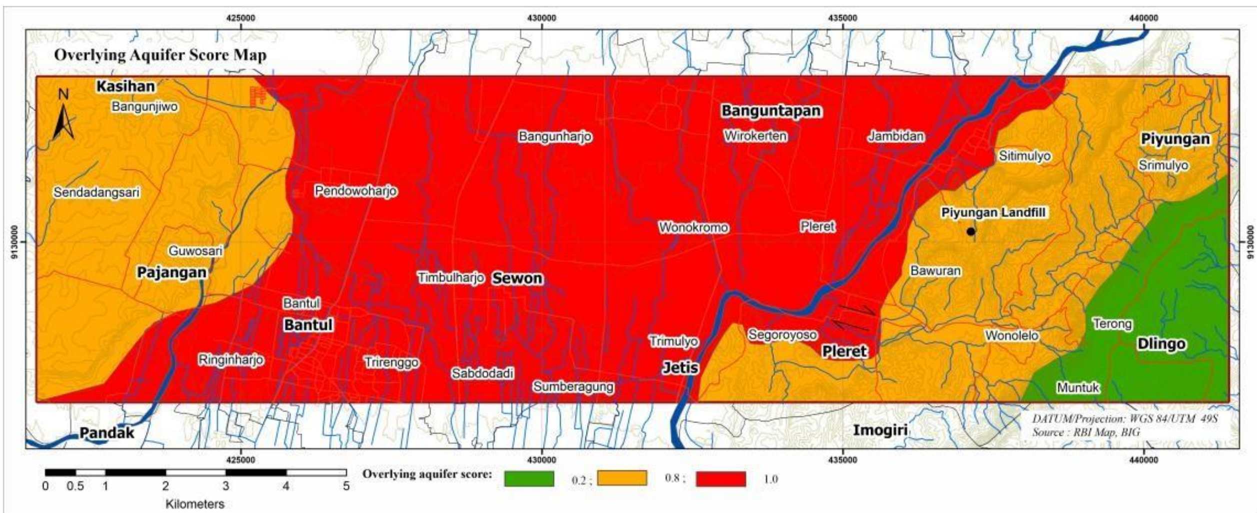

Figure 3 GOD-based overall aquifer class map

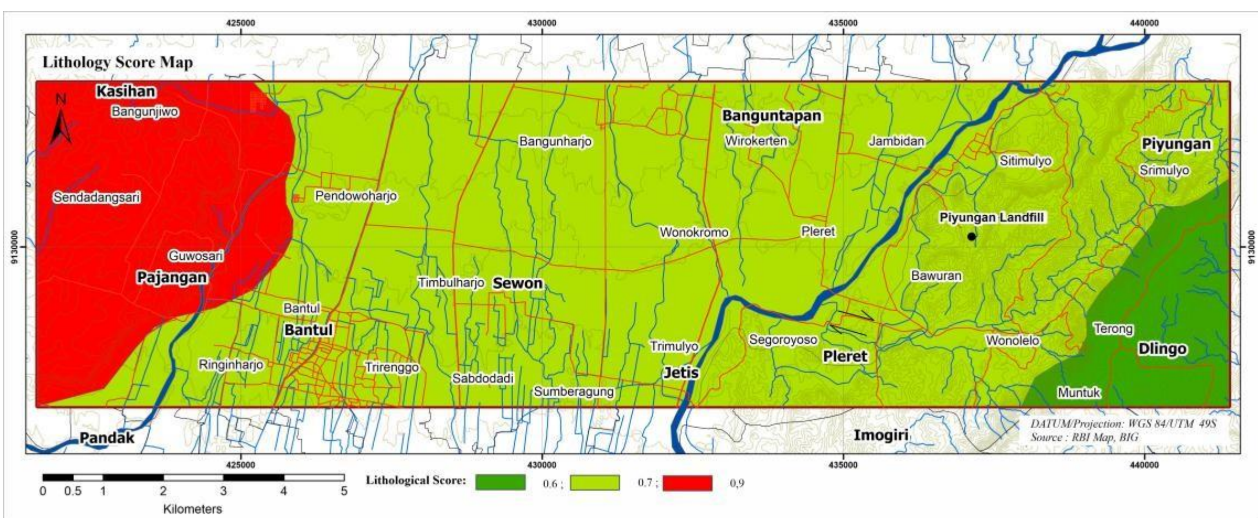

Figure 4 GOD-based groundwater occurrence

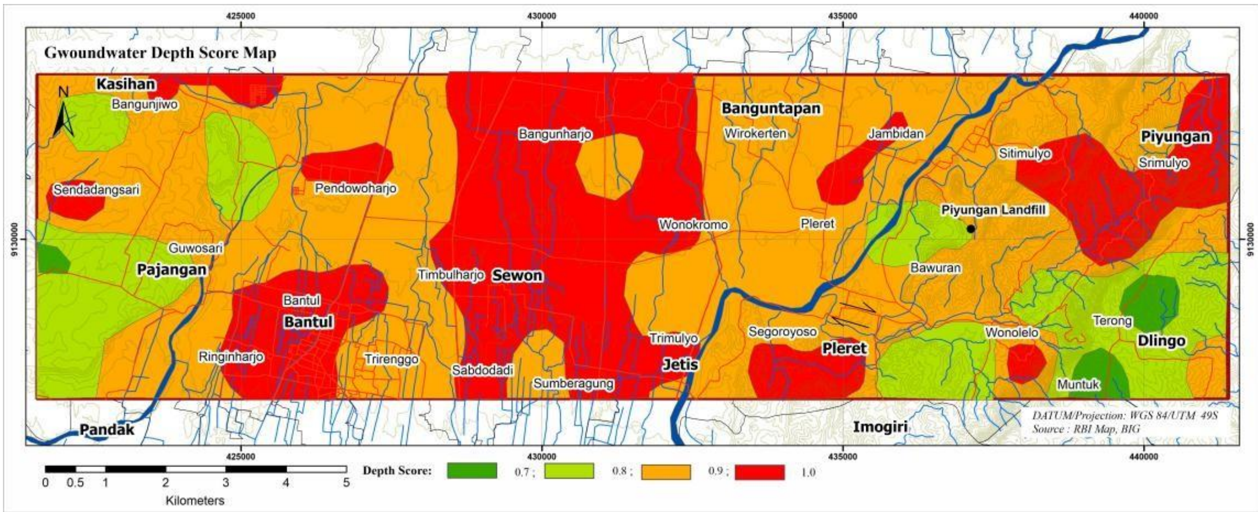

Figure 5 GOD-based depth to groundwater table

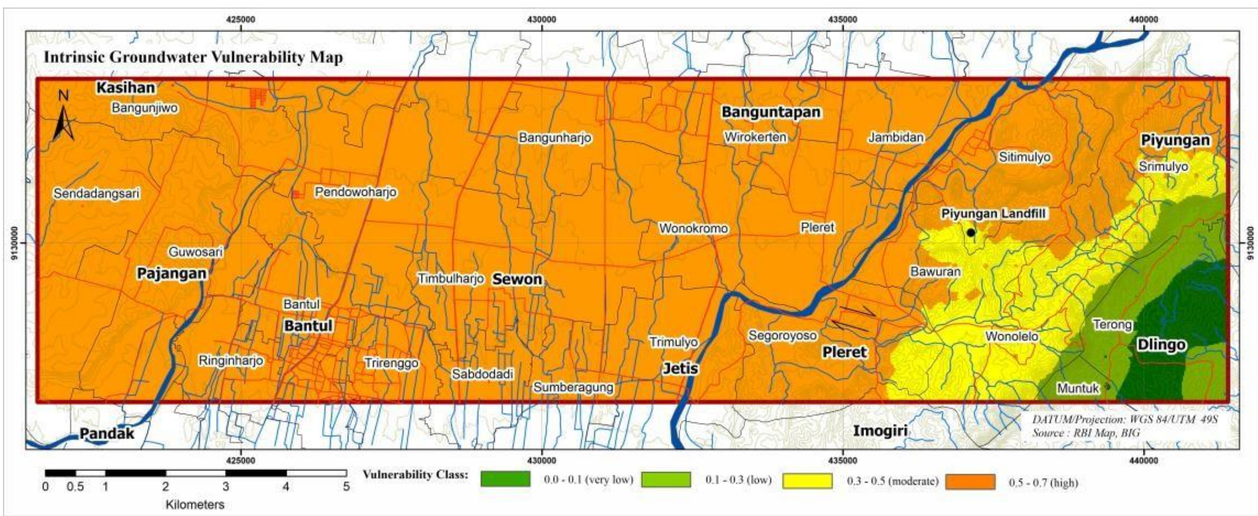

Figure 6 GOD-based intrinsic vulnerability map

5.5. Relationship of Groundwater Vulnerability, Water Geochemistry and Land Use

The relationship between groundwater vulnerability, geochemistry, and land use can be explained by a certain correlation model. One of commonly used correlation models is produced by directly comparing vulnerability classes and actual contamination data to validate and optimize existing vulnerability maps. In this study, a logistic regression method was used to estimate groundwater contamination based on the relationship between intrinsic vulnerability (GOD method vulnerability) and contaminant loads originating from land use.

Logistic regression is a statistical method used to predict the likelihood of contamination. The logistic regression method was chosen due to the fact that it can accommodate binary/dichotomous variables. The use of this method can clarify whether a well has a concentration of contamination greater than the standard value, which can prove the presence of contamination in a particular area.

The research was conducted in the study area, using the dependent variables in the form of Nitrate, TOC, Iron, Manganese, and Copper concentrations (Table 4). The independent variables used are GOD vulnerability values and land use. Each element is then assigned a standard value of contamination where if the concentration value of the element has passed the standard limit, it can be said that the groundwater at that location has been contaminated. Then the dependent variable in the form of binary data will be given a value of 1 if there is contamination and a value of 0 if it is not contaminated. The next paragraph will describe the limit of the concentration value of each element and its binary classification.

Any nitrate concentrations of > 10 mg/L is assigned a value of 1, assuming that the water at the sample location has been contaminated with nitrate. On the contrary, nitrate concentrations of less than 10 mg/L are assigned a value of 0, assuming that there slight to none nitrate contamination. This is also done for other elements, that is TOC, Fe, Mn, and Cu. TOC concentrations > 4 mg/L are assigned a value of 1 and concentrations of less than 4 mg/L are assigned a value of 0. Concentration of Iron (Fe) > 0.3 mg/L is assigned a value of 1 and concentrations below 0.3 mg/L are assigned a value of 0. Manganese concentrations of more than 0.4 mg/L are assigned a value of 1 and concentrations of less than 0.4 are assigned a value of 0. Concentration Copper more than 0.02 mg/L is assigned a value of 1 and concentrations less than 0.02 mg/L are assigned a value of 0.

The independent variable data in the form of vulnerability index and land use (Figure 7) are given weight in each class. The variable data used is nominal and interval data which is converted into numerical data so that it can be used for weighting. The variable data used for the calculation of the probability of contamination are presented in Table 5.

Table 5 Independent variable class assessment

No	Variable	Variable Class	Variable Class Weight
1	Vulnerability Index	High (0.5 – 0.7)	4
		Moderate (0.3 – 0.5)	3
		Low (0.1 – 0.3)	2
		Very low (0.0 – 0.1)	1
2	Land Use	Settlements	6
		Paddy field	5
		Rainfed paddy field	4
		Pasture	3
		Plantation	2
		Shrubs	1

Table 4 Summary of analysis results of Nitrate, TOC and Metallic substances in the research area

Units		NO_3^- (mg/L)	TOC (mg/L)	Mn (mg/L)	Fe (mg/L)	Cu (mg/L)
Alluvium & Volcanic deposits (Loose sand-silt)	Min.	0.1	2	0.153	0.0087	0.0
	Maks.	95.6	6.3	0.4	0.129	0.1083
	Mean	20.9	3.5	0.126	0.0424	0.0246
	n	10	10	10	10	10
Marly sandstone	Min.	0.6	2.7	0.0103	0.0143	0.0
	Maks.	25.9	5.2	0.047	0.1166	0.018
	Mean	8.8	4.1	0.0284	0.0504	0.0068
	n	6	6	6	6	6
Volcanic breccia	Min.	0.0	1.6	0,0	0,0043	0,0
	Maks.	25.2	2.6	0.155	0.630	0.042
	Mean	8.0	2.2	0.0459	0.1363	0.0102
	n	6	6	6	6	6
Tuffaceous sandstone	Min.	0.0	2.6	0.0127	0.0093	0,0
	Maks.	40.3	6	0.5	0.320	0.1113
	Mean	5.8	3.7	0.113	0.0709	0.0431
	n	8	8	8	8	8
Total	Min.	0.0	1.6	0.0	0.0043	0.0
	Maks.	95.6	6.3	0.5	0.630	0.1113
	Mean	11.9	3.4	0.087	0.0704	0.0231
	n	30	30	30	30	30

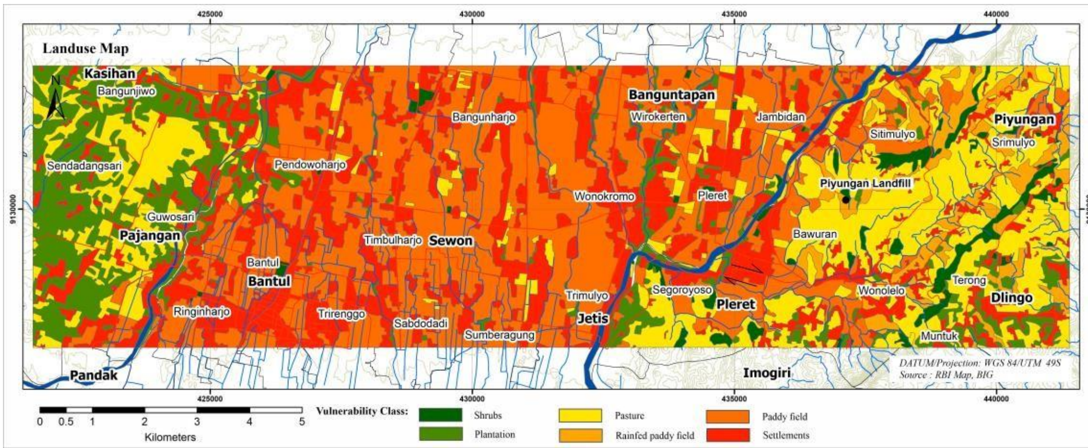

Figure 7 Landuse map of the research area

To find out the best model that supports groundwater contamination in the research area, a test called the overall test was carried out. The overall test implemented are the Omnibus test, the Hosmer- Lemeshow test, and the Maximum Log-Likelihood test.

The omnibus test is a test that compares the calculated chi-square value and the chi-square value from the table, where the hypothesis is accepted if the P-Value value is <0.05. The accepted Hosmer-Lemeshow test significance value is P-value > 0,05. The Maximum Log-Likelihood test is said to be significant if there is a decrease in the value of -2 Log-Likelihood (-2LL) from Block 0 to Block 1. The results of testing each contaminant parameter are presented in Table 6:

Table 6. Summary of statistical test results with SPSS

Dependent variable	Overall test			Nagelkerke R Square	Model fit percentage
	Omnibus (P-Value)	Hosmer-Lemeshow (P-Value)	Maximum Log Likelihood		
Nitrate (NO_3)	0.166	0.611	36.6 to 24.9	0.457	73.3
TOC	0.096	0.258	34.8 to 21.3	0.527	90.0
Iron (Fe)	0.559	0.978	16.6 to 8.2	0.498	93.3
Manganese (Mn)	0.960	0.959	16.6 to 12.1	0.210	93.3
Copper (Cu)	0.063	1.0	38.1 to 23.3	0.541	80.0

Based on the three Overall tests, the 2-variable model meets the Hosmer-Lemeshow test and the Maximum Log-Likelihood test, yet does not meet the Omnibus test. In this modeling, the Nagelkerke R Square value is 0.210 – 0.541 and the Pseudo-R^2 value in this model shows that the independent variable has aneffect of 21% - 54% on the model and as much as 46% -79% is the influence of other factors outside of theindependent variables used in making this model.

The independent variable with P-Value <0,05 has a strong significance on the dependent variable in the model. Based on the 2-variable model that has been made, the significance value of the model in this study is P-Value > 0,05 which indicates the two independent variables used (GOD index and land use) are not significant in relation to nitrate contamination, TOC, and heavy metal content.

6. CONCLUSION

The content of substances such as Nitrate, Iron, Manganese, Copper, and Total Organic Carbon in large concentrations can contaminate and even pollute the groundwater in a certain area. Based on the intrinsic groundwater vulnerability analysis, most of the research areas (84.65%) especially the western and central parts have a high groundwater vulnerability index. However, the results of logistic regression analysis that was enacted to examine the relationship between the level of vulnerability and the occurrence of contamination in the study area generally showed insignificant results. It is interpreted that the research area has the potential to experience groundwater contamination, but since the current data do not show widespread high contamination, a contamination has not happened yet in this area. Therefore, it can be safe to conclude that the groundwater vulnerability index in the study area currently is still more influenced by geogenic factors than anthropogenic factors.

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