Intrinsic vulnerability assessment of shallow groundwater to pollution using the GOD Method by utilizing geoelectric data: a case study of the city of Pasuruan, East Java, Indonesia

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Abstract. Groundwater is one kind of clean water resource. The increased development of human activities, such as agriculture, industry, and settlements, has a cumulative impact on groundwater conditions. The main purpose of this research is to assess the intrinsic vulnerability of shallow groundwater to pollution in the City of Pasuruan. The utilized method in the intrinsic vulnerability assessment of shallow groundwater is the GOD method, by utilizing geoelectric data. The parameters used in the calculation are aquifer layer type (G), soil layer type above the aquifer layer (O), and groundwater depth (D). The City of Pasuruan has a moderate to high index of intrinsic vulnerability, and shallow water at the study site is categorized as vulnerable to pollutants.

Keywords: Shallow groundwater, GOD method, intrinsic vulnerability index

1. Introduction

Groundwater is one kind of water source that is widely used by humans in their activities [1]. Global groundwater use has grown exponentially from 100 km³/year in the 1950s to more than 1000 km³/year in the 21st century [2], with an estimated 2 billion people relying on groundwater for their basic water needs [3]. Contamination of groundwater and surface water by domestic waste and industrial as well as agricultural activities is a growing problem [3].

The City of Pasuruan is located in the eastern part of the island of Java, which is bordered to the north by the Java Sea, while the rest is bordered by Pasuruan Regency. The administrative area of the City of Pasuruan is divided into four sub-districts: Gadingrejo, Bugul Kidul, Purworejo, and Panggungrejo. Indonesia is a tropical country with two seasonal changes, from the dry season (May - October) to the rainy season (November - April) and back. As with small towns in East Java, land use in Pasuruan is composed of 50.93% settlements, 32.27% rice fields, 3.49% dry land, and 13.31% other uses [4]. Regional development will also increase human activities, such as residential, industrial and agricultural activities, which cumulatively have an impact on groundwater conditions [2].

The level of vulnerability of groundwater to pollution is based on hydrogeological conditions [5]. Vulnerability of groundwater is divided into two kinds: intrinsic and specific vulnerability [1]. The intrinsic vulnerability of groundwater emphasizes the factor of physical conditions (rock, soil, and hydrogeology) that naturally protect soil water from pollution. The level of vulnerability of
groundwater to pollution in porous media in an area can be measured using several methods that have been widely used, among others DRASTIC, GOD, SINTACS, and so on. The assessment of groundwater susceptibility in this study utilized the GOD method. The GOD method is used to determine the groundwater vulnerability index value based on three parameters: aquifer type (groundwater confinement), aquifer lithology limitation (overlaying strata), and groundwater depth for free aquifers or the depth to layers of groundwater for confined aquifers or semi-groundwater tables up to water strike. This method is simple in terms of concepts and applications, and has been extensively tested for measuring groundwater susceptibility to pollution in Latin America and the Caribbean during the 1990s [6].

The purpose of this study is to assess the level of intrinsic vulnerability of shallow groundwater to pollution in the City of Pasuruan using the GOD method. The results of this study are expected to be the basis for maintaining the sustainability of groundwater as a source of clean water.

2. Material and Methods

2.1. Time and Location of Research

The utilized research method in this study is the survey method, which involves data collection of primary data and secondary data. Primary data collection was carried out by conducting geoelectric measurement activities in August 2016, which were carried out at 22 points in 4 sub-districts of the City of Pasuruan in the Province of East Java (Figure 1):

a. Gadingrejo Sub-District: 9 points
b. Purworejo Sub-District: 7 points
c. Bugul Kidul Sub-District: 5 points
d. Panggungrejo Sub-District: 1 point

Secondary data collection involved existing or published data.

Figure 1. Research location and data collection points
2.2. Tools and Materials
The equipment used to obtain data in this study include a geoelectric device to measure rock resistivity values at the research sites to a depth of 100 m, and global positioning system (GPS) to determine the coordinates of geoelectric measurement points. The materials needed in this study include a Geological Map of Malang at a scale of 1:100,000 published by the Geological Research and Development Centre in 1992 and Hydrogeological Map of Kediri at a scale 1:250,000 published by the Directorate of Environmental Geology in 1984.

2.3. Work Procedures
The rock layer type, aquifer type, and shallow aquifer depth at the location of the study were determined by geoelectric survey. Investigation of geoelectric type resistivity was performed by recording the electrical potential arising from the ground in order to obtain information about the resistivity of the structure in the soil [7]. The utilized geoelectric configuration is Schlumberger. This configuration is carried out with M and N electrodes (potential) which are adjacent to the centre point and do not move, while the electrodes A and B (currents) move outwards (Figure 2).

![Figure 2. Arrangement of Schlumberger Electrodes](image)

The Schlumberger configuration resulted in \( r_1 = R_2 = na \) and \( r_2 = R_1 = a(n+1) \); then, the apparent resistivity equation for this configuration is formulated as:

\[
\rho_a = \pi(n+1)a \frac{\Delta V}{I} \text{ or } \rho_a = K \frac{\Delta V}{I}
\]  

where:

- \( \rho_a \): Apparent resistivity of the Schlumberger electrode configuration (Ωm)
- K: \( \pi(n+1)a \): Geometry factors (m)
- I: The amount of current inserted into the earth (mA)
- \( \Delta V \): Potential difference (mV)
The resulting apparent resistivity value ($\rho_a$) and current electrode distance ($AB / 2$) were then processed using the matching curve method; the depth and the actual resistivity values were obtained from each rock layer. The determining of rock type based on resistivity value, or what is referred to as interpretation of geoelectric data, is adjusted to the geology of the research location and the table of rock resistivity values (Table 1).

| Material                | Resistivity (Ohm meter) |
|-------------------------|-------------------------|
| **Sedimentary Rock**    |                         |
| Shale                   | $10 - 10^3$             |
| Sandstone               | $1 - 10^8$              |
| Limestone               | $50 - 10^7$             |
| Dolomite                | $10^2 - 10^4$           |
| Lavas                   | $10^5 - 5.10^4$         |
| Tuffs                   | $2.10^4 - 2.10^2$       |
| **Unconsolidated Sediment** |                     |
| Sand                    | $1 - 10^3$              |
| Clay                    | $1 - 10^2$              |
| Marl                    | $1 - 10^2$              |
| **Groundwater**         |                         |
| Portable well water     | $1.10^3$                |
| Brackish water          | $2.1$                   |
| Sea water               | $0.2$                   |
| Supersaline brine       | $0.5 - 0.2$             |

The GOD method is one of the methods used to determine the level of susceptibility of aquifers to pollution. The empirical GOD methodology (Figure 3) used in estimating aquifer susceptibility to pollution [6] includes the following stages:

1. Identifying the type of aquifer (index value $G$), with an index value of 0.0 - 1.0
2. Describing the layer above the aquifer layer based on the level of consolidation and type of lithology (index value $O$), with an index value of 0.4 - 1.0. The $O$ parameter representing the lithology conditions is determined weighted, from different lithology conditions.
3. Estimating groundwater depth for free aquifers or top aquifer depths for confined and semi-confined aquifers (index value $D$), with an index value of 0.6 - 1.0.

The GOD index value is the multiplication of the $G$ index value, $O$ index value, and $D$ index value. The interpretation of the level of aquifer susceptibility based on the GOD index value is shown in Table 2.
Table 2. GOD Index Value Intervals and Vulnerability Level Classifications

| Index  | Vulnerability level | Description |
|--------|---------------------|-------------|
| 0 – 0.1| Very Low            | Limited to places without significant vertical groundwater (leakage) |
| 0.1 – 0.3| Low            | Only susceptible to conservative pollutants in the long term when they are disposed of extensively and continuously |
| 0.3 – 0.5| Moderate        | Susceptible to several pollutants but only when continuously discharged |
| 0.5 – 0.7| High            | Vulnerable to many pollutants in many pollution scenarios |
| 0.7 – 1.0| Very High       | Vulnerable to most water pollutants with rapid impact in various pollution scenarios |

3. Results and Discussion
Based on the Malang Geological Map of 1:100,000 scale published in 1992 by the Geological Research and Development Centre, the geomorphology of the study site is on the Solo-quarter quarter lane flanked by the Kendeng lanes in the northern and southern mountainous lanes [9]. The morphology of the Malang map area can be divided into 6 units: volcanic cones, mountains, hills, highlands, sandy plains, and lowlands. The research location is in the lowlands that occupy the northern part of the map and around the northern coast. The land has an altitude between 0 m and 25 m above sea level, and is occupied by extensive alluvium deposits. This land is mostly in the form of agricultural land, plantations and ponds. The poor sheet stratigraphy is exposed to clastic, epiclastic, pyroclastic and alluvium rocks that are from the early Pleistocene to resent. The measurement points are in the alluvial (Qa) region with rock lithology in the form of pebbles, gravel, sand, clay, and mud,
while in the Rabano tuff area (Qvtr), the rock lithology is in the form of passive tufts, pumice tufts, breccias, and fine tufts.

The results of the interpretation of geoelectric measurement data from 22 points in the City of Pasuruan, Province of East Java, were obtained by rock lithology, which was dominated by the intersection of clay and silt layers. The type of shallow aquifer layer in the study location is a confined aquifer with the upper and lower layers of the aquifer in the form of aquiclude clay. Aquiclude refers to a layer of rock that is only able to hold water but is unable to release it [10].

Rock layers that are capable of storing and channelling sufficient amounts of water are called aquifers [10]. A silt layer as a shallow aquifer layer was found at all geoelectric measurement points. The Gadingrejo Sub-District aquifer layer is in the depth range of 5.69 m - 37.67 m; in Bugul Kidul Sub-District, it is in the depth range of 5.93 m - 39.45 m; in Purworejo Sub-District, it is in the range of 15.18 m - 27.97 m; and in Panggunrejo Sub-District, it is in the range of 21.89 m - 33.30 m.

Based on the results of the lithology identification of each geoelectric point, information was obtained regarding the type of aquifer layer (G), the type of soil layer above the aquifer layer (O) and the depth of groundwater (D). The index of each parameter in the GOD method were calculated. Then, the vulnerability index in each location was obtained by calculating the obtained values of the G, O, and D parameters. The groundwater vulnerability index from the calculation results is presented in Table 3.

### Table 3. Vulnerability Index for Groundwater in the City of Pasuruan

| No | Parameters                  | Location | Gadingrejo | No. of Points | Bugul Kidul | No. of Points | Purworejo | No. of Points | Panggunrejo | No. of Points |
|----|-----------------------------|----------|------------|--------------|-------------|--------------|-----------|--------------|-------------|--------------|
| 1  | Aquifer Type (G)            |          | Confined   | 9            | Confined    | 5            | Confined  | 7            | Confined    | 1            |
| 2  | Weight Value                |          | 0.2        | 9            | 0.2         | 5            | 0.2       | 7            | 0.2         | 1            |
| 3  | Groundwater Depth (D)       |          | 5 - 20 meters | 5       | 5 - 20 meters | 2       | 5 - 20 meters | 3       | 5 - 20 meters | 0            |
|    |                             |          | 20 - 50 meters | 4       | 20 - 50 meters | 3       | 20 - 50 meters | 4       | 20 - 50 meters | 1            |
| 4  | Weight Value                |          | 0.7        | 5            | 0.7         | 2            | 0.7       | 3            | 0.7         | 0            |
|    |                             |          | 0.8        | 4            | 0.8         | 3            | 0.8       | 4            | 0.8         | 1            |
| 5  | Type of Soil Layer above the Aquifer (O) |      | 0.8        | 9            | 0.8         | 5            | 0.8       | 7            | 0.8         | 1            |
| 6  | Weight of Vulnerability     |          | 0.3 - 0.5  | 5            | 0.3 - 0.5   | 3            | 0.3 - 0.5 | 7            | 0.3 - 0.5   | 1            |
|    |                             |          | 0.5 - 0.7  | 4            | 0.5 - 0.7   | 2            | 0.5 - 0.7 | 0            | 0.5 - 0.7   | 0            |
| 7  | Vulnerability Classification |          | Moderate   | 5            | Moderate    | 3            | Moderate  | 7            | Moderate    | 1            |
|    |                             |          | High       | 4            | High        | 2            | High     | 0            | High        | 0            |

The overall shallow aquifer layer in the research location is a confined aquifer with a vulnerability index weight of 0.2. The depth of shallow groundwater at some points is at a depth of 5-20 meters with a vulnerability index weight of 0.7 and a depth of 20-50 meters with a vulnerability index weight of 0.8. The uniformity of the rock layer above the shallow aquifer layer, being a clay layer, results in a vulnerability index weight of 0.8, which is then multiplied by the thickness of each layer. Based on Table 3, the level of vulnerability of groundwater to pollution of the four Sub-Districts of the City of Pasuruan ranges from moderate to high. Gadingrejo and Bugul Kidul Sub-Districts have moderate to high groundwater vulnerability, while Purworejo and Panggunrejo Sub-Districts have only moderate groundwater vulnerability.
The area of the City of Pasuruan is traversed by three major rivers: the Welang River, Petung River, and Gembong River [4]. The upstream regions of the river flows are in the lithology area of Rabano tuff rock (Qvtr), through which the flow carries material that is then deposited along the watershed and estuary area. River material deposits are the main constituent of alluvial (Qva) lithology, especially in the surface layer. The groundwater in hilly areas with volcanic rock lithology is intrinsically vulnerable, while it is highly susceptible in the rocky alluvial plains, where aquifer media is in the form of sand and gravel, and the area has a flat slope [11]. The results of this study showed that the classification of groundwater susceptibility is in the medium to high category, with a distribution of 16 moderately vulnerable areas and 6 highly vulnerable areas. The vulnerability distribution of shallow groundwater does not follow the pattern of rock lithology; this is due to the fact that the area of the City of Pasuruan is downstream from the three major rivers, and thus the surface layer of rock in the alluvial (Qa) region is uniform with the surface layer of the upstream region (Qvtr).

The moderate to high shallow groundwater vulnerability at all observation points provides information to the people and the local government that the condition of shallow groundwater in the City of Pasuruan is vulnerable to pollution from pollutants produced by agricultural, industrial, and residential activities.

4. Conclusion

Geoelectric measurement results identified that the surface rock layer of the study site is dominated by clay and silt nesting, with a silt layer as a shallow aquifer layer. The depth of the shallow aquifer layer varies with depths of 5 - 20 m and 20 - 50 m. The lithological rock layer at the top of the aquifer layer is generally in the form of a cover layer and clay layer.

The intrinsic vulnerability index of groundwater in Pasuruan City is moderate to high. The groundwater susceptibility is spread evenly in alluvial (Qa) geology and Rabano tuff (Qvtr), which is caused by a uniform layer of rock composition at all observation points.

The shallow groundwater of the City of Pasuruan in the Province of East Java is susceptible to pollutants resulting from human activities in the form of agricultural, industrial, and residential activities.

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