Estimation of intrinsic vulnerability of shallow groundwater in Jombang District, Jombang Regency, East Java, Indonesia based on Aquifer Vulnerability Index

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Abstract. The level of safety of groundwater to pollution hazards can be identified based on the level of vulnerability of the groundwater to pollution. Determination of groundwater vulnerability intrinsically can be done by using the Aquifer Vulnerability Index (AVI) method based on two physical parameters i.e. the thickness of each layer above the uppermost of saturated aquifer surface and the estimated hydraulic conductivity of each of these sedimentary layers. The objective of this study was to determine the level of groundwater vulnerability intrinsically based on the vulnerability index value of aquifers by using the AVI method. This study was conducted based on sample of 25 dug wells scattered in the Jombang District of Jombang Regency, East Java, Indonesia. Based on the results of the analysis using the AVI method, it can be stated that the hydraulic resistance logarithm in the study area were found to be in the range from -5.22 to 3.84 with the intrinsic vulnerability of groundwater to pollution hazards from extremely high to low.

1. Introduction
Jombang District is one of the districts in the Jombang Regency, East Java Province with an area of 36.40 km². The level of population density in the Jombang District area reached 4,015 people/km² with land use dominated by settlements covering 32.33% and rice fields covering 50.10% of the total area. The use of groundwater potential for domestic needs is still widely used in the area, which can be shown based on household classification according to the source of water used, namely 12,621 households use water from the Regional Drinking Water Company, 21,115 households use water from wells, and 6,490 households use water from pump wells [1].

The potential of groundwater resources used to meet domestic water needs, especially for drinking water, must be in accordance with the requirements as stated in the Regulation of the Minister of Health of the Republic of Indonesia Number 492/MENKES/PER/IV/2010. In addition to having to meet health requirements, the availability of groundwater resources potential must be safe from the pollution hazards. To know the level of groundwater safety from pollution hazards in the Jombang District area, it is necessary to identified the level of groundwater vulnerability to pollution, in particular its intrinsic factors, namely related to the presence and condition of the groundwater.

Determination of groundwater vulnerability intrinsically can be done using the Aquifer Vulnerability Index (AVI) Method. The AVI method is a measure of groundwater vulnerability based on two physical
parameters i.e. the thickness of each layer above the uppermost of saturated aquifer surface and the estimated hydraulic conductivity of each of these sedimentary layers [2]. This method has been widely used in a number of previous studies to assess groundwater vulnerability intrinsically [3,4,5,6,7,8]. This study was conducted with the aim to determine the level of groundwater vulnerability intrinsically based on the vulnerability index value of aquifers in the study area by using the AVI Method.

2. Materials and methods

The study area falls in Jombang District, Jombang Regency, East Java Province, Indonesia. The total region of the study area covers 36.40 km² and consists of 20 villages in Jombang District. Map of the study area is given in figure 1.

The samples used in this study were dug wells in the scattered in the study area that represented shallow groundwater conditions. The number of samples was determined as many as 25 dug wells, where each village at least represented by one sample. Field surveys for determining the location of samples and observations of these samples were carried out during December 2018 until January 2019.

The equipment used in this study included: Global Positioning System (GPS) to determine the coordinates and elevation of the ground surface in each dug well, meter and rope well equipped with ballast to measure the depth of the groundwater level in each dug well, and digital camera used to document activities. The materials needed in this study include the Indonesian Topographic Map of a scale of 1:25,000 which was published by the Coordinating Agency of National Surveying and Mapping as much as 2 sheets (Sheet 1508-334 Jambang and Sheet 1508-343 Mojoagung) used as a base map in the study and production well log-lithology data in the study area and around the study area was used as a basis for estimating rock formations in each sample of the dug well based on interpolation and extrapolation techniques.
Each dug well was determined the position of the latitude, longitude, and elevation of the ground surface by using GPS. Groundwater depth was measured by using a rope equipped with ballast, where after the rope position reaches the groundwater level then the rope was lifted and its length was measured by using the meter. The elevation of groundwater level was calculated based on the difference in elevation of the ground surface with the depth of the groundwater level in each dug well.

The thickness of each layer above the uppermost of saturated aquifer surfaces was determined based on the rock layers above the groundwater level to the ground surface. The types of rock layers in each location of the study sample were estimated based on the log lithology data of production wells that is in the area of the Jombang District and around the area. Estimation of rock layer type and thickness of each layer is done by interpolating and extrapolating production well log-lithology data using the Rock Work 16 (trial version) computer program. Based on the results of the estimation, it can be determined the thickness of each type of layer above the groundwater level up to the ground level. The types of rocks in each layer are estimated its hydraulic conductivity based on table 1.

| Table 1. Hydraulic Conductivity (K) Estimates for Various Sediments [2][9]* |
|-----------------------------------------------|
| Sediment Type/Material          | K (m/day) |
| *Gravel, coarse                | 150       |
| *Gravel, medium                | 270       |
| *Gravel, fine                  | 450       |
| *Sand, coarse                  | 45        |
| *Sand, medium                  | 12        |
| *Sand, fine                    | 2.5       |
| *Tuff                         | 0.2       |
| **Silty sand                   | 1         |
| **Silt                        | 10⁻¹      |
| **Fractured till, clay or shale (0 to 5 m from ground surface) | 10⁻³ |
| **Fractured till, clay or shale (5 to 10 m from ground surface) | 10⁻⁴ |
| **Fractured till, clay or shale (10 m from ground surface, but weathered based on colour: brown or yellow) | 10⁻⁵ |
| **Massive till or mixed sand-silt-clay | 10⁻⁶ |

Based on the two physical parameters i.e. the thickness of each layer above the uppermost of saturated aquifer surface and the estimated hydraulic conductivity of each of these sedimentary layers, the hydraulic resistance "c" can be calculated [2]:

\[ c = \sum_{i=1}^{n} \frac{d_i}{K_i} \]  \hspace{1cm} (1)

in which
\begin{align*}
  c &= \text{hydraulic resistance (days)} \\
  d &= \text{thickness of each sedimentary layer above the uppermost, saturated aquifer surface (m)} \\
  K &= \text{estimated hydraulic conductivity of each of these sedimentary layers (m/day)}
\end{align*}

The interpretation of the aquifer vulnerability index based on the calculation of hydraulic resistance value is carried out based on table 2.
Table 2. Relationship of Aquifer Vulnerability Index to Hydraulic Resistance [2].

| Hydraulic resistance (c) (years) | log (c) | Vulnerability (AVI)          |
|----------------------------------|---------|-----------------------------|
| 0–10                             | < 1     | extremely high              |
| 10–100                           | 1–2     | high                        |
| 100–1,000                        | 2–3     | moderate                    |
| 1,000–10,000                     | 3–4     | low                         |
| > 10,000                         | > 4     | extremely low               |

Mapping the distribution of intrinsic groundwater vulnerability based on the value of hydraulic resistance logarithm that represents the aquifer vulnerability index is done using the Kriging Method. This method used to estimate the magnitude of the value representing of a non-sampled point based on sampled points surrounding it by considering the spatial correlation in the data [10,11].

Figure 2. Spatial distribution of dug well samples in the study area.

3. Results and discussion
Based on the results of a survey of conditions in the field, a total of 25 samples were determined with the distribution as shown in figure 2. The depth of groundwater level in the study area was found to be in the range 0.70–4.37 m below ground level, with the elevation of groundwater level to be in the range
32.84–47.26 m above sea level. The depth of groundwater level and elevation of groundwater level in the study area are shown on table 3.

Table 3. The depth and elevation of groundwater level in every location of sample.

| Sample ID | Villages      | Depth of groundwater level (m below ground level) | Elevation of groundwater level (m above sea level) |
|-----------|--------------|--------------------------------------------------|---------------------------------------------------|
| SG-1      | Tunggorono   | 1.97                                             | 45.03                                             |
| SG-2      | Tunggorono   | 1.13                                             | 46.87                                             |
| SG-3      | Jabon        | 2.74                                             | 47.26                                             |
| SG-4      | Sengon       | 1.62                                             | 42.38                                             |
| SG-5      | Jombatan     | 2.00                                             | 43.00                                             |
| SG-6      | Plandi       | 2.86                                             | 41.14                                             |
| SG-7      | Kaliwungu    | 1.84                                             | 45.16                                             |
| SG-8      | Jelakombo    | 3.44                                             | 41.56                                             |
| SG-9      | Kepanjen     | 2.66                                             | 40.34                                             |
| SG-10     | Kepatihan    | 1.60                                             | 40.40                                             |
| SG-11     | Pulo Lor     | 1.30                                             | 38.70                                             |
| SG-12     | Denanyar     | 0.97                                             | 39.03                                             |
| SG-13     | Denanyar     | 4.37                                             | 42.63                                             |
| SG-14     | Jombang      | 1.44                                             | 38.56                                             |
| SG-15     | Candi Mulyo  | 2.06                                             | 37.94                                             |
| SG-16     | Mojongapit   | 0.70                                             | 37.30                                             |
| SG-17     | Dapur Kejambon | 2.16                                          | 32.84                                             |
| SG-18     | Sambong Dukuh| 0.61                                             | 38.39                                             |
| SG-19     | Tambakrejo   | 0.47                                             | 38.53                                             |
| SG-20     | Plosogeneng  | 3.95                                             | 34.05                                             |
| SG-21     | Banjardowo   | 1.47                                             | 33.53                                             |
| SG-22     | Banjardowo   | 5.12                                             | 39.88                                             |
| SG-23     | Banjardowo   | 8.42                                             | 40.58                                             |
| SG-24     | Banjardowo   | 0.97                                             | 34.03                                             |
| SG-25     | Sumberjo     | 0.95                                             | 34.05                                             |

Determination of groundwater vulnerability intrinsically in the study area based on the aquifer vulnerability index calculated using the AVI method is based on the thickness of each layer above the uppermost of saturated aquifer surface and the estimated hydraulic conductivity of each of these sedimentary layers. The results of the calculation of the logarithmic values of hydraulic resistance and the level of aquifers vulnerability in the study area can be shown in table 4.
Table 4. Vulnerability of shallow groundwater in each location of the sample

| Sample ID | Log (c) | Vulnerability (AVI) |
|-----------|---------|---------------------|
| SG-1      | -4.60   | Extremely High      |
| SG-2      | -4.84   | Extremely High      |
| SG-3      | -4.46   | Extremely High      |
| SG-4      | -4.72   | Extremely High      |
| SG-5      | -4.62   | Extremely High      |
| SG-6      | -4.50   | Extremely High      |
| SG-7      | -4.66   | Extremely High      |
| SG-8      | -3.87   | Extremely High      |
| SG-9      | -4.51   | Extremely High      |
| SG-10     | -4.69   | Extremely High      |
| SG-11     | 1.91    | High                |
| SG-12     | -4.91   | Extremely High      |
| SG-13     | 3.11    | Low                 |
| SG-14     | -4.78   | Extremely High      |
| SG-15     | 1.22    | High                |
| SG-16     | -2.02   | Extremely High      |
| SG-17     | 2.44    | Moderate            |
| SG-18     | -5.11   | Extremely High      |
| SG-19     | -5.22   | Extremely High      |
| SG-20     | 3.77    | Low                 |
| SG-21     | 2.61    | Moderate            |
| SG-22     | 3.49    | Low                 |
| SG-23     | 3.84    | Low                 |
| SG-24     | 3.42    | Low                 |
| SG-25     | 2.42    | Moderate            |

The logarithmic value of hydraulic resistance in the study area ranges from -5.22 to 3.84 with the level of vulnerability being extremely high to low. Based on table 4, it can be shown intrinsically the level of groundwater vulnerability to pollution with the Extremely High category as many as 15 samples (60%), High category as many as 2 samples (8%), Moderate category as many as 3 samples (12%), and Low category as many as 5 samples (20%). The spatial distribution of hydraulic resistance logarithm values that represent the level of vulnerability of shallow groundwater in the study area is shown in figure 3.

Based on the results of mapping of the level of groundwater vulnerability as shown in figure 3 above, it can be shown that in 18 villages from 20 villages in the study area, it was dominated by areas with a very high category of groundwater vulnerability. Meanwhile, in two villages, namely Banjardowo and Sumberjo Villages, they were dominated by areas with a low to moderate level of groundwater vulnerability to pollution. The level of groundwater vulnerability to pollution is not determined by the
depth of the groundwater level from the ground surface. The results of the analysis on SG-12 well and SG-24 well that have the same groundwater level are 0.97 m but the category of groundwater vulnerability level to pollution is different, where SG-12 well is extremely high while SG-24 well is low. The level of vulnerability in the SG-8 well with a groundwater depth of 3.44 m is extremely high, while in the shallower SG-25 well (0.95 m), it has a moderate level of vulnerability. The level of groundwater vulnerability is more determined by the type of sedimentary layers above the groundwater level to the surface of the ground.

In general, the results of this study indicate that most of the study area have high to very high groundwater vulnerability levels. The results of this study are in line with the results of similar studies conducted based on research samples in the form of dug wells, where the level of vulnerability high to very high dominates most of the study area [5]. The AVI method doesn't take into account the following critical issues that are rapidly changing as a result of human activities [4].

4. Conclusion
The aquifer vulnerability index value in the study area represented by the hydraulic retention logarithm value ranges from $-5.22$ to 3.84. There are four levels of intrinsic vulnerability of groundwater to pollution in Jombang District i.e. extremely high, high, moderate, and low with spatial distribution as shown in figure 3. Based on the results of this study, it can be given suggestions that in areas with levels
of vulnerability of high and very high must be made efforts to prevent the occurrence of groundwater pollution.

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