Estimation of 3D hydraulic conductivity distribution of unconfined aquifer using the geostatistical method and its relation to water quality and flooding in Upper Citarum River

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Abstract. The 3D distribution of hydraulic conductivity in the unconfined aquifer is needed to understand the interaction between groundwater and Citarum River, which may relate to water contamination and flooding. In this study, it was estimated using the geostatistical method. The data used are the hydraulic conductivity parameter from thirteen large-diameter dug wells determined using the slug test method. Further analysis was conducted using groundwater and Citarum River physical parameters, i.e. total dissolved solids, pH, and temperature. The results show that the hydraulic conductivity of the unconfined aquifer in the Upper Citarum River ranges from $8.34 \times 10^{-7}$ to $2.19 \times 10^{-5}$ m/s. The area with relatively high hydraulic conductivity, i.e. Ciparay and Solokan Jeruk Sub-districts, will have a greater possibility of groundwater or river water contamination depending on their interaction. Meanwhile, the area with relatively flat topography and low hydraulic conductivity, i.e. Majalaya and Baleendah Sub-districts, will be more susceptible to flood. Therefore, the mitigation of water contamination and flooding in the Upper Citarum River should consider the 3D hydraulic conductivity distribution, e.g. by monitoring the groundwater quality in some dug wells located in high hydraulic conductivity area and installing recharge or injection well to eliminate the artificial runoff.

1. Introduction

Citarum River was called the most polluted river in the world in 2013 [1]. The reason was its water quality had greatly exceeded the USEPA (the United States Environmental Protection Agency) standard for drinking water. Moreover, flooding also threatens the area surrounding the Citarum River, such as Baleendah and Majalaya Sub-districts in the Upper Citarum River [2,3]. Commonly, the groundwater and surface water are hydraulically connected [4]. Therefore, the water contamination and flood that happened in the Upper Citarum River may be related to groundwater and surface water interaction.

Many studies had been conducted in the Upper Citarum River, but only a few studies discussed the hydraulic conductivity distribution of the unconfined aquifer. The previous studies showed that the
hydraulic conductivity ranges from 10^{-8} to 10^{-4} m/s [5-7]. However, the three dimensional (3D) hydraulic conductivity distribution was not discussed clearly.

The 3D hydraulic conductivity distribution is needed to analyze the groundwater and surface water interaction. However, the hydraulic conductivity data, either from field tests or laboratory tests, are usually limited. This study discusses the estimation of 3D hydraulic conductivity distribution and its relation to water contamination and flooding in the Upper Citarum River. Moreover, the interaction between groundwater and surface water was also analyzed based on the groundwater and Citarum River physical parameters, i.e. total dissolved solids (TDS), pH, and temperature.

The study area was located in the Upper Citarum River passes through seven sub-districts: Kertasari, Pacet, Majalaya, Solokan Jeruk, Ciparay, Bojong Soang, and Baleendah (Figure 1). There were 13 points of large-diameter dug wells for field hydraulic conductivity tests and water quality observation.

Figure 1. The study location map.

2. Methods
In general, this study consists of three stages, i.e. the hydraulic conductivity and water quality data collection, the 3D hydraulic conductivity estimation, and the groundwater and surface water interaction analysis. The hydraulic conductivity parameter from large-diameter dug wells was measured in the field using the slug test based on Rice and Bouwer's method [8]. The hydraulic conductivity (K) was calculated using two equations:

\[
\ln \left( \frac{R_e}{r} \right) = \left( \frac{1.1}{\ln \left( \frac{H}{r} \right)} + \frac{C}{(L/r)} \right)^{-1}
\]

\[
K = \frac{r^2 \ln \left( \frac{R_e}{r} \right) \ln \left( \frac{Y_e}{Y_r} \right)}{2L}
\]

where:
- \( r \) : Well radius
- \( R_e \) : Effective radius

\( \frac{R_e}{r} \) : Well radius ratio
\( H \) : Slug height
\( C \) : Constant
\( L \) : Well depth
\( Y_e \) : Slug position at end of test
\( Y_r \) : Slug position at start of test
H : Distance from the bottom of the well to the water table
L : The length of the perforated zone or the distance from the bottom of the well to the water table
T : Time
y₀ : Well water depth below the water table at the beginning of the slug test (t=0)
yₜ : Depth to water or drawdown at time t
C : Dimensionless parameter as a function of L/r (x), calculated as:

\[ C = 2 \times 10^{-15}x^5 - 2 \times 10^{-11}x^4 + 5 \times 10^{-8}x^3 - 6 \times 10^{-6}x^2 + 0.0415x + 0.7339 \]

All the dug wells were assumed to be fully penetrating well based on the unconfined aquifer thickness from five deep wells data [9]. The unconfined aquifer thickness was interpolated using ArcGIS 10.6.1. Moreover, the slope distribution was created from Digital Elevation Model (DEM) using the spatial analyst tool in ArcGIS.

The 3D distribution of the hydraulic conductivity parameter was estimated using the geostatistical method. The estimation was conducted using Stanford Geostatistical Modeling Software (SGeMS), an open-source software used to solve problems related to the spatial variable [10]. The algorithm used was ordinary kriging. Kriging is a method to estimate values in locations without the availability of data using linear regression [10]. Ordinary kriging is widely used because it does not require a mean stationary value and can follow the data fluctuation, compared to simple kriging [11]. Two main requirements in using kriging are the normal distribution data and the best-fit variogram model [12]. The cross-validation was conducted to validate the 3D estimation result at the end.

The interaction between groundwater and surface water was analyzed qualitatively by comparing the groundwater and surface water data. The data repository of this study can be accessed through osf.io/gdtbw. This study has some limitations, e.g. the hydraulic conductivity values in the dug wells were assumed to be homogeneous and isotropic. The locations of the dug wells are close to Citarum River; thus, the uncertainty of the estimation will be high in the locations which are far enough from the river. Moreover, the hydraulic conductivity of the surface should be validated using the infiltration test data.

3. Results and discussion
The distributions of unconfined aquifer thickness and topographic slope are shown in Figure 2. The unconfined aquifer thickness ranges from 2 to 12 meters, while the slope ranges from 0 to 43.6 degrees.

![Figure 2](image_url)

**Figure 2.** The distribution of the unconfined aquifer thickness (left) and the slope of the topography (right).
The summary of the hydraulic conductivity test on the field and the groundwater and Citarum River water quality are shown in Table 1. The estimation of the 3D distribution of the hydraulic conductivity parameter of the unconfined aquifer in the Upper Citarum River is shown in Figure 3. The estimated hydraulic conductivity ranges from $8.34 \times 10^{-7}$ to $2.19 \times 10^{-5}$ m/s, which is still following the result of the previous study [5-7]. The cross-validation shows that the estimation result is underestimated at some points (Figure 4), which means that the estimated hydraulic conductivity values are lower than the measured hydraulic conductivity data.

Figure 5 shows the relationship between groundwater and the Upper Citarum River water quality data, which can imply that there is an interaction between them [13,14]. In the dry season, the groundwater table elevation was higher than the elevation of the Citarum River [15]. Based on field observation, in the rainy season, the groundwater table elevation was still higher than the elevation of Citarum River. This implied that the interaction between them was gaining stream, i.e. the streams gain water from the inflow of groundwater [4]. Almost all the groundwater TDS were higher than the Upper Citarum River TDS, while all the pH values of the Upper Citarum River were higher than the pH of groundwater (Table 1).

### Table 1. The summary of hydraulic conductivity parameter and water quality data.

| No. | Well Name | X     | Y     | Z     | K (m/s) | TDS (ppm) | pH   | Temperature (°C) |
|-----|-----------|-------|-------|-------|---------|-----------|------|-------------------|
|     |           |       |       |       |         | GW | CR |        |        | GW | CR |        |        |        |
| 1   | DW1       | 798086.9 | 9209433.2 | 1049.4 | 4.00E-06 | 125 | 91 | 7 | 7.9 | 22.8 | 21.5 |
| 2   | DW2       | 798276.0 | 9212697.2 | 919.9 | 4.73E-06 | 146 | 87 | 6.5 | 8 | 23.5 | 22.8 |
| 3   | DW3       | 799436.2 | 9213805.5 | 862.0 | 6.57E-07 | 116 | 96 | 5.3 | 7.5 | 25 | 25.1 |
| 4   | DW4       | 800634.3 | 9215247.7 | 809.6 | 8.28E-06 | 115 | 96 | 7.1 | 7.8 | 25.6 | 25.5 |
| 5   | DW5       | 802467.4 | 9216815.1 | 763.5 | 5.55E-06 | 111 | 93 | 7.4 | 7.8 | 24.5 | 26.7 |
| 6   | DW6       | 803694.5 | 9217372.7 | 702.1 | 8.63E-06 | 131 | 92 | 6.7 | 7.9 | 26.8 | 26.4 |
| 7   | DW7       | 804966.0 | 9218014.9 | 688.1 | 1.13E-05 | 176 | 87 | 6.9 | 7.8 | 27.4 | 26.4 |
| 8   | DW8       | 804386.2 | 9220537.9 | 671.5 | 8.14E-06 | 287 | 108 | 6.7 | 7.6 | 27.8 | 28.2 |
| 9   | DW9       | 802485.1 | 9222813.6 | 668.3 | 2.25E-05 | 337 | 129 | 6.9 | 7.4 | 26.4 | 26 |
| 10  | DW10      | 800649.4 | 9224391.9 | 663.1 | 3.16E-05 | 99 | 164 | 6.8 | 7.4 | 28.4 | 29 |
| 11  | DW11      | 797406.3 | 9226763.0 | 662.5 | 1.23E-05 | 267 | 236 | 6.7 | 7.3 | 26.5 | 26.3 |
| 12  | DW12      | 794360.9 | 9225075.1 | 661.5 | 7.93E-06 | 287 | 186 | 6.9 | 7.3 | 26.6 | 25.5 |
| 13  | DW13      | 793788.0 | 9224155.0 | 660.8 | 8.14E-06 | 279 | 182 | 6.7 | 7.1 | 24.6 | 24.4 |

**Note:**
* X,Y,Z using WGS84 datum, Zone 48S
* GW for groundwater; CR for Citarum River

**Figure 3.** The 3D distribution of hydraulic conductivity parameter of the unconfined aquifer in the Upper Citarum River. The purple polygon shows the upstream area (Kertasari and Pacet Sub-districts), the orange polygon is in Majalaya Sub-district, and the red polygon is in Baleendah Sub-district.
The high hydraulic conductivity value in DW9 and DW10 (Figure 3) can increase the possibility of water contamination. Since the interaction between the groundwater and the Upper Citarum River was gaining stream, the contaminated groundwater could contaminate the Upper Citarum River. But during the flooding, the interaction between them can change to losing stream, i.e. the streams lose water to groundwater by outflow through the streambed [4]. In this period, the contaminated Citarum River can contaminate the groundwater.

The topography and 3D distribution of the hydraulic conductivity parameter in Figures 2 and 3 could explain the yearly flooding in Majalaya and Baleendah Sub-districts. The hydraulic conductivity in these two districts was relatively low and the topography was relatively flat. These conditions will decrease the volume of infiltrated rainwater in the two sub-districts and cause flooding. Moreover, the hydraulic conductivity in the upstream was also relatively low and the topography was moderately steep. These will also decrease the volume of infiltrated rainwater and increase the runoff volume, which can cause flooding in the Majalaya and Baleendah Sub-district.

4. Conclusion
The hydraulic conductivity of the unconfined aquifer in the Upper Citarum River ranges from $8.34 \times 10^{-7}$ to $2.19 \times 10^{-5}$ m/s. The high hydraulic conductivity values will increase the possibility of groundwater contamination.
or Upper Citarum River contamination, depends on their interaction, whether it is gaining or losing stream. Meanwhile, the relatively low hydraulic conductivity and flat topography in the Majalaya dan Baleendah Sub-districts cause them to be more susceptible to flooding. Therefore, these findings suggest that the mitigation of the water contamination and flooding in the Upper Citarum River should consider the 3D hydraulic conductivity distribution, e.g. by monitoring the groundwater quality in some dug wells located in high hydraulic conductivity area using automatic water quality recorder and eliminating the artificial runoff by installing recharge or injection wells.

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