Analysis Of Potential Unconfined Aquifer And Safe Yield Groundwater Exploitation In Bogor

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Abstract
The population of the city of Bogor is currently 1 million people. The increasing population growth in the city has an impact on water requirements. One of the alternatives for the water resources to be used in fulfilling the water needs is the utilization of groundwater. Even though groundwater is a renewable resource, the environmental conditions will be unbalanced if the groundwater is excessively used. This research aims to determine the groundwater storage potential in Bogor through unconfined aquifers. It also aims to calculate the safe yield that could be exploited. The study was conducted through data collection and analysis. Secondary data were obtained from the interpretation of geo-electric measurement results and annual average water table fluctuation. The calculation of potential groundwater storage used the dynamic method with Darcy's legal approach, while the safe yield used static method calculated by multiplying the value of the specific yield, area, and annual average fluctuations of the water table. Based on the results, the prediction of groundwater storage in Bogor in unconfined aquifers was 0.287 m³/second, while the safe yield of groundwater exploitation was 144 333 000 m³/year.

Keywords: Bogor, groundwater, groundwater storage unconfined aquifer, safe yield

INTRODUCTION
Urban development will occur following the increase in the number and activities of the population. The city of Bogor is proliferating, causing an increase in population. In 2016, the population of Bogor exceeded 1 million people, reaching 1,064,687 or an increase of 1.60% from the previous year [1]. Based on SNI 19-6728.1.2002 [2], the water need of urban communities is 150L/day/person. The basic needs of clean water will always increase in line with population growth and regional development. The water demand varies among regions and depends on factors such as place, time, and social condition of the population [3].

The city life is very dynamic so that the presence of clean water in urban areas is an economic good playing a strategic role in urban society. Also, water is a natural resource that is very vital, yet indispensable in supporting the life and economic development of the community. According to [4], water is a universal component of every living creature, so that the management challenges in water supply in urban areas depend on economic, social, and government policies [5].

The people in Bogor currently get water for domestic needs from PDAM Tirta Pakuan. However, not everyone has access to that service. Some people use dug wells or pantek or drill wells to reach groundwater as an alternative. Besides their easy access, dug wells and pantek/drilling wells have groundwater potential.

Groundwater is a renewable resource as part of the hydrological cycle on earth [6]. However, if the exploitation of groundwater is carried out excessively, it will undoubtedly create an imbalance in environmental conditions [7] thus, environmental management of groundwater is necessary.

Based on the description above, it is necessary to have an environmentally sound groundwater management plan.
According to [8], groundwater management includes several kinds of aspects. An important aspect is the support of groundwater management programs, which is an evaluation of groundwater reserves. As stated in paragraph (3) article 8 of West Java Province Regulation No. 1 of 2017 concerning groundwater management, groundwater inventories are conducted to determine potential groundwater reserves through various stages. Those stages include soil lithology investigation, aquifer characteristics and the determination of the value of hydraulic conductivity as the quantity of groundwater in an area is closely related to the system and characteristics of its constituent rock aquifers [9].

This research was conducted to predict potential groundwater reserves in free aquifers in the city of Bogor. It is also necessary to determine the safe yield of groundwater to be sustainably exploited for optimum utilization without causing adverse impacts.

MATERIALS AND METHODS

Data Analysis

The present research was conducted in Bogor, West Java province, which is geographically located between 6.36° 30' 30" -6° 41' 00" S and 106° 43' 30" -106° 51.00" E. It covers an area of 118.50 km² (Fig 1).

Source : [10]

Figure 1 Location of Study Area
The stages in this study included data collection, data processing, data analysis, and conclusion. This research used secondary data. The first secondary data was the average annual data on groundwater fluctuations derived from the research results, and the second was the data on the results of geoelectric measurement at 36 points around the city of Bogor. Those data were obtained from various sources from both the results of the research, Investigation of groundwater, and the licensing of groundwater utilization obtained from Department of Energy Mineral Resources (ESDM) of West Java Province. Other secondary data were Earth Rupa Map Of Indonesia Bogor 1209-143 scale 1:25,000, a regional geological map of Bogor scale 1:100,000, regional hydrogeology map of Bogor scale 1:100,000, groundwater basin map of Bogor, and National Digital Elevation Model (DEMNAS).

The tools used in this research were computer equipped with Microsoft Office software, ArcGIS, Surfer, Global Mapper, and Google Earth Pro.

Calculation of Potential Groundwater Storage

The characteristics of aquifers can be seen from the results of the interpretation of data on the type of resistance of the geoelectric estimation and the type of soil-forming the layer. The results of geoelectric interpretation were combined with geological and hydrogeological maps. By determining the lithology of the soil layer, the distribution and thickness of the aquifer layer at the study site can be predicted. Groundwater is usually found in aquifer layers which are composed of sandstone. Aquifers in a layer are usually found in sandy or porous layers.

After the aquifer layer was determined, the depth data of aquifers and the thickness of aquifers in the study location were assessed. The aquifer cross-section was determined to evaluate the value of the length of the aquifer crossing (W) and the length of the groundwater path (δL) in the Darcy equation (Equation 1).

Figure 2. Application of the Darcy equation in the field [11]
Groundwater in the aquifers derived from infiltrated water. Groundwater flowing in the aquifers comes from upstream to downstream. Each rock has a different ability in letting water through water. Thus, the movement of groundwater is also influenced by the condition of rocks in the soil.

Furthermore, the parameter used in calculating water discharge with the Darcy equation (Equation 1) was hydraulic conductivity. The Hydraulic conductivity \( K \) is often referred to as im-permeability or the permeability coefficient. Hydraulic conductivity is the rate at which groundwater flows through an area unit of aquifer or aquitard below the gradient of a hydraulic unit.

The Darcy equation (Equation 1) is used in the data analysis process to estimate groundwater storage in unconfined aquifers. The parameters used to fill the equation are hydraulic conductivity, hydraulic gradients, and cross-sectional area of aquifers. Hydraulic gradients can be obtained through equation 2, which aims to divide the depth of the water table of the groundwater track. Meanwhile, the cross-sectional area of the aquifer is calculated with equation 3, multiplying the value of the length of the aquifer \( W \) by the thickness of the aquifer \( b \). The following Darcy formula can determine the debit value:

\[
Q = K \times A \times i
\]

\[
i = \frac{\delta h}{\delta L}
\]

\[
A = W \times b
\]

Description:

\[
Q = \text{Debit (m}^3/\text{second)}
\]

\[
A = \text{Broad cross-section of aquifer (m}^2\text{)}
\]

\[
W = \text{Long cross-section aquifer (m)}
\]

\[
b = \text{The thickness of aquifer (m)}
\]

\[
K = \text{Hydraulic conductivity (m/hari)}
\]

\[
i = \text{Hydraulic gradient}
\]

\[
\delta h = \text{Different depths of water table (m)}
\]

\[
\delta L = \text{Groundwater track length (m)}
\]

The soil water distribution pattern analyzed with Surfer 11 software revealed soil contour and flow of groundwater (flownet). Groundwater flow serves to show the direction of flowing water.

**Calculation of Safe Yield**

The safe yield based on \([12,13]\) is calculated through the static method as follows:

\[
HA=L \times \text{Fat} \times \text{Sy}
\]

Description:

\[
HA = \text{Safe yield (m}^3/\text{year)}
\]

\[
L = \text{Wide aquifer (m}^2\text{)}
\]

\[
\text{Fat} = \text{Annual water table fluctuation (m/year)}
\]

\[
\text{Sy} = \text{specific yield (\%)}
\]

**RESULTS AND DISCUSSIONS**

**Regional Geological Analysis of studies**

Bogor is located in a hilly and wavy area with varying heights, a minimum elevation of 150 m and a maximum elevation of 380 m above sea level (MASL). The area with a height of > 300 MASL is mostly in the southern region which is at the bottom of Mount Salak.

In Physiography, Bogor is included in the Anticlinorium Zone which generally has a hilly morphology, extending east-west of Bogor \([14]\).

The geological structure of Bogor consists of andesite flow, alluvial fan, sediment, tufa, and silt of Tufan and Capili. In general, the city is covered by volcanic rocks derived from the sedimentary rocks (rock) from Mount Salak and Mount Pangrango in the form of the Kpal Breksi Rocks. This rock layer is slightly more profound from the ground and away from the river flow. The surface deposition is usually an alluvial composed of soil, sand, and gravel weathering deposits, which are undoubtedly suitable for vegetation. The land in the whole area of Bogor generally is sensitive to erosion which mostly contains clay, with a soil texture that is generally smooth or a bit rough, except in District of West Bogor, Land of Sareal and central Bogor, where there is rocky soil textured.

Based on the geological map of Bogor by \([15]\) in Figure 1, there are only 2 (two) groups of rock, namely surface sedimentary rocks and volcanic rocks.
Surface deposition consists of the alluvium fan Formation (QAV), while the volcano rocks consist of Mount Pangrango and Mount Salak volcanic rocks. Mount Pangrango volcanic rocks consist of volcanic units of Pangrango Mountain (QVPO), and Mount Salak volcano rock consisting of lava unit, Breksi Tufan and Lapilli (QVSB), lava flow (QVSL), and Sandy (Qvst) Tuf. The description of the formation and the sequence of stratigraphy of the formation are as follows:

1. Qav : Formation of conglomerates and sandstone tuffaceous or alluvium fans of Holocene. Aluvium fans are mainly Silt, sandstone, gravel and boulders from quaternary volcanic rocks re-deposited as alluvial fans.

2. Qvpo : The volcanic unit of Mount Pangrango is composed of lava and with minerals such as plagioclase and Mafik minerals, basal andesite with Oligoklas-Andesin, Labradorit, olivine, Pyroksen, and Horenblenda derived from volcanic rock of Mount Pangrango and holocene-aged.

3. Qvsb : Mount Salak has a formation unit composed of basal andesite which is generally quite weathered and pleistocene-aged.

4. Qvsl : Mount Salak formation unit is in the form of basal andesite with pyroxia (augit) and holocene-aged.

5. Qvst : Mount Salak formation unit is in the form of basal andesite lava flows with pyroxia and Pleistocene-aged.

Hydrogeology Analysis of Studies

The rainwater that permeated into the soil in the area of balance (recharge area) is stored in the aquifer as groundwater or partly to the outside in the area of the freelance (discharge area).

The groundwater is formed in the suffix area and flows into the discharge area through the space between the constituent stone of aquifer. The groundwater journey dissolves rock minerals that are influenced by environmental conditions. Therefore, the physical and chemical properties of the groundwater from one place to another vary greatly depending on the type of rock in which the groundwater permeates, flows, and accumulates.

The type of lithology on the aquifer layer affects the hydrogeological conditions. Based on the map of the hydrogeology of Bogor [16] and Figure 4 published by the Directorate of Environmental Geology, Bogor is composed of lithology in the form of inseparable young volcanic rock, consisting of tufa. The hydraulic conductivity of the compound aquifer ranges from 0.8 to 36.4 m/day. The good yields can be categorized as follows:

1. Well Yields less than 5 l/sec.
   Aquifer in which flow through intergranular, locally through fissures and solution channels, composed of multilayers of young volcanic rock of sanstone and breccia, coralline limestone and sandy limestone.
   Thickness between 1 and 10 m, transmissivities range between 0.8 and 94 m²/day. Static water level varies, from 28 m below ground level up to 0.9 m in above ground level (self flowing)

2. Well Yields between 5-25 l/sec.
   Aquifer in which flow through intergranular, locally through fissures, extend in the southern-western foot of Gede-Pangrango volcano and northern part of Salak volcano, generally extending on young volcanic rock composed of multilayer aquifers
   Total thickness range between 2-77 m with the deep of well 70-180 m below ground level, specific capacity of well can reach 329.18 m²/day, transmisivities can reach more than 659 m²/day. Static water level, from 40 m below ground level up to 1.3 m in above ground level (self flowing)

3. Nir Aquifer layer. This layer is meaningless because it cannot let groundwater pass through.
Prediction of Groundwater Flow (flownet)

Knowing the groundwater movement, the cross section of the aquifer from groundwater movement can be identified as recharge and discharge areas. Cross section of aquifer (W) is one of the parameters needed in measuring groundwater reserves using the Darcy equation.

Groundwater requires energy to move through the inter-pore space. This driving force comes from potential energy. The potential of groundwater is reflected in the water level (piezometric) in a given place. Groundwater flows from a point with high potential energy to a point with low potential energy. Between points with the same potential energy, there is no groundwater flow [17]. The movement of groundwater is shown in the flow line (flownet).
The estimated pattern of groundwater flow is made with Surfer 11 software with the data in the form of coordinates and altitude of the measurement points presented in Fig 5 and Fig 6.

Figure 5 and Figure 6 showed that groundwater flow is predicted to move from south to north. The south is a recharge area that serves as a catchment area, while the northern area is a catchment area. It is exhibited in the direction of the flow of water from high elevations to low elevations.

There are basins in some parts, and the basin is a container or place of water gathering known as the groundwater basin. The groundwater basin at the research site is a condition of the local aquifer, which is thick enough to allow the gathering of groundwater. The river basin area is better known as an area that utilizes the potential of groundwater because the region is relatively exposed.

The description of the pure event in the flow system can be done through the application of groundwater model, one of which used the Graphical User Interface (GUI) Modflow model Muse. Also, the flow of groundwater can also determine the water table and zone budget.

**Characteristics of aquifer in the research area**

Bogor is included in the groundwater basin through the Presidential decree of the Republic of Indonesia No. 26 the year 2011 on the determination of groundwater basin. According to [18], the groundwater basin in Indonesia is generally comprised of an unconfined and confined aquifer. An aquifer is a layer that let water pass through the soil [19].

An unconfined aquifer is a water-saturated aquifer (saturated). The limiting layer is an aquitard only found on the lower part. There is no aquitar barrier in the upper layer. The boundary at the top of the layer is the water table. In other words, an aquifer has groundwater. The distressed aquifer is a water-saturated aquifer that is bordered by the upper layer and the water-resistant lower layer of aqueous, where the water pressure is higher than the atmospheric pressure. In the boundary layer, there is no flux [20].
The characteristics of aquifer include parameters such as hydraulic conductivity, the thickness of the aquifer, aquifer material, transmissivity, and specific yield. The thickness of aquifer and the type of aquifer material are obtained from the Geo-electric estimations [21].
Further analysis in this study was only focused on the unconfined aquifer. The interpretation of the geo-electric data was made to determine the vertical section of the soil layer. Vertical cross-section of the soil layer is often referred to as borlog or fence diagram. Borlog can measure the thickness of aquifer and the depth of aquifer in the measurement area. The thickness of the aquifer is obtained from the difference between the upper and lower boundaries of the aquifer. The rock lining of the aquifer is obtained from the estimation of lithology and the type of data in Borlog. The value of hydraulic conductivity is derived from the average value of the hydraulic conductivity of the aquifer layer in the research site.

The results of the analysis and interpretation of constituent rocks in the form of borlog based on the map of cross-section aquifer analysis are presented in Figure 8 and Figure 9. Those figures gave the idea that the unconfined aquifer in Bogor is dominated by sand, sandstone, rough sand, sticky clay, and tufa. Furthermore, based on the depth data of aquifer, the thickness of the aquifer, and the value of hydraulic conductivity, the unconfined aquifer in Bogor can be determined. The upper limit of the coating can be found at a depth ranging between 2-78 m of below ground level. The layer thickness of aquifer ranged from 4 – 42 m. The value of hydraulic conductivity in an unconfined aquifer is 0,0002–45m/day.

![Figure 7 Analysis Map Of the Cross-Section Aquifer in Bogor](image_url)
Figure 8 East-West Borlog Section

Figure 9 South-North Borlog section
Groundwater Storage Potential

The groundwater storage in the free aquifer was analyzed and estimated using Darcy's pressure. The parameter values of the Darcy equation were obtained from the results of the analysis of the characteristics of aquifers in the study area.

The length of the aquifer cross-section (W) is depicted with a green line and the length of the groundwater path (δL) with yellow lines, as shown in Fig 7. The cross-section of the aquifer is 8,092.5 m while the length of the groundwater path is 16,475.2 m. Based on the calculation, the thickness of a free aquifer is 15.2 m. Thus, the cross-sectional area of the aquifer (A) in the free aquifer is 123,208.31 m².

The difference in depth of groundwater based on the calculation had a value of 420.05 m, with a hydraulic gradient value of 0.025. The complete parameter values of the Darcy equation are presented in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unconfined aquifer</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic conductivity (K)</td>
<td>7.89</td>
<td>m/day</td>
</tr>
<tr>
<td>Layer thickness (b)</td>
<td>15.22</td>
<td>m</td>
</tr>
<tr>
<td>Long-section Aquifer (W)</td>
<td>8,092.1</td>
<td>m</td>
</tr>
<tr>
<td>Different depth of Water Table (δh)</td>
<td>420.05</td>
<td>m</td>
</tr>
<tr>
<td>Groundwater trajectory length (δL)</td>
<td>16,475.2</td>
<td>m</td>
</tr>
<tr>
<td>Hydraulic gradient (i)</td>
<td>0.025</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: The value of the Darcy equation parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Prediction Groundwater Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m³/day</td>
</tr>
<tr>
<td>Unconfined aquifer</td>
<td>24,807.73</td>
</tr>
</tbody>
</table>

The calculation of the potential value of groundwater storage is calculated with the Darcy equation (equation 1). Based on the calculation, the potential value of groundwater storage in Bogor in the unconfined aquifer was 24,807.73 m³/day or 0.287 m³/second. Table 2 showed the potential value of groundwater storage in the unconfined aquifer.

SAFE YIELD ANALYSIS

Safe yield calculations are only done based on static methods (equation 4). The parameters used to calculate the results were the static methods such as region-wide parameters, annual average water table fluctuations, and specific yield.

The area of research areas is 118.5 km², while the average annual rate of the water table is 6 m and the specific yield (Sy) value of 20.3% of the calculated result is presented in table 3.

<table>
<thead>
<tr>
<th>Location</th>
<th>Area (m²)</th>
<th>Annual Water Table Fluctuation Average (m)</th>
<th>Sy (%)</th>
<th>Safe Yield (m³/Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bogor</td>
<td>118,500,000</td>
<td>6</td>
<td>20.3</td>
<td>144,333,000</td>
</tr>
</tbody>
</table>

Based on the calculation of the safe yield of groundwater exploitation in the research area was 144,333,000 m³/year.
CONCLUSIONS

The conclusion that can be drawn from this study is that the geological formations in Bogor is dominated by the formation of the alluvium Fan (QAV), the volcanic unit of the Pangrango Mountain (QVPO), the lava unit, the Breksi Tufa and the Lapilli (QVSB), the flows (QVSL), and Coal (QVST). Those generally contain sand and tufa. The hydrogeological conditions were dominated by small and medium productive aquifer domination.

The unconfined aquifer is dominated by layers of sand, sandstone, coarse sand, pasty loam, pasting tufa, and tufa at a depth of 4-42 meters below local land with a hydraulic conductivity value of 7.89 m/day and a hydraulic gradient 0.025. The prediction of groundwater storage in Bogor in the unconfined aquifer is obtained in the Darcy equation was 0.287 m³/second with a safe yield with a static method of 144,333,000 m³/year.

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