Understanding Kendal aquifer system: a baseline analysis for sustainable water management proposal

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Abstract. North coast of Java has been grown as the center of economic activities and major connectivity hub for Sumatra and Bali. Sustainable water management must support such role. One of the basis is to understand the baseline of groundwater occurrences and potential. However the complex alluvium aquifer system has not been well-understood. A geoelectric measurements were performed to determine which rock layer has a good potential as groundwater aquifers in the northern coast of Kaliwungu Regency, Kendal District, Central Java province. Total of 10 vertical electrical sounding (VES) points has been performed, using a Schlumberger configuration with the current electrode spacing (AB/2) varies between 200 - 300 m and the potential difference electrode spacing (MN/2) varies between 0.5 to 20 m with depths target ranging between 150 - 200 m. Geoelectrical data processing is done using Ip2win software which generates resistivity value, thickness and depth of subsurface rock layers. Based on the correlation between resistivity value with regional geology, hydrogeology and local well data, we identify three aquifer layers. The first layer is silty clay with resistivity values vary between 0 - 10 ohm.m, then the second layer is tuffaceous claystone with resistivity value between 10 - 60 ohm.m. Both layers serve as impermeable layer. The third layer is sandy tuff with resistivity value between 60 - 100 ohm.m which serves as a confined aquifer layer located at 70 - 100 m below surface. Its thickness is vary between 70 to 110 m. The aquifer layer is a mixing of volcanic and alluvium sediment, which is a member of Damar Formation. The stratification of the aquifer system may change in short distance and depth. This natural setting prevent us to make a long continuous correlation between layers. Aquifer discharge is estimated between 5 - 71 L/s with the potential deep well locations lies in the west and southeast part of the study area. These hydrogeological settings should be used as the main starting point in managing water supply in this area.

1. Introduction
Java island has a nearly 2000 km coast line, stretching from east to west, which also the location of many industrial areas. With very established road network and flat lowland terrain, Kendal Regency (Mid Java Province) is one of the favorable area. With such condition, Kendal Regency needs a detail groundwater resource mapping to fulfill the daily water needs of the area. Research location located in the northern coast of Kendal Regency about 14 Km from Semarang to the northwest (figure 1). Our specific is to evaluate the hydrogeological setting of this coastal alluvium system in the research area with the specific interest in identifying groundwater resources beneath the location.
2. Research Area

2.1. Research Location Description

Administratively, the research location is located in Wonorejo Distric, Kendal Regency about 5 to 6 Km from the coast line. It consist of flat coastal and swamp plain with very low slope gradient. Such condition are controlled by soft overlaid rock lies below the ground, eroded and deposited by river-tides-waves current energy. The locals grow rice field and fish pond in the northern part of the area, the measurements done in two major part in the wide area described with yellow dots and the narrow area described with orange dots (see map in figure 2). This research talk about the result of field measurements in the orange dots area, there are ten total geoelectrical measurement points.

2.2. Regional Condition

Two formations were identified based on previous studies: Damar formation (Qtd) and alluvium formation (Qa). Both were deposited in the Quarternary period, however, the Damar fm is older than alluvium fm. [5] from Geological Survey of Indonesia (figure 3). Damar fm consists of tuffaceous claystone, volcanic breccia, tuffaceous sandstone, tuff, conglomerate and a few laharik deposit in various area. This formation is distributed from the volcanic highland toward the coast, forming a
volcanic-river-coastal depositional system. Aside to the hard and compact breccias and lavas, this formation has high groundwater potential stored in the porous volcanic sand layers.

Figure 3. Regional geological map of the research location [5].

The younger alluvium fm consists of gravel, sand, silt and clay material which was deposited in the river and riverbanks as well as swampy area in the coast of Kendal. This formation is composed of unconsolidated carbonicous silty clay material that usually produce unpermeable layer. The maximum thickness of this formation can reach more than 50 m. The hydrogeology of the area consists of two aquifer systems: alluvium system (swampy and lake deposits) and volcanic system (tuff, tuffaceous sandstone and volcanic breccia). The first system is a shallow aquifer with low permeability, whereas the second system has higher permeability. Based from previous studies, we could come up with three classes of aquifer productivity [4] (figure 4):

- moderate to high (green): fracture zones, deep groundwater table, various well yields and spring discharge;
- high (light blue): moderate transmissivity, shallow water level, wells yield 5 to 10 l/s;
- very high (dark blue): moderate to high transmissivity, very shallow water level, wells yield more than 10 l/s.

Figure 4. Hydrogeological map of research location [4].

There were 27 geotechnical boreholes (drilled in 2013) with depth varied between 45 to 70 m, contains: standard penetration test (SPT), physical properties of soil, and groundwater level. According
to the those data, generally, silty clay soil with a bit of sandy materials are found at 0-45 m of depth with SPT value range between 13 to 20, which are common for coastal-swampy alluvium deposit. The groundwater level is located at 10 m below the surface, flowing in shallow aquifers (figure 5).

![Figure 5](image1.png)

**Figure 5.** Drilling log correlation from previous geotechnical survey (drilled in 2013), it is known that at the shallow depth in the subsurface of research area dominated by clay with a little sand intercalation which probably act as shallow local aquifer.

To support deeper resistivity interpretation, we used one deep drill hole with depth of 125 m, located south of the area (figure 6). From the drilling log below, it shows that tuffaceous claystone with a bit sandy intercalations at shallow depth, which are equivalent with our resistivity values. Sandy tuff layers intercalated with volcanic breccia known as Damar fm, are found deeper. From the log, we identify the potential of deep aquifer.

![Figure 6](image2.png)

**Figure 6.** Drilling log from deep production well at the southern part of the research location, showing the same pattern with local geotechnical drilling result and some sandy tuff (probably as a member of Damar Formation) at the deeper part as the main aquifer layer in the location.
3. Material and Methods

3.1. Methods

3.1.1 Field Measurement Process. Geoelectrical measurement was conducted using four electrodes: two current electrodes (A and B) and two potential electrodes (M and N). Schlumberger configuration used in the study with distance of potential electrodes (MN/2) 0.5 to 10 m and distance of current electrodes (AB/2) 150 to 200 m (see figure 7). The principles of the method is to inject electrical current in below the surface through current electrodes (AB). Electrical currents propegeate in the layers with different resistivity values, in which recorded by the receiving electrodes. Such values, the apparent resistivity, are guided by Ohm's Law and they are controlled by the injected current values, potential differences and geometrical factor. It can be calculated using equation 1 [3].

\[
\rho = K \frac{\Delta V}{I}
\]

(1)

Where \( \rho \) is the value of apparent resistivity (Ohm.m), \( I \) is electrical current (mA), \( \Delta V \) is differences of potentials (mV), and \( K \) is the geometrical factor. The value of geometrical factor of Schlumberger configuration can be calculated using equation 2.

\[
K = \pi \frac{\left( \frac{AB}{2} \right)^2 - \left( \frac{MN}{2} \right)^2}{2 \left( \frac{MN}{2} \right)}
\]

(2)

Where:
- \( K \) = geometrical factor
- \( AB \) = Distance between current electrodes (m)
- \( MN \) = Distance between potential electrodes (m)

Geoelectrical measurements in the area using the following equipments:
- Two sets of Resistivity meter (Naniura NRD 300 HF), each with 2 pieces of potential electrodes, 2 pieces of current electrodes, and four cable rolls @ 500 m;
- 1 unit GPS (Garmin 76 Csx)
- 1 set AVO meter, TDS meter anda water level detector

3.1.2 Data Processing. Resistivity values are plotted onto apparent resistivity curve log vs AB/2. The curve is used as a temporary interpretation in the field. Depth of penetration is proportional with a
third of AB/2 distance. The algorithm used in the interpretation is forward modeling and inversion modeling. This will determine the actual resistivity value, thickness and depth from the surface.

The resistivity values are derived from the fluid content and type of layer (eg: sand or clay). They also resembles the fluid salinity values as well. Moreover, resistivity of rock is related to porosity, mineral composition and water saturation. Sedimentary rock with high porosity has lower resistivity than igneous or metamorph rocks. Resistivity value of sedimentary rock is between 10 Ohm.m until 1000 Ohm.m. Clay has lower resistivity value than sandstone. Water has resistivity value between 10 to 100 Ohm.m, on the other hand, sea water has resistivity value of 0.2 Ohm.m. Low resistivity at sea water is because of high salt content [2].

Microsoft Excel spreadsheet software was used to process apparent resistivity values from equation 1 and equation 2 (Table 1). Values of AB/2, MN/2 and apparent resistivity were then processed with IP2win software to obtain actual resistivity value, depth and thickness of earth surfaces with correlate the inversion model (line) with the apparent resistivity path (dots) in the software. Furthermore, aquifer layer can be interpreted based on its resistivity value. Inversion from software IP2win will provide correlation between sounding points to produce 2D and 3D model using Rockwork 16 software.

| Client | KIK | DATE | INSTRUMENT | AB/2 | MN/2 | K | I | V | Rho.App |
|--------|-----|------|------------|------|------|---|---|---|---------|
| Province | Central Java | 14-1-2016 | Naniura | 1    | 0.3  | 4.76 | 653 | 1479 | 10.79 |
| Location | Kawasan Industri Kendal | X | 417750 | 1.5  | 0.3  | 11.31 | 593 | 246.6 | 4.7 |
|          | Y | 9234062 | | 2    | 0.3  | 20.47 | 582 | 48.2 | 1.7 |
|          |   |      | | 2.5  | 0.3  | 32.25 | 520 | 25.5 | 1.58 |
|          |   |      | | 3    | 0.3  | 46.65 | 645 | 12.7 | 0.92 |
|          |   |      | | 4    | 0.3  | 83.3  | 605 | 3.8  | 0.52 |
|          |   |      | | 5    | 0.3  | 130.43 | 554 | 1.8  | 0.42 |
|          |   |      | | 5    | 1    | 37.7  | 555 | 7.3  | 0.5 |
|          |   |      | | 6    | 1    | 54.98 | 840 | 6.6  | 0.43 |
|          |   |      | | 8    | 1    | 98.96 | 1058 | 3.3  | 0.31 |
|          |   |      | | 10   | 1    | 155.51 | 1268 | 4.3  | 0.53 |

Table 1. Schlumberger data sheet example to get apparent resistivity value from field measurement.
4. Result and Analysis

Based on our interpretation, first layer from 0 to 70 m mostly consists of alluvium material with resistivity value at $0 \text{–} 10 \text{ Ohm.m}$ and it is interpreted as alluvium sediment with clay to sand grain size according to the soil investigation borehole data as key interpretation. Very low resistivity values are expected to be sea water intrusion.

Second layer from depth 70 to 200 m mostly consists of more rigid rock material with medium to high resistivity value range at $10 \text{–} 200 \text{ Ohm.m}$. It is interpreted as sandy-clay and sandy-tuff lithology of Damar fm as also shown by existing deep water well. The interpreted resistivity and its lithological classification is shown in the following Table 2.

Table 2. Processed geoelectrical data in the research location.

| No | line Number | Coordinates (UTM) | Depth | Thickness | Resistivity | Lithology          |
|----|-------------|-------------------|-------|-----------|-------------|--------------------|
| 1  | GL-1        | 417700 9234096    | 0 0   | 99.84 99.84 | 0.65 20.2 | Silt Clay Tuffaceous claystone |
|    |             |                   |       | 99.84 197.51 |            |                    |
|    |             |                   |       | 197.51 200   | 2.49 273.52 | Breccia            |
| 2  | GL-2        | 417750 9234062    | 0 0   | 37.51 37.51 | 0.45 44.66 | Sandy tuff Tuffaceous claystone |
|    |             |                   |       | 37.51 58.52 | 21.01 22.19 |                    |
|    |             |                   |       | 58.52 159.44| 100.92     |                    |
|    |             |                   |       | 159.44 200  | 40.56 28.92 |                    |
| 3  | GL-3        | 417839 9234050    | 0 0   | 50.47 50.47 | 0.52 16.55 | Silt Clay Silt Clay |
|    |             |                   |       | 50.47 93.63 | 43.16 19.22 |                    |
|    |             |                   |       | 93.63 150.81| 57.18      |                    |
|    |             |                   |       | 150.81 200  | 49.19 67.21 |                    |
| 4  | GL-4        | 417883 9234088    | 0 0   | 52 52      | 0.65 45.32 | Sandy tuff         |
|    |             |                   |       | 52 81.32   | 29.32      |                    |
|    |             |                   |       | 81.32 124.32| 43 21.29   |                    |
|    |             |                   |       | 124.32 186.96| 62.64 48.29|                    |
|    |             |                   |       | 186.96 200 | 13.04 293.12|                    |
| 5  | GL-5        | 417910 9234130    | 0 0   | 160 160    | 0.58 35.23 | Silt Clay Sandy tuff |
|    |             |                   |       | 160 186    | 26 17.31  |                    |
|    |             |                   |       | 186 200    | 14 0.58   |                    |
| 6  | GL-6        | 417829 9234106    | 0 0   | 67.61 67.61| 0.63 46.99 | Silt Clay Sandy tuff |
|    |             |                   |       | 67.61 88.41| 20.8 71.04 |                    |
|    |             |                   |       | 88.41 118.98| 30.57 94.59|                    |
|    |             |                   |       | 118.98 195.25| 76.27 194.85|                    |
|    |             |                   |       | 195.25 200 | 4.75 27    |                    |
| 7  | GL-7        | 417783 9234146    | 0 0   | 35 35      | 0.41 44.43 | Silt Clay Sandy tuff |
|    |             |                   |       | 35 64      | 29 27     |                    |
|    |             |                   |       | 64 102     | 38 0.41   |                    |
North to south section shows layers of clay (light green – dark green) at shallow depth and sandy-clay and sandy-tuff (yellow) from Damar fm with good porosity and permeability. The second layer is predicted as an aquifer (Figure 8).

| Layer | GL-8 | GL-9 | GL-10 |
|-------|------|------|-------|
| Depth (m) | 102 | 162 | 124 |
|         | 162 | 200 | 145 |
| Porosity (%) | 60 | 38 | 20 |
| Permeability (mD) | 122 | 156 | 190 |
| Sediment Type | Sandy tuff | Sandy tuff | Sandy tuff |

| Layer | GL-8 | GL-9 | GL-10 |
|-------|------|------|-------|
| Depth (m) | 99 | 93 | 93 |
|         | 124 | 123 | 165 |
| Porosity (%) | 99 | 30 | 145 |
| Permeability (mD) | 0.5 | 35.85 | 0.5 |
| Sediment Type | Silt Clay | Sandy tuff | Silt Clay |

| Layer | GL-8 | GL-9 | GL-10 |
|-------|------|------|-------|
| Depth (m) | 99 | 123 | 177 |
|         | 124 | 177 | 200 |
| Porosity (%) | 0.5 | 54 | 23 |
| Permeability (mD) | 35.85 | 33.64 | 59.13 |
| Sediment Type | Sandy tuff | Sandy tuff | Sandy tuff |

| Layer | GL-8 | GL-9 | GL-10 |
|-------|------|------|-------|
| Depth (m) | 20 | 165 | 184 |
| Porosity (%) | 20 | 145 | 19 |
| Permeability (mD) | 0.5 | 7.53 | 70.24 |
| Sediment Type | Silt Clay | Silt Clay | Sandy tuff |

Cross-Section A-A’

Figure 8. North to south cross section.

The east-west section presents similar condition as previous section. The first layer is dominated by silty clay and tuffaceous claystone as an aquitard layer and the second one at the deeper part is dominated by sandy tuff which is predicted as potential aquifer.
From the correlation we identified some sand lenses with north-south trend. Those lenses are interpreted as channel sand from the older river system in the area. The width is from 4 to 7 m with 2 - 4 m of thickness. We believe that the sand lenses are good aquifer for communal well water.

5. Discharge Estimation

Estimation of the discharge of proposed well is conducted by assuming the hydraulic conductivity range from $3.10^{-10}$ to $6.10^{-6}$ m/sec \cite{1} which shown in table below. The following discharge estimation is a very rough due to the data availability, therefore pumping test later on should be used as the main guidance.

Table 3. Hydraulic Conductivity of Sedimentary Rocks.

| Sedimentary Rocks       | Hydraulic Conductivity (m/sec) |
|-------------------------|--------------------------------|
| Karst and reef limestone| $1 \times 10^{-6}$ to $2 \times 10^{-2}$ |
| Limestone, dolomite     | $1 \times 10^{-9}$ to $6 \times 10^{-6}$ |
| Sandstone               | $3 \times 10^{-10}$ to $6 \times 10^{-6}$ |
| Siltstone               | $1 \times 10^{-11}$ to $1.4 \times 10^{-8}$ |
| Salt                    | $1 \times 10^{-12}$ to $2 \times 10^{-10}$ |
| Anhydrite               | $4 \times 10^{-13}$ to $2 \times 10^{-8}$ |
| Shale                   | $1 \times 10^{-14}$ to $2 \times 10^{-9}$ |

The discharge estimation is following Sichardt Formula described below.

$$Q_{maks} = \frac{2\pi rb \sqrt{k}}{15} \quad (3)$$

Where:
- $Q_{maks}$ = maximum discharge of water extracted (m$^3$/s)
- $r_e$ = effective radius (m)
- $b$ = aquifer thickness (m)
- $k$ = hydraulic conductivity

Discharge estimation calculation give result of discharge range depend on the hydraulic conductivity value used. Other than that the calculation also use several assumption as follows:
- Aquifer Thickness is 70 meter
- Effective radius is 10 meter
- Hydraulic conductivity value $3.10^{-10}$ m/sec and $6.10^{-6}$ m/sec

Table 4. Discharge estimation

| Hydraulic Conductivity | Q (m$^3$/s) | Q (l/s) |
|------------------------|------------|---------|
| $3.10^{-10}$ m/sec     | 0.005076   | 5.076   |
| $6.10^{-6}$ m/sec      | 0.071786   | 71.786  |
The different value of discharge depends on the following conditions:

- Porosity and permeability rate of aquifer.
- Fragment size of sandstone
- Matrix percentage of the sandstone.

6. Conclusion
Based on our preliminary results, the geoelectrical method has successfully identified the lateral and vertical distribution of the aquifer. We find volcanic sand from Damar fin forms a good aquifer in more than 70 m of depth. We also find several ancient north-south river channels which could be used as a strong lead for further water supply exploration in Kendal coastal area. Discharge estimation calculation gives results of discharge range depend on the hydraulic conductivity value assumption used, discharged estimation ranged between 5.076 L/s to 71.786 L/s, for further analysis it’s needed to do the pumping test to get the real discharge value.

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