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Prediction criteria for groundwater potential zones in Kemuning District, Indonesia using the integration of geoelectrical and physical parameters

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Abstract: The presence of groundwater is strongly related to its geological and geohydrological conditions. It is, however, important to study the groundwater potential in an area before it is utilized to provide clean water. Werner-Schlumberger's method was used to analyze the groundwater potential while hydraulic properties such as soil porosity and hydraulic conductivity were used to determine the quality and ability of the soil to allow water's movement in the aquifer. The results show that the aquifer in the Sekara and Kemuning Muda is at a depth of more than 6 meters below the ground level with moderate groundwater potential. It is also found that the aquifer at depths of over 60 m have high groundwater potential. Moreover, soil porosity in Kemuning is found to be average while the ability to conduct water was moderate. This makes it possible for some surface water to seep into the soil while the remaining flows to the rivers and ditches.

Keywords: Geoelectrics; Groundwater; Hydraulic property; Aquifer Werner-Schlumberger's configuration

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Introduction

Water scarcity has become a serious problem in many regions around the world. Currently, several regions in Africa and India are facing severe droughts which have triggered the water crisis in those regions (Silliman *et al*. 2010; Udmale *et al*. 2014). Water scarcity is one impact of climate change on our planet because of the overexploitation of natural resources, including water. Water sources, *i.e*. surface-water and groundwater, should be managed sustainably to avoid further water scarcity (Juandi *et al*. 2017).

Sustainable exploitation of groundwater must be based on the understanding of the geological and hydrological conditions of the aquifer, because the productivity of aquifer in different areas largely depends on the layer of soil below the surface (Lenkey *et al*. 2005; Juandi and Syahril, 2017; Juandi, 2020). It is important to state that groundwater is usually stored in the aquifer for exploitation (Udmale *et al*. 2014). However, to analyze the aquifer conditions, there is a need to evaluate methods that are capable of investigating geological formations to determine water availability (Juandi, 2019). These include geological, magnetic, gravity, seismic, and geoelectric methods. The geoelectric method has been reported to have a high level of sensitivity in groundwater exploration (Lenkey *et al*. 2005).

Indragiri Hilir is a suitable region for research due to its complex conditions as well as

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swamps and tidal rivers often found in the area. Furthermore, Kemuning is a village located in this region with a population highly dependent on underground water and this made it necessary to research the presence of groundwater in the region (Heriyanto *et al*. 2019).

Groundwater occurs in the peatland region of Kemuning district. Therefore it should be properly managed to keep the balance between the water demand and the sustainability of this resource (Muhammad, 2020; Sheriff, 2002). Kemuning has several rock formations which have more dominant peat swamp deposits appearing on the surface and consist of peats, mud, clay, and sand. The thickness of the peat layer in the region reaches 5 m and at several locations peat appears in the clay layer with the thickness varying from 50 cm to 300 cm. The depth of the bedrock is estimated to be at a depth of more than 60 m (Heriyanto *et al*. 2019).

To reveal the groundwater profile in Kemuning soil, we conducted a geoelectric survey using Werner-Schlumberger's configuration and studied porosity and hydraulic conductivity of soil samples from 12 locations of the district. This survey produced an image of the vertical profile of geological formations below the surface where groundwater can be determined by the electrical properties of the rocks and the soil. The distances between the electrode potentials and also between the electrode currents have been made to change gradually in this method (Islami *et al*. 2011). Moreover, the efficiency of the geoelectric resistivity method to map the subsurface layer provides more precise information to characterize the aquifer layer, illustrate the depth of bedrock, and determine the resistivity values (Sultan and Santos, 2008). By interpreting resistivity, porosity, and hydraulic conductivity of the soil, groundwater can be qualitatively estimated.

1 Materials and methods

1.1 Study area

This research was conducted in the rural areas of Kemuning, a district of Indragiri Hilir regency as shown in Fig. 1. This district was located at a latitude of 0°55'57.56" S and longitude of 102°34' 36.18" E in the south part of Riau Province, the mid-eastern of Sumatra. The district is commonly covered by peatland. The local climate is classified as tropical wet with moderately humid air. The highest rainfall was recorded in March of 2017 with 4 422 mm while the lowest was in July with 80 mm (Revil *et al*. 2012).

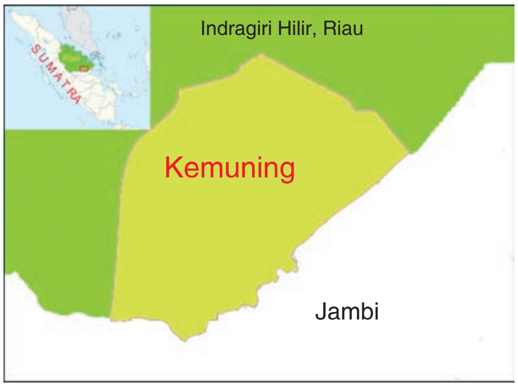

Fig. 1 Research location in Kemuning district of Indragiri Hilir regency, Indonesia

Table 1 Coordinates of 12 measuring points in Kemuning

No.	Location	Latitude	Longitude
1	Kerintang	00°51'35.81" S	102°39'21.29" E
2	Sekara	00°52'05.90" S	102°44'41.30" E
3	Kemuning Tua	00°54'14.23" S	102°47'19.03" E
4	Air Balui	00°53'46.67" S	102°45'47.70" E
5	Batu Ampar	00°58'20.49" S	102°42'40.49" E
6	Selensen	00°58'23.70" S	102°45'22.74" E
7	Tuk Jimun	00°54'52.46"S	102°48'02.06" E
8	Kemuning Muda	00°53'48.90" S	102°49'27.67" E
9	Lubuk Besar	00°52'45.62" S	102°50'05.44" E
10	Talang Jangkang	00°51'20.83" S	102°49'24.84" E
11	Limau Manis	00°52'19.67" S	102°48'24.63" E
12	Sekayan	00°51'15.26" S	102°41'03.11" E

The research locations are distributed in 12 villages from where soil samples were collected, as depicted in Table 1. The soil resistivity was measured at two coordinates (00°52'2.59"S, 102°44'85"E, 00°54'8.59"S and 102°49'47.33”E) using Werner-Schlumberger’s method. Soil samples were obtained from several coordinates to determine the porosity while hydraulic conductivities were measured on samples from 12 village areas in Kemuning as shown in Table 1.

1.2 Model development

In this research, a geoelectric measurement was applied to obtain the data (Wada *et al*. 2014) through the utilization of geoelectric sounding (vertical) Werner-Schlumberger’s configurations. The number of sounding points includes 12 for porosity and hydraulic conductivity in Kemuning and another 48 for soil porosity in the district. Werner-Schlumberger’s method was used to analyze the groundwater potential while the porosity and the conductivity were measured to analyze the quality and permeability of the soil and its effects on the presence of groundwater (Alley *et al*. 2002).

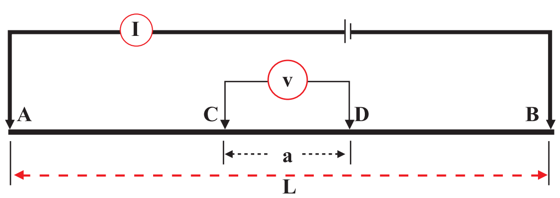

Fig. 2 Electrode configuration of Werner-Schlumberger’s method (Islami *et al*. 2011)

The electrode arrangement in Fig. 2 shows the distance L between the same current electrodes A and B and the distance a between the voltage electrodes of C and D. The parameters measured are the distance between the stations with the current electrodes (I) and the potential difference (V), while the calculated parameters include the geometry factor (*Ks*) and apparent resistivity (ρ_s). The resistivity method of Werner-Schlumberger’s configuration was conducted by gradually changing the current while the distance between the electrodes remains constant). The Werner-Schlumberger’s configuration equation is as follows:

$$K_s = \frac{\pi}{4}\frac{(L^2 - a^2)}{a} \tag{1}$$

$$\rho_s = \frac{\pi}{4}\frac{(L^2 - a^2)}{a}\frac{\Delta V}{I} \tag{2}$$

1.3 Aquifer parameters

Aquifer parameters are frequently used in predicting water storage capacity and estimating flow velocities within each layer (Loke *et al*. 2013). These parameters include resistivity, hydraulic conductivity, and porosity with dependence on each other and are correlated in the construction of a good model. The resistivity of rocks, minerals, soil, and chemical elements is generally obtained through several measurements that can be used as a reference for the conversion process (Telford *et al*. 1991).

Porosity is the proportion of total void space contained in a unit volume of soil allowing the passage and storage of water and air. It determines the amount of water content in the soil and is influenced by the size of the constituent materials. Moreover, soil with high porosity is preferable because it allows plant roots to penetrate the soil more easily while searching for organic matter. This process makes it possible for the soil to receive and hold rainwater. The porosity is calculated using the following equation.

$$\phi = (1 - \frac{\rho_b}{\rho_p}) \times 100\% \tag{3}$$

Where: ρ_b is the Soil Density (gram/cm^3); ρ_p is the density of Particles (gram/cm^3); ϕ is the Soil Porosity (%).

Soil hydraulic conductivity is a parameter which denotes the slow speed of water infiltration or seepage into the soil through horizontal or vertical micropores. It depends on the granular nature of the soil as well as other factors like water bond to clay. Different types of soil have varying hydraulic conductivities (Wagner *et al*. 2001). The conductivity of saturated soil is determined by Darcy’s law:

$$k = \frac{V \times L}{A \times h \times t} \tag{4}$$

Where: V is the volume of water collected (m^3); L is the soil sample length (m); A is the Tube cross-sectional area (m^2); t is the time (second); h is the constant water level in the tube (m); k is the permeability (m/s).

1.4 Data modeling

Porosity and resistivity are linearly related to the logarithm of hydraulic conductivity. In some conditions, the relationship between porosity and *log*(*k*) is weak. In addition to porosity and resistivity, hydraulic conductivity also depends on grain size, sorting and lithology *e.g*. sand against clay while the increased hydraulic conductivity and porosity are strongly influenced by the type of rock (LU Chuan *et al*. 2014). Empirical relationship of porosity (ϕ) and resistivity (ρ) to hydraulic conductivity (k) was obtained from several samples tested in the laboratory using linear relationship of $log(k) = aX_i + b$ (Bechte and Nico, 2017), where Xi indicates porosity and resistivity. Furthermore, the empirical relationship of resistivity (ρ) and porosity (ϕ) was obtained from $\phi = a.\rho^b$ relation. This equation used linear regression to calibrate the model.

2 Results

The soil samples collected in this study are shown in Fig. 3. The peatland soil samples are characterized by brown-black color. In terms of geology, the locations where the measurements were made consist of many peatlands which are valuable environment but with fragile ecosystems, diverse bio-geochemical, and hydrological functions, which requirs non-destructive investigation for characterization (Krüger *et al*. 2017). Peatland soil plays an important role in conserving global carbon storage and contains a huge portion of organic materials. The conversion of peat land soil for any purpose should be minimized to avoid the loss of carbon from the soil to the atmosphere (Powlson *et al.* 2011).

The geoelectric measurements of two villages in Kemuning district, *i.e*. Sekara and Kemuning Muda are depicted in Fig. 4. Several soil layers were found according to the resistivity profile which shows different values for different lithologic types and water saturation. Furthermore, a high groundwater potential zone has been identified in the regolith layer at a depth of 110 m in Sekara and 96 m in Kemuning Muda.

The contour maps of porosity and hydraulic conductivity of the study area are shown in Fig. 5. According to the observation, the location has high porosity to store and conduct water which further influences the hydrology of the peatland as well as the interflow in the subsurface. The geoelectrical monitoring data, in combination with the precipitation and temperature data, indicate that several forces are driving the hydrogeological system of peatland (Sheriff, 2002). In this research, geoelectric measurements were implemented at two locations (Sekara and Kemuning Muda) as described in Fig. 3 to understand the distribution of groundwater.

Fig. 3 Soil sample collection (a) and the collected soil samples (b) the soils are collected from 48 locations in the Kemuning District

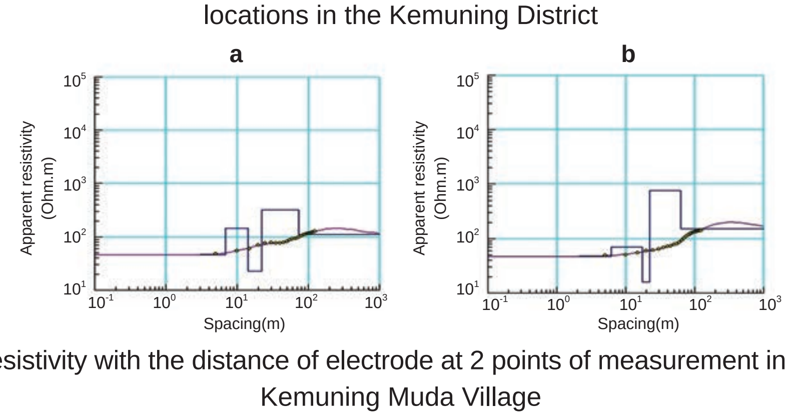

Fig. 4 A plot of resistivity with the distance of electrode at 2 points of measurement in (a) Sekara and (b) Kemuning Muda Village

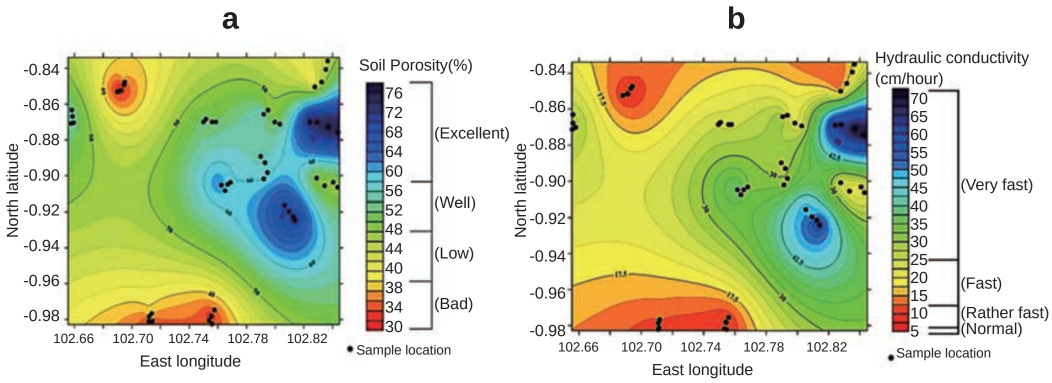

Fig. 5 Contour map of (a) porosity and (b) hydraulic conductivity, created from 48 soil samples in Kemuning district

The peatland was characterized by large variability in the thickness of the deposit over a very small area in each layer. The thickness was further used as a reliable parameter to determine the composition in a layer so that a thicker layer could have a greater potential for groundwater.

3 Discussions

Based on the 1-dimensional data analysis, the depth and type of the groundwater were obtained at two measurement points. At the first point, sands and pebbles were found to have resistivity of 145.59 Ωm in the second layer and 112.47 Ωm in the fifth layer. At the second point of measurement in Kemuning Muda, groundwater was found in the second and fifth layers.

Table 2 Criteria of groundwater potential at Sekara and Kemuning Muda

Resistivity (Ωm)	Type of layer	Depth (m)	Thickness (m)	Location	Potential criteria
145.59	Sand and pebble with enough water	6.88~14.29	7.41	Sekara at Layer 2	Medium
112.47	Sand and pebble with abundant water	73.18~110	36.82	Sekara at Layer 5	Large
70.79	Sand and pebble with enough water	6.20~17.31	11.11	Kemuning Muda at Layer 2	Medium
153.79	Sand and pebble with abundant water	63.38~96	32.62	Kemuning Muda at Layer 5	Large

Furthermore, the groundwater potential is classified into three rankings with the first being the large potential which refers to an aquifer layer with thickness above 20 m. The second is the medium potential, referring to aquifer layers with thickness between 5~20 m. The third is the small potential while the thickness of aquifer layers are less than 5 m. This shows that the prediction of groundwater potential is depending on the thickness and depth of the layer.

Table 2 also shows the groundwater potential increases with depth and thickness of the land. The potential of the shallow aquifer in the district of Sekara and Kemuning Muda was found to be at a depth of over 6 m below the ground level with medium yield. An aquifer at a depth of over 60 m has a higher potential as shown in Fig. 4.

Ground resistivity is associated with several geological media and has been reported to be dependent on the moisture and its distribution pattern in the medium. For the case of peat land, the electrical resistivity depends on water conductivity in the peat pores, moisture content Electric conductivity of the peat matrix depends on the organic and mineral content, mineral composition, degree of peat decomposition, structure and porosity (Muhammad, 2020). Moreover, the variations in electrical resistivity (or conversely, conductivity) typically correlate with the changes in the lithology, water saturation, fluid conductivity, porosity, and hydraulic conductivity of the soil. The maximum depth was found to be sensitive to hydraulic conductivity are shown in Table 3, *i.e.* maximum depth is larger if the conductivity is larger. Thus, the ability of peatland to store water is larger due to the high value of porosity.

Soil samples from Sekara and Kemuning Muda were found to have good quality and medium permeability. The land is able to drain water from the surface to underground layers to recharge groundwater aquifers and also able to discharge water to rivers, ditches and other surface water bodies.

Table 3 Characteristics of hydraulic properties in Kemuning

Location	Porosity (%)	Description of soil porosity	Hydraulic conductivity (cm/h)	Ability to conduct water
Kerintang	55.75	Good	4.91	Medium
Sekara	54.10	Good	4.21	Medium
Kemuning Tua	61.00	Porosity	6.76	Fairly fast
Air Balui	65.22	Porosity	7.63	Fairly fast
Batu Ampar	37.25	Bad	2.31	Medium
Selensen	33.51	Bad	2.10	Medium
Tuk Jimun	71.00	Porosity	9.95	Fairly fast
Kemuning Muda	51.19	Good	3.52	Medium
Lubuk Besar	76.25	Porosity	12.77	Fairly fast
Talang Jangkang	42.10	Porosity	2.70	Medium
Limau Manis	50.72	Good	3.34	Medium
Sekayan	35.75	Bad	2.12	Medium

The criteria for groundwater potential of each layer were determined based on the rocks according to the geological map of the research area and the range of resistivity values which show the water saturation level of a layer. The hydraulic properties in this study are summarized from the soil's physical parameters including resistivity, porosity, and hydraulic conductivity. Moreover, the geoelectric measurements showed that the aquifers in Sekara and Kemuning Muda include a shallow aquifer in the second layer and a deep one in the fifth layer while the sand and pebble layers are of low resistivity to meet the criteria for groundwater potential. The information presented in Table 3 shows high water potential was influenced by surrounding rivers and streams of Indragiri Hilir.

Furthermore, porosity values are positively related to hydraulic conductivities in the soil, which could be explained by the effect of rainfall on the soil.

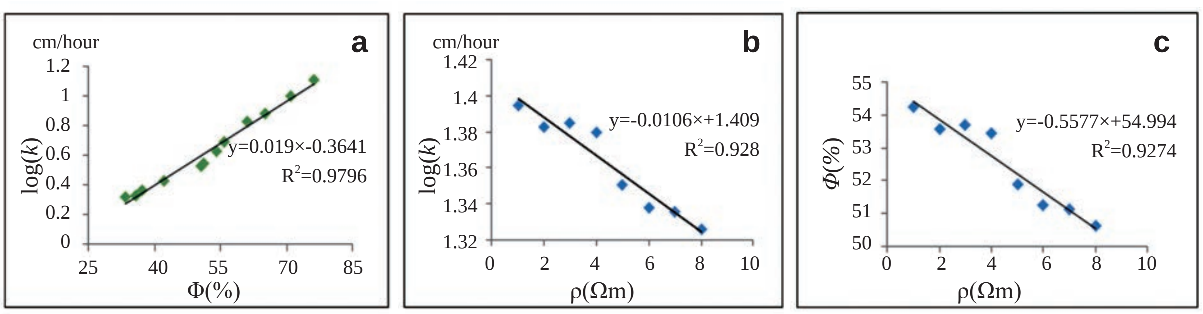

Fig. 6 Relationship among physical parameters of soil in the Kemuning District

a. Relation of hydraulic conductivity and porosity, b. hydraulic conductivity and resistivity, and c. porosity and resistivity

The empirical analysis was conducted to determine the relationship between each pair of physical soil parameters as shown in Fig. 6. The soil porosity and hydraulic conductivity are calculated using Equation (3) and Equation (4), while the resistivity was measured by Werner-Schlumberger's configuration. As mentioned in section 1.2, there are linear relationships among the three parameters. The plot of porosity and hydraulic conductivity to the conductivity *log(k)* shows a linear relationship with the correlation coefficients (R^2) of 0.92 to 0.98. These findings revealed that the soil in Kemuning district is able to store water under subsurface where the presence of porous peatland soil is dominated.

4 Conclusions

In this study, groundwater potential is determined using soil physical parameters such as resistivity, porosity, and hydraulic conductivity. The successful application of Werner-Schlumberger's geoelectric configuration method to determine the resistivity of each soil layer showed that water exists in the soil. The lithology of aquifer layers also showed sand and pebble layers contain fresh water. Moreover, the soils in Kemuning were found to have an average level of porosity and hydraulic conductivity which allows the passage of water at medium speed. It was further discovered that porosity is the main parameter in exploring fresh groundwater in any area that a higher value of porosity generally increases the chances of finding water in the soil. Furthermore, each pair of physical parameters of soil was found to have a linear relationship with high correlation coefficient (R^2) of 0.92 to 0.98.

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