

USING SMOOTHNESS-CONSTRAINT LEAST-SQUARES INVERSION OF SCHLUMBERGER CONFIGURATION RESISTIVITY GEOELECTRIC METHOD TO ANALYZE GROUNDWATER DISTRIBUTION AT PADANG SELATAN

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ABSTRACT

This research aims to analyze the distribution of groundwater in the South Padang area through the application of the Smoothness-Constraint Least-Squares Inversion (SCLSI) method to the Schlumberger configuration geoelectric data. This method was chosen because of its ability to produce a smoother and more accurate resistivity model, and to overcome noise problems in geoelectric data. Measurements were taken at several points with the Schlumberger configuration, which were then processed using SCLSI to map the soil layers and the presence of groundwater. The analysis results showed significant resistivity variations, where areas with low resistivity were identified as potential groundwater accumulation zones. This study makes an important contribution to water resources management, especially in determining the location of exploration and sustainable groundwater management. The results of this study are expected to serve as a reference for the development of groundwater management policies in the area.

Keywords: Groundwater, Resistivity, Schlumberger, Smoothness-Constraint Least-Squares Inversion.

INTRODUCTION

Groundwater is water that fills the spaces and gaps between soil particles [13]. Its presence is highly dependent on rainfall as well as the amount of water that can seep into the ground. The percolating water then combines to form a geological formation known as an aquifer. An aquifer is a layer capable of storing and draining large amounts of water, and its ability depends on the type of rock and soil where the water gathers. Based on the ability to drain water, aquifers can be divided into depressed aquifers and free

aquifers. A free aquifer is a rock formation bounded by impermeable layers above and below, with the groundwater table at the top. This aquifer can trigger landslides, as the water in it can seep out through the groundwater table.

The condition of the soil materials has a significant effect on the flow and amount of groundwater. The amount of water stored in bedrock, sediments and soils depends largely on permeability, which describes the ability of rocks to shed water. The permeability value of a material is influenced by several factors,

including the average pore size. Generally, the grain size of a particle is proportional to its pore size and permeability value; coarse-grained soil layers, such as gravel and sand, have large pore sizes and high permeability, while fine-grained layers, such as clay, have small pore sizes and low permeability. Rocks with high permeability usually also have high porosity, but not all rocks with high porosity have high permeability [8]. The nature of permeability greatly affects the amount of groundwater in a rock layer; low porosity tends to result in low permeability, but high porosity does not necessarily mean high permeability. The connectedness of the space between pores plays an important role in determining the permeability value of a material [11].

The condition of the soil constituent material greatly affects the flow and amount of groundwater. Rocks that can be used as a source of groundwater are rocks that contain spaces between grains or rocks that have high porosity and permeability, and there is a layer of impermeable rock [8]. Sandstones are sedimentary rocks that have high porosity and permeability, this can be seen in Table 1.

Table 1. Permeability values for some materials [10].

Rocks	Permeability
Clay	0,0005
Sand	50
Gravel	5000
Gravel & Sand	500
Sandstone	5
Limestone, shale	0,05
Quartzite, granite	0,0005

Table 2: Specific resistance values of various minerals [17].

Minerals	Resistivity(Ω m)
Precipitation	30 – 1000
Surface waters, in areas of	30 – 500
Surface waters, in areas of	10 – 100
Groundwater, in areas of	30 – 150
Groundwater, in areas of	1 – 100
Sea water	0,2
Drinking water (max. salt	>1,8

Water for irrigation and stock watering >0,65

RESEARCH METHOD

Groundwater distribution can be predicted using geoelectric methods. One of the commonly used techniques to measure electricity flow and analyze subsurface geological conditions is the resistivity method. Resistivity is a physical property that describes a rock's ability to conduct electric current; the harder the rock is to conduct electricity through, the higher the resistivity value. The resistivity of a material measures how effectively it inhibits the flow of electricity. Resistivity variations differ greatly between materials, so resistivity measurements on unknown materials can provide valuable information for material identification with little additional data [16]. Resistivity values can be seen in Table 3.

Tabel 3. The Resistivity of Rocks[20]

Rocks	Resistivity Values(Ω m)
Andesite	4.5×10^4 (wet) – 1.7×10^2 (dry)
Sandstone	$1 - 6.4 \times 10^8$
Limestone	$0 - 10^7$
Consolidated shale	$0.2 - 10^3$
Clays	1-100
Granite	$3 \times 10^2 - 10^6$
Dolomite	$3.5 \times 10^2 - 5 \times 10^3$
Tuffs	2×10^3 (wet) – 10^5 (dry)
Alluvium and Sand	10-800

Resistivity can be utilized to estimate subsurface geological conditions by leveraging the conductive properties of rocks when an electric current is applied [15], [20]. By introducing an electric current into the ground, the type of rock and other subsurface parameters can be identified. Figure 1 provides an overview of the electric current distribution in the subsurface.

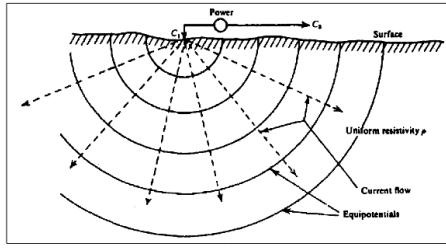


Figure 1. Point source of current at the surface of a homogeneous medium[20]

Figure 1 illustrates the flow of current from an electrode, which spreads in all directions and forms an equipotential hemisphere beneath the earth's surface. This spreading occurs perpendicular to the direction of the current and electric field, assuming the earth is electrically homogeneous and isotropic [16]. Since air has an extremely high specific resistance, currents do not flow through it. The earth is composed of layers, each with distinct specific resistance values that vary between layers [3]. The apparent resistivity value can be determined using Equation (1)

$$\rho_a = K \frac{\Delta V}{I} \quad (1)$$

K is a geometry factor whose value depends on the type of electrode configuration used. In this study, the Schlumberger configuration is employed, where the distance between the current electrodes is greater than that of the potential electrodes. The arrangement of the Schlumberger array is illustrated in Figure 2.

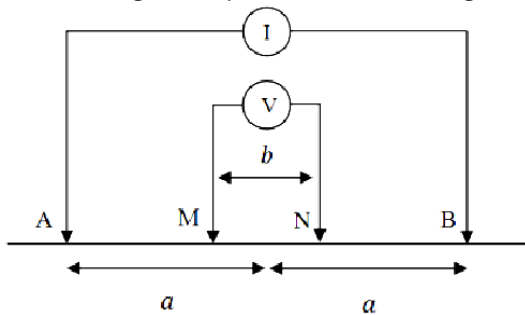


Figure 2. Schlumberger Array

Figure 2 presents the equation along with the corresponding labels: A represents the positive current electrode, B represents the negative current electrode, M represents the positive potential electrode, and N represents the negative potential electrode. The geometry factor can be calculated using Equation (2)

$$K = \frac{\pi(L^2 - l^2)}{2l} \quad (2)$$

Where $L=AB/2$ is half of the current electrode distance, $l=MN/2$ is half of the potential electrode distance. If Equation (2) is substituted into Equation (3), the apparent density resistance formula for the Schlumberger configuration geoelectric method can be obtained as follows:

$$\rho_a = \frac{\pi(L^2 - l^2)}{2l} \frac{\Delta V}{I} \quad (3)$$

Interpretation of apparent resistance values obtained during the measurement is done with the inverse Smoothness - Constraint Least Squares method. This method is an inversion method that tends to produce a model with smooth variations in resistivity values [11]. This method is formulated with the following equation:

$$(J^T J + \lambda F) \Delta q = J^T g - \lambda F q \quad (4)$$

Where q is the model resistivity values, J is the Jacobian matrix, λ is the damping factor, Δq is the model parameter change vector and g the discrepancy vector $F = \alpha_x C_x^T C_x + \alpha_y C_y^T C_y + \alpha_z C_z^T C_z$. where C_x , C_y and C_z are the smoothing matrices, α_x , α_y , and α_z are the relative weights assigned to the smoothnet filters.

The advantage of this method is that in addition to producing smooth resistivity values, the damping factor and filter can be adjusted to various types of data. Damping factor is a variable related to the process of dampening instability that may arise due to data limitations in underdetermined inversion [1]. Damping factor can be determined by trial and error. To minimize the error, a small value of damping factor can be used.

This research is an exploratory study. Data were collected through direct surface measurements using the Schlumberger Configuration Geoelectric Resistivity Method and the ARES tool, resulting in four successful passes. The data were interpreted using the Smoothness-Constraint Least Squares Inversion Method. Measurements were conducted by moving the current electrode along the cross-section while keeping the potential electrode distance fixed [2]. Subsequently, the potential electrode was shifted to the next n spacing, followed by the movement of the current

electrode, continuing this process until the final measurement point on the track was reached. The resistivity data were used to determine the distribution and depth of groundwater. The measurement locations are illustrated in Figure 3.



Figure 3. Measurement Location

Track 1 is located at coordinates 00° 58' 0.54" LS and 100° 22' 14.5" East to coordinates 00° 58' 3.7" LS and 100° 22' 10.3" East. Track 2 is located at coordinates 00° 58' 08.7" LS and 100° 22' 10.3" East to the coordinates 00° 57' 58.9" LS and 100° 22' 10.2" East. The sounding point is located at coordinates 00° 58' 3.7" LS and 100° 22' 10.3" East. Track 3 is located at coordinates 00° 58' 08.3" N-S and 100° 22' 07.0" East to coordinates 00° 58' 09.1" N-S and 100° 22' 13.6" East. The sounding point of track 3 is located at the coordinates 00° 58' 08.2" N-S and 100° 22' 10.0" East. Traverse 4 is located at coordinates 00° 58' 00.4" LS and 100° 22' 06.5" East to the coordinates 00° 57' 55.9" LS and 100° 22' 12.1" East. The sounding point of track 4 is located at 00° 57' 58.6" N-S and 100° 22' 09.3" East.

The collected data have been processed up to the data processing stage. The steps involved in processing the data are as follows:

- Download the data from the ARES Multi-electrode system by connecting it to a Windows XP interface.
- Save the data in *.dat file format.
- Integrate topography data into the resistivity data to generate an inversion that incorporates topographic features.
- Convert field data into model data using the Smoothness-Constraint Least Squares method with the assistance of RES2DINV software to determine specific resistivity values and groundwater depth.
- Save the inversion image in BMP format.

- Perform data estimation using a reference table of rock resistivity values and geological condition maps of the measurement area.

After processing, the data needs to be estimated by comparing the interpretation results with Table 1 and geological conditions. Based on this, the two-dimensional subsurface resistivity value and depth will be known. The inversion result is a two-dimensional cross section that has shown the relationship between line length and depth.

RESULT AND DISCUSSION

In this regard, the objective of this study is to analyze groundwater distribution and depth in South Padang. To achieve this objective, groundwater distribution and depth will be identified through four measurement passes. Results and discussion will be presented by track.

Line 1

Line 1 is located at coordinates 00° 58' 0.54" LS and 100° 22' 14.5" East to coordinates 00° 58' 3.7" LS and 100° 22' 10.3" East, with a track length of 295 m and using an electrode spacing of 5 m. The applied damping factor is 0.01. The applied damping factor is 0.01. The elevation of Track 1 ranges from 72 to 123 m above sea level (msl), with the penetration depth reaching 58.7 m. The 2D cross-sectional results of Track 1 can be seen in Figure 4.

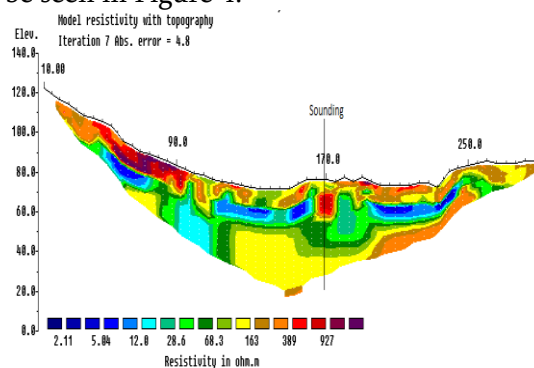


Figure 4. Subsurface Profile of Line 1 with Topography

The condition of the soil material has a significant influence on the flow and quantity of groundwater. Rocks that can function as groundwater sources are those that have space between grains or that have a high level of

porosity and permeability, and are covered by impermeable rocks [8], with resistivity values of $1 - 6.4 \times 10^8 \Omega\text{m}$ [20], [3], [7], [14], [18].

Groundwater distribution in Track 1 at point $y = 45 - 75 \text{ m}$ was detected at a depth of $11.9 - 22.9 \text{ m}$ with a thickness of 11 m . At point $y = 92 - 108 \text{ m}$, groundwater distribution was found at a depth of $22.9 - 40.3 \text{ m}$ with a thickness of 17.4 m . At point $y = 92 - 108 \text{ m}$, groundwater distribution was found at a depth of $22.9 - 40.3 \text{ m}$ with a thickness of 17.4 m . At point $y = 117 - 142 \text{ m}$, groundwater distribution is at a depth of $11.9 - 22.9 \text{ m}$ with a thickness of 11 m . At point $y = 148 - 152 \text{ m}$ and point $y = 194 - 249 \text{ m}$, groundwater distribution is found at a depth of $11.9 - 22.9 \text{ m}$ with a thickness of 11 m each. From the entire length of Track 1, the maximum depth of groundwater is located at point $y = 92 - 108 \text{ m}$, which is $22.9 - 40.3 \text{ m}$ with a thickness of 17.4 m . Specific resistance values between $2.1 - 20 \Omega\text{m}$ are thought to indicate layers containing groundwater, because these values are relatively low and are found in rocks that have high porosity and permeability. The direction of groundwater movement in Track 1 moves from the northeast to the southwest, in line with the bedrock structure that also points in the same direction.

Line 2

Line 2 is located at coordinates $000 58' 08.7'' \text{ LS}$ and $1000 22' 10.3'' \text{ East}$ to the coordinates $000 57' 58.9'' \text{ LS}$ and $1000 22' 10.2'' \text{ East}$. The sounding point is located at coordinates $000 58' 3.7'' \text{ LS}$ and $1000 22' 10.3'' \text{ East}$. The length of track 2 is 305 m with electrode spacing of 5 m . Track 2 has an altitude between $63 - 107 \text{ meters}$ above sea level and a depth of up to 58.7 m . The results of the 2D cross section of Track 2 can be seen in Figure 5.

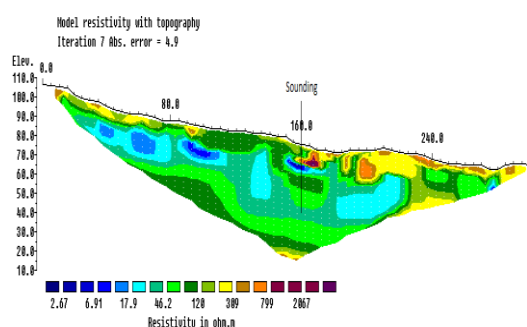


Figure 5. Subsurface Profile of Line 2 with Topography

Rocks that can function as groundwater sources are those that have space between grains or that have a high level of porosity and permeability, and are coated by impermeable rocks [8], with a resistivity value of $1 - 6.4 \times 10^8 \Omega\text{m}$ [20], [3], [7], [14], [18].

The distribution of groundwater in line 2 at point $y = 28 - 80 \text{ m}$ was detected at a depth of $6.3 - 20 \text{ m}$ with a thickness of 13.7 m . At point $y = 84 - 104 \text{ m}$, groundwater distribution was found at a depth of $9.6 - 17 \text{ m}$ with a thickness of 7.4 m . At point $y = 118 - 130 \text{ m}$, groundwater distribution is at a depth of $9.6 - 34.4 \text{ m}$ with a thickness of 24.8 m . At point $y = 150 - 175 \text{ m}$ and point $y = 182 - 221 \text{ m}$, groundwater distribution was found at depths of $11.9 - 14.9 \text{ m}$ and $11.9 - 38 \text{ m}$ with thicknesses of 3 m and 26.1 m respectively. From the entire length of Track 2, the maximum depth of groundwater is located at point $y = 182 - 221 \text{ m}$, which is $11.9 - 38 \text{ m}$ with a thickness of 26.1 m . The direction of groundwater movement in Traverse 2 is from west to east. This is influenced by the structure of the constituent bedrock from west to east. So that the subsurface water flow pattern will flow in the direction of the constituent bedrock structure.

Line 3

Line 3 is located at coordinates $000 58' 08.3'' \text{ LS}$ and $1000 22' 07.0'' \text{ East}$ to the coordinates $000 58' 09.1'' \text{ LS}$ and $1000 22' 13.6'' \text{ East}$. The sounding point of traverse 3 is located at the coordinates $000 58' 08.2'' \text{ N-S}$ and $1000 22' 10.0'' \text{ East}$. The length of line 3 is 235 m with the electrode spacing used is 5 m . Line 3 has an altitude of $92 - 137 \text{ meters}$ above sea level and a depth of 49.4 meters . The results of the 2D cross section of Track 3 can be seen in Figure 6.

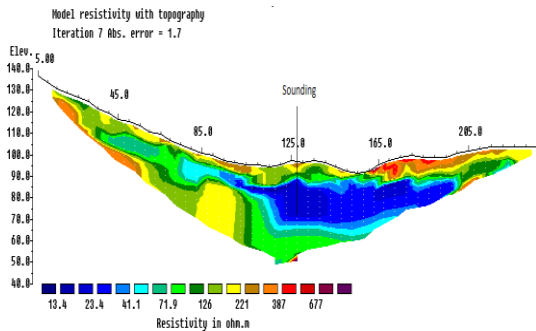


Figure 6. Subsurface Profile of Line 3 with Topography

Rocks that can function as groundwater sources are those that have space between grains or that have a high level of porosity and permeability, and are coated by impermeable rocks [8], with a resistivity value of $1 - 6.4 \times 10^8 \Omega m$ [20], [3], [7], [14], [18].

Groundwater distribution in line 3 at point $y = 77 - 200$ m was detected at a depth of $3 - 34$ m with a thickness of 31 m. The direction of groundwater movement in Trajectory 3 is from the Northeast to the Southwest. The direction of groundwater movement in Trajectory 3 is from the northeast to the southwest. This is influenced by the structure of the constituent bedrock leading from the Northeast to the Southwest. So that the subsurface water flow pattern will flow in the direction of the bedrock structure.

Line 4

Traverse 4 is located at coordinates $00^\circ 58' 00.4''$ N-S and $100^\circ 22' 06.5''$ East to the coordinates $00^\circ 57' 55.9''$ N-S and $100^\circ 22' 12.1''$ East. The sounding point of track 4 is located at $00^\circ 57' 58.6''$ LS and $100^\circ 22' 09.3''$ East. The length of track 4 is 244 m with the electrode spacing used is 4 m. The results of the 2D cross section of Track 4 can be seen in Figure 7.

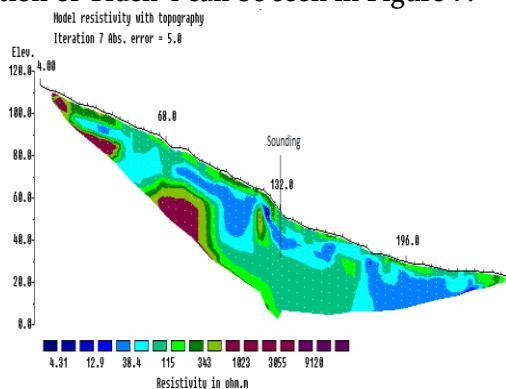


Figure 7. Subsurface Profile of Line 4 with Topography

Rocks that can function as groundwater sources are those that have space between grains or that have a high level of porosity and permeability, and are coated by impermeable rocks [8], with a resistivity value of $1 - 6.4 \times 10^8 \Omega m$ [20], [3], [7], [14], [18].

The distribution of groundwater in line 4 at point $y = 22 - 66$ m was detected at a depth of $3 - 21.7$ m with a thickness of 18.7 m. At point $y = 72 - 232$ m, groundwater distribution was found at a depth of $3 - 35$ m with a thickness of 32 m, and is the maximum depth of groundwater on line 4. The direction of groundwater movement on Track 4 is from the Northeast to the Southwest. This is influenced by the structure of the constituent bedrock leading from the Northeast to the Southwest.

CONCLUSION AND SUGGESTION

Based on the results obtained from this research, several conclusions can be drawn that, the distribution of groundwater with a range of specific gravity values of $2.6 - 20 \Omega m$ can be found on Tracks 1, 2, 3 and 4. The pattern of groundwater distribution on parallel tracks, namely Tracks 1, 3, and 4, each tends to lead from the Northeast to the Southwest. The groundwater distribution pattern on the tie track, Track 2, is from West to East.

Groundwater distribution in Trajectory 1 can be found at a depth of $11.9 - 40.3$ m. Track 2 groundwater distribution can be found at a depth of $6.3 - 38$ m. Trajectory 3 groundwater distribution at a depth of $3 - 34$ m. Groundwater distribution in Trajectory 4 is found at a depth of $3 - 35$ m.

The aquifer type of groundwater distribution in Trajectory 1 is a free aquifer at a distance of $45 - 75$ m. Distance $92 - 249$ m aquifer type is a depressed aquifer. Trajectory 2, 3, and 4 aquifer types were found to be depressed aquifers.

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