Physical Soil Parameter and Resistivity Profile in the Vadose Zone: Preliminary Result of Groundwater Recharge Study

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Abstract. In tropical-volcanic-dominated areas, such as Java Island in Indonesia, aquifer recharge is highly impacted by rainfall intensity and soil characteristics. The first stage of recharge begins with the soil surface's response to rainwater until it percolates to the deep layer. The primary objective of this research was to study groundwater recharge processes from the soil surface to deep percolation in the volcanic deposit at the northwest flank of Mount Pangrango, West Java, Indonesia. The present study also includes the 2D geoelectrical survey results combined with the soil core drilling. A vertical undisturbed soil profile 4 to 4.5 meters deep was drilled to determine parameters such as soil water content, total porosity, permeability, organic content, and soil texture. Results from core drilling activities confirmed that resistivity values are in the range of 80 to 360 ohm.m, which is related to wet soil layers at 1 to 4 meters below the surface. It is found that the most significant difference between organic and mineral soils in terms of resistivity value is that of organic content. Depth and radius of *Pinus merkusii* and *Melia azedarach* tree according to resistivity and soil drilling result confirmed at 2.5; 4.5 meter and 0.9; 2.2 meters respectively. By profiling these factors, the behavior of water movement may be better described, allowing the net recharge rate from rainwater to the water table in the unsaturated zone to be estimated.

1 Introduction

The extensive use of groundwater for human needs, industries, and agriculture has had a significant impact on groundwater availability and quality. Land-use changes for industrial and urbanization reasons have reduced rainwater infiltrating the soil while increasing surface runoff as stormwater. Rainwater also percolates deeper into the soil layer, stored as groundwater. Since this process took a long journey, their occurrences in aquifers are prone

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to decrease due to natural and anthropogenic factors. Eventually, a comprehending groundwater recharge initiative becomes a fundamental task in managing groundwater resource sustainability on a watershed scale [11].

The first stage of recharge begins with the soil surface's response to rainwater. Physical soil parameters such as porosity and permeability (hydraulic conductivity) control rainwater movement in an unsaturated or vadose zone which is generally defined as an intermediate area between the soil surface and the water table. Vadose zone thickness varies from several centimeters to hundreds of meters, depending on the depth of the water table [1]. Rainwater infiltrates into soil layers stored as soil water, which creates moisture content relative to changes in temperature and precipitation rate. Therefore, this zone is not always saturated but tends to fluctuate due to changes in moisture content. In soil, less than two meters deep or more, tree roots continually use soil water for their nutrient uptake and transpiration of CO_2 - O_2 exchange [2]. Tree roots play a pivotal role in disseminating soil water distribution from a few centimeters to several meters in both lateral and vertical sections of the soil layers [3]. Therefore, concerning the deep percolation process of soil water to reach the water table, the initial hypothesis was that a net recharge should be calculated after the soil water passthrough zone of tree roots.

Tree roots also known as rhizosphere are part of the vadose zone, which has continuously been studied as a multi-disciplinary approach in hydro(geo)logy, eco-hydrology, and soil-plant science due to its complexity and reclaimed status as the critical part that poses potential threats to the saturated or water table beneath [4,5,6]. Invasive methods such as Induced Polarization, Electrical Tomography, and Ground Penetrating Radar have been used to characterize spatial tree root zone distribution and also compare it with the soil's physical properties, notably soil water content, permeability, and total porosity [7,8,9], hence the evaporation and or percolation processes can be approached by simulating numerically the soil properties profile [10,11,12]. This paper describes the finding of an early result of electrical resistivity tomography measurement to map tree root zone combined with soil properties collected using core drilling at a surface area where two types of tree species were planted: *Pinus merkusii* and *Melia azedarach*, in volcanic environments.

1.1 Site description

The study area is located at the agro-forestry conservation park with an elevation of 800 meters above sea level, on the northwest flank of the Quaternary Pangrango mountain in Bogor, West Java Province, Indonesia. Meteorological and Geophysical Agency (BMKG) rainfall statistics from 2010 to 2017 show that the average annual rainfall is around 3,000 mm. The rainy period usually occurs from September to April and enters the short rainfall period from May to August, the lowest rainfall rate is in June or July, 150 mm/month. The maximum and minimum temperature were 30 °C and 22 °C, respectively, with an annual average humidity of 90% in 2022.

According to the geological map of the Bogor sheet [17], the western part of the study area is composed of tuffaceous breccia, lapilli tuff, and andesitic lava. Soil texture is dominated by silty clay and clay as a product of volcanic rock weathering, mainly lapilli tuff. In the study location, unconfined aquifers are dominated by tuff breccia, the water table height follows the elevation of the topography; the average water table from dug wells is from 1 to 8 meters below ground level at elevations less than 450 meters and 10 to 15 meters at elevations from 500 to 650 meters above sea level. None of the water tables were found at

an elevation of 700 meters, instead of contact spring sources being used as the primary water supply for the village community.

2 Material and Methods

This research employed two methods: resistivity in two dimensions (2D) and drilling undisturbed soil. The main objective of resistivity measurement was to identify the tree root radius and depth while undisturbed soil drilling was carried out to assess physical soil parameters conducted in the Indonesian Centre for Biodiversity and Biotechnology (ICBB) laboratory in Bogor. The equipment for resistivity measurement was an IRIS Syscal Pro with 64 electrodes, spaced 50 cm apart, and a line length of 31.5 meters. Two array configurations were applied: Wenner-Schlumberger and multiple gradients [13]. Data processing was done using Res2dinv version 4.11, and a least squares inversion method was applied with an RMS error of 0.5–1.2% for seven-time iterations. Measurement was commissioned during the rainy season from October 17 to 21, 2022 where the *Pinus Merkusii* and *Melia azedarach* trees were planted in the area, both trees being 170 meters apart.

Undisturbed soil sampling was conducted using a portable hydraulic rig with a drill rod diameter of 42 mm x 1.5 meters and a core barrel diameter of 46 mm. The method involved hydraulically pushing and rotating the core barrel into the soil until reached a maximum length of 50 cm before switching to a different core barrel for the following depth of up to 4 to 5 meters according to resistivity data measurement. The drilled hole was inserted with a 2-inch PVC screen 50 cm below for further analysis e.g. infiltration test [14]. All the soil inside the barrel was coated with paraffin on both sides and wrapped to prevent evaporation before testing in the laboratory, notably for soil water content, organic content, total porosity, and permeability.

Fig. 1. Study location for resistivity measurement and soil sampling at agroforestry park, Bogor.

Fig. 2. Soil core drill rig and samples conservation in tube size 46 mm for laboratory analysis.

According to [15] and [16] root radius (r_{radius}) and depth (r_{depth}) from the stem diameter can be estimated as:

$$r_{radius} = 5.9(dbh)^{0.59} \quad \ldots(1)$$
$$r_{depth\ in\ (feet)} = 0.3x(dbh)_{in} \ldots(2)$$

dbh is the diameter stem height that measured 1.3 meters from the ground.

3 Result and Discussion

The resistivity result is shown in Figure 3 and 5. Maximum depth of about 6 meters for each line. The rainfall rate that occurred in October was 500 mm; it frequently rained between 2 p.m. and 5 p.m. during the measurement date.

3.1 Tree root resistivity

Tree root zone resistivity value is interpreted differently for *Melia azedarach* (planted in 2018) and *Pinus merkusii* (planted in 1984). The Melia stem diameter was 0.27 meters with heights up to 5 to 7 meters. Applying equations (1) and (2), the tree depth and radius estimation are 0.9 and 2.2 meters, respectively, with resistivity ranging from 80 to 360 ohms. This tree has a surface root system that appears when the soil is trenched at about 20 cm in depth and 2 meters in radius, as shown in Figure 4.

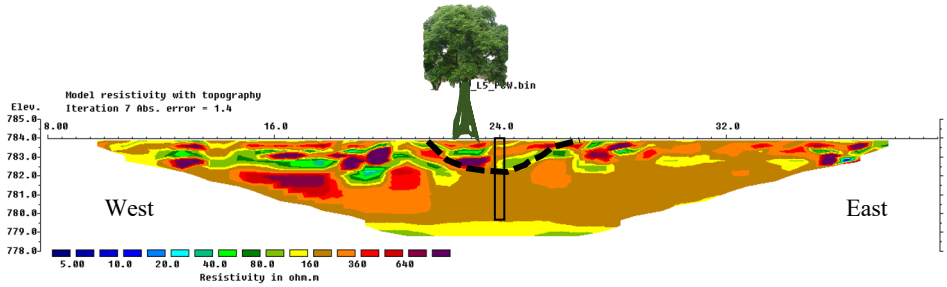

Fig. 3. Resistivity inversion in the west to the east direction at *Melia azedarach* tree, undisturbed soil sampling marked as a straight line at electrode #24, 1 meter from tree stem. The tree root zone is indicated as a black dashed line with a depth of about 0.8 meters and a radius of 2.2 meters.

Fig. 4. An example of another Melia tree root in the trenched soil, visibly 20 cm below the surface.

The Pinus stem diameter measured was 0.7 meters and varies with each tree; the height was 15–20 meters in approximation. It is known for taproot systems where a strong main root descends vertically from underneath the trunk and is distributed laterally. Since it was planted 40 years ago, the structure beneath the trunk confirms relatively high water content with a resistivity value ranging from 40 to 360 ohm. When the soil was drilled, a tree root was discovered inside the barrel when drilling ran from 2 to 3 meters deep. Therefore, radius and depth estimation using equation (1) and (2) look to match positively with the Pinus tree case.

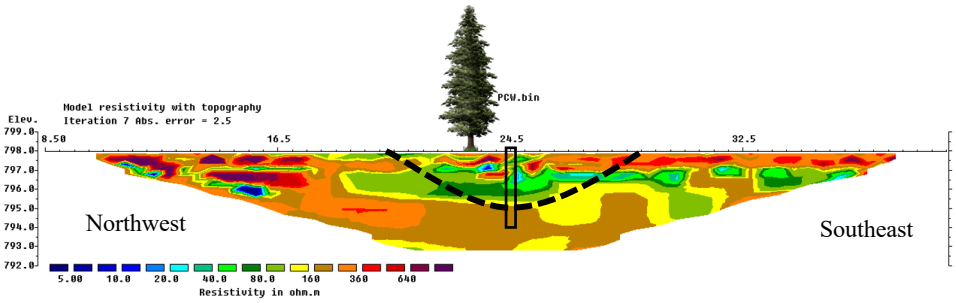

Fig. 5. Resistivity inversion in relative northwest to southeast direction at *Pinus merkusii* tree, undisturbed soil sampling marked as a straight line at electrode #24.5, 1 meter from tree stem. The tree root zone is indicated as a black dashed line with a depth of around 2.5 meters and a radius of 4.5 meters.

3.2 Physical soil parameters

Undisturbed soil samples were analyzed at the Indonesia Centre for Biodiversity and Biotechnology (ICBB) laboratory in Bogor. Table 1 summarizes the findings of the *Melia azedarach* and *Pinus merkusii* tree physical parameters in a vertical direction, amongst other gravimetric water content, permeability, total porosity, and organic content. The constant head method was used to measure permeability, while total porosity was calculated by comparing bulk density to soil particle density in percentage, and organic content was calculated using the Walkley and Black method [18]. The predominant soil textures are clay

and silty clay, which is consistent with the low vertical values for the permeability of both trees.

Table 1. Physical soil parameters result.

Depth (cm)	Gravimetric water content (%)		Permeability (cm/s)		Total porosity (%)		Organic content (%)	
	Melia azedarach	*Pinus merkusii*	*Melia azedarach*	*Pinus merkusii*	*Melia azedarach*	*Pinus merkusii*	*Melia azedarach*	*Pinus merkusii*
50	38.72	45.32	2.92E-06	3.08E-06	59.50	61.99	0.42	2.40
100	38.45	47.12	1.83E-06	3.06E-06	53.06	61.93	0.42	1.42
150	34.22	40.11	1.61E-06	2.56E-06	50.97	56.70	0.17	1.02
200	45.42	36.57	2.81E-06	2.64E-06	55.63	55.49	0.00	1.32
250	28.35	34.27	2.61E-06	2.53E-06	49.31	53.57	0.00	0.74
300	30.11	33.18	1.53E-06	3.53E-06	49.23	55.71	0.00	0.21
350	32.43	38.25	1.92E-06	4.31E-06	51.55	54.50	0.12	0.81
400	29.53	37.92	1.47E-06	4.50E-06	48.86	54.09	0.21	0.00
450	22.65	35.68	4.64E-06	4.75E-06	52.04	53.58	0.00	0.00

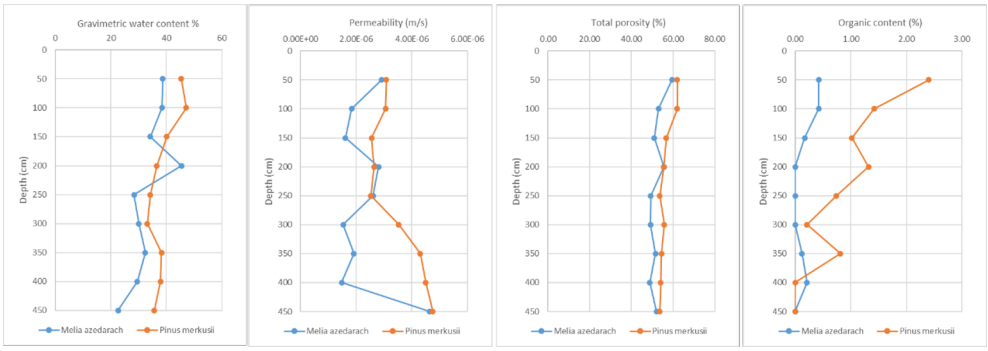

Fig. 6. Vertical soil parameter profile comparison between *Melia azedarach* and *Pinus merkusii*.

Although the organic content profiles of the two trees are identical and decrease from top to bottom (Figure 6), the Pinus soil has a higher organic content than the Melia tree, or, in other words, Melia's soil tends to be categorized as a mineral soil type. Due to the richness of organic material filling the soil's void between 50 and 250 cm deep, soil permeability decreased. Conversely, from 300 to 450 cm, organic content is slightly lower than increased permeability. This is uniquely made up because the Pinus tree has been around for 40 years and has long adapted to the environment where it was planted, including the soil humification process, compaction, and root development for water uptake, which grows significantly to redistribute water from soil layers to the xylem. The tree gets nourishment through the roots' absorption of nutrients and moisture, which helps the tree grow. On the other hand, the *Melia azedarach* tree is richer in mineral soil resulting from the weathering of rocks. Due to the presence of organic soil, the Pinus tree's soil water content and total porosity had a better correlation with one another than the Melia tree's.

4 Conclusion

Our result shows that imaging the tree root zone is possible with a resistivity measurement utilizing a multi-electrode space of 50 cm. A comparison between the factual soil core from 50 to 450 cm and the resistivity improves the understanding of the physical soil's role in managing root water uptake and its response to absorbing rainwater into the soil. An additional significant finding of this preliminary study was the organic soil content, which can differentiate between organic and mineral soil types. The information on the physical characteristics of the soil is consistent with the hypothesis that precipitation recharges the water table after passing through the zone of the tree roots.

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