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Effect of Land Use on Soil Water Storage in the Effective Depth (0–60 cm) Using the Water Balance Method

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ABSTRACT

Land use changes significantly impact groundwater storage, which is crucial for maintaining ecosystem balance and supporting agriculture. This study aims to evaluate groundwater storage capacity across various land uses in the Gunting Sub-watershed, Wonosalam District, Jombang Regency, East Java. Field surveys and soil sampling were conducted across three land use types: pine-coffee agroforestry, pine monoculture, and annual crops at effective soil depths (0-60 cm). The study was conducted using a water balance method and lasted for one year, from August 2022 to July 2023. Water balance components consisting of effective rainfall, surface runoff, percolation, and evapotranspiration, as well as soil properties such as organic carbon content, porosity, and texture, were analyzed. The results showed that agroforestry had the highest water storage (370,863.44±176.67 mm/year), followed by pine monoculture (307,153.36±229.98 mm/year), and annual crops (239,497.30±222.26 mm/year). Statistical tests showed that differences between land uses were not significant ($p > 0.05$). Organic matter content was the dominant factor influencing soil water storage ($R^2 = 0.9189$), followed by porosity ($R^2 = 0.3019$) and clay fraction ($R^2 = 0.0172$). All land use types showed a positive water balance throughout the year, with peak water storage occurring in February–May.

1. INTRODUCTION

The concept of the hydrological cycle demonstrates that water storage can fluctuate and can be determined using the water balance equation, which is the ratio between the amount of water entering and leaving a land area over a specific period. The water balance describes the relationship between inflow and outflow during a specific period of the water circulation process (Paski *et al*., 2018). Rainfall, evapotranspiration, soil physical properties, and vegetation type are crucial factors in determining water storage in the soil. The land water balance, used on agricultural land, is useful as a basis for determining crop types, regulating planting seasons, and quantifying irrigation needs.

Land use plays a crucial role in hydrological processes because it influences infiltration and evapotranspiration. Changes in land use result in a decrease in the baseflow index. The lower the vegetation cover, the smaller the groundwater contribution to river flow, which reduces groundwater storage capacity (Yusuf *et al*., 2021). The extent of interception is influenced by vegetation type, canopy density, and rainfall intensity and duration (Asdak, 2023). Plants with larger stems have greater stem flow potential than annual plants or shrubs (Ata *et al*., 2015).

Globally, forest land conversion has been shown to cause significant changes in annual surface runoff and flood discharge, by 45±14% and 16±5.5%, respectively (Guzha *et al*., 2018). Land use change in Wonosalam District, Jombang Regency, is a significant concern, given that this area is one of the upstream areas of the Brantas River, dominated by livestock and agricultural activities with high potential. Between 2009 and 2014, agricultural land use decreased by 0.389% and plantations by 1.511%, while residential areas increased by 2.278%. These changes were accompanied by a 35.15% increase in flood discharge (Wirosoedarmo *et al*., 2020).

Land cover changes from forest to residential and agricultural areas have led to significant increases in runoff (Nurhamidah *et al*., 2018). Surface runoff occurs when water infiltration into the soil is hampered by low infiltration, while rainfall intensity exceeds the soil's infiltration capacity, resulting in surface flow (Rizkiah *et al*., 2015). The next stage in the hydrological cycle is percolation, the movement of water through the saturated zone to deeper layers. Percolation rates in well-managed, heavy clay soils can reach 1–3 mm per day, while in lighter soils, percolation rates can be faster (Bella *et al*., 2018).

Although numerous studies have been conducted on the relationship between land use change and hydrological response, most research has focused on large watershed scales or on specific hydrological parameters, such as flood discharge. Studies specifically measuring groundwater storage capacity at an effective depth (0–60 cm) using a water balance approach in areas with a mix of agricultural, plantation, and residential land uses, such as Wonosalam District, are still limited.

The novelty of this research lies in the use of a water balance equation to estimate groundwater storage capacity at an effective depth (0–60 cm) across various land uses, as well as identifying periods of groundwater surplus and deficit throughout the year. This approach yields more detailed quantitative information than previous studies and can serve as a scientific basis for water conservation-based land management strategies.

The study aimed to assess groundwater storage capacity at an effective depth (0–60 cm) over one year in pine-coffee agroforestry, pine monoculture, and annual crops. Through this approach, it is hoped that the land use types with the best groundwater storage capacity will be identified. Furthermore, the study aims to identify periods of groundwater deficit and surplus throughout the year, which are closely related to fluctuations in rainfall and water demand on the land. This is expected to serve as a useful reference for farmers in implementing agricultural activities, particularly determining planting times and soil and water conservation activities.

2. MATERIALS AND METHODS

2.1. Research Location and Time

The research was conducted in the Gunting Sub-watershed, Wonosalam District, Jombang Regency, East Java, from August 2022 to July 2023. Wonosalam District has an average elevation of 500-600 meters above sea level, with an average annual rainfall of 2,361 mm. Wonosalam District has a total area of 72.74 km^2, most of which is used for agricultural land (gardens, dry fields, and rice fields) and livestock (dairy cattle, goats, and chickens). The slope gradient at the research site ranges from 16-56%.

2.2. Equipment and Materials

The equipment and materials used for the research included soil sampling equipment (soil auger, sample ring, camera, GPS, clinometer, and roll meter). Equipment and materials for determining soil chemical and physical properties (organic carbon, texture, porosity, and water content) included drying oven, analytical balance, and spectrophotometer.

2.3. Research Methods

The research was conducted by surveying several land use units. The basis for determining land use units is based on land use, some of which are as follows Table 1. Field survey and soil sampling activities were carried out using a purposive random sampling method, namely random sampling. The survey was conducted on three types of land use units (SPL) with three replications, resulting in 9 observation areas. Observations and soil sampling were carried out three times on each land, resulting in 27 sampling points. Soil sampling was carried out at three depths: 0–20 cm, 20–40 cm, and 40–60 cm. Samples for porosity analysis were taken using a 48 mm diameter and 65 mm high sample ring. Meanwhile, for other parameters, a soil auger was used. Soil samples for the actual water content parameter were tightly wrapped to minimize the risk of evaporation before the analysis and drying process in the oven. Observation points can be seen in Figure 1.

Table 1. Land use, main crop, and sampling location coordinates

Land Use	Main Commodity	Sampling Location Coordinates
Pine-coffee agroforestry	Coffee	7°41’23” S, 112°22’51” E
Pine monoculture	Pine	7°41’20” S, 112°22’59” E
Annual cropping	Maize	7°41’35” S, 112°21’51” E

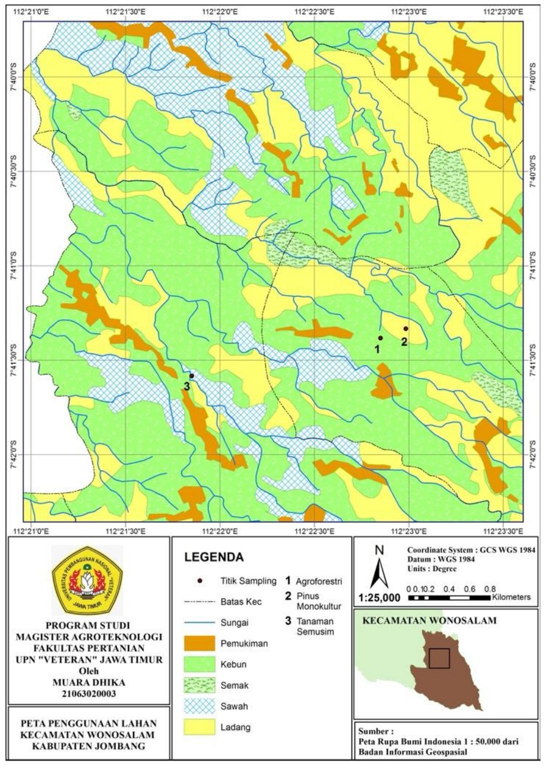

Figure 1. Land use map of Wonosalam District, Jombang Regency

2.4. Field Observation Parameters

Based on the water balance components, rainfall is a relatively difficult, if not impossible, component to modify. Therefore, to increase the amount of water stored in the soil, it can be regulated through (1) effective rainfall, (2) evapotranspiration, (3) surface runoff, and (4) percolation.

Effective rainfall is calculated by subtracting daily rainfall from interception, where interception is the sum of rainfall through the canopy and stemflow. Evapotranspiration is obtained by adding evaporation from the soil (E), measured using a micro-lysimeter, and actual transpiration (T) from the plant, measured directly by covering part of the plant. Then, converting the amount of water collected to obtain the transpiration value. Surface runoff is monitored using a chin-ong meter, which is used to channel runoff into a reservoir, with the remainder being discharged to the bottom of the chin-ong meter. The amount of runoff can be determined by calculating the ratio of the amount of water collected in the reservoir to the amount of water lost. Therefore, it is necessary to calibrate the chin-ong meter by pouring 10 liters of water from the top of the gutter and measuring the overflow that enters the reservoir, and then measuring the ratio. By knowing the components of effective rainfall (He), surface runoff (LP), and evapotranspiration (ET), initial water content (W_i) as well as the water content that the soil can retain at field capacity (W_{kl}), the percolation value (P) was determined using the following equation:

$$P = (He + W_i) - LP - ET - W_{kl} \quad (1)$$

The water balance in an area was written using Equation (2), where δS is water storage (mm).

$$\delta S = He - LP - P - ET \quad (2)$$

2.5. Observation Parameters and Data Analysis

Soil property observation in the Land Resources Laboratory included parameters listed in Table 2. Research data was analyzed using a *t*-test processed through SPSS version 24, and a simple regression test using Microsoft Excel 2019.

Table 2. Laboratory observation parameters

Parameter	Determination Method	Reference
C-organic (%)	Walkley and Black	(Eviati *et al.*, 2023)
Porosity (%)	Volumetric and Gravimetric	(Kurnia *et al.*, 2023)
Soil texture (%)	Pipette	(Kurnia *et al.*, 2023)
Field capacity water content (%)	Free drainage	(Soil Science Division Staff, 2018)
Actual water content (%)	Gravimetric	(Kurnia *et al.*, 2023)

3. RESULTS AND DISCUSSION

3.1. Land Use Characteristics

Land use has a significant influence on the dynamics of the water balance in a region. Changes in land use, such as from forest to agricultural or residential areas, impact the balance between water entering and exiting the soil system. Differences in land cover will determine the extent of infiltration, surface runoff, and evapotranspiration, which ultimately affects groundwater storage capacity. The development of preferential flow pathways (PFPs) due to the activity of soil biota and plant roots increases infiltration capacity in areas with dense vegetation cover, such as forests and agroforests. Conversely, in areas with open cover, infiltration tends to be shallow and surface runoff is greater, thus reducing the effectiveness of water infiltration into the soil (Litt *et al*., 2020). The litter layer covering the soil surface plays a crucial role in increasing infiltration by preventing the formation of an impermeable layer (soil sealing) and reducing surface runoff. The thicker the litter layer, the greater the soil's infiltration capacity, thus providing an effective natural barrier for water and soil conservation (Wang *et al*., 2020).

Agroforestry is a forest land management model that aims to increase the productivity of agricultural, livestock, and fishery land, thereby achieving short- and long-term results. The principle of agroforestry is economic, ecological, and social balance (Fikry & Sarjan, 2024). Planting using agroforestry patterns can significantly reduce surface runoff. This is due to several factors. Among them, litter tends to improve soil structure and increase infiltration and permeability. Litter also plays a role in absorbing rain and inhibiting surface runoff, allowing water to infiltrate into the soil. Furthermore, agroforestry patterns with diverse plant layers protect the soil from the kinetic energy generated by rain (Naharuddin, 2018).

The pine plantations at the study site have an average slope of 23.5%, which is considered moderately steep and the gentlest of all the study sites. The shade percentage in the monoculture pine plantations is recorded at 80%, equivalent to that in agroforestry areas, resulting in relatively similar light intensity reaching the ground surface. The annual crop plantations at the study site, planted with corn under a monoculture system, have an average slope of 26%, which can be categorized as steep. This topographical condition directly increases the risk of surface runoff, especially during periods of heavy rainfall.

Corn plants have a short lifespan and a shallow root system, providing low ground cover and suboptimal protection from rainwater. According to Anika *et al.* (2024), the root system of annual crops, particularly corn, is relatively shallow, preventing roots from reaching the subsoil, resulting in compacted soil in annual agricultural areas, resulting in reduced soil pore space and reduced infiltration.

3.2. Rainfall, Surface Runoff, Percolation, and Evapotranspiration Factors

Five years of rainfall data were used as a comparison for the data applied in the water balance equation. Rainfall and other climate data (humidity and air temperature) were obtained from satellite data provided by the United States

Space Agency (NASA). The data obtained were daily data, which were then summed to obtain monthly rainfall data for each year. The monthly rainfall graph for 2020-2024 can be seen in Figure 2.

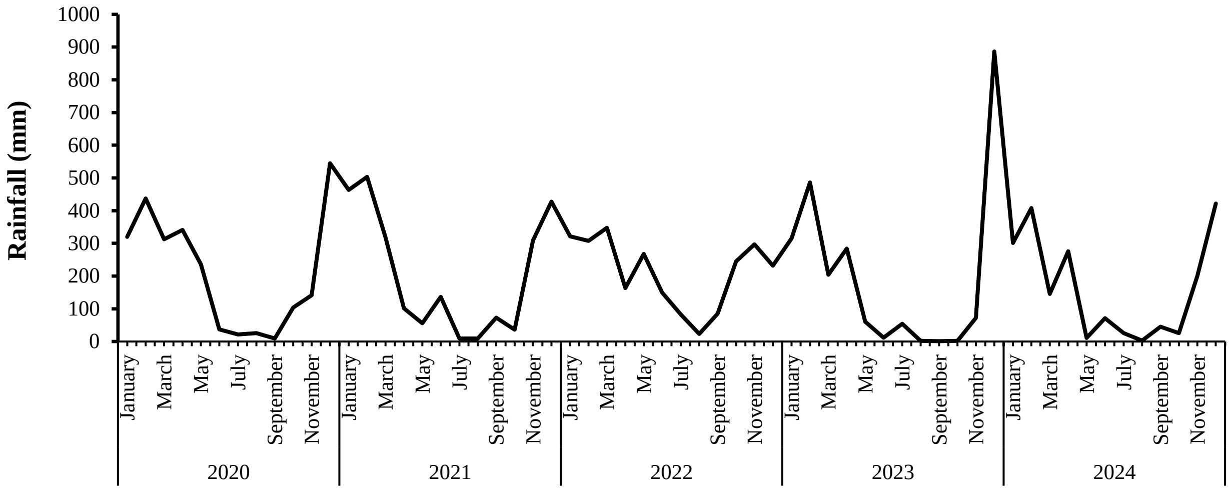

Figure 2. Rainfall in the Wonosalam region over the past 5 years

The highest effective rainfall was found in the pine monoculture area, and the lowest in the pine-coffee agroforestry area. The *t*-test results for the interception parameter yielded a significance value (sig.) of 0.207, which is greater than 0.05. Therefore, it can be concluded that the effective rainfall values do not show a significant difference. This result is because effective rainfall is obtained by subtracting the interception from the total rainfall. The values of effective rainfall, evapotranspiration, surface runoff, and percolation can be seen in Table 3. The parameters of effective rainfall, evapotranspiration, runoff, and percolation in the study area. Effective rainfall is rainfall that causes direct runoff (Delani & Dasanto, 2015). According to Khoirunnisak (2018), the magnitude of the interception value is influenced by canopy density and plant canopy area. The interception value in agroforestry is greater than in monoculture pine with annual crops.

Table 3. Parameters of effective rainfall, evapotranspiration, runoff, and percolation in the study area

Land Use	**Effective Rainfall (mm)**	**Evapotranspiration (mm)**	**Runoff (mm)**	**Percolation (mm)**
Pine-coffee agroforestry	1860.63±7.53	1103.31±0.37	23.57±0.14	608.64±5.45
Pine monoculture	2017.35±8.16	1010.12±0.66	437.32±2.57	232.75±2.43
Annual cropping	1998.35±8.09	843.34±0.22	723.61±3.41	36.00±0.72
t-test (α = 0.05)	0.207	0.095	0.191	0.211

The highest evapotranspiration value was found in pine plantations at 1,103.31 mm, and the lowest in annual crop plantations at 843.34 mm. The *t*-test for the evapotranspiration parameter yielded a significant value of 0.095, exceeding the 0.05 significance limit. Evapotranspiration is influenced by climate, plant type, plant growth, plant variety, plant population density, ground cover, and groundwater availability (Harfia & Prijono, 2022). Monoculture pine plantations have higher evapotranspiration values than agroforestry due to different planting densities. Therefore, even though agroforestry plantations have additional coffee vegetation, they still cannot achieve higher transpiration than monoculture pine plantations. According to Huang *et al.* (2021), pine plantations experience a significant decrease in groundwater storage, which can lead to plant death due to water shortages. The highest surface runoff values were obtained in the annual crop area at 723.61±3.41 mm, followed by the monoculture pine area at 437.32±2.57 mm, and the agroforestry area at 23.57±0.14 mm. However, the *t*-test results showed a significance value of 0.191, higher than the 0.05 threshold, thus concluding that there were no significant differences between the tested land uses. This is suspected to occur because the studied areas are located in adjacent locations, thus having similar rainfall intensity and rainfall. According to Harfia & Prijono (2022), surface runoff is strongly influenced by rainfall; the greater the rainfall intensity, the greater the surface runoff rate.

Data processing results showed that percolation in the agroforestry area had the highest value, at 608.64±5.45 mm, and the smallest in the annual crop area, with a percolation value of 36±0.72 mm. However, the *t*-test results showed a significance value of 0.211, which is greater than 0.05, and it can be concluded that the percolation values for each land use were not significantly different. This result is suspected to occur because the three land uses also had similar amounts of water input. Xu *et al*. (2017) stated that percolation is highly dependent on water input, including rainwater and agricultural irrigation. Rahmadani *et al*. (2020) added that percolation values are influenced by high levels of soil organic matter, which supports the soil's ability to retain water.

3.3. Soil Chemical and Physical Properties

Soil organic matter is a material in the soil derived from the remains of living organisms that have decomposed or are in the process of decomposition (Solekhah *et al*., 2024). The results of the regression analysis between soil organic matter content and groundwater storage, shown in Figure 3, indicate a very strong relationship, with a coefficient of determination (R^2) of 0.9189. This indicates that 91.89% of the variation in groundwater storage is influenced by organic matter content, while the remainder is influenced by other factors such as soil texture, aggregate structure, porosity, and topography and vegetation conditions. The regression equation obtained, $y = 212.202x + 120.454$, shows a positive relationship between the two variables, in accordance with the statement by Rahmadani *et al*. (2020), that the ability of the soil to store water is influenced by the content of soil organic matter. The average values of chemical and physical properties of the soil can be seen in Table 4.

Soil organic matter content is directly proportional to aggregate stability and reduces soil erodibility (Udawatta *et al*., 2017). Udawatta *et al*. (2017) added that planting systems with diverse species contribute greater organic matter through root exudates and microbial activity. Soil organic matter influences various soil properties, including soil water-holding capacity, aggregate stability, erosion resistance, and so on (Navarro-Pedreño *et al*., 2021).

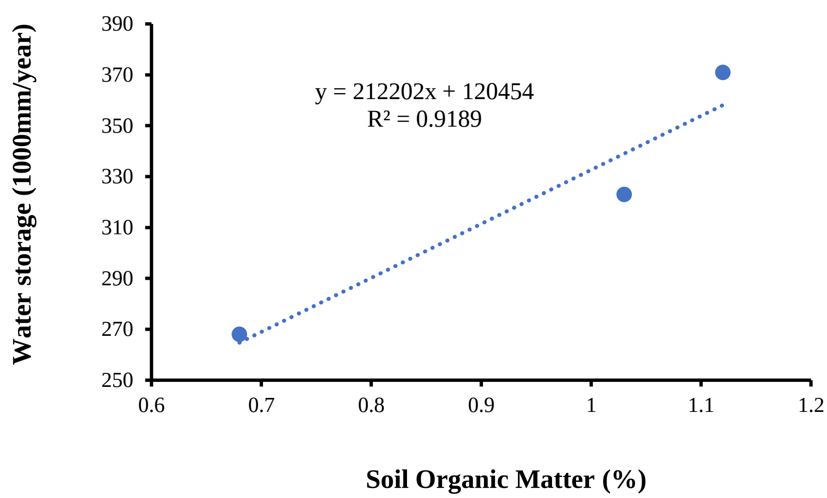

Figure 3. Regression analysis of water storage and organic matter content

Table 4. Soil chemical and physical properties

Land Use	Soil Organic Matter (%)	Soil Texture	Porosity (%)
Pine-coffee agroforestry	1.12	Silty clay loam	61.84
Pine monoculture	1.03	Silt loam	62.30
Annual cropping	0.68	Silty clay loam	61.35

Clay fraction is a component of soil texture that plays a crucial role in determining water retention capacity. Soils with a higher clay fraction have a greater water-holding capacity than coarse-textured soils dominated by sand. This is reflected in the ability of clay soils to maintain hydraulic conductivity at lower soil water potentials, thus making water available to plants for longer periods (Wankmüller *et al*., 2024). The results of the regression analysis between clay fraction and groundwater storage (Figure 4a), show a coefficient of determination of 0.0172, meaning the clay fraction only has a 1.72% effect on groundwater storage. The regression equation obtained is $y = 1{,}152.3x + 288{,}752$, indicating a positive but insignificant relationship between the two variables. This indicates that the clay fraction contributes very little to increasing water storage, and that other factors are more dominant.

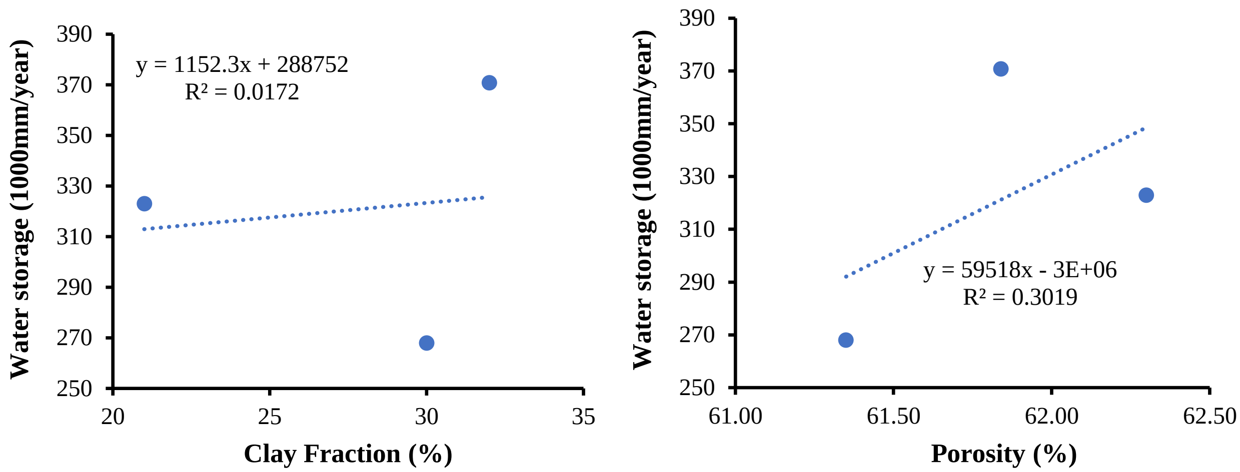

Figure 4. Regression analysis of: (a) water storage and clay fraction, (b) water storage and soil porosity

Soil porosity plays a crucial role in determining the soil's water storage capacity, as it is directly related to the volume of space between soil particles that can be filled with water. Soils with high porosity tend to have a better ability to absorb and store rainwater that falls on the ground surface. The regression analysis between porosity and groundwater storage yielded the equation y = 59,518x - 3,000,000, with a coefficient of determination (R^2) of 0.3019 . This indicates that 30.19% of groundwater storage is influenced by soil porosity, while the remainder is influenced by other factors such as texture, soil structure, organic matter content, and vegetative factors on the land surface. The regression analysis between soil porosity and water storage can be seen in Figure 4b.

3.4. Water Balance

Groundwater storage is the amount of water available in the soil as stored water. Water storage is obtained through calculations using the water balance equation. The results of the groundwater storage calculations using the water balance equation. The highest groundwater storage value was found in the pine-coffee agroforestry area, with groundwater storage of 370,863.44±176.67 mm/year and an average of 1,016.06 mm/day. Meanwhile, in the pine monoculture area, water storage decreased significantly to 307,153.36±229.98 mm/year with an average of 841.52 mm/day. The lowest groundwater storage value was found in the annual crop area, at 239,497.30±222.26 mm/year, with an average water storage of 656.16 mm/day.

Table 5. Soil water storage values under different land uses

Land Use	Soil Water Storage (mm/year)	Average (mm/day)
Pine-coffee agroforestry	370,863.44±176.67	1,016.06
Pine monoculture	307,153.36±229.98	841.52
Annual cropping	239,497.30±222.26	656.16
t-test ($\alpha = 0.05$)	0.221	0.221

Although the low groundwater storage in annual croplands does not show significant differences as shown in Table 5, it still warrants attention. This condition has the potential to accelerate land degradation by increasing the risk of erosion and reducing water availability for plants. Therefore, soil and water conservation efforts are necessary to maintain sustainable land productivity.

The *t*-test results for the water storage results showed a significance value of 0.221, which is greater than the 0.05 threshold. Therefore, it can be concluded that groundwater storage in the three areas was not significantly different. This result is likely due to the relatively similar soil textures: fine-textured, silty loam in the agroforestry area, and silty clay loam in the monoculture pine and annual crop areas. This is consistent with research (Biswas, 2019) that soil texture influences water storage in the soil; the higher the percentage of fine fractions, the higher the groundwater storage. Zhang *et al*. (2018) added that groundwater storage is influenced by several factors, namely climate, rainfall, evaporation, and land use.

These research results align with the findings of Fitch *et al*. (2022), which showed that the pine-coffee agroforestry system can improve the provision of environmental services (carbon stocks, sediment, nitrogen retention, and surface runoff) compared to monoculture. These similar results are thought to be due to the role of tree cover in agroforestry systems, which can improve soil structure, increase infiltration, and provide litter that contributes to water and nutrient retention. Therefore, both this study and Fitch *et al*. (2022) confirm that agroforestry functions as a system that provides better environmental services than monoculture. Zhang *et al*. (2018) added that agroforestry can maximize water utilization. Furthermore, agroforestry can store more water, preventing soil from experiencing drought at the same time as monoculture land. Agroforestry protects the soil from high surface runoff on steep and long slopes, and increases soil infiltration (Udawatta *et al*., 2017).

Water storage in pine monoculture is lower than in pine-coffee agroforestry. This difference in storage values indicates the limitations of monoculture planting systems in supporting optimal groundwater availability. Although pine trees have a fairly deep and strong root system, the high plant density and homogeneous canopy result in low diversity and a lack of litter contribution from various vegetation types, thus affecting soil structure and water absorption capacity, resulting in lower water storage. In pine vegetation, high evapotranspiration rates result in a significant reduction in groundwater storage. This is due to the large leaf surface area. According to Huang *et al*. (2021), pine vegetation experiences a significant reduction in groundwater storage, which in some areas can lead to plant death due to water shortages.

4. CONCLUSION

The highest water storage at effective soil depth (0-60 cm) was found in pine-coffee agroforestry land (370,863.44 mm/year), 20.74% higher than in pine monoculture land (307,153.36 mm/year), and 54.85% higher than in annual land (239,497.30 mm/year). The three land use types did not experience a groundwater storage deficit because their storage values were consistently positive throughout the year. Peak water storage occurred in February–May, except for the annual land which reached its maximum in April–May due to high runoff and low infiltration. The main factor influencing groundwater storage was organic matter content with a coefficient of determination of 91.89%. In contrast, clay fraction and soil porosity showed a weaker influence with R^2 values of 0.0172 and 0.3019, respectively. Land management through planting trees on annual land is recommended as a conservation strategy to increase the soil's ability to store water in Wonosalam. Suggestions for further research should be to use climate data through direct measurements in each land use, because satellite data has poor accuracy.

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