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A Critical Distribution of Groundwater Infiltration Status on Agricultural Land Use in Manyaran, Indonesia

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Abstract - Agricultural land is vulnerable to drought disasters, and effective groundwater management is needed by identifying soil characteristics that support water infiltration. This study aims to assess the criticality of groundwater infiltration distribution in agricultural land in Manyaran District, and the relationship between soil physical characteristics and soil infiltration criticality, so that management strategies can be formulated to increase groundwater infiltration. The assessment uses an assessment method based on The Regulation of The Minister of Forestry P. 32/Menhut-II/2009, which combines parameters such as soil type, permeability, slope, rainfall, and land use. It is modified by observations of important soil physical properties that affect hydrological processes, including soil texture, bulk density, and porosity, integrated into the analysis. Sampling points were determined using purposive random sampling in the land map unit obtained from thematic map overlay. The influence of land use factors on groundwater infiltration criticality using ANOVA data processing, while the physical properties that most determine infiltration conditions were identified through the Pearson correlation test. The results classify groundwater infiltration status into six categories: good, normal, light critical, moderate critical, critical, and heavy critical. Heavy essential catchment areas, especially in rice fields, are characterized by low soil permeability, porosity, and bulk density. These findings underscore the need for improved soil management practices for groundwater infiltration, such as the addition of organic matter and the implementation of ecological drainage systems, to increase water infiltration and reduce the risk of drought in the area.

Keywords: hydrological soil components, paddy field, heavy critical land, management

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Introduction

Groundwater areas are crucial for maintaining sustainable water resources (Awanda *et al.*, 2017). They replenish water reserves, which are vital for various uses, including agricultural irrigation (Adunya and Benti, 2020). Accurate identification of suitable water resource areas is essential for effective water management, especially for artificial recharge initiatives (Mehrabi *et al.*, 2012). Land use significantly influences the water resources capacity of an area, and also triggers a decrease in the ability of the soil to absorb water. Environmental factors since land use management, such as soil salinity conditions and water availability for different land use needs, have been shown to determine the growth and yield of crops globally, accounting for 50 % of the world crop production (Khetsha *et al.*, 2024). Different land practices can alter soil properties, such as increasing bulk density and disrupting soil structure, thereby reducing infiltration rates (Jeloudar *et al.*, 2018). It can lead to waterlogging during the dry season. Manyaran District, Indonesia, experiences water scarcity during the dry season (Sigit *et al.*, 2015; Wonogiri District Regulation, 2020). It has negatively impacted agricultural production, particularly paddy crop yields, which declined from 19,052 tons of 3,056 ha (in 2017) to 15,693 tons of 2,763 ha (in 2020) (Central Bureau of Statistics of Wonogiri, 2018; Communication and Information Agency of Wonogiri Regency, 2021).

Nowadays, the problem of climate change affecting water availability is a challenge for farmers and various lands used for agricultural activities, especially for producing food crops such as rice (Pratama *et al*., 2024). Paddy cultivation has a high water demand throughout its growth cycle (Kamran *et al*., 2022), and the continuous use of chemical fertilizers reduces the quality of the soil in absorbing water (Oco *et al*., 2024). Water losses through surface drainage, percolation, evapotranspiration, and seepage must be replenished through rainfall and irrigation (Singha *et al*., 2014). While irrigation from surface and water sources can boost productivity (Alattar *et al*., 2020), insufficient water supply can severely impact plant growth and even lead to crop failure (Viandari *et al*., 2022). Enhancing groundwater infiltration capacity is crucial to ensure adequate water availability for irrigation in the studied area.

GIS-based techniques offer a highly efficient approach for analyzing and visualizing groundwater recharge distribution (Rendana *et al.*, 2022). Previous studies have successfully employed GIS-based methods for groundwater recharge assessment. Aini *et al.* (2020) research in Kulon Progo combines weighting techniques, and overlay maps using ArcGIS software like in India, maps of groundwater recharge zone in the Loni and Morahi watersheds, Unnao and Rae Bareli Districts (Agarwal and Garg, 2015). Still, the existing studies have not paid attention to the actual soil conditions, especially soil physical properties, so there are very few references to proper land management regarding soil conditions.

Groundwater infiltration status aims to rehabilitate water management in forests and watershed areas by assessing water catchment areas using a spatial approach to map the level of water criticality based on various environmental and hydrological factors. The assessment is adjusted to local conditions in the studied area. It adopts the weighting scoring from the Regulation of The Minister of Forestry of the Republic of Indonesia P. 32/Menhut-II/2009. The parameters analyzed include rainfall as the primary source of water, soil type that determines its absorption capacity, slope gradient that affects runoff speed, groundwater potential as an indicator of subsurface water availability, and land use that regulates the balance between infiltration and surface flow. Considering and supporting these factors by integrating spatial methods with Geographic Information Systems (GIS) allows for more accurate spatial analysis in mapping an area with high water catchment potential or areas vulnerable to water criticality.

The research has been conducted on groundwater infiltration criticality in watershed areas (Santosa *et al*., 2021)**,** zoning of water infiltration areas in Semarang City using The Analytical Hierarchy Process (AHP) method (Amin *et al*., 2023), and criticality of water catchment areas referring to the Indonesian Regional Spatial Planning and using The Regulation of The Minister of Environment and Forestry Number 10 of 2022 method (Rawung *et al*., 2023). This study modifies the assessment of water infiltration criticality factors based on soil physical characteristics that can describe the ability of the soil to absorb and store water, namely soil permeability, texture, soil volume weight, specific gravity, and soil porosity. Soil permeability and texture determine the infiltration rate, because the size, shape, and stability of soil aggregates that assess the infiltration rate affect the space and speed of water infiltration (Musa *et al*., 2017). Soil bulk density and porosity affect the water storage capacity in the soil, because soil macropores will support the infiltration rate and vice versa (Cleophas *et al*., 2021).

The purpose of this study is to determine the distribution of the groundwater infiltration criticality, to determine the effect of land use on the groundwater infiltration criticality, and to find critical determinant factors of groundwater infiltration to develop appropriate land management strategies and focus on the characteristics that determine the criticality of groundwater infiltration. The results of this study are expected to be the basis for planning water conservation and more sustainable land resource management to maintain ecosystem balance and water resilience in areas with similar conditions in the future.

Methods and Materials

The research was conducted in Manyaran District, Wonogiri Regency, Central Java, Indonesia (Figure 1a and Figure 1b). Geographically,

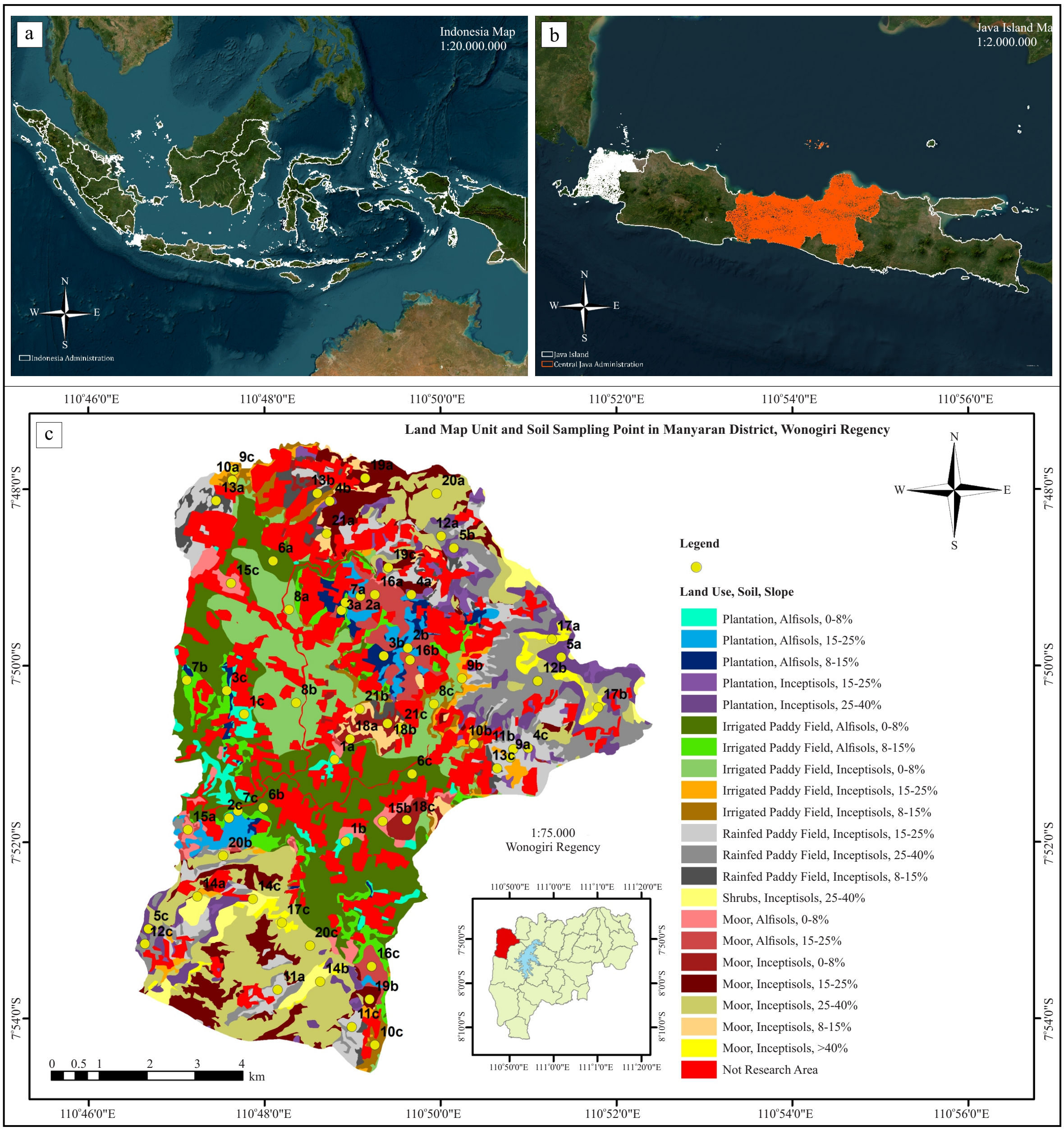

Figure 1. Research Location in; (a) Indonesian Maps; (b) Java Island Map; (c) Sampling Point for Observation and Sampling Points.

Manyaran District is located between 7° 46' 00" - 7° 54' 00" South Latitude and 110° 46' 00"-110° 52' 00" East Longitude with an average elevation of 238 m above sea level (m asl). A mountainous and hilly terrain characterizes the topography. According to data from The Geospatial Information Agency of the Republic of Indonesia (2019), Manyaran District encompasses an area of 8,087 ha. The land use of the district is predominantly agricultural, including paddy fields (3,388 ha), moors (1,952 ha), shrubs (145 ha), plantation (852 ha), and areas excluded from this study, totaling 1,750 ha, including water bodies, built-up areas, and another non-agricultural land.

This research employed an exploratory, descriptive approach. The data collection involved direct environmental morphological observations and laboratory analyses of soil physical properties. Soil physical parameters were analyzed in the laboratory adhere method to the guidelines outlined in The BBSDLP (The Indonesian Soil and Land Resource Research and Development Agency) Manual Book (2016), including soil permeability (using a constant head permeameter method), soil texture (using pipette method), soil bulk density (using clod method), particle density (using pycnometer method), and soil porosity (using bulk density and particle density measurements; clod and pycnometer method) (BBSDLP, 2016). Soil sampling points were selected using a purposive random sampling method. The effective land area for this study encompassed 6,300 ha, including irrigated and rainfed paddy fields, moors, shrubs, and plantations. To ensure representative sampling, the studied area was divided into twenty-one Land Map Units (LMUs) (Figure 1c). In each LMU, three sampling points were randomly selected, resulting in sixty-three sampling points across the studied area.

Analysis of Critical Groundwater Infiltration

A scoring method was employed to assess the criticality of groundwater infiltration in the analysis. This method involved summing the scores of individual parameters, each weighted according to its relative importance (Formula 1). The resulting scores were then classified into different criticality levels using the Sturgess interval formula (Formula 2) to determine the appropriate range values for each class (Table 2). Higher scores indicate greater groundwater infiltration capacity and, consequently, higher groundwater infiltration potential. The scoring and weighting system was adapted from The Regulation of the Minister of Forestry of the Republic of Indonesia Number 32 of 2009. This approach has been successfully applied in previous studies by Adibah *et al*. (2013) and Saputra *et al.* (2019). The analysis used ArcGIS software to overlay and to integrate various parameters, including land use, slope, rainfall infiltration, soil type, and soil permeability (Table 1). This research uses a geographic information system to provide a comprehensive overview of spatial data and information in a location (Romadhon and Aziz, 2022).

$$TV = (Ss \times Sw) + (Ps \times Pw) + (Rs \times Rw) + (Ls \times Lw) + (Ts \times Tw) \quad ..(1)$$

Description:
TV = total value
S = soil type
P = soil permeability
R = infiltration rainfall
L = land use
T = slope
s = score value
w = weight value

$$Ni = \frac{X_{max} - X_{min}}{k} \quad ....(2)$$

Description:
Ni = range interval
X_{max} = highest data of total value
X_{min} = lowest data of total value
k = expected number of classes

Critical Determinant Factors for Groundwater Infiltration

Statistical analyses were conducted to identify the influence of environmental factors (land use

Table 1. Assessment of Critical Scores and Weights of Groundwater Infiltration Parameters (Source: Adibah *et al*., 2013; Saputra *et al*., 2019; Minister of Forestry of the Republic Indonesia Number 32, 2009)

Parameters	Weight	Subparameters	Score	Total value (Score x weight)	Criteria
Soil type	5	Regosols	5	25	Very fast
		Aluvials and andosols	4	20	Fast
		Latosols	3	15	Medium
		Litosols and mediterans	2	10	Low
		Grumusols	1	5	Very low
Soil permeability (cm/hours)	5	> 12,7	5	25	Very fast
		6,3 – 12,7	4	20	Fast
		2,0 – 6,3	3	15	Medium
		0,5 – 2,0	2	10	Low
		< 0,5	1	5	Very low
Rainfall (mm/years)	4	> 5500	5	20	Very fast
		4500 - 5500	4	16	Fast
		3500 - 4500	3	12	Medium
		2500 - 3500	2	8	Low
		< 2500	1	4	Very low
Land use	3	Dense forest	5	15	Very fast
		Production Forest and plantation	4	12	Fast
		Shrubs and grassland	3	9	Medium
		Moor	2	6	Low
		Paddy field and settlement	1	3	Very low
Slope (%)	2	0-8%	5	10	Very fast
		8-15%	4	8	Fast
		15-25%	3	6	Medium
		25-40%	2	4	Low
		>40%	1	2	Very low

Table 2. Critical Criteria for Groundwater Infiltration in Manyaran District, Wonogiri Regency (Source: Minister of Forestry of the Republic Indonesia Number 32, 2009; with the modification according to the conditions of the researched area)

Total Value	Critical Criteria for Groundwater Infiltration
64-67	Good
60-63	Normal
56-59	Light critical
52-55	Medium critical
48-51	Critical

in this research) and the relationship between soil physical conditions and water infiltration criticality. Analysis of Variance (ANOVA) was employed to determine whether significant differences in groundwater infiltration criticality exists among land use types. If significant differences were found (p-value < 0.05), a Duncan Multiple Range Test (DMRT) was performed at a 95 % confidence level to identify which land use types exhibited significantly different mean values of groundwater infiltration criticality. Pearson Correlation was used to assess the correlation between soil physical parameters (such as soil texture, bulk density, and porosity) and the groundwater infiltration criticality criteria. Significant correlations (p-value < 0.05) were identified to determine the key soil physical factors significantly influencing groundwater infiltration in the studied area.

Results And Discussion

Water Sources

Water sources are integral to the hydrological cycle, a continuous process involving water circulation through the atmosphere, land, and oceans (Bruce and Clark, 1966). Nace (1976) identified rainwater, groundwater, and surface water as the primary sources of earth water. While all three sources play a role, surface soil, and groundwater are typically the most significant sources for human used. Surface water encompasses various bodies, including rivers, lakes, swamps, and the sea. Spatial location information of water resources is very important in identifying the most effective areas as water catchment areas and assessing the sustainability of long-term groundwater availability, since an area protected as a groundwater conservation area. The infiltration process does not only depend on rainfall intensity, but also on the physical characteristics of the soil, land cover, geology, and on the availability of surface water (such as rivers, lakes, or irrigation systems), which can affect the infiltration rate and support the potential of water catchment zones in an area. The definition of a groundwater infiltration zone according to Meles *et al*., (2024) is soil or land that is quite large and permeable to be used as a surface infiltration system. By the integration of spatial data between the distribution of zones and levels of water catchment, geological conditions includes soil type, and distribution of water resources, will support a complete understanding of the local water cycle.

In the studied area, several rivers exist, although some exhibit dry conditions during specific periods (Figure 2), indicating potential limitations in groundwater reserves. Data from The Central Bureau of Statistics of Wonogiri (2020) reveals that the primary water sources for irrigation in the studied area are artificial underground springs (borewells) and irrigation systems. Traditional irrigation systems dominate (179 ha), with a smaller portion utilizing semi-technical irrigation systems (136 ha). Given the predominance of paddy fields, which require significant water inputs, it is crucial to implement proper land management practices to ensure the sustainable availability of water resources. Slow handling will cause prolonged natural disasters and hamper the economic growth of the agricultural communities around the land (Utami *et al*., 2024). Figure 2 is one of the water sources for local people for agricultural irrigation in the researched area, Manyaran. According to Viandari *et al*. (2022), irrigated rice fields are very dependent on water sources around the land, because they are vulnerable to the risk of plant stress due to drought, which causes a lack of soil nutrient availability and plant loss of water in the leaves, functional cells become inactive, and the leaves roll up. In addition, water sources such as rivers (Figure 2a) greatly determine the balance of aquifer recharge and actual water use for agricultural irrigation needs (Figure 2b) (Anshori *et al*., 2023).

Critical Distribution of Groundwater Infiltration

The distribution of groundwater infiltration criticality across the twenty-one Land Map Units (LMUs) is summarized in Table 3. Soil types as geology charcteristics in the studied area, as identified through The InaAgriMap WebGIS Soil Map (BBSDLP, 2018) and subsequent field verification, are predominantly Inceptisols and Alfisols. According to The National Soil Classification System (*SKTN*), these correspond to Latosols (Inceptisols) and Mediterans (Alfisols). Inceptisols are dominant in the studied area, covering 4,252 ha (67.1 % of the total area).

Inceptisols (Latosols) generally exhibit higher water infiltration rates than Alfisols (Mediterans). This difference can be attributed to the higher clay content in Alfisols. An argillic horizon, characterized by the accumulation of clay particles, significantly influences soil hydraulic properties (Rodríguez *et al*., 2019). The high clay content

Figure 2. Water sources in the form of (a) rivers and (b) irrigation of irrigated paddy fields.

Table 3. The Criteria of Critical Groundwater Infiltration in Various Land Map Units (LMU)

Land Use	Land Map Unit	Soil Type	Soil Permeability (cm/hours)	Infiltration Rain (mm/ years)	Slope (%)	Total Value	Criteria
Plantation	1	Alfisols	14.502	2.798	2	65	Good
	2	Alfisols	17.385	2.798	19	61	Normal
	3	Alfisols	9.782	2.798	11	58	Light critical
	4	Inceptisols	10.712	2.798	17	61	Normal
	5	Inceptisols	11.384	2.798	30	59	Light critical
Irrigated paddy field	6	Alfisols	7.081	2.798	3	51	Critical
	7	Alfisols	6.026	2.798	10	44	Heavy critical
	8	Inceptisols	7.620	2.798	3	56	Light critical
	9	Inceptisols	5.948	2.798	17	47	Heavy critical
	10	Inceptisols	5.765	2.798	10	49	Critical
Rainfed paddy field	11	Inceptisols	7.411	2.798	21	52	Medium critical
	12	Inceptisols	6.446	2.798	30	50	Critical
	13	Inceptisols	7.834	2.798	9	54	Medium critical
Shrubs	14	Inceptisols	12.924	2.798	34	61	Normal
Moor	15	Alfisols	7.637	2.798	3	54	Medium critical
	16	Alfisols	7.308	2.798	20	50	Critical
	17	Inceptisols	3.538	2.798	43	46	Heavy critical
	18	Inceptisols	12.742	2.798	2	64	Good
	19	Inceptisols	8.675	2.798	20	55	Medium critical
	20	Inceptisols	6.890	2.798	33	53	Medium critical
	21	Inceptisols	8.725	2.798	9	57	Light critical

within the argillic horizon restricts water movement due to the small size of clay particles, which reduces pore space and consequently decreases both porosity and permeability (Defersha *et al*., 2012; Massah and Azadegan, 2016).

In the researched area with rice field land use, it is known to have a high clay fraction (shown in Table 3). The high clay content in the soil makes the percentage of macro pores less which compared to the sand fraction which has more macro pores and a high permeability value. Soil with a dominant clay texture, the permeability is actually low. Based on the texture that has been observed, Manyaran District has four texture categories, namely loam, clay loam, silty loam, and silty clay, with a range of texture fraction percentages, including silt (44.49 - 67.92 %), clay (17.96 - 39.37 %), and sand (3.51 - 29.68 %).

Soil permeability, a critical factor governing the rate of water movement through soil pores (Arshad *et al*., 2020), exhibited a wide range in the studied area, varying from 3.538 cm/hour (medium) to 17.385 cm/hour (fast). Higher permeability values generally indicate faster groundwater infiltration rates. This finding aligns with the observations of Thakur *et al*. (2013), who emphasized the crucial role of permeability in facilitating groundwater infiltration through enhanced infiltration from the soil surface to the underlying bedrock.

Infiltration water, originating from irrigation and rainfall, plays a significant role in groundwater infiltration (Bedbabis *et al*., 2014). However, the annual rainfall in the studied area (2,798 mm/year) suggests relatively low infiltration rates. This observation is consistent with the findings of Hou *et al*. (2019), who reported an inverse: the lower the rainfall, the slower the infiltration rate.

The criticality of groundwater infiltration distribution in the researched area is classified into six criteria (presented in Figure 3), namely good (4 %), normal (6.62 %), light critical (18.28 %), medium critical (32.56 %), critical (32.04 %), and heavy critical (6.5 %). The critical condition of groundwater infiltration is dominated by medium critical criteria covering an area of 2,063 ha, and a critical area has 2,029 ha. The area still functioning well for groundwater infiltration has the smallest area of 256 ha, while the area with normal criteria is 419 ha. In addition, the area included in the light critical criteria has 1,159 ha, and a heavy critical area has 411 ha.

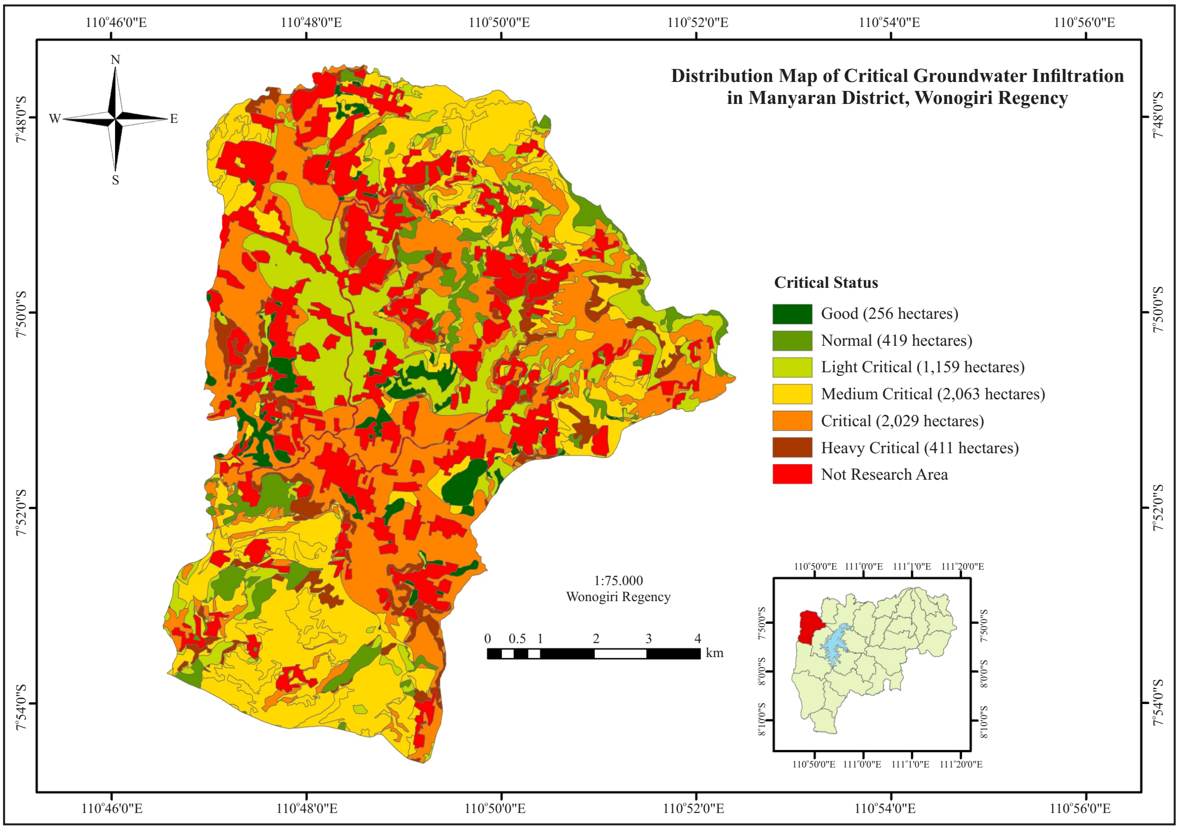

Figure 3. Distribution of The Critical Groundwater Infiltration.

Land that is still functioning well in absorbing water is in plantation land use (LMU 1) and moorland (LMU 18), with a gentle slope (0-8 %), moderate annual infiltration rainfall of 2,798 mm/year, and has Alfisols and Inceptisols. Plantations and shrubs have normal criteria for absorbing water capacity. Plantations and shrubs have dense and diverse vegetation cover. As a result, the soil structure is not quickly broken, because dense canopy plants or grasses and leaves can reduce the destructive power of rainwater on the soil surface, the surface runoff rate can be minimized, and the infiltration rate will increase (Arham *et al.*, 2019). Meanwhile, areas with heavy critical groundwater infiltration criteria are spread out at LMU 7, 9, and 17 using irrigated paddy fields and dry fields on gentle to very steep slopes.

The Effect of Land Use on The Critical Status of Groundwater Infiltration

Land use has a very significant impact on water issue (flood and drought), since changes in the coverage of the area causing changes the hydrological structure, such as disrupting the flow path, flow speed, and water storage into the soil in the area, and also reducing the scale of water catchment. The effects of agricultural practices on each land use in the studied area will change the properties of the soil surface, then the hydraulic aspects (Sun *et al.*, 2018). Intensive soil tillage changes the infiltration rate and root depth, since soil compaction and soil cracks. According to Rogger *et al.*, (2017), information on land use, soil tillage, and physical characteristics of the soil will increase the ability of the soil to absorb water, measure water flow in the soil, and estimate potential issue of water catchment zone in the area. Figure 4 illustrates the significant differences in the critical status of groundwater infiltration in various land use types. Statistical analysis revealed that irrigated paddy fields (49.07a), rainfed paddy fields (49.78a), and moorland (52.71a) did not exhibit significant differences in their recharge criticality. However, all three land

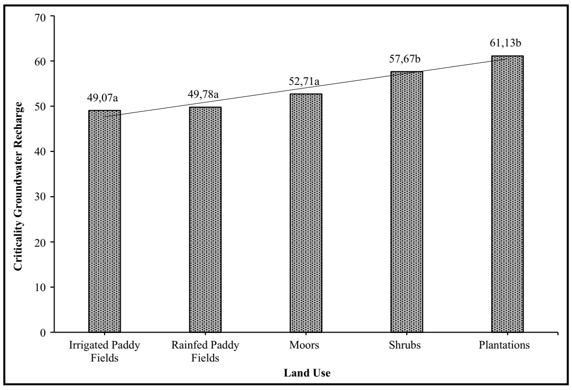

Figure 4. Differences of the critical groundwater infiltration based on land use. (Numbers followed by different letter notations are significantly different).

use types showed significantly lower recharge criticality than scrubland (57.67b) and plantations (61.13b). This variation in recharge can criticality be attributed to differences in vegetation cover and associated soil properties. Paddy fields and moorland are characterized by seasonal and non-vegetation canopy, such as rice, corn, peanuts, cassava, and ginger. In contrast, plantations and scrubland are dominated by annual and canopied vegetation, including dense stands of teak, mahogany, sengon, coconut, and cashew trees.

Plantations covering 13.29 % of the studied area exhibited the highest average groundwater infiltration criticality (61.13), indicating superior groundwater infiltration capacity. It can be attributed to a thick layer of leaf litter within plantations, which contributes to increased organic matter content, enhanced soil aggregation stability, and improved soil porosity. Notably, plantations in this studied area exhibited the highest porosity values (39.48 %), facilitating higher infiltration rates (La Manna *et al*., 2016). Conversely, irrigated paddy fields displayed the lowest groundwater infiltration criticality. Chen *et al*. (2022) reported the formation of a plow tread layer at depths of 20 to 40 cm in irrigated paddy fields due to the combined effects of heavy machinery and continuous flooding. This layer can significantly reduce water infiltration rates. Furthermore, soil analysis revealed that paddy fields in the studied area had a high clay content, reaching 36.42 % (Figure 5). High clay content can impede water infiltration due to the small size of clay particles, which limits the development of macropores and micropores.

The critical assessment of groundwater infiltration in the studied area considers water input from rainfall and the land ability to infiltrate water without considering water balance conditions. As a comparison, the assessment of water infiltration that takes into account the water balance shows that the total recharge from paddy fields is the highest during the irrigation and non-irrigation periods, namely 254.66 million m^3 or equivalent to 33.61 % of the total catchment area (Amano and Iwasaki, 2022). In line with Lerner *et al.* (1990) who state that in irrigated paddy fields, in the calculation of the water balance, there is additional irrigation regularly that enters the irrigated paddy area, causing an increase in the amount of water that can be absorbed into the soil (earth recharge). Based on the results, the recommendation for land improvement is not only to convert paddy fields into other lands but also to maximize the ability of paddy field to infiltrate water based on determining factors.

The Correlation of Soil Physical Properties with Critical Groundwater Infiltration

Soil management practices significantly influence soil physical, chemical, and biological properties. For instance, continuous plowing in paddy fields can degrade soil quality, reducing its overall performance and compromising the sustainability of its functions (Cardoso *et al*., 2013). The use of heavy machinery in tillage operations can lead to soil compaction, resulting in decreased soil permeability (Imamul Huq and Md. Shoaib, 2013). The observed variations in soil physical properties, particularly soil permeability, bulk density, porosity, and texture, provide a clear representation of infiltration dynamics in the studied area. These parameters are critical indicators of the soil ability to absorb and transmit water, which directly influences the potential for groundwater recharge. Higher permeability and porosity, coupled with favourable textural compositions, facilitate water infiltration and percolation into

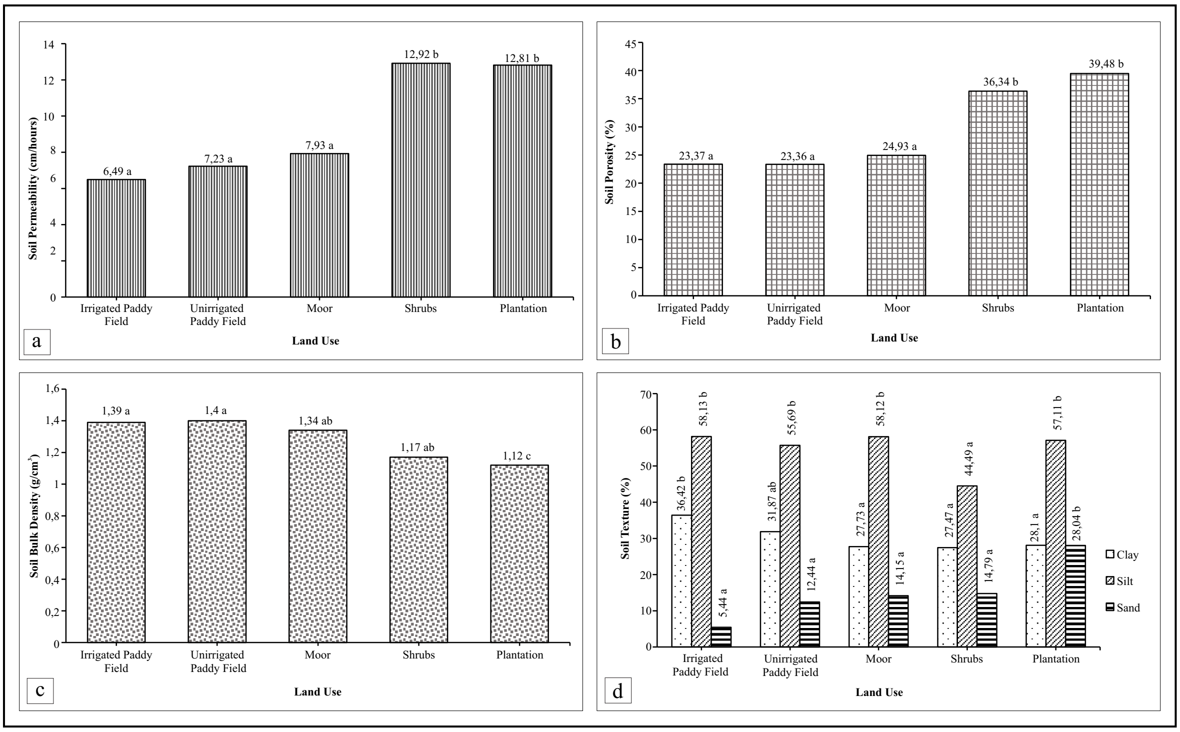

Figure 5. Differences in mean values; (a) soil permeability; (b) soil porosity; (c) soil bulk density; (d) soil texture in various land use.

deeper soil layers, enhancing recharge potential (Sun *et al*., 2018). Therefore, the data presented in this study provide a solid basis for understanding the spatial variability of infiltration capacity and its implications for groundwater replenishment across different land use types in the region. The research results revealed the high effects of land use on key soil physical properties. Differences value (p-value < 0.01) were significantly observed in soil permeability, bulk density, and porosity across land use types. Additionally, significant differences value (p-value < 0.05) were found in soil texture (silt, clay, and sand fractions) among the land use categories.

Plantations and scrubland exhibited higher permeability values (12.81 cm/hour and 12.92 cm/hour) compared to irrigated paddy fields (6.49 cm/hour), rainfed paddy fields (7.23 cm/hour), and moorland (7.93 cm/hour), indicating a more significant potential for groundwater infiltration. This higher permeability in plantations can be attributed to reduced soil disturbance due to minimal tillage activities, as Kusumandari *et al*. (2021) suggested. Permeability is directly related to soil porosity. Soils with higher porosity generally exhibit more excellent permeability, as the interconnected pore spaces facilitate water movement through the soil profile (Panigrahi *et al*., 2018). Plantations and scrublands exhibited higher porosity values, ranging from 36.34 % to 39.48 %, compared to 23.36 to 24.93 % in irrigated, rainfed, and moorland fields.

Furthermore, plantations exhibited the lowest average soil bulk density (1.12 g/cm³). This finding aligns with the observations of Schoonover and Crim (2015), who stated a strong inverse relationship between bulk density and porosity. Higher bulk density indicates increased soil compaction, reducing pore space and decreasing infiltration rates.

Soil texture is pivotal in determining soil and water characteristics, significantly affecting permeability, structure, and water-holding capacity (Greve *et al*., 2012). Soil texture is classified based on the soil relative proportions of clay, silt, and sand particles. In the studied area, soil texture analysis revealed that silt was the most dominant fraction across agricultural land uses, ranging from 44.49 to 58.13 %. Clay content varied from 27.47 to 36.42 %, and sand texture ranged from 5.44 to 28.04 %.

With its larger particle size compared to clay, the dominance of silt can contribute to the development of a more significant number of mesopores within the soil profile (Hartmann *et al*., 2012). Mesopores, intermediate in size between micropores and macropores, play a crucial role in water infiltration and movement within the soil. This textural characteristic contributes to the relatively fast permeability observed in the studied area.

This study identified key soil physical properties that significantly correlate with the critical status of water infiltration in the researched area. Statistical analysis revealed strong positive correlations between soil permeability and groundwater infiltration criticality. A highly significant positive correlation (r= 0.807, p-value= 0.000, N=63) was observed between these two parameters, indicating that higher permeability values are associated with higher water infiltration potential.

Soil porosity and water infiltration critical status parameters have a very strong positive correlation (r= 0.827, p-value= 0.000, N=63) between these variables. This relationship is expected, as higher porosity, characterized by a greater volume of interconnected pores within the soil, facilitates the infiltration and movement of water through the soil profile. Specifically, abundant macropores, large pores filled with air or water, significantly enhance the water infiltration rate into deeper soil layers (Rab *et al*., 2014).

Conversely, a strong negative correlation was observed between soil bulk density and water infiltration critical status with a highly significant negative correlation (r= -0.774, p-value= 0.000, N=63), indicating that higher bulk density values are associated with lower water infiltration potential. This finding aligns with the observations of Githinji (2014), who emphasized that increased soil bulk density, resulting from compaction, reduces soil pore space, hindering water infiltration and root growth.

Management Strategy of Groundwater Infiltration

This study identified critical factors limiting water infiltration, particularly in paddy fields, with the lowest mean critical infiltration. These vital factors include slow soil permeability, high bulk density, and low porosity. A multifaceted approach is necessary to address these limitations and enhance water infiltration, optimizing soil health and improving water management practices. The land management strategy is a recommendation based on the critical factors of water infiltration, thereby minimizing the critical status of infiltration. The principle of providing recommendations for increasing water infiltration in this study is to maximize rainwater that falls on the soil surface, so it can be optimally absorbed into the soil without large amounts of surface runoff. Groundwater utilization is used as alternative land management to support plant growth and production, the use of which can be increased by adding organic soil material (Anshori and Suswatiningsih, 2022).

Land management practice recommendations include (1) enhancing soil health through organic matter incorporation and (2) optimizing water management practices. Increasing soil organic matter content is crucial for improving soil structure, enhancing water infiltration, and increasing water-holding capacity (Fitria and Soemarno, 2022). Incorporating crop residues by utilizing paddy straw as organic matter can effectively reduce soil bulk density (Xu *et al*., 2018), improve soil structure and aggregation (Bass *et al*., 2016), and ultimately enhance groundwater infiltration (Alghamdi, 2018). Planting cover crops between cropping seasons can increase organic matter input, improve soil structure, and reduce soil erosion. Also, promoting agroforestry practices by integrating trees or shrubs with crops can enhance soil organic matter content and improve soil biodiversity. In addition, organic materials support sustainable agriculture through resource efficiency and enhance farmer welfare by empowering creativity (Fadhallah *et al*., 2025).

Optimizing water management practices by implementing eco-drainage systems: Eco-drainage systems, such as bio-swales and infiltration trenches, can effectively capture and utilize excess rainwater runoff. As advocated by Sudarmanto *et al*. (2013), this approach allows the controlled release of water into the soil profile, maximizing infiltration and minimizing surface runoff. Improving irrigation efficiency techniques, such as drip or sprinkler irrigation, can reduce water losses through evaporation and runoff and ensure adequate water supply for crop growth. Also, water-conserving cropping practices should be promoted by adopting drought-tolerant crop varieties.

Conclusions

This study demonstrates the effectiveness and efficiency of Geographic Information System (GIS) technology in assessing the critical distribution of water infiltration within The Manyaran District, Indonesia. Through a scoring and a weighting approach, this study successfully identified areas with varying degrees of water infiltration potential by integrating five key thematic maps - soil type, permeability, slope, rainfall, and land use. The critical status of water infiltration is a significant concern in the researched area, which frequently experiences drought disasters leading to water scarcity and decreased agricultural productivity. This study evaluated the water infiltration potential of several land use types, including irrigated paddy fields, rainfed paddy fields, moorland, shrubs, and plantations, based on their infiltration capacity. The results revealed that a substantial portion of the researched area (64.6 %) falls within the medium critical (32.56 %) and critical (32.04 %) categories for water infiltration. It highlights the region vulnerability to water scarcity and the need for targeted interventions to enhance water infiltration. Regarding infiltration capacity, plantations, shrubs, moorland, rainfed paddy fields, and irrigated fields exhibit varying infiltration potential. However, it is essential to note that this assessment primarily focused on the potential for infiltration based on soil properties and rainfall characteristics.

For future considerations, this study provides a static assessment of water infiltration. Future researches should incorporate dynamic factors such as seasonal variations in rainfall, changes in land use patterns, and the impacts of climate change to provide a more comprehensive understanding of groundwater recharge dynamics. Also, water balance modeling would allow a more accurate assessment of water infiltration.

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References

Adibah, N., Kahar, S. and Sasmito, B., 2013. Application of remote sensing and geographic information system for analysis water catchment area (Case Study: Pekalongan City). *Jurnal Geodesi Undip*, 2 (2), p.141-153.

Adunya, T. and Benti, F.C., 2020. The Impacts of Climate-Induced Agricultural Drought on Four Cereal Crops: A Case Study in Bako Tibe District, Oromia National Regional State, Ethiopia. *Caraka Tani: Journal of Sustainable Agriculture*, 35 (1), p.135. DOI: 10.20961/carakatani.v35i1.35749.

Agarwal, R. and Garg, P.K., 2015. Remote sensing and GIS based groundwater potential &

recharge zones mapping using multi-criteria decision making technique. *Water Resources Management*, 30 (1), p.243-260. DOI: 10.1007/s11269-015-1159-8.

Aini, L.N., Sekarsari, R., and Isnawan, B.H., 2020. Identification of changes in water catchment areas in Kulon Progo District using Geographic Information Systems. *Planta Tropika : Jurnal Agrosains (Journal of Agro Science)*, 8 (2), p.103-113. DOI: 10.18196/pt.2020.120.103-113.

Alattar, M.H., Troy, T.J., Russo, T.A., and Boyce, S.E., 2020. Modeling the surface water and groundwater budgets of the US using MODFLOW-OWHM. *Advances in Water Resources*, 143, p.1-13. DOI: 10.1016/j.advwatres.2020.103682.

Alghamdi, A.G., 2018. Biochar as a potential soil additive for improving soil physical properties—a review. *Arabian Journal of Geosciences*, 11 (24), p.1-16. DOI: 10.1007/s12517-018-4056-7.

Amano, H. and Iwasaki, Y., 2022. Estimation of groundwater recharge in Kumamoto area, Japan in 2016 by mapping land cover using GIS data and SPOT 6/7 satellite images. *Sustainability*, 14 (1), p.1-19. DOI: 10.3390/su14010545.

Amin, M.F.F., Dharmawan, K.I., Budianta, W., and Hendrayana, H., 2023. Pemetaan Kekritisan Zonasi Resapan Air di Kota Semarang. *Jurnal Wilayah dan Lingkungan*, 11 (3), p.264-278.

Anshori, A. and Suswatiningsih, T.E., 2022. Irigasi air tanah mendukung pertanaman kacang tanah, jagung dan kedelai di lahan kering pada musim kemarau. *AgriHealth: Journal of Agri-food, Nutrition and Public Health*, 3 (2), p.124-132.

Anshori, A., Srihartanto, E., Fibrianty, F., Suswatiningsih, T.E., Budiarti, S.W., Riyanto, D., Cahyaningrum, H., and Suradal, S., 2023. Increase of Cropping Index in Dryland Supported by Groundwater Irrigation. *Caraka Tani: Journal of Sustainable Agriculture*, 38 (1), p.1-13.

Arham, A., Ramlan, R., and Thaha, A.R., 2019. Perubahan sifat fisik tanah pada lahan tambang di Desa Bahomoahi Kecamatan Bungku Timur Kabupaten Morowali. *Agrotekbis: E-Jurnal Ilmu Pertanian*, 7 (6), p.704-711.

Arshad, A., Zhang, Z., Zhang, W., and Dilawar, A., 2020. Mapping favorable groundwater potential recharge zones using a GIS-based analytical hierarchical process and probability frequency ratio model: a case study from an agro-urban region of Pakistan. *Geoscience Frontiers*, 11 (5), p.1805-1819. DOI: 10.1016/j.gsf.2019.12.013.

Awanda, D., Anugrah Nurul, H., Musfiroh, Z., and Dinda Dwi, N.P., 2017. Spatial analysis for potential water catchment areas using GIS: weighted overlay technique. *IOP Conference Series: Earth and Environmental Science*, 98 (1), p.1-11. DOI: 10.1088/1755-1315/98/1/012054.

Bass, A.M., Bird, M.I., Kay, G., and Muirhead, B., 2016. Soil properties, greenhouse gas emissions and crop yield under compost, biochar and co-composted biochar in two tropical agronomic systems. *Science of the Total Environment*, 550, p.459-470. DOI: 10.1016/j.scitotenv.2016.01.143.

BBSDLP, 2016. *Soil Physical Properties and Analysis Methods*. Bogor: Agriculture Department.

BBSDLP, 2018. *InaAgriMap WebGIS Soil Map in Indonesia scale 1:50.000*.

Bedbabis, S., Rouina, B. Ben, Boukhris, M., and Ferrara, G., 2014. Effect of irrigation with treated wastewater on soil chemical properties and infiltration rate. *Journal of Environmental Management*, 133, p.45-50. DOI: 10.1016/j.jenvman.2013.11.007.

Bruce, J.P. and Clark, R.H., 1966. *Introduction to Hydrometeorology:* California: Elsevier Science & Technology.

Cardoso, E.J.B.N., Vasconcellos, R.L.F., Bini, D., Miyauchi, M.Y.H., dos Santos, C.A., Alves, P.R.L., de Paula, A.M., Nakatani, A.S., Pereira, J. de M., and Nogueira, M.A., 2013. Soil health: looking for suitable indicators.

what should be considered to assess the effects of use and management on soil health? *Scientia Agricola*, 70 (4), p.274-289. DOI: 10.1590/S0103-90162013000400009.

Central Bureau Statistics of Wonogiri, 2018. *Manyaran District in Numbers 2018*. Wonogiri.

Central Bureau Statistics of Wonogiri, 2020. *Manyaran District in Numbers 2020*. Wonogiri.

Chen, K., Yu, S., Ma, T., Ding, J., He, P., Dai, Y., and Zeng, G., 2022. Effects of water and nitrogen management on water productivity, nitrogen use efficiency and leaching loss in rice paddies. *Water*, 14 (10), p.1-15. DOI: 10.3390/w14101596.

Cleophas, F., Isidore, F., Musta, B., Ali, B. M., Mahali, M., Zahari, N. Z., and Bidin, K., 2022. Effect of soil physical properties on soil infiltration rates. *In*: Journal of physics: conference series, 2314 (1), p.012020. IOP Publishing. https://iopscience.iop.org/article/10.1088/1742-6596/2314/1/012020/pdf.

Communication and Information Agency of Wonogiri Regency, 2021. *Agricultural Statistics of Wonogiri Regency in 2021*. Wonogiri.

Defersha, M.B., Melesse, A.M., and McClain, M.E., 2012. Watershed scale application of WEPP and EROSION 3D models for assessment of potential sediment source areas and runoff flux in the Mara River Basin, Kenya. *Catena*, 95, p.63-72. DOI: 10.1016/j.catena.2012.03.004.

Fadhallah, E.G., Zuidar, A.S., Hidayati, S., Haidawati, H., Dameswary, A.H., and Ramadhani, A.T. 2025. Development of Sustainable Bioplastic Composite Films from Cocoa Pod Husk Waste Cellulose and Kappa-Carrageenan. *Caraka Tani: Journal of Sustainable Agriculture*, 40 (1), p.34-51.

Fitria, L. and Soemarno, S., 2022. Effects of Lime and Compost on Chemical Characteristics and Soil Hydraulic Conductivity of Alfisols at ATP Jatikerto Coffee Plantation. *Caraka Tani: Journal of Sustainable Agriculture*, 37 (1), p.48. DOI: 10.20961/carakatani. v37i1.54010.

Geospatial Information Agency of the Republic Indonesia, 2019. *Indonesia's Digital Topographic Map. Bogor, West Java scale 1:50.000.* Bogor, Jawa Barat.

Githinji, L., 2014. Effect of biochar application rate on soil physical and hydraulic properties of a sandy loam. *Archives of Agronomy and Soil Science*, 60 (4), p.457-470. DOI: 10.1080/03650340.2013.821698.

Greve, M.H., Kheir, R.B., Greve, M.B., and Bøcher, P.K., 2012. Quantifying the ability of environmental parameters to predict soil texture fractions using regression-tree model with GIS and LIDAR data: the case study of Denmark. *Ecological Indicators*, 18, p.1-10. DOI: 10.1016/j.ecolind.2011.10.006.

Haghnazari, F., Shahgholi, H. and Feizi, M., 2015. Factors affecting the infiltration of agricultural soils: review. *International Journal of Agronomy and Agricultural Research*, 6 (5), p.21-35. Available at: http://www.innspub.net.

Hartmann, P., Zink, A., Fleige, H., and Horn, R., 2012. Effect of compaction, tillage and climate change on soil water balance of Arable Luvisols in Northwest Germany. *Soil and Tillage Research*, 124, p.211-218. DOI: 10.1016/j.still.2012.06.004.

Hou, J., Zhang, Y., Tong, Y., Guo, K., Qi, W. and Hinkelmann, R., 2019. Experimental study for effects of terrain features and rainfall intensity on infiltration rate of modelled permeable pavement. *Journal of Environmental Management*, 243, p.177-186. DOI: 10.1016/j.jenvman.2019.04.096.

Imamul Huq, S.M. and Md. Shoaib, J.U., 2013. Problem Soils. in *The Soils of Bangladesh, World Soils Book*, p.57-70. DOI: 10.1007/978-94-007-1128-0_7.

Jeloudar, F.T., Sepanlou, M.G,. and Emadi, S.M., 2018. Impact of land use change on soil erodibility. *Global Journal of Environmental Science and Management*, 4 (1), p.59-70. DOI: 10.22034/gjesm.2018.04.01.006.

Kamran, M., Ahmad, S.R., Chohan, K., Akhtar, A., Hassan, A. and Khan, R.M.A., 2022.

Assessment of water stress in rice fields incorporating environmental parameters. *International Journal of Innovations in Science and Technology*, 4 (2), p.212-223.

Keesstra, S.D., Geissen, V., Mosse, K., Piiranen, S., Scudiero, E., Leistra, M. and Schaik van, L., 2012. Soil as a filter for groundwater quality. *Current Opinion in Environmental Sustainability*, 4 (5), p.507-516. DOI: 10.1016/j.cosust.2012.10.007.

Khetsha, Z., Van Der Watt, E., Masowa, M., Legodi, L., Satshi, S., Sadiki, L., and Moyo, K. 2024. Phytohormone-Based Biostimulants as an Alternative Mitigating Strategy for Horticultural Plants Grown Under Adverse Multi-Stress Conditions: Common South African Stress Factors. *Caraka Tani: Journal of Sustainable Agriculture*, 39 (1), p.167-193.

Kusumandari, A., Purwanto, R.H. and Widayanti, W.T., 2021. The influence of grass plantation harvesting to soil in relation to sustainable forest management. *IOP Conference Series: Earth and Environmental Science*, 662 (1), p.1-7. DOI: 10.1088/1755-1315/662/1/012015.

La Manna, L., Buduba, C.G. and Rostagno, C.M., 2016. Soil erodibility and quality of volcanic soils as affected by pine plantations in degraded rangelands of NW Patagonia. *European Journal of Forest Research*, 135 (4), p.643-655. DOI: 10.1007/s10342-016-0961-z.

Lerner, D.N., IAH., I.A. of H., Issar, A.S. and Simmers, I., 1990. *Groundwater Recharge: a guide to understanding and estimating natural recharge*. Heise (International contributions to hydrogeology).

Massah, J. and Azadegan, B., 2016. Effect of chemical fertilizers on soil compaction and degradation. *Agricultural Mechanization in Asia, Africa and Latin America*, 47 (1), p.44-50.

Mehrabi, H., Zeinivand, H., and Hadidi, M., 2012. Site selection for groundwater artificial recharge in Silakhor Rangelands using GIS technique. *Journal of Rangeland Science*, 2 (4), p.687-695.

Meles, M.B., Bradford, S., Casillas-Trasvina, A., Chen, L., Osterman, G., Hatch, T., Ajami, H., Octavia Crompton, O., Levers, L., and Kisekka, I., 2024. Uncovering the gaps in managed aquifer recharge for sustainable groundwater management: A focus on hillslopes and mountains. *Journal of Hydrology*, 131615. DOI: 10.1016/j.jhydrol.2024.131615.

Minister of Forestry of The Republic Indonesia Number 32, 2009. in *Procedures for Formulating a Technical Plan for the Rehabilitation of Forest and Watershed Lands*.

Nace, R.L., 1976. *Hydrology (Handbook of Water Resources and Pollution Control)*. New York: Van Nostrad Reinhold Company Inc.

Oco, R.G., Devanadera, M.K., and De Grano, R.V.R. 2024. Utilization of *Nostoc piscinale* as Potential Biofertilizer to the Growth and Development of *Oryza sativa* L. *Caraka Tani: Journal of Sustainable Agriculture*, 39 (1), p.22-37.

Öztürk, M., Copty, N. K., and Saysel, A. K. (2013). Modeling the impact of land use change on the hydrology of a rural watershed. *Journal of Hydrology*, 497, p.97-109. DOI: 10.1016/j.jhydrol.2013.05.022

Panigrahi, S., Kumar, S., Panda, S. and Borkataki, S., 2018. Effect of permeability on primary processing of wood. Journal of Pharmacognosy and Phytochemistry, 7 (4), p.2593-2598. *Available at: http://www.timber.lk.*

Pratama, I. A., Suryantini, A., and Perwitasari, H. 2024. Sustainability of the Different Rice Cultivation Practices in Yogyakarta, Indonesia. *Caraka Tani: Journal of Sustainable Agriculture*, 39 (2), p.321-342.

Rab, M.A., Haling, R.E., Aarons, S.R., Hannah, M., Young, I.M., and Gibson, D., 2014. Evaluation of X-ray computed tomography for quantifying macroporosity of loamy pasture soils. *Geoderma*, 213, p.460-470. DOI: 10.1016/j.geoderma.2013.08.037.

Rawung, B. Y., Rogi, O. H., & Gosal, P. H. (2023). Analisis Kekritisan Daerah resapan air di Kota Manado. *SPASIAL*, 11 (1), p.40-47. https://ejournal.unsrat.ac.id/index.php/spasial/ article/view/ 51444.

Rendana, M., Rahim, S.A., Idris, W.M.R., Rahman, Z.A. and Lihan, T., 2022. Agricultural Land Evaluation Using GIS-Based Matching Method in Highland Areas for Oil Palm Cultivation. *Caraka Tani: Journal of Sustainable Agriculture*, 37 (1), p.100. DOI: 10.20961/carakatani.v37i1.57441.

Rodríguez, D., Schulz, G.A., Aleksa, A. and Vuegen, L.T., 2019. Distribution and classification of soils. *The Soils of Argentina*, p.63-79. DOI: 10.1007/978-3-319-76853-3_5.

Rogger, M., Agnoletti, M., Alaoui, A., Bathurst, J. C., Bodner, G., Borga, M., … and Blöschl, G., 2017. Land use change impacts on floods at the catchment scale: Challenges and opportunities for future research. *Water resources research*, 53 (7), p.5209-5219. DOI: 10.1002/2017WR020723

Romadhon, M.R., and Aziz, A., 2022. Determination of flood susceptibility index using overlay-scoring data method based on geographic information system (gis) in Semarang city, Central Java, Indonesia. *AgriHealth: Journal of Agri-food, Nutrition and Public Health*, 3 (2), p.104-123.

Santosa, S.S., Suryadi, E., and Kendarto, D.R., 2021. Analisis kekritisan daerah resapan air menggunakan metode skoring di sub das cikeruh. *Journal of Tropical Agricultural Engineering and Biosystems*, 9 (1), p.79-89. DOI: 10.21776/ ub.jkptb.2021.009.01.09.

Saputra, A.E., Ridwan, I., and Nurlina, N., 2019. Analysis of the level water infiltration using a geographic information system in Tabunio Basin. *Jurnal Fisika FLUX*, 1 (1), p.149-158. DOI: 10.20527/flux.v1i1.6158.

Schober, P., Boer, C. and Schwarte, L.A., 2018. Correlation coefficients: appropriate use and interpretation. *Anesthesia and Analgesia*, 126 (5), p.1763-1768. DOI: 10.1213/ ANE.0000000000002864.

Schoonover, J.E. and Crim, J.F., 2015. An introduction to soil concepts and the role of soils in watershed management. *Journal of Contemporary Water Research & Education*, 154 (1), p.21-47. DOI: 10.1111/j.1936-704x.2015.03186.x.

Sigit, A.A., Priyono, K.D., and Priyana, Y., 2015. Utilization of the underground river water of Suruh Cave for the people in Pucung Village, Eromoko, Wonogiri. *Warta LPM*, 18 (1), p.10-20. DOI: 10.23917/warta.v18i1.1162.

Singha, A., Islam, S.M.H., Ahmed, M. and Akter, T., 2014. Seepage and percolation loss in the rice field of Bangladesh Agricultural University Farm. *Journal of Sylhet Agricultural University*, 1 (1), p.117-122.

Sudarmanto, A., Buchori, I., and Sudarno, 2013. Analysis of land infiltration capability based on hydrometeorological conditions and physical characteristics of the watershed in Kreo sub-watershed, Central Java. *Prosiding Seminar Nasional Pengelolaan Sumberdaya Alam dan Lingkungan*. Semarang.

Sun, D., Yang, H., Guan, D., Yang, M., Wu, J., Yuan, F., Jin, C., Wang, A., and Zhang, Y., 2018. The effects of land use change on soil infiltration capacity in China: A meta-analysis. *Science of the Total Environment*, 626, p.1394-1401. DOI: 10.1016/ j.scitotenv.2018.01.104.

Thakur, K.K., Arora, S., Pandita, S., and Goyal, V., 2013. Infiltration characteristics of erosion prone soils of Balwal watershed in relation to soil loss and runoff. *Journal of Soil and Water Conservation*, 12 (3), p.207-211.

Utami, A. W., Widjanarko, N. P. A., Indradewa, D., Dhamira, A., Arum, M. R., Rizqi, F. A., komarudin N. A., and Prabaningtyas, D. 2024. Traditional Ecological Knowledge and Farm Household Resilience to Natural Hazards. *Caraka Tani: Journal of Sustainable Agriculture*, 39 (1), p.154-166.

Viandari, N. Al, Wihardjaka, A., Pulunggono, H.B., and Suwardi, S., 2022. Sustainable Development Strategies of Rainfed Paddy Fields in Central Java, Indonesia: A Review. *Caraka Tani: Journal of Sustainable Agriculture*, 37 (2), p.275. DOI: 10.20961/ carakatani. v37i2.58242.

Wonogiri District Regulation 2020. in *Wonogiri Regency Spatial Plan 2020-2040*.

Xu, X., Pang, D., Chen, J., Luo, Y., Zheng, M., Yin, Y., Li, Yanxia, Li, Yong, and Wang, Z., 2018. Straw return accompany with low nitrogen moderately promoted deep root. *Field Crops Research*, 221, p.71-80. DOI: 10.1016/j.fcr.2018.02.009.