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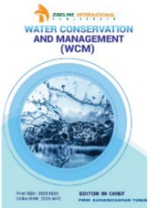

RESEARCH ARTICLE

THE WATER BALANCE, DROUGHT INDEX, AND RUNOFF COEFFICIENT OF THE WANAGAMA REHABILITATED FOREST, GUNUNG KIDUL, INDONESIA

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ABSTRACT

The Wanagama Forest represents a notable success in the rehabilitation of degraded karst landscapes. This restoration effort has not only enhanced vegetation cover but also contributed to the development of a favorable microclimate that supports ecological functions and human well-being. Over time, the forest has played an important role in improving water availability, which is essential for meeting the needs of nearby communities. Karst regions, including Wanagama, are typically characterized by limited water retention capacity and are highly vulnerable to seasonal drought, particularly during prolonged dry periods. Despite its recognized success in land restoration, studies focusing on the hydrological dynamics of the Wanagama Forest remain relatively scarce. Therefore, this study aims to (1) assess the water balance, (2) evaluate the drought index, and (3) determine the runoff coefficient within the rehabilitated forest area. The analysis applies the Thornthwaite–Mather approach to estimate water balance components, alongside calculations of the dryness index (Ia) and runoff coefficient (C). The results indicate an increasing trend in annual water surplus, reaching approximately 15.654 mm/year, accompanied by a rise in water deficit of about 9.014 mm/year. The calculated drought index of 1.15% suggests that the area experiences low drought stress and can be classified as having a non-critical water condition. In addition, the runoff coefficient ranges between 0.3 and 0.5, indicating a moderate proportion of rainfall contributing to surface runoff while a substantial amount infiltrates into the soil.

KEYWORDS

Dryness, Karst, Reforestation, Degraded, Land

1. INTRODUCTION

Land degradation has emerged as a pressing environmental concern in recent decades (Gupta, 2019). It represents a substantial challenge to ecological sustainability while simultaneously affecting the livelihoods of millions of people, particularly in developing regions. This phenomenon is characterized by a gradual decline in land quality and productivity, largely driven by human-induced activities such as deforestation, excessive grazing, and unsustainable farming practices. As a result, land degradation leads to substantial losses by depleting soil fertility and increasing farming costs, which further exacerbates food insecurity (Naik et al., 2025). The researcher concluded that converting forest cover to agricultural or non-forest land without sustainable planning often results in the loss of soil fertility and disrupt the balance of ecosystem (Gerwing et al., 2022).

Land degradation refers to the significant deterioration or loss of biological and economic productivity resulting from land use or human activities that do not adhere to conservation principles (Shao et al., 2020). Each year, the amount of critically degraded land continues to increase due to various factors. One major cause is the lack of data and information regarding the land's capacity for sustainable development in relation to land use. A key strategy to address critical land issues is land rehabilitation. In Indonesia, critical land areas are receiving significant attention due to the substantial impacts of global warming. To tackle this problem, several priority efforts are essential, including critical land rehabilitation programs (Mursyid et al., 2025). Land rehabilitation efforts through the introduction of pioneer vegetation have contributed to noticeable improvements in soil quality. These initiatives have shown positive outcomes, including increased vegetation cover, enhanced soil fertility, reduced erosion rates, and the development of a more favorable microclimate. One well-recognized example of successful rehabilitation of degraded land in Indonesia is the Wanagama Forest.

Wanagama is an educational forest administered by the Faculty of Forestry at Universitas Gadjah Mada, situated within a karst hill landscape along the southern mountain range of Yogyakarta. Karst terrains, which are primarily composed of porous limestone, present inherent challenges for water retention due to their high permeability, allowing water to rapidly infiltrate into the subsurface. Historical accounts describe the area, at the onset of its development, as predominantly dry and barren. The distinctive characteristics of karst ecosystems limit the capacity for water storage and often lead to recurring drought conditions. In the case of Wanagama, these hydrological constraints have a direct effect on the availability of water resources, which are vital for sustaining both ecological systems and human livelihoods (Purnomo and Usmadi, 2012).

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The study point out that the influence of forest cover expansion or restoration on water provisioning services is still not fully understood and continues to be widely debated. In the case of Wanagama, empirical data related to water balance and overall water resource conditions remain limited. This gap highlights the need for further investigation into how forest rehabilitation contributes to enhancing water resource potential, particularly as a basis for more effective and sustainable water conservation planning in the future (Filoso et al., 2017).

Forest hydrology, which examines the movement and distribution of water within forested catchments, plays a fundamental role in explaining the complex interactions between vegetation cover and water balance. Over the past century, global shifts in climate, land use, and land cover have increasingly disrupted forest ecosystems, reducing their capacity to regulate water effectively. These changes underline the growing relevance of forest hydrology as an important field of scientific inquiry (Farooqi, 2024). In the Wanagama area, water scarcity remains a pressing concern, particularly during the dry season. Communities living in proximity to the forest frequently rely on purchasing water to meet their daily needs. Considering these conditions, along with the environmental characteristics of the study area and the limited availability of water resources, this research becomes highly necessary. This study is designed to assess the role of land rehabilitation in improving hydrological conditions, particularly water balance. Specifically, it focuses on evaluating the water balance, examining the drought index, and estimating the runoff coefficient within the Wanagama forest. The findings of this research are expected to provide meaningful contributions to practical forest management. A clearer understanding of water dynamics in Wanagama can assist managers in selecting suitable plant species and determining appropriate planting schedules. In addition, timely management strategies based on anticipated water shortages can help reduce environmental risks, including soil erosion and land degradation.

2. MATERIAL AND METHODS

2.1 Research Sites

The study took place in the Wanagama rehabilitated forest, which is located in Banaran Village, Bunder Hamlet, Gunung Kidul Regency. The forest covers around 600 hectares and has been gradually restored through rehabilitation programs that have been ongoing since 1963. Land cover data was sourced from map documents provided by the Wanagama Management. The various types of land cover and their respective areas in Wanagama reveal that the dominant land cover is composed of stands of Gliricidia (*Gliricidia sepium*), which cover 103 hectares (ha). This is followed by stands of teak (*Tectona grandis*), covering 92 ha, and mixed stands that occupy 80 ha. The mixed stands include eucalyptus (*Eucalyptus pellita*), Gliricidia (*Gliricidia sepium*), calliandra (*Calliandra calothyrsus*), acacia (*Acacia mangium* and *Acacia auriculiformis*), mahogany (*Swietenia macrophylla*), and teak (*Tectona grandis*).

2.2 Data Collecting

The data used in this study includes climatological information such as rainfall and temperature, as well as land use and soil type. Rainfall data were collected from four climatological stations: Kedung Keris, Wanagama, Terong, and Playen. Air temperature data were obtained from observation stations. Land use and soil type data was determined based on available data and the map from the Wanagama office.

2.3 Data Analysis

2.3.3 Rainfall and Air Temperature Analysis

The annual rainfall was calculated using the Algebraic average method, while the monthly average temperature was determined subsequently. If a specific observation station lacked temperature data, the Mock Equation (1973) can be applied to estimate temperatures using the following formula:

$\Delta T = 0.006 (z1 – z2)$

ΔT = Temperature difference between the measuring station and the station being analyzed (^oC)

z1 = Elevation of the temperature measuring station (m)

z2 = Elevation of the station being analyzed (m)

2.3.4 Thornthwaite Mather Methode

This research employed the Thornthwaite-Mather water balance calculation method, which is effective for determining water balance at a specific location based on temperature and precipitation data collected at monthly or daily intervals, as well as information on the soil's water holding capacity (Burak et al., 2022). Moreover, other studies indicate that the Thornthwaite-Mather method shows a strong correlation with significance levels ranging from over 70% to 90%. Therefore, this study utilized the Thornthwaite-Mather water balance method to assess water availability on the island of Java. The calculations involved in this method take into account both the monthly average rainfall and the monthly heat index (Pramono and Adi, 2010).

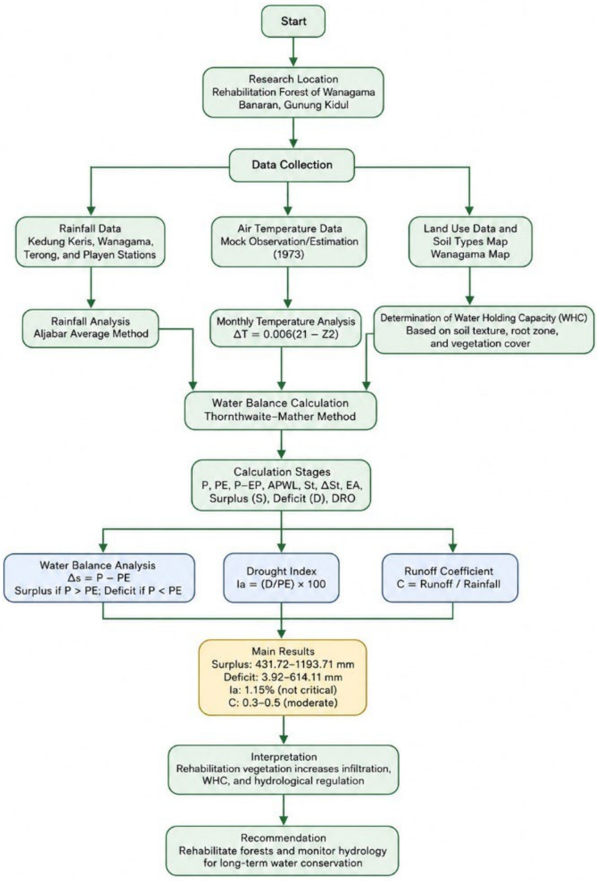

Figure 1: Flowsheet diagram of research.

The steps for calculating the water balance using the Thornthwaite-Mather method. The primary calculation stages include:

- Calculating monthly rainfall thickness (P)
- Calculating monthly potential evapotranspiration (PE)

Potential evapotranspiration was determined using the Thornthwaite-Matter method, which is based on the following equation:

$I = (T/5)1.514$

PE = f . PEx with the value, PEx = 16 (10T/I)a

PEx: Potential Evapotranspiration (mm/month)

f: Latitude and time correction factor

T: Air temperature (^oC)

I: Total heat index in a year

a: Heat index, a = (0.675 . 10-6 . I3) (0.77. 10-4. I2) + 0.01792. I + 0.49239

- Calculating the difference between P and EP (P- EP)
- Calculating Accumulated Potential Water Loss (APWL), by:

The first negative (P-EP) value after the positive (P-EP) is derived as the absolute value of the first APWL Then, the first APWL value added to the next negative |(P–EP)| is the second APWL value, and so on until the negative (P-EP) value runs out.

If (P-EP) is positive, then APWL is zero.

- Determining the Sto (WHC) value which is a function of soil texture and root zone depth (mm/m)

Calculating the value of soil moisture storage (St), that is:

$St = Sto \ X \ e - (APWL/ \ Sto)$, if $APWL \neq 0$

$St = Sto$, if $APWL = 0$

$e = 2.178$ (coefficient according to Thornthwaite & Mather)

- Counting ΔSt every month

$\Delta St =$ St of the month in question –St last month

For January minus December

- Calculating actual evapotranspiration (EA)

For wet months (P>EP), then EA = EP

For dry months (P<EP), then $EA = P + |\Delta St|$

- Calculating water Surplus (S)

$S = (P-EP) - \Delta St$

- Calculating the water Deficit (D)

$D = EP – EA$

- Calculating the Direct Run Off (DRO) value with the formula:

(0.5 previous month surplus + 0.5 current month surplus)

2.3.5 Water Balance

The water balance analysis evaluates the use of water resources in a specific area by comparing water demand to water availability. The calculation results from the difference between rainfall (P) and potential evapotranspiration (PE). This analysis indicate whether there is a surplus or deficit of water during both wet and dry periods. Where the cumulative amount of rainfall (P), measured in millimeters, exceeds the value of potential evapotranspiration (PE), the water balance analysis produces a positive result, signifying surplus of water in the area. This surplus indicates the amount of excess water present during a certain period of the year, which can help replenish soil moisture and surface water flows. The water balance analysis can be mathematically expressed as follows:

$\Delta s = P – PE$

$\Delta s < 0$, $P < PE$, then there is a Deficit

$\Delta s > 0$, $P > PE$, then there is a Surplus

If the cumulative rainfall (P) is less than the potential evapotranspiration (PE), the water balance analysis indicates a negative value. This means that the area is experiencing a water deficit, where the amount of precipitation cannot meet the potential water needs of the vegetation in the region (Anna et al., 2016). Typically, during dry months, P is less than PE, while in wet months, P exceeds PE.

2.3.6 Drought index

Droughts results in significant ecological and social damage. Drought indices are essential tools for measuring drought severity, however, they are primarily applicable over monthly or longer timescales (Zhang et al., 2023). The drought index (Ia) is calculated using the relationship between water deficit and potential evapotranspiration, as follows:

$Ia = (D/PE) \ x \ 100$

2.3.7 Runoff Coefficient

The runoff coefficient (C) is a numerical value that represents the ratio of surface runoff to the amount of rainfall. It is calculated using the formula:

C = runoff (mm)/ rainfall (mm).

The maximum value of runoff is 1, indicating that all rainfall contributes to surface runoff.

3. Result And Discussion

3.1 Rainfall Depth in Wanagama

According to the Schmidt and Ferguson classification, the climate type of the study area is classified as C. Rainfall data for the last ten years (2013-2022) in Wanagama is shown in Figure 2. Using the algebraic average method, the annual rainfall was calculated, ranging from 1,355.42 mm to 2,749.63 mm. Rainfall in Wanagama generally reaches its highest levels at the beginning and the end of the year, whereas lower precipitation is typically recorded during the mid-year period. Throughout the 2013–2022 observation period, the maximum annual rainfall was documented in 2022 at 2,749.63 mm, while the minimum occurred in 2019 at 1,355.42 mm. Overall, the data indicate a gradual increase in annual rainfall, with a total rise of approximately 43.545 mm over the ten-year period.

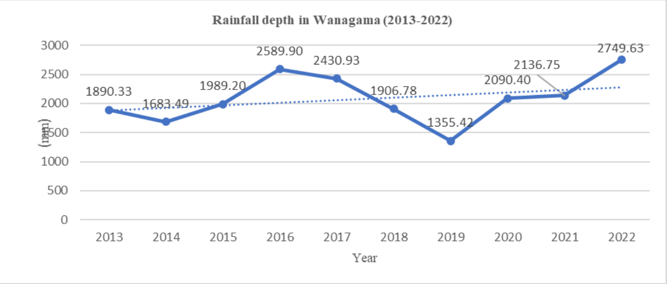

Figure 2: Rainfall depth recorded in Wanagama over the period 2013–2022. (Source: Results of the analysis of the Algebraic Average method)

3.2 Temperature in Wanagama

Air temperature plays a crucial role in regulating evaporation processes from both soil and vegetation, thereby affecting water availability at the surface and within the soil profile. Due to the absence of a climatological station in the Wanagama area, direct temperature observations were not available. Therefore, air temperature values were estimated using the empirical equation proposed by Mock (1973). The calculation was supported by climatological data obtained from the Playen station. The elevation of the Wanagama site was determined to be approximately 169.29 meters above sea level. Over the period from 2013 to 2022, the recorded annual air temperature exhibited variability, ranging between 21.70°C and 30.31°C. The most pronounced temperature fluctuation occurred in 2019, when the minimum temperature reached 23.59°C and the maximum peaked at 30.31°C as refer in Figure 3.

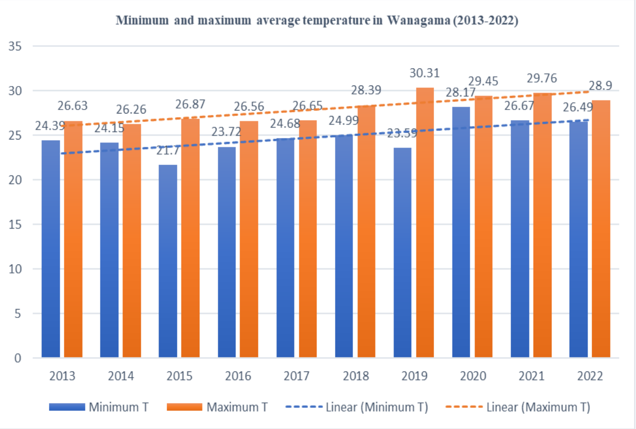

Figure 3: Line graph illustrating the mean monthly temperature variation in Wanagama over the period 2013–2022.

3.3 Water Balance Analysis

3.3.1 Water Holding Capacity (WHC) in Wanagama

Adequate soil water availability is fundamental for plant development, particularly in regions that rely heavily on rainfall as the primary water supply (Dwiratna et al., 2024). In this study, the available water and rooting zone values are based from the table developed by Thornthwaite & Mather (1957). It is assumed that the available water for each type of land cover is 300 mm per year, as the soil in the study area has a clay texture. The land use types in this research are classified according to vegetation cover, which includes deep-rooted plants, plantation crops, and forests. The rooting zone depth is 0.67 m for both deep-rooted plants and plantation crops, while forest land use has a rooting zone depth of 1.17 m. additionally, building land use is considered in these calculations, with the assumption that vegetation may still be present in these areas, resulting in a rooting zone depth of 0.1 m.

Based on the analysis results, the Water Holding Capacity (WHC) was determined to be 256.254 mm. According to Thornthwaite and Mather (1957), the value of water holding capacity (WHC) is governed by both soil texture and the type of vegetation covering the land surface. Soil texture, in particular, is a key factor that determines how effectively the soil can absorb water through infiltration as well as retain it for subsequent use.

When the same type of vegetation grows in different soil types, the depth of the plant roots can vary, which in turn affect the WHC. Generally, plants in sandy soils tend to have deeper root systems compared to those in silt and clay soils.

At the study site, the soil has a clay texture characterized by numerous small pores, contributing to its low porosity. Smaller soil particles result in a denser structure with a higher number of particles and surface area. The less porous soil tends to exhibit poor drainage and aeration due to challenges related to water and air circulation; however, it retains water more effectively and does not easily lose (Hanafiah, 2014). The estimation of WHC is shown in Table 1.

Table 1: Estimation of the Water Holding Capacity (WHC) for various vegetation combinations.

	Soil texture	Water available (mm)	Root zone (m)	Area percentage (%)	Available Water Capacity (mm)
Vegetation with deep root					
Shrubs	Clay	300	0.67	0.059413	11.942
Bambussa sp	Clay	300	0.67	0.001889	0.380
Agroforestry	Clay	300	0.67	0.048289	9.706
Plantations					
Syzygium cumini (Duwet)	Clay	300	0.67	0.0022	0.442
Syzygium polyanthum (Salam)	Clay	300	0.67	0.001655	0.333
Gliricidea	Clay	300	0.67	0.167024	33.572
Forest plantations					
Acasia sp	Clay	300	1.17	0.106457	37.366
Casuarina equisetifolia, Linn (Cemara udang)	Clay	300	1.17	0.007	2.457
Eucalyptus sp	Clay	300	1.17	0.059752	20.973
Gmelina sp	Clay	300	1.17	0.001312	0.461
Neolamarckia cadamba (Jabon)	Clay	300	1.17	0.004344	1.525
Tectona grandis, L.f. (Jati)	Clay	300	1.17	0.149301	52.405
Melaleuca leucadendra (Kayu putih)	Clay	300	1.17	0.039129	13.734
Eucalyptus deglupta (Leda)	Clay	300	1.17	0.002536	0.890
Swietenia mahagoni (Mahoni)	Clay	300	1.17	0.068394	24.006
Mixed planting (Tegakan campur)	Clay	300	1.17	0.129203	45.350
Albizia saman (Trembesi)	Clay	300	1.17	0.001137	0.399
Structured Land					
Museum kayu	Clay	300	0.1	0.000653	0.020
Rumah peneliti (house for researcher)	Clay	300	0.1	0.001669	0.050
Buildings	Clay	300	0.1	0.001155	0.035
Wanagama paksi	Clay	300	0.1	0.000132	0.004
Wisma cendana (buildings)	Clay	300	0.1	0.001792	0.054
Road	Clay	300	0.1	0.003572	0.107

Source: Data analysis based on Thornthwaite & Mather method.

Table 1 shows that the existence of vegetation, plantations and forest plantations have a higher available water capacity compared to structured land. Soil Water Holding Capacity (WHC) improved through conservation agriculture (CA) practices (Abdallah et al., 2021).

3.3.2 Water Balance of Wanagama

Understanding hydrological processes is essential for effective watershed management (Kardhana et al., 2024). Forests play a vital role in ensuring water security within the watershed area. Reducing forest biomass in currently overgrown forests can help mitigate the severity and impact of wildfires while providing additional competing eco hydrological benefits. A reduction in canopy interception and transpiration resulting from forest management can lead to an increase in available water for the remaining trees and can also enhance runoff. However, the effect of forest management on the water balance can vary significantly due to differences in climate, topography, location, and vegetation (Casirati, 2025).

The results of the water balance calculations are shown in Figure 4. Between 2013 and 2022, annual rainfall varied from 1,355.42 mm to 2,749.63 mm. Rainfall that reaches the earth's surface is a crucial input for the water balance. Peak rainfall typically occurs at the beginning and end of the year, while the lowest levels are generally observed in the middle of the year. The annual potential evapotranspiration (ETP) ranged from 1,320.98 mm to 1,769.06 mm, while the annual actual evapotranspiration (ETA) ranged from 715.05 mm to 1,275.89 mm.

Meteorological conditions, including solar radiation, air temperature, atmospheric humidity, and wind velocity, play a fundamental role in controlling evapotranspiration processes. In general, an increase in these climatic variables tends to elevate potential evapotranspiration (ETP) (Asdak, 2024). Elevated temperatures, in particular, enhance the rate of evapotranspiration, provided that sufficient soil moisture is available (Edwards et al., 2015). In contrast, actual evapotranspiration (ETA) is more closely associated with vegetation characteristics and soil properties, which regulate water availability within the system (Asdak, 2024). Periods in which precipitation exceeds potential evapotranspiration are typically identified as wet conditions, whereas rainfall amounts lower than ETP indicate dry conditions. Based on the analysis conducted, the Wanagama area generally experiences wetter conditions at the beginning and end of the year, while the mid-year period is predominantly characterized by drier conditions.

During periods of low rainfall, soil moisture storage (St) tends to decline as vegetation continues to draw water through evapotranspiration. This condition is reflected in negative values of ΔSt. With the onset of wetter periods and increased precipitation, soil water reserves are gradually restored through infiltration, resulting in positive ΔSt values. Any excess rainfall, after meeting evapotranspiration demands and replenishing soil moisture, is considered as water surplus.

According to the Thornthwaite-Mather method, it is assumed that 50% of this surplus will become surface runoff, while the other 50% will infiltrate into the soil, contributing to surface runoff in the following month. The total annual surface runoff observed in Wanagama ranges from 431.17 to 1187.99 mm shown in Figure 4.

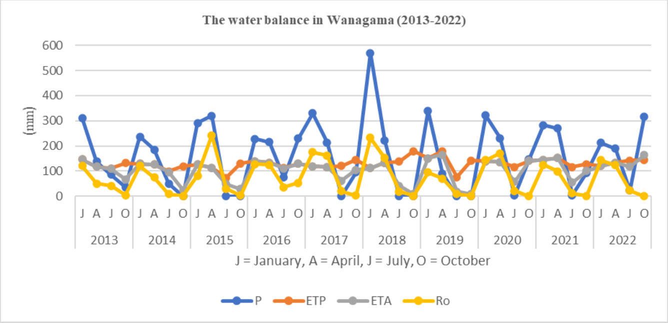

Figure 4:The water balance in Wanagama (2013 – 2022)

3.3.3 Surplus dan Deficit

Changes in forest cover can impact not only the total runoff from a watershed, but also its individual components, such as surface runoff, interflow, and groundwater flow (Ding et al., 2022). Generally, the study area experiences periods of water surplus at the beginning and end of the year, while water deficits are more common during the middle of the year. Figure 5 illustrates the trends of surplus and deficit from 2013 to 2022. The annual water surplus ranges from 431.72-1193.71 mm, while the annual water deficit varies between 3.92 mm and 614.11 mm.

The water balance analysis reveals that Wanagama has seen an increasing trend in annual water surplus, rising by 15,654 mm/year. In contrast, the annual water deficit has also increased by 9,014 mm/year. The presence of a water deficit suggests that plants are experiencing water shortages and may require irrigation as shown in figure 5 (Singh et al., 2004).

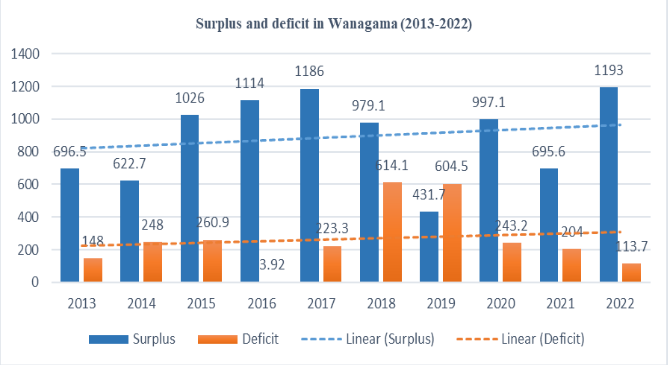

Figure 5: Surplus and Deficit in Wanagama (2013-2022)

3.3.4 Drought Index

The estimates of water storage derived from surface water and groundwater processes by using the Soil and Water Assessment Tool (SWAT) and groundwater flow models, suggest that the water storage capacity ranks in the following order: forest, orchard, grassland, and agricultural land, from largest to smallest (Wu et al., 2025). The relationship between water deficit and potential evapotranspiration produces a drought index (Ia). The drought index for the period of 2013-2022 is illustrated in Figure 6. The analysis indicates that Wanagama experienced a low drought in 2016, with an index value of 0.26%. This indicates minimal to no water shortage, based on the Thornthwaite Mather drought index (1957), since the Ia value ranges from 0 to 16.7% (Maru et al., 2015). A pronounced drought event was observed in 2019, as indicated by a drought index value of 34.86%. This level reflects a severe water deficit, exceeding the 33.3% threshold defined within the same classification system. During that year, the study area experienced its most extended dry period, lasting approximately eight months from April to November. According to reports from the Yogyakarta Meteorology, Climatology, and Geophysics Agency (BMKG), this condition was primarily associated with below-average rainfall. Indeed, total annual precipitation in 2019 was recorded at 1,355.42 mm, representing the lowest value within the 2013–2022 observation period shown in Figure 6.

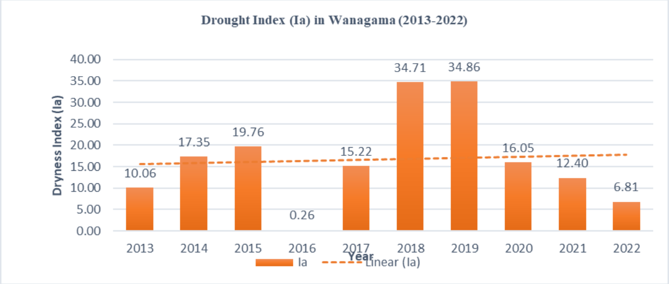

Figure 6: Drought Index (Ia) in Wanagama (2013-2022)

3.3.5 Runoff Coefficient (C)

Forest hydrology represents an important branch of environmental science that examines the role of forest ecosystems in governing the movement and distribution of water. Forests contribute significantly to the global hydrological cycle by functioning as natural regulators that influence water flow, quality, and overall availability. In addition to supporting diverse biological communities, forest systems provide essential ecosystem services, including flood mitigation, stabilization of groundwater reserves, and improvement of water quality. As pressures from climate change, deforestation and urbanization increase, it become vital to understand the complex relationship between forests and the hydrological cycle for effective sustainable land and water management (Calie,2024). Additionally, forest cover impacts not only the quantity of surface runoff, but also its quality (Trenciansky, 2021).

The runoff coefficient (C) is a numerical value that represents the ratio of surface runoff to the amount of rainfall. The results of the runoff coefficient analysis are presented in Figure 7. During the period from 2013 to 2022, the C value ranged from 0.3 to 0.5. When the C value is 0, it means there is no runoff in a watershed, while a C value of 1 indicates significant runoff, meaning that all rainfall becomes runoff. Wanagama experiences moderate surface runoff, with only 30-50% of the total rainfall contributing to this runoff. The remaining water infiltrates into the soil. Figure 7 shows several factors influence runoff, including the amount of rainfall, the shape and size of the area, topography, geology, and land use (Asdak, 2024).

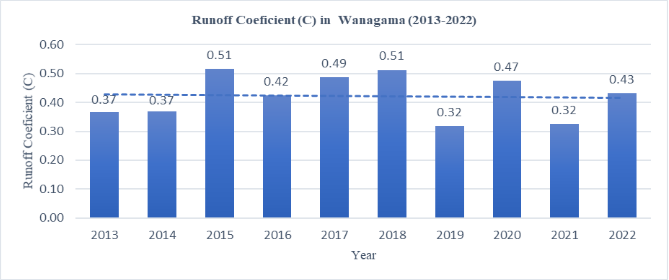

Figure 7: Runoff Coefficient (C) in Wanagama (2013-2022)

In recent years, climate change and human activities have significantly altered the runoff in forested headwater watersheds. However, the combined impacts of these environmental changes on the ecologically sensitive headwater zones have not been sufficiently addressed. (Zhang et al., 2025). Run off is crucial component of the hydrological cycle, directly influencing the distribution and availability of freshwater resources globally (Allen et al. 2021; Lin et al. 2021). It plays an essential role in maintaining ecosystem balance by supporting agricultural irrigation and supplementing groundwater reserves (Feng and Beighley 2020; Xia et al. 2022). Nowadays, climate change and human activities have significantly altered hydrological processes (Han et al. 2018; Kim et al. 2023). In this case, runoff is increasingly affected by these changes (Alamdari et al. 2022; Liu et al. 2025). Moreover, these changes affect both the natural hydrological processes and have profound implications for human water resource management as well as flood disaster prevention (Saraswat et al. 2016 and Xue et al., 2021).

Droughts pose significant challenges to agriculture, water resources, ecosystems, and communities worldwide. There are various types of droughts- meteorological, hydrological, agricultural, socio-economic, ecological, urban, environmental, and flash- each with distinct impacts. We recognized an urgent need for improve prediction and modeling tools to enhance drought risk assessment and management (Rahman et al., 2025). To effectively address critical water conditions, it is essential to consider the use of available water resources. This effort requires the implementation of policies that adhere to ecosystem rehabilitation principles. Moreover, restoration efforts should be carefully planned in terms of location and integrated with broader landscape-level conservation strategies (Palmer and Stewart, 2020).

3.5.6 Comparative Hydrological Performance Between Rehabilitated and Non-Rehabilitated Land

To better interpret the effects of rehabilitation, the hydrological characteristics identified in the Wanagama restored forest were conceptually compared with those reported for non-rehabilitated karst landscapes in earlier studies conducted under comparable climatic and geological conditions as shown in Table 2 (Asdak, 2024; Ding et al., 2022).

Table 2: Hydrological comparison framework

Parameter	Rehabilitated Forest (Wanagama)	Typical Degraded Karst*
Runoff coefficient	0.3–0.5	>0.6
Water holding capacity	High	Low
Drought index	Low	Moderate–High
Soil infiltration	Improved	Limited

Source: Data analysis based on Thornthwaite & Mather method (Asdak, 2024; Ding et al., 2022)

Karst landscapes that have not undergone rehabilitation are generally characterized by limited vegetation cover, shallow soil profiles, and low organic matter content, which collectively contribute to a pronounced surface runoff response. Such conditions reduce the soil's capacity to retain water and increase hydrological losses during rainfall events (Asdak, 2024; Ding et al., 2022). Previous research has also indicated that degraded karst areas often exhibit runoff coefficients greater than 0.6 and are more susceptible to drought due to restricted infiltration capacity (Zhang et al., 2025).

In contrast, the rehabilitated forest at Wanagama exhibits runoff coefficients in the range of 0.3 to 0.5, reflecting a moderate hydrological response. This pattern suggests that a considerable proportion of rainfall is able to infiltrate into the soil rather than being lost as surface runoff. Such conditions indicate that long-term vegetation recovery has contributed to improvements in soil structure and root system development, thereby enhancing infiltration processes and increasing subsurface water storage capacity (Abdallah et al., 2021; Filoso et al., 2017).

These improvements can be attributed to several underlying ecohydrological processes. First, the development of vegetation canopy reduces the kinetic energy of rainfall, thereby limiting surface sealing. Second, the expansion of root systems enhances soil macroporosity and facilitates the formation of preferential flow pathways. Third, the accumulation of organic matter promotes better soil aggregation and increases the soil's capacity to retain water (Abdallah et al., 2021). Finally, microclimatic regulation within the forest environment helps to alleviate evapotranspiration stress, particularly during dry periods (Wu et al., 2025).

In comparison with degraded landscapes, where water deficits typically begin earlier and persist longer throughout the dry season, the rehabilitated forest shows a delayed onset of deficit conditions and maintains soil moisture for an extended period. The estimated drought index (Ia = 1.15%) suggests a non-critical level of water stress, contrasting with the more severe drought conditions commonly reported in unmanaged karst environments (Zhang et al., 2025). These results reinforce the view that forest rehabilitation contributes not only to ecological restoration but also to improve hydrological regulation, as rainfall is increasingly partitioned toward infiltration and storage rather than rapid surface runoff (Filoso et al., 2017).

3.5.7 Hydrological Insights into Rehabilitation Effectiveness and Their Contribution to Scientific Knowledge

Although this study focuses on a single rehabilitated site, the hydrological indicators obtained offer consistent indirect evidence of the effectiveness of the rehabilitation process. Several key observations support this interpretation, including an increasing trend in annual water surplus, a moderate range of runoff coefficients, a low drought index classification, and a relatively high water holding capacity (256 mm). Taken together, these findings suggest that forest rehabilitation has improved the hydrological performance of the watershed, leading to a more regulated and resilient system. Comparable patterns have also been reported in restored forest ecosystems, where vegetation recovery contributes to enhance groundwater recharge and greater stability in seasonal water availability (Filoso et al., 2017; Wu et al., 2025).

The hydrological dynamics observed in Wanagama indicate a shift from a degraded system primarily characterized by surface runoff to a rehabilitated system where infiltration processes play a more dominant role. This transition highlights the importance of ecological restoration in enhancing soil structure, improving infiltration capacity, and increasing subsurface water storage (Asdak, 2024). Beyond merely quantifying individual hydrological components, this study underscores the functional significance of ecological rehabilitation in reshaping water partitioning processes within karst landscapes. In contrast to conventional water balance approaches that focus on rainfall, evapotranspiration, surplus, and deficit, the findings demonstrate that long-term vegetation recovery can alter how rainfall is distributed among infiltration, soil storage, and runoff pathways (Filoso et al., 2017).

These results offer compelling support for the use of restoration-based approaches in water conservation within tropical dryland forest systems. From a management perspective, several practical considerations arise. Rehabilitation efforts should prioritize the establishment of deep-rooted vegetation, as this can enhance the soil's capacity to store water and facilitate more effective infiltration pathways. In addition, ecological restoration initiatives should be complemented by continuous hydrological monitoring to assess the recovery of ecosystem services over time. In karst environments, where water limitations are a persistent concern, incorporating ecological restoration into water management planning represents a promising strategy for improving long-term water availability (Palmer and Stewart, 2020).

Investigating the interactions between karst landscapes and hydrological processes, particularly in the context of forest rehabilitation, is of considerable importance given the distinctive and dynamic nature of these systems. This relevance is further amplified by the ongoing impacts of global climate change. Future research should therefore broaden its scope by incorporating social dimensions to provide a more comprehensive understanding of these interactions.

4. CONCLUSIONS

The results of the water balance analysis show that the annual water surplus ranges from 431.72 mm to 1193.71 mm, while the annual water deficit ranges from 3.92 mm to 614.11 mm. Typically, the period of water surplus occurs at the beginning of the year, followed by a water deficit in the middle of the year, and another surplus towards the end of the year. Total annual rainfall fluctuates between 1355.42 mm to 2749.63 mm, with expected annual runoff between 431.17 mm and 1187.99 mm. To improve water conservation management, it is important to rehabilitate forest areas to reduce runoff and enhance water retention. Furthermore, it is projected that Wanagama will see an annual increase in water surplus of 15.654 mm and a rise in water deficit of 9.014 mm. Fortunately, the forested area of Wanagama has a drought index of 1.15% which is not considered critical.

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AUTHORS' CONTRIBUTIONS

Ambar Kusumandari: Conceptualization (Leader); Data curation; Formal analysis; Investigation; Methodology; Validation; Writing – original draft; Writing – review and editing.

Hatma Suryatmojo and Hero Marhaento: Data curation (Supporting), Investigation (Supporting); Methodology (Supporting); Validation (Supporting); Writing – review and editing (Supporting).

Junun Sartohadi: Conceptualization (Equal); Data curation (Supporting), Investigation (Supporting); Methodology (Equal); Supervisor.

Sri Endayani: Writing review, editing and finalizing the manuscript.

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