Jurnal Teknik Indonesia

Volume 5 Nomor 2 April 2026

https://jti.publicascientificsolution.com/index.php/rp

Analysis of the Water Balance of the Prumpung River Area (DAS) in Tuban Regency Using the Thornthwaite-Mather Method

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Abstract

Water is a vital resource whose availability is increasingly uneven due to climate variability, land-use changes, and rising water demand. This condition leads to water surplus during the rainy season and deficit during the dry season, including in the *Prumpung Watershed*, Tuban Regency. This study aims to *analyze the monthly and annual water balance* and evaluate the relationship between water availability and water demand in the study area. A descriptive quantitative approach was employed using the *Thornthwaite–Mather method*, based on rainfall and air temperature data from 2015 to 2024, combined with domestic and non-domestic water demand data for 2024. The results indicate that *potential evapotranspiration* fluctuates in accordance with air temperature, while *actual evapotranspiration* is influenced by groundwater availability. Groundwater storage increases during the rainy season and decreases during the dry season. The annual water balance reveals a dominance of deficit conditions in most observation years, although surplus occurs during certain periods. The *Prumpung Watershed* is vulnerable to water deficits due to uneven rainfall distribution. Sustainable water resource management strategies, focusing on conservation, are required to maintain a long-term hydrological balance.

Keywords: *Water balance, Prumpung watershed, Thornthwaite-Mather method, water surplus, water deficit.*

INTRODUCTION

Water is a vital resource that plays a crucial role in the sustainability of human life, ecosystems, and various socio-economic activities (Kurniyaningrum & Kurniawan, 2023). However, its availability is uneven across Indonesia, including in the Prumpung River Basin (DAS) in Tuban Regency, East Java. This imbalance is triggered by climate variations, changes in land use, and local soil characteristics, resulting in a water surplus during the rainy season and a water deficit during the dry season (Indarto et al., 2023). This phenomenon is exacerbated by the conversion of vegetative land to agricultural and residential areas, which reduces soil infiltration capacity and increases surface runoff (Ridwansyah et al., 2020).

To quantitatively understand the dynamics of water availability, a water balance analysis approach is required. A water balance is a quantitative calculation that links inputs (rainfall) with outputs (evapotranspiration, runoff, and changes in water storage) in a hydrological system (Permana & Susetyaningsih, 2024). One method widely used for water balance analysis at the watershed level is the Thornthwaite–Mather method, due to its applicability in areas with limited climatological data (Aalimah et al., 2022; Mammoliti et al., 2021). This method relies on rainfall and air temperature data to calculate potential and actual evapotranspiration and to identify periods of water surplus and deficit (Hendrayana et al., 2021).

Water has become one of the most strategic natural resources in the twenty-first century because it directly determines food security, ecosystem stability, public health, and regional economic resilience. Yet water availability is increasingly threatened by climate variability, prolonged drought, land conversion, and rising sectoral demand (Abdissa & Chuko, 2024). The global situation is becoming more serious, as UNESCO reported that by 2022 roughly half of the world's population experienced severe water scarcity for at least part of the year, while one quarter lived under extremely high water stress. This condition indicates that water management can no longer rely solely on annual averages but must be supported by temporal and spatial analyses capable of identifying periods of surplus and deficit more accurately (Marselina et al., 2024).

The urgency of water-balance-based analysis is further reinforced by the growing frequency of hydrometeorological extremes worldwide. UNESCO's 2024 World Water Development Report notes that, during 2002–2021, droughts affected more than 1.4 billion people and generated around US$170 billion in economic losses, while floods affected approximately 1.6 billion people and caused losses of US$832 billion. These figures indicate that the challenge of water resources is not merely the absolute quantity of water but also the instability of its distribution across seasons and years (Pereira et al., 2020). In watershed-based regions, this instability often appears as alternating wet-season surpluses and dry-season deficits, creating pressure on agriculture, domestic water supply, and ecological functions (Wiwoho et al., 2023).

Indonesia reflects this global problem in a highly complex tropical monsoon setting. Variability in Indonesian monsoon rainfall is strongly influenced by large-scale climate drivers such as ENSO and the Indian Ocean Dipole, with their impacts being especially substantial during the dry season months of June–August (Kurniadi et al., 2021). In practice, this means many Indonesian watersheds face increasing uncertainty in recharge, runoff, and evapotranspiration patterns. Such conditions make watershed-scale water balance studies essential, particularly in areas where seasonal water stress affects local livelihoods and land-use sustainability.

Within this broader context, the Prumpung Watershed in Tuban Regency represents a specific and relevant case. The uploaded manuscript shows that the watershed is characterized by uneven water availability, driven by climate variation, land-use change, and soil characteristics, and that preliminary annual calculations for 2015–2024 indicate a net negative water balance in most observation years. The manuscript also records large annual deficits in several years, including 2023 and 2024, indicating persistent hydrological pressure and vulnerability during longer dry seasons. This local condition demonstrates that the Prumpung Watershed is not only a theoretical hydrological unit but also a practical management area where seasonal imbalance may affect domestic, agricultural, and environmental water needs.

Several previous studies have confirmed that water balance analysis is an effective approach for understanding watershed vulnerability in Indonesia. Indarto et al. examined three major watersheds in Jember, East Java, and showed that land-use change combined with increasing water demand significantly altered watershed water balance conditions. Kurniyaningrum and Kurniawan, in the Upper Bogowonto Watershed, found that climate change influences water balance and contributes to increasing water criticality. Meanwhile, Aalimah et al. demonstrated in the Cikeruh Sub-watershed that the Thornthwaite–Mather meteorological water balance approach is useful for evaluating regional water carrying capacity and identifying imbalances between availability and demand. Together, these studies show that watershed water balance assessment has become an important analytical route for sustainable water-resource planning in Indonesia.

Methodologically, the Thornthwaite–Mather approach remains attractive because it can be applied in data-limited regions using relatively accessible variables, especially rainfall and temperature (Nugroho et al., 2019; Mammoliti et al., 2021). This is important in many Indonesian watersheds where complete hydrological observation data are not always available. However, previous scholarship also suggests that direct application of the method in tropical regions still requires contextual interpretation (Astuti et al., 2019). Hendrayana et al. reported that the Thornthwaite–Mather method has long been used in Indonesia, but its performance in tropical settings may need adaptation and longer climate records to better represent local hydrological behavior. Therefore, using this method in the Prumpung Watershed is both practical and scientifically relevant, provided the results are interpreted within the local climatic context (Taufiq & Susanto, 2023).

Despite the relevance of previous studies, an important research gap remains. Existing studies have largely focused on other watersheds, broader regional simulations, or water-carrying-capacity assessments, whereas specific long-term monthly and annual water balance analysis for the Prumpung Watershed in Tuban Regency is still limited in the current literature. In addition, many earlier works emphasize either availability or demand, but not both in an integrated local planning framework. The uploaded manuscript indicates that this study not only evaluates monthly and annual water balance during 2015–2024 but also links the results with domestic and non-domestic water needs based on population, livestock, and rice field area data for 2024. This integration makes the study more applicable for local decision-making than a purely descriptive hydrological account.

The urgency of this research is therefore high. A watershed that repeatedly experiences a negative annual balance is exposed to risks of reduced groundwater storage, seasonal water scarcity, agricultural disturbance, and increasing competition among water users (Monir et al., 2024; Gleeson et al., 2016). If such conditions are not quantitatively mapped, local water-resource management may remain reactive rather than anticipatory. For Tuban Regency, where watershed resilience is closely connected to settlement, farming, and land-use dynamics, a robust water balance analysis can provide an early scientific basis for conservation, allocation, and adaptation strategies under climate uncertainty (Rahmawati et al., 2023).

The novelty of this research lies in its focus, temporal scope, and analytical integration. First, it specifically addresses the Prumpung Watershed, a local basin that has not been widely discussed in prior indexed studies. Second, it employs a ten-year observation window from 2015 to 2024, allowing interannual fluctuations to be examined rather than relying on short-term snapshots. Third, it combines meteorological water balance estimation with local water-needs calculation, so the findings can move beyond identifying surplus and deficit periods toward evaluating the ability of available water to meet actual regional demand. In this sense, the study offers a more operational contribution for watershed governance in Tuban Regency.

Based on this background, the purpose of the study is to analyze the monthly and annual water balance of the Prumpung Watershed using the Thornthwaite–Mather method and to assess whether available water can support domestic and non-domestic needs in the study area. The main objectives are to calculate potential evapotranspiration, actual evapotranspiration, groundwater storage change, surplus, and deficit, and then interpret these components in relation to local water demand. The expected contribution of the study is twofold: academically, it enriches watershed-based water balance literature in tropical Indonesia; practically, it provides evidence for water conservation planning, groundwater reserve protection, and more sustainable regional water allocation. Ultimately, the benefit of this research is to support better policy and technical decisions for maintaining hydrological balance in the Prumpung Watershed over the long term.

RESEARCH METHODS

This study employed a quantitative descriptive research design with a hydrological approach to analyze the water balance of the Prumpung Watershed in Tuban Regency (Sari et al., 2022). The population of the study consisted of all climatological and hydrological data within the watershed area, particularly monthly rainfall and average air temperature data over a 10-year period (2015–2024), as well as supporting data on population, livestock, and agricultural land use for water demand estimation. The sample was determined using a purposive sampling technique, focusing on complete and consistent datasets obtained from relevant meteorological and statistical agencies. The primary research instruments included secondary data records, data tabulation sheets, and computational formulas based on the Thornthwaite–Mather method (Nugroho et al., 2019). Data validity was ensured through completeness and consistency testing of rainfall data, while reliability was assessed by cross-checking data sources and verifying temporal consistency across the observation period.

Data collection was conducted through documentation techniques, involving the systematic retrieval of climatological and socio-economic data from official institutions such as meteorological agencies and regional statistical offices. The research procedure began with data collection and verification, followed by data preprocessing to ensure accuracy and consistency. Subsequently, potential evapotranspiration (ETP) was calculated using the Thornthwaite–Mather formula based on temperature data (Mammoliti et al., 2021). This was followed by the computation of actual evapotranspiration (AE), changes in groundwater storage (ΔS), and the identification of water surplus and deficit conditions. In parallel, water demand was calculated using standard coefficients based on population size, livestock units, and agricultural land area (Fahmi et al., 2024). All data were organized into monthly and annual analytical formats to facilitate interpretation.

The study utilized Microsoft Excel and supporting statistical software for data processing, tabulation, and visualization. Data analysis was conducted through water balance analysis using the Thornthwaite–Mather method, which integrated rainfall input, evapotranspiration output, and groundwater storage dynamics to determine hydrological conditions (Abdissa & Chuko, 2024). The analysis was performed both monthly and annually to capture seasonal variability and interannual fluctuations. Descriptive statistical analysis was also applied to interpret patterns of water availability and demand. The results were presented in the form of tables, graphs, and comparative interpretations to evaluate whether water availability in the Prumpung Watershed was sufficient to meet regional needs and to identify critical periods of water deficit and surplus for sustainable water resource management (Wiwoho et al., 2023; Astuti et al., 2019).

RESULTS AND DISCUSSION

Potential evapotranspiration (ETP) describes the maximum amount of water loss to the atmosphere if water availability were not a limiting factor. In this study, ETP was calculated using the Thornthwaite–Mather method using average monthly air temperature data (Nugroho et al., 2019). The calculation steps include determining the monthly heat index and the annual heat index, and applying empirical constants to generate ETP values for each month during the analysis period.

Tabel 1. Recapitulation of potential evapotranspiration (ETP) calculations (mm)

Month	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
01	127,909	165,763	131,307	142,060	145,359	163,904	131,391	145,931	145,619	169,285
02	129,383	145,577	130,141	129,253	154,056	157,855	134,092	141,517	133,129	165,942
03	135,188	161,393	143,113	144,211	141,778	167,633	146,141	150,471	146,725	165,278
04	144,237	161,043	151,204	170,222	165,417	168,233	156,123	165,506	161,244	181,817
05	135,188	162,686	149,599	114,663	166,142	168,386	165,034	169,306	160,583	129,692
06	95,015	148,382	122,731	51,713	107,477	124,785	84,441	148,111	59,389	25,506
07	0,00	135,118	37,206	0,00	5,588	16,375	18,677	143,596	23,761	3,458
08	0,00	27,037	0,595	1,667	0,592	20,974	17,690	84,160	0,056	0,871
09	0,00	88,288	3,441	4,866	0,00	45,4480	41,027	20,180	0,423	22,431
10	0,00	153,593	73,171	14,177	0,00	59,315	41,630	158,879	0,280	10,790
11	39,268	155,445	154,596	175,402	51,498	184,353	161,116	158,419	80,110	125,594
12	164,493	137,414	141,423	164,332	94,113	143,791	155,810	150,689	149,085	161,044

Source: Analysis results, 2025

The obtained ETP values indicate seasonal variations that follow changes in air temperature. Periods with higher air temperatures produce higher ETP values, while months with lower temperatures tend to decrease. This pattern indicates that air temperature is a dominant factor in determining the potential evapotranspiration in the Prumpung watershed (Abdissa & Chuko, 2024; Pereira et al., 2020).

To determine the amount of water evapotranspired, the analysis is then continued with the calculation of actual evapotranspiration (AE). The AE value represents actual conditions in the field because it is directly influenced by soil water availability and does not always equal the ETP value.

Actual evapotranspiration (AE) is calculated as part of the water balance, considering rainfall, groundwater reserves, and potential evapotranspiration (Mammoliti et al., 2021). When groundwater reserves are sufficient, the AE value will approach the ETP value, while when water is scarce, the AE value will be lower due to limited water availability.

Table 2. Summary of actual evapotranspiration (AE) (mm)

Month	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
01	127,909	165,763	131,307	142,060	145,359	163,904	131,391	145,931	145,619	169,285
02	129,383	145,577	130,141	129,253	154,056	157,855	134,092	141,517	133,129	165,942
03	135,188	161,393	143,113	144,211	141,778	167,633	146,141	150,471	146,725	165,278
04	144,237	161,043	151,204	170,222	165,417	168,233	156,123	165,506	161,244	181,817
05	135,188	162,686	149,599	114,663	166,142	168,386	165,034	169,306	160,583	129,692
06	95,015	148,382	122,731	51,713	107,477	124,785	84,441	148,111	59,389	25,506
07	0,00	135,118	37,206	0,00	5,588	16,375	18,677	143,596	23,761	3,458
08	0,00	27,037	0,595	1,667	0,592	20,974	17,690	84,160	0,056	0,871
09	0,00	88,288	3,441	4,866	0,00	45,4480	41,027	20,180	0,423	22,431
10	0,00	153,593	73,171	14,177	0,00	59,315	41,630	158,879	0,280	10,790
11	39,268	155,445	154,596	175,402	51,498	184,353	161,116	158,419	80,110	125,594
12	164,493	137,414	141,423	164,332	94,113	143,791	155,810	150,689	149,085	161,044

Source: Analysis results, 2025

The calculation results show that the AE value during the rainy season is relatively high and close to the ETP value. Conversely, during the dry season, the AE value decreases due to limited groundwater reserves. This condition confirms that actual evapotranspiration in the Prumpung watershed is strongly influenced by the availability of groundwater as the main source of evapotranspiration (Gleeson et al., 2016). The large difference between ETP and AE subsequently affects changes in groundwater reserves (Pereira et al., 2020). Therefore, the analysis continues with an evaluation of groundwater storage dynamics to understand the process of replenishment and depletion of water reserves throughout the year.

Changes in groundwater reserves (ΔS) are calculated from the difference in groundwater storage between months, which is a direct response to the balance between rainfall and evapotranspiration. If rainfall exceeds actual evapotranspiration, the excess water will be used to replenish groundwater reserves. Conversely, if rainfall is lower, groundwater reserves will decrease to meet evapotranspiration needs (Monir et al., 2024; Jasechko & Perrone, 2021).

Table 3. Summary of calculations of changes in groundwater reserves (ΔS)

Month	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
01	0,000	-26,499	118,742	81,492	93,622	-21,079	116,615	62,237	175,000	-17,619
02	-10,297	117,347	85,838	24,616	0,000	57,547	0,000	20,015	0,000	128,073
03	-68,940	-57,236	0,000	0,000	0,000	0,404	0,000	0,000	0,000	31,109
04	79,238	-28,304	-47,968	-77,744	0,000	138,128	-45,562	-39,866	0,000	-31,657
05	-91,097	-45,926	-66,302	-97,256	-68,645	-51,355	-129,438	18,682	-127,138	-109,907
06	-83,903	78,011	-60,729	0,000	-106,355	-123,645	0,000	-35,531	-47,862	0,000
07	0,000	-78,011	0,000	0,000	0,000	0,000	0,000	-74,634	0,000	0,000
08	0,000	0,000	0,000	0,000	0,000	0,000	0,000	-43,651	0,000	0,000
09	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
10	0,000	51,689	0,000	0,000	0,000	0,000	0,000	141,359	0,000	0,000
11	0,000	-4,844	106,108	0,000	0,000	67,674	82,252	33,641	0,000	0,000
12	40,618	-29,580	68,892	81,378	0,000	58,385	92,748	0,000	0,000	162,884

Source: Analysis results, 2025

The calculations show that increases in groundwater reserves predominantly occur during the rainy season, while decreases occur primarily during the dry season. This pattern reflects the role of groundwater reserves as temporary storage, maintaining water balance during periods of limited rainfall. These changes in groundwater reserves have direct implications for the overall water surplus and deficit conditions. To obtain a more comprehensive picture of the water balance, further analysis focused on compiling the annual water balance for the Prumpung Watershed.

The annual water balance is compiled by accumulating all monthly water balance components, including evapotranspiration, changes in groundwater reserves, and the magnitude of water surpluses and deficits. This annual approach is used to identify trends in water surpluses and deficits within a hydrological year.

Table 4. Annual water balance of the Prumpung watershed

Month	ETP	AE	ΔS	Surplus	Deficit	Net balance
2015	1935,967	970,681	734,99	208,823	965,286	-756,463
2016	1841,645	1641,739	459,55	247,047	199,906	47,141
2017	1832,12	1238,527	908,03	509,314	593,593	-84,279
2018	1919,965	1112,566	679,02	251,584	807,399	-555,815
2019	1910,867	1032,02	806,35	721,705	878,847	-157,142
2020	1953,191	1421,052	544,64	330,106	532,139	-202,033
2021	1883,282	1253,172	911,69	565,817	630,110	-64,293
2022	1847,84	1636,765	1447,23	659,576	211,075	448,501
2023	1955,126	1060,404	747,86	317,837	894,722	-576,885
2024	2104,697	1161,708	507,19	322,066	942,989	-620,923

Source: Analysis results, 2025

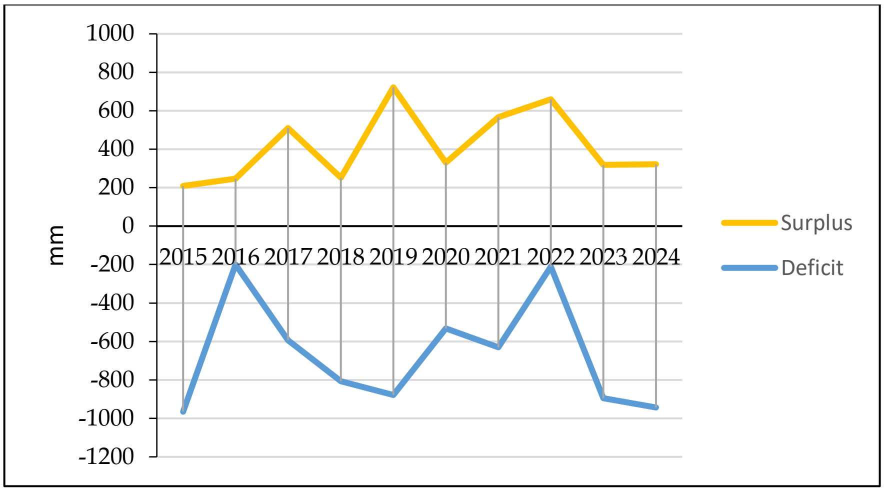

Figure 1. Graph of annual surplus and deficit 2015-2024

The annual water balance results in Table 4 indicate that the Prumpung Watershed experiences fluctuations in water surpluses and deficits influenced by interannual climate variability. This fluctuation pattern is also clearly illustrated in the annual water balance graph, which shows differences in hydrological conditions from one year to the next. Years with significant water surpluses, such as 2016 (+47,141 mm) and 2022 (+448,501 mm), are generally characterized by high rainfall and relatively even rainfall distribution throughout the year (Taufiq & Susanto, 2023). Conversely, years with large water deficits, such as 2023 (–576,885 mm) and 2024 (–620,923 mm), are associated with longer and more intense dry seasons (Kurniadi et al., 2021). Overall, both the calculation results and the graphical visualization show that the net water balance of the Prumpung Watershed tends to be negative in most of the observation years, indicating the dominance of deficit conditions and the presence of hydrological pressure on the watershed system.

CONCLUSION

Water balance analysis in the Prumpung River Basin (DAS) using the Thornthwaite–Mather method shows that water balance conditions are largely determined by the interaction between rainfall, evapotranspiration, and groundwater reserves. Fluctuating potential evapotranspiration values throughout the year reflect the influence of air temperature as the primary controlling factor for potential water loss to the atmosphere. As air temperature increases, potential evapotranspiration also increases, ultimately increasing the likelihood of groundwater reserves decreasing if not offset by adequate rainfall. Actual evapotranspiration reflects the actual response of a hydrological system to water availability. During periods of high rainfall, actual evapotranspiration approaches potential values because groundwater reserves are relatively full. Conversely, during the dry season, actual evapotranspiration is limited due to decreased groundwater reserves. This explains why, in certain periods, the difference between potential and actual evapotranspiration can be quite large, indicating the hydrological system’s limitations in maintaining evapotranspiration when water supplies are reduced (Abdissa & Chuko, 2024). Positive changes in groundwater reserves during the rainy season and negative changes during the dry season indicate a natural cycle of replenishment and depletion of water reserves (Jasechko & Perrone, 2021). The decline in groundwater reserves during the dry season indicates that groundwater serves as the primary source of water balance support when rainfall is insufficient. This condition contributed to the emergence of annual water deficits in several observation years, although in certain periods, water surpluses were still recorded due to high rainfall. The dominance of annual deficits indicates that the uneven distribution of rainfall throughout the year is a major factor influencing the imbalance in the Prumpung watershed (Marselina et al., 2024). Based on these results, it can be concluded that the annual water balance of the Prumpung Watershed is still vulnerable to climate variations, particularly during the long dry season. As a recommendation, these water balance results should be used as a basis for further studies on improving the function of groundwater reserves, particularly in the context of conservation of catchment areas (Suparyogi et al., 2020; Rahmawati et al., 2023), so that the natural water balance of the Prumpung Watershed can be maintained optimally in the long term.

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