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***Short communication***

# Water balance assessment of Malang, Sumenep, and Sumbawa Regencies of Indonesia

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Sustainable agricultural practices in highland areas play a significant role in ensuring food security and the sustainability of water resources. Highland agriculture in Indonesia faces significant challenges in water resource management owing to seasonal fluctuations, often leading to an ecological crisis, water scarcity in the dry season, and excess water in the rainy season (Summase *et al.,* 2019). Water balance provides an overview of the relationship between precipitation, evapotranspiration, and water storage dynamics, which are important in determining the feasibility of crop production and irrigation scheduling (Leatemia *et al.,* 2025; Pereira *et al.,* 2020; Rank *et al.,* 2023). Groundwater basins are vital in areas with surface water shortages, particularly during the dry season. Monitoring and assessing the sustainability of groundwater basins are key to the long-term management of water resources (Zaki *et al.,* 2020) as well as meeting irrigation water needs in the highlands. Several studies in Indonesia have only partially discussed water balance (Nugroho *et al.,* 2019).

This study is aimed to assess the climatic water balance in Malang, Sumenep, and Sumbawa Regencies (Fig. 1), which have different climate types across Indonesia using the Thornthwaite-Mather (1957) method. The monthly climatic data, including rainfall, temperature, humidity, wind speed, and solar radiation for 5 years (2019-2023) were obtained from the Indonesian Agency for Meteorological, Climatological and Geophysics (BMKG). These variables were used to calculate potential evapotranspiration (PET) using the FAO Penman-Monteith method, which provides a more physically based and accurate estimate of PET. Regional land characteristics and soil water holding capacity data were sourced from the Statistics Indonesia (BPS), Regent Regulation Number 45 of 2022, and UMY Repository.

***Water balance computation***

The monthly water balance for three regencies were computed using Thornthwaite and Mather (1957) method (Nugroho *et al.,* 2019) in which the potential evapotranspiration (PET) was calculated using Penman-Monteith evapotranspiration (PM-$ET_o$) (Pereira *et al.,* 2020) as given below;

$$ET_o = \frac{0.408\,\Delta(R_n - G) + \gamma \frac{900}{T+273}(e_s - e_a)}{\Delta + \gamma(1 + 0.342\,u_2)}$$

Where $ET_o$ is evapotranspiration, T is mean daily air temperature (°C), and  is wind speed (knot).  is net radiation (mm $day^{-1}$), G is soil heat flux (MJ $m^{-2}$ $day^{-1}$), γ is psychometric constant (kPa°$C^{-1}$), (es-ea) represents the vapor pressure deficit (VPD) of air (kPa), and Δ represents the slope of the temperature-saturation vapor pressure relationship at the mean air temperature.  calculator by FAO version 3.2 was used to calculate PM-$ET_o$. The potential evapotranspiration ($ET_P$) has the same value as evapotranspiration ($ET_o$) under ideal conditions.

Using rainfall (P) and potential evapotranspiration (PET), the various water balance parameters like change in soil moisture storage (ΔST), actual evapotranspiration (AE), water surplus (S) and water deficit (D) were calculated following book keeping

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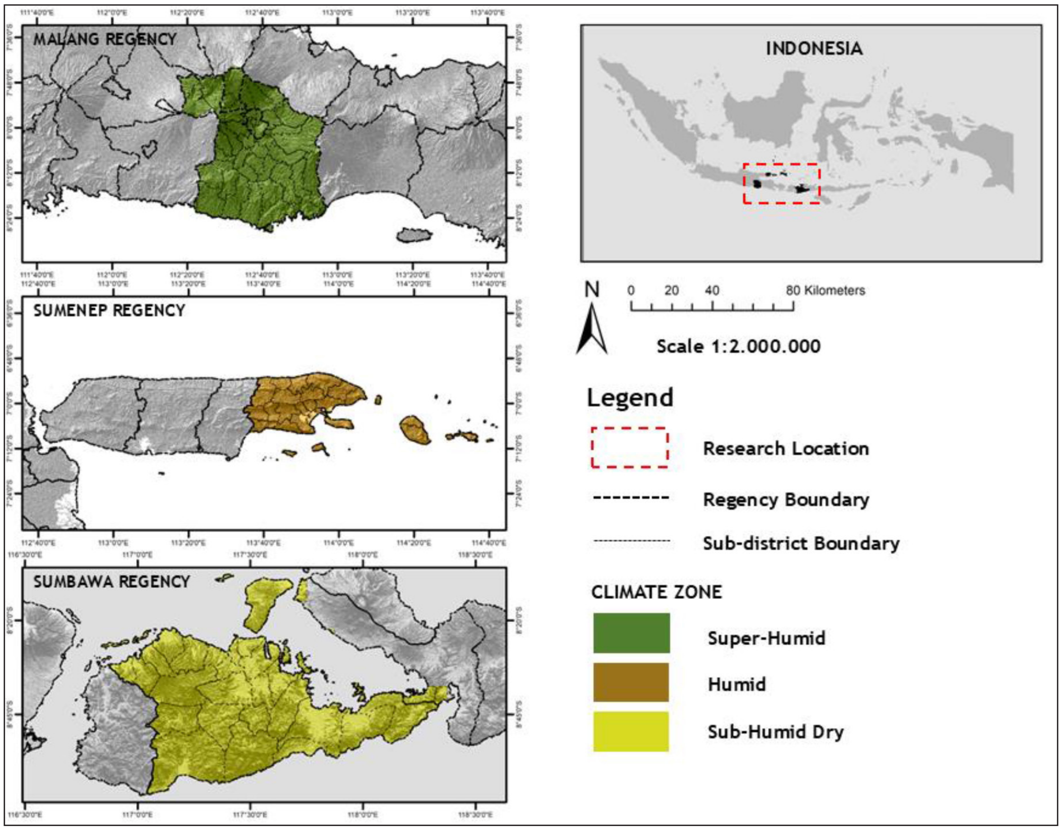


**Fig. 1:** Location of the study area

procedure of Thornthwaite and Mather (1957). The available water capacity (AWC) of three regencies were 136.6 mm, 103.1 mm, and 185.8 mm for Malang, Sumenep, and Sumbawa, respectively. The runoff (R) was calculated from water surplus assuming that 50% of surplus water will be runoff during a month and rest will be available for runoff in the next month as given below;

$$R=50\%R_i+50\%R_{i-1}$$

The water balance also includes information related to water demand for domestic, irrigation, and groundwater recharge. Water demand for irrigation($K_{ai}$), water demand for domestic water ($WD_d$), and groundwater recharge ($U_N$).

$$K_c = \frac{ET_c}{ET_0}$$

$$K_{ai} = \frac{(ET_c+I_r+W_{lr}+U_N-Re)\times A_i}{Eff}$$

The effective rainfall (Re) was calculated as;

If $P\leq 12.7$ *mm*, $Re=0$ *(ineffective rainfall)*

*If* $P>12.7$ *mm*, $Re=0.8\times(P-12.7$ *mm*)

$WD_d = Population \times Q \times A_R$

$I_r$ is water requirement for land preparation (mm day$^{-1}$), is water requirement to replace the water layer (mm day$^{-1}$), *Re* is effective rainfall (mm) calculated using the Burma method. Percolation is assumed to be the same as natural groundwater recharge ($U_N$) (mm), *Eff* is irrigation efficiency (%), is irrigation area (km$^2$), is the domestic water demand (mm), population is the number of residents per regency (people), *Q* is the discharge of raw water needs (l person$^{-1}$ day$^{-1}$), and is the area of the regency (km$^2$).

***Monthly water balance components***

The monthly water balance comparisons in Malang, Sumenep, and Sumbawa show all regencies experience severe droughts during the dry season, especially in September and October, with water deficits exceeding 100 mm (Fig. 2). Sumenep faces the most critical ground water depletion, losing nearly all reserves by December. Evapotranspiration increases in all areas, with Sumbawa recording the highest rates. These conditions highlight major irrigation challenges and the need for efficient water management. Runoff during wet periods also presents potential for surface water storage through reservoirs or ponds.

A comparison of the water balances in the Malang, Sumenep, and Sumbawa regency shows that all areas experienced severe drought during the dry season, but with different characteristics. The Malang regency has a longer rainy season and more evenly distributed rainfall, with peak rainfall at the end of the year. At the same time, Sumenep and Sumbawa experience more extreme dry seasons, characterized by very low rainfall over several months during the rainy season. The highest irrigation water demand occurred during the dry season, particularly in Sumenep and Sumbawa, indicating a significant dependence on the rainy season to meet water needs. The most considerable water deficits occurred in September and October in all areas (above 100

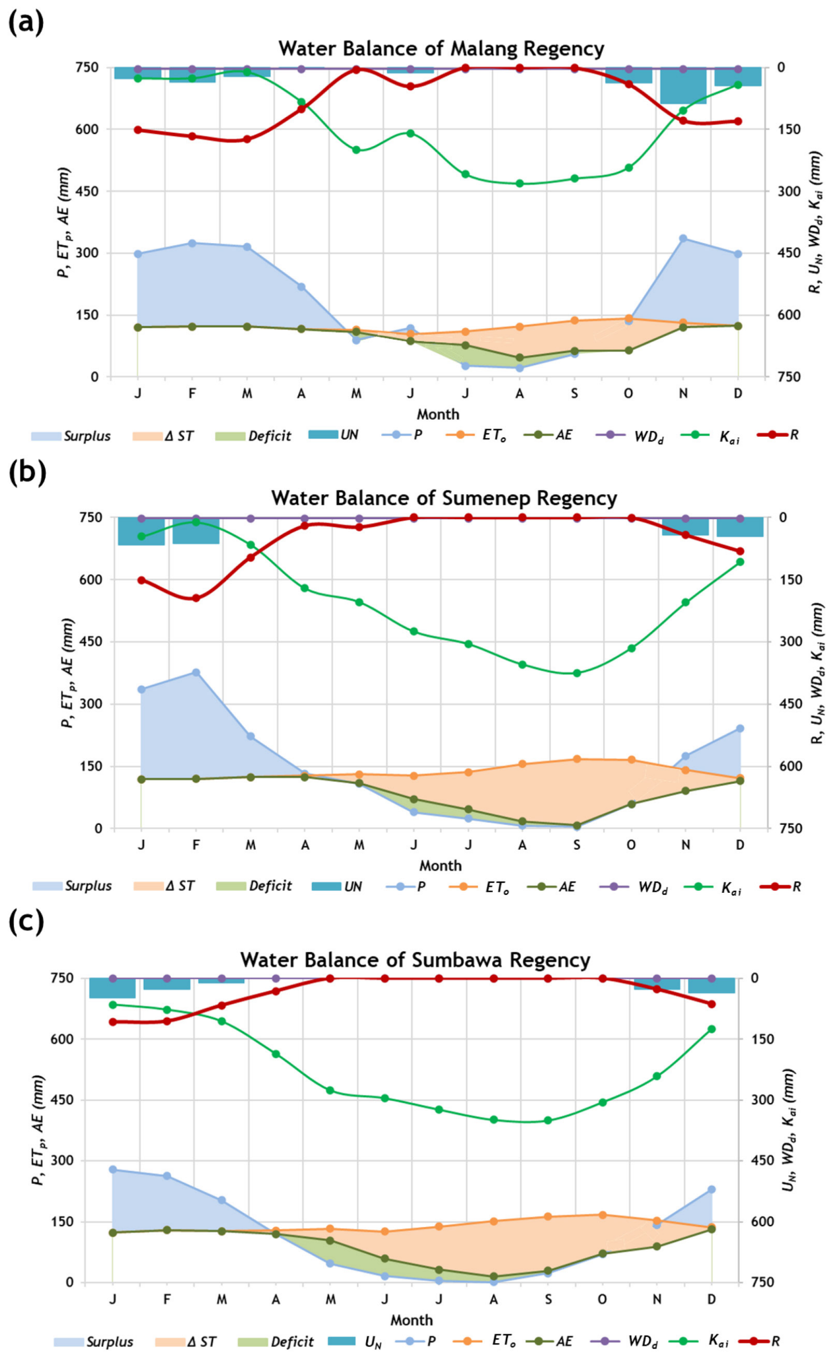


**Fig. 2:** Monthly water balance components of (a) Malang, (b) Sumenep, and (c) Sumbawa regency

mm), with a drastic decline in groundwater storage, especially in Sumenep, where nearly all groundwater reserves were depleted by December. Evapotranspiration also increases during the dry season, with Sumbawa showing higher evapotranspiration rates than the other two regencies. Overall, all regencies face significant challenges in water management, especially for irrigation, and require more efficient water management strategies, especially in optimizing groundwater storage during the rainy season, to meet the very high demand in the dry season (Fig. 2).

Based on the conditions of water surplus and deficit and the existing climate differences, Malang Regency, with a super humid climate, has a stable water surplus during the rainy season, especially in December (167.6 mm), although there is a significant water deficit during the dry season, peaking in October (151.7 mm). The main challenge in Malang is the management of excessive water runoff during the rainy season and the maintenance of soil moisture during the dry season. Sumenep Regency, with a humid climate, is highly dependent on high rainfall at the beginning of the year, but experiences extreme drought in the dry season, especially in August and September, with a peak water deficit in October (146.1 mm). The irrigation needs in Sumenep were very high during the dry season, reflecting a large dependence on the rainy season. The Sumbawa Regency, which has a sub-humid dry

**Table 1:** Annual water balance values (mm) in Malang, Sumenep, and Sumbawa regency

| Water balance parameter | Annual water balance (mm) | | | | | |
|---|---|---|---|---|---|---|
| | 2023 | 2022 | 2021 | 2020 | 2019 | Average |
| **Malang (AWC=136.6 mm)** | | | | | | |
| Precipitation (P) | 1687.9 | 3098.0 | 2409.0 | 2120.0 | 1881.9 | 2239.4 |
| Potential evapotranspiration ($ET_O$) | 1470.0 | 1410.0 | 1485.0 | 1428.0 | 1527.0 | 1464.0 |
| Actual evapotranspiration (AE) | 1087.5 | 1245.3 | 1287.9 | 1167.3 | 976.3 | 1152.9 |
| Water deficit (D) | 382.5 | 164.7 | 197.1 | 260.7 | 550.7 | 311.1 |
| Water surplus (S) | 733.9 | 1894.0 | 1294.0 | 1081.4 | 1041.3 | 1208.9 |
| Runoff (R) | 574.6 | 1520.5 | 984.9 | 811.7 | 823.6 | 943.1 |
| Deep percolation ($U_N$) | 159.3 | 373.5 | 309.1 | 269.7 | 217.7 | 265.8 |
| Water demand for irrigation ($K_{ai}$) | 2013.6 | 991.6 | 1623.1 | 1772.2 | 2122.2 | 1704.5 |
| Water demand for domestic water ($WD_d$) | 42.1 | 41.8 | 41.5 | 41.3 | 45.6 | 42.5 |
| **Sumenep (AWC=103.1 mm)** | | | | | | |
| Precipitation (P) | 1261.9 | 2254.2 | 1971.5 | 1954.4 | 1191.0 | 1726.6 |
| Potential evapotranspiration ($ET_O$) | 1503.0 | 1593.0 | 1515.0 | 1791.0 | 1782.0 | 1636.8 |
| Actual evapotranspiration (AE) | 931.1 | 1292.6 | 918.2 | 1144.1 | 722.1 | 1001.6 |
| Water deficit (D) | 571.9 | 300.4 | 596.8 | 646.9 | 1059.9 | 635.2 |
| Water surplus (S) | 433.8 | 1062.6 | 1156.3 | 913.4 | 572.0 | 827.6 |
| Runoff (R) | 293.5 | 816.0 | 877.6 | 681.3 | 380.1 | 609.7 |
| Deep percolation ($U_N$) | 140.3 | 246.6 | 278.7 | 232.1 | 191.9 | 217.9 |
| Water demand for irrigation ($K_{ai}$) | 2539.1 | 1834.5 | 2168.5 | 2468.4 | 3166.4 | 2435.4 |
| Water demand for domestic water ($WD_d$) | 29.2 | 29.1 | 29.1 | 28.8 | 29.1 | 29.1 |
| **Sumbawa (AWC=185.8 mm)** | | | | | | |
| Precipitation (P) | 952.6 | 1309.0 | 1797.0 | 1377.9 | 1559.4 | 1399.2 |
| Potential evapotranspiration ($ET_O$) | 1665.0 | 1539.0 | 1548.0 | 1917.0 | 1710.0 | 1675.8 |
| Actual evapotranspiration (AE) | 927.6 | 1095.4 | 1112.0 | 1079.1 | 948.5 | 1032.5 |
| Water deficit (D) | 737.4 | 443.6 | 436.0 | 837.9 | 761.5 | 643.3 |
| Water surplus (S) | 209.5 | 392.9 | 864.0 | 483.8 | 795.5 | 549.1 |
| Runoff (R) | 131.2 | 294.8 | 633.3 | 324.7 | 622.6 | 401.3 |
| Deep percolation ($U_N$) | 78.3 | 98.1 | 230.7 | 159.1 | 172.9 | 147.8 |
| Water demand for irrigation ($K_{ai}$) | 3075.0 | 2506.8 | 2210.1 | 3128.4 | 2586.2 | 2701.3 |
| Water demand for domestic water ($WD_d$) | 4.3 | 4.3 | 4.2 | 3.4 | 3.7 | 4.0 |

climate, shows a more extreme pattern with an earlier and longer water deficit, peaking in October (167.5 mm) accompanied by a significant decrease in groundwater storage. Despite a water surplus during the rainy season, Sumbawa faces a major challenge in meeting the highest irrigation needs compared with the other three regencies during the dry season. Overall, all three regencies face challenges in water management, with Malang experiencing high water runoff, Sumenep depending on the rainy season, and Sumbawa requiring highly efficient irrigation (Fig. 2).

Table 1 presents the annual water balance fluctuations in the regencies of Malang, Sumenep, and Sumbawa over five years (2019–2023). Overall, the highest precipitation was recorded in 2022 across all areas, except for Sumbawa Regency, where the peak occurred in 2021. This significant increase in rainfall during 2021–2022 was directly correlated with higher values for actual evapotranspiration (*AE*), water surplus, runoff (*R*), and percolation ($U_N$). Conversely, high potential evapotranspiration ($ET_0$) directly impacted the magnitude of water deficits and irrigation water demand ($K_{ai}$). Sumbawa Regency, which registered the highest average ETo, showed the largest irrigation water demand compared to the other two regencies. While Malang had the highest average precipitation, it still experienced a water deficit. However, its deficit was significantly smaller than that of Sumenep and Sumbawa, where the deficit was more than twice as large. The average runoff value in Malang, Sumenep, and Sumbawa regency are 943.1, 609.7, and 401.3 mm Moreover, the runoff conditions potentially used for surface water storage/reservoir or pond to keep water. Furthermore, Sumenep and Sumbawa are characterized by smaller runoff and percolation values, which indicates more limited availability of both surface and groundwater resources.

This study compares three regencies in the tropics with different climate characteristics and shows the impact of climate variations on water balance (Leatemia *et al.,* 2025; Rank *et al.,* 2023; Lykhovyd, 2021). Information on water surplus, deficit, and irrigation water needs provides an important basis for water resource management planning, especially for overcoming water shortages and providing irrigation water, especially in the dry season (Pereira *et al.,* 2020). The results of this study indicate distinct climatic and water availability conditions across the regions. The Malang Regency, which has a super-humid climate, experiences a water surplus for eight months (October to May). Sumenep and Sumbawa Regency have a six-month surplus (November to April). Water surpluses contribute to groundwater recharge and significant runoff, whereas water deficits lead to increased irrigation demands, although domestic water needs remain stable throughout the year.


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***Data availability:*** The data supporting this study's findings are available from the corresponding author upon reasonable request.

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