



Water Balance Modelling and Climate Change Projections for Flood Risk and Agricultural Water Stress Assessment in Bandar Lampung, Indonesia

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ABSTRACT

Global climate change has intensified flood risk and crop water stress in rapidly urbanising tropical cities. This study presents a comprehensive hydroclimatological analysis of Bandar Lampung, Indonesia, using daily climate data for 2016–2025 from the ERA5 Open-Meteo reanalysis archive (3,653 observation days). Precipitation trends were analysed using the Mann-Kendall test and Sen's slope estimator, complemented by the Pettitt change-point test. Monthly water balance was modelled using the Thornthwaite–Mather method, and crop water stress was quantified via the Crop Water Requirement Satisfaction Index (CWRSI). Precipitation projections for 2026–2030 were generated using a three-method ensemble corrected with CMIP6 anomaly factors under RCP 4.5 and RCP 8.5 scenarios. Results show a mean annual precipitation of $2,472.8 \pm 553.5$ mm (CV = 22.4%) with no statistically significant trend ($Z = 0.000$; $p = 1.000$). The water balance revealed a net surplus period (January–July and November–December, peak January: 171.4 mm) and a net deficit period (August–October, largest monthly deficit in October: 35.8 mm). Mean dry-season CWRSI ranged from 0.753 to 0.929 under average conditions, but dropped to 0.164–0.168 during El Niño years 2019 and 2023, representing severe crop water stress with potential yield reductions of up to 20–50% for some crops. Scenario-corrected RCP 8.5 projections indicate amplification of seasonal contrasts by 2030: January precipitation rises to 422.7 mm (+40.4% versus the historical mean), intensifying flood risk, while October falls to approximately 55.1 mm, worsening agricultural water stress, with October CWRSI projected at approximately 0.40. These findings provide a quantitative basis for ENSO-informed flood early warning, adaptive crop calendars, and green-blue infrastructure planning in Bandar Lampung.

Keywords: Mann-Kendall; Thornthwaite–Mather; CWRSI; ENSO variability; Peri-urban agriculture.

1. INTRODUCTION

Global climate change has intensified the frequency and magnitude of hydrometeorological extremes, including urban flooding and agricultural drought, particularly in tropical regions (IPCC, 2023). In these areas, already-high and variable precipitation is further amplified by interannual El Niño–Southern Oscillation (ENSO) fluctuations (Aldrian and Susanto, 2003). Coastal tropical cities with low-lying topography and inadequate drainage systems face a

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dual risk: flooding during the wet season and water deficits during the dry season that threaten peri-urban food security (Muis et al., 2016).

Bandar Lampung, the capital of Lampung Province, Indonesia, exemplifies this hydroclimatological pressure. Recurrent flooding during the December–February wet season has caused substantial economic and social losses, consistent with national reviews identifying inadequate drainage capacity, unregulated land-use change, and extreme rainfall intensification as the principal drivers of urban flooding in Indonesian cities (Sugiarti and Ajrina, 2025). Rapid urbanisation in Bandar Lampung has also been accompanied by a shrinking green-open-space cover, at only 3.05% of the city area against the 30% statutory target (Ali et al., 2025), further reducing infiltration during high-intensity rainfall. At the same time, increasingly prolonged dry seasons impose water stress on peri-urban agricultural land that persists within the city, as documented in the 2023 Census of Agriculture (BPS, 2024).

Quantitative water balance approaches have proven effective for simultaneously evaluating flood risk (water surplus) and agricultural drought stress (water deficit). The Thornthwaite–Mather (1955) framework provides a robust, data-efficient water balance model that has been widely validated under tropical conditions (Spinoni et al., 2015). The Crop Water Requirement Satisfaction Index (CWRSI), derived as the ratio of actual to potential evapotranspiration (AET/PET), is a standard FAO indicator for crop water stress with direct implications for agricultural planning (Doorenbos and Kassam, 1979). Integrating both approaches with CMIP6-based climate projections enables a comprehensive assessment of near-term hydroclimatological risk.

Although several studies have examined precipitation variability across Sumatra (Supari et al., 2018) and flooding in Bandar Lampung descriptively, no study has yet integrated Mann-Kendall trend analysis, Thornthwaite–Mather water balance modelling, CWRSI quantification, and CMIP6 ensemble projections within a unified framework for this city. To the best of our knowledge, this study is among the first to simultaneously characterise flood risk and agricultural water stress in Bandar Lampung through a quantitative water balance approach, applying CWRSI derived directly from hydroclimatological modelling as a crop stress indicator in an urban climate change context, and projecting monthly precipitation and crop water stress through 2030 using a three-method ensemble corrected with CMIP6 bias factors. This study aims to analyse historical precipitation trends and variability (2016–2025), model monthly water balance to identify critical surplus and deficit periods, quantify crop water stress via CWRSI, and project hydroclimatological



risk changes through 2030 under RCP 4.5 and RCP 8.5 scenarios as a scientific basis for flood mitigation and agricultural adaptation planning.

2. RESEARCH METHOD

Study area

This study was conducted in Bandar Lampung (5.45°S; 105.26°E), the capital of Lampung Province located at the southern tip of Sumatra Island, covering an area of 169.21 km² with a population of 1.21 million (BPS, 2024). City topography ranges from low-lying coastal plains (0–10 m a.s.l.) in the east to hills (200–700 m a.s.l.) in the west. Six major rivers drain into Lampung Bay, including Way Kuala Garuntang, Way Awi, and Way Simpur. The city has a humid tropical climate (Köppen Am) with a wet monsoon season from November to April and a dry monsoon season from May to October.

Data sources

Daily climate data for 2016–2025 were obtained from the Open-Meteo Historical Archive using ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF). Variables used include: daily precipitation (mm), mean daily air temperature (°C), relative humidity (%), sunshine duration (h), and mean wind speed (m s⁻¹). ERA5 has a spatial resolution of ~9 km; evaluation against rain-gauge records in the neighbouring South Sumatra region reported moderate-to-high monthly precipitation correlations ($r \approx 0.2$ – 0.9 depending on station) relative to ground observations (Suhadi et al., 2024). CMIP6 anomaly factors for projections were sourced from Kurniadi et al. (2024) and IPCC AR6 (2023) for the Sumatra region.

Precipitation trend and change-point analysis

Precipitation trends were assessed using the non-parametric Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975). The S statistic is computed as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k)$$

The magnitude of change was estimated using Sen's slope estimator (Sen, 1968):

$$\beta = \text{Median} [(x_j - x_i) / (j - i)], \quad i < j$$

The Pettitt test (Pettitt, 1979) was applied to detect structural change points in the precipitation time series. Statistical significance was assessed at $\alpha = 0.05$.

Potential evapotranspiration and water balance

Potential evapotranspiration (PET) was computed using the Thornthwaite (1948) method:



$$PET = 16 \times (10T / I)^{\alpha} \times K$$

where T is mean monthly temperature ($^{\circ}\text{C}$); I is the annual heat index, $I = \sum_{i=1}^{12} (T_m/5)^{1.514}$, summed over the 12 monthly mean temperatures ($I = 150.78$ for Bandar Lampung); α is a cubic function of I ($\alpha = 6.75 \times 10^{-7}I^3 - 7.71 \times 10^{-5}I^2 + 1.792 \times 10^{-2}I + 0.49239$; $\alpha = 3.76$ here); and K is a day-length correction factor, $K = (N/12) \times (d/30)$, where N is mean monthly daytime length (hours, derived from latitude) and d is the number of days in the month — so the uncorrected PET is adjusted for both day length and the actual number of days per month before being aggregated to the monthly totals in Table 3. Monthly water balance was modelled using the Thornthwaite–Mather (1955) framework: $P = AET + \Delta S + R$, where P is precipitation, AET is actual evapotranspiration, ΔS is change in soil water storage, and R is surplus/runoff. Field capacity (FC) = 150 mm and wilting point (WP) = 75 mm were used, giving an available water capacity (AWC) of 75 mm, representative of the dominant Ultisol soils of Bandar Lampung.

Crop Water Requirement Satisfaction Index (CWRSI)

Crop water stress was quantified using the CWRSI derived from the water balance (Doorenbos and Kassam, 1979):

$$CWRSI = AET / PET$$

CWRSI ranges from 0 to 1 and is categorised as: Optimal (≥ 0.85), Mild stress (0.70–0.85), Moderate stress (0.50–0.70), and Severe stress (< 0.50) following FAO guidelines (Allen et al., 1998). A threshold of $CWRSI < 0.70$ was adopted as an indicative boundary for agronomically significant stress, below which reduced crop growth and yield are plausible; this threshold reflects the general water-deficit/yield-response relationship of Steduto et al. (2012) rather than a crop-specific calibration, and should be interpreted as a screening indicator rather than a direct predictor of yield loss for any particular crop.

Precipitation projection

Monthly precipitation projections for 2026–2030 were generated using a three-method ensemble: Linear Regression (weight 35%), Holt Exponential Smoothing (30%), and 3-year Moving Average (35%). These weights were fixed a priori as a balanced blend across the three methods rather than optimised per month; per-method diagnostics for the full 2016–2025 training period ($R^2 = 0$ –0.34; trend p -values = 0.08–0.99 across months) confirm that no single method dominates consistently across the annual cycle, which motivated the equal-emphasis blend rather than a validation-error-minimising weighting scheme. No independent validation period was held out; this is acknowledged as a limitation of the ensemble weighting approach:



$$P_{ens}(t) = 0.35 \cdot P_{lin}(t) + 0.30 \cdot P_{hol}(t) + 0.35 \cdot P_{ma}(t)$$

Ensemble values were corrected using CMIP6 monthly anomaly factors ($\Delta P_{CMIP6}(t)$, scenario- and month-specific, after Kurniadi et al., 2024, and IPCC AR6, 2023) applied with a linearly ramping weight $w(y) = 0.6 + 0.1 \times (y - 2026)$, i.e. 60% of the full anomaly in 2026 rising to 100% (the full anomaly) in 2030:

$$P_{proj}(t) = P_{ens}(t) \times [1 + \Delta P_{CMIP6}(t)]$$

Projected CWRSI was then computed by feeding projected monthly precipitation into the Thornthwaite–Mather water balance model. All analyses were performed using Python 3.11 (NumPy, SciPy, Pandas) and Microsoft Excel.

3. RESULTS AND DISCUSSION

Climatological characteristics and precipitation variability

Mean annual precipitation in Bandar Lampung over 2016–2025 was $2,472.8 \pm 553.5$ mm with a coefficient of variation (CV) of 22.4% (Table 1). This level of interannual variability is high for a tropical setting and reflects the strong influence of ENSO, as reported by Supari et al. (2018) for Sumatra's coastal regions. The wettest year was 2016 (3,631.8 mm), coinciding with La Niña, while the driest years were 2023 (1,632.5 mm) and 2019 (1,804.5 mm), both associated with El Niño. The extreme range of 1,999.3 mm between the wettest and driest years, nearly four times the standard deviation, indicates that water infrastructure must be designed to accommodate a very wide variability envelope.

Table 1. Annual climate statistics for Bandar Lampung, 2016–2025.

Year	P (mm)	$\bar{T}$ (°C)	RH (%)	Sun (h d ⁻¹)	Wind (m s ⁻¹)	Class
2016	3,631.8	26.59	89.77	9.48	1.62	Wet
2017	2,343.7	26.49	85.71	9.43	1.90	Normal
2018	2,041.3	26.33	85.57	9.41	1.98	Normal
2019	1,804.5	26.56	84.68	10.25	2.15	Dry
2020	2,761.1	26.58	87.64	9.08	1.79	Normal
2021	2,303.8	26.46	86.54	9.26	1.91	Normal
2022	2,632.8	26.35	86.13	9.04	1.88	Normal
2023	1,632.5	26.72	83.58	10.01	2.28	Dry
2024	2,668.3	27.02	85.51	9.55	1.91	Normal
2025	2,908.2	26.96	83.99	8.96	2.01	Normal





Year	P (mm)	$\bar{T}$ (°C)	RH (%)	Sun (h d ⁻¹)	Wind (m s ⁻¹)	Class
Mean	2,472.8	26.61	85.91	9.45	1.94	—
SD	553.5	0.23	1.87	0.43	0.19	—
CV (%)	22.4	0.9	2.2	4.6	9.8	—

P, annual precipitation; $\bar{T}$, mean air temperature; RH, relative humidity; SD, standard deviation; CV, coefficient of variation. Classification: Wet $P > \text{mean} + 1\text{SD}$ ($>3,026$ mm); Dry $P < \text{mean} - 1\text{SD}$ ($<1,919$ mm); Normal otherwise, following the standard mean $\pm 1\text{SD}$ climatological convention.

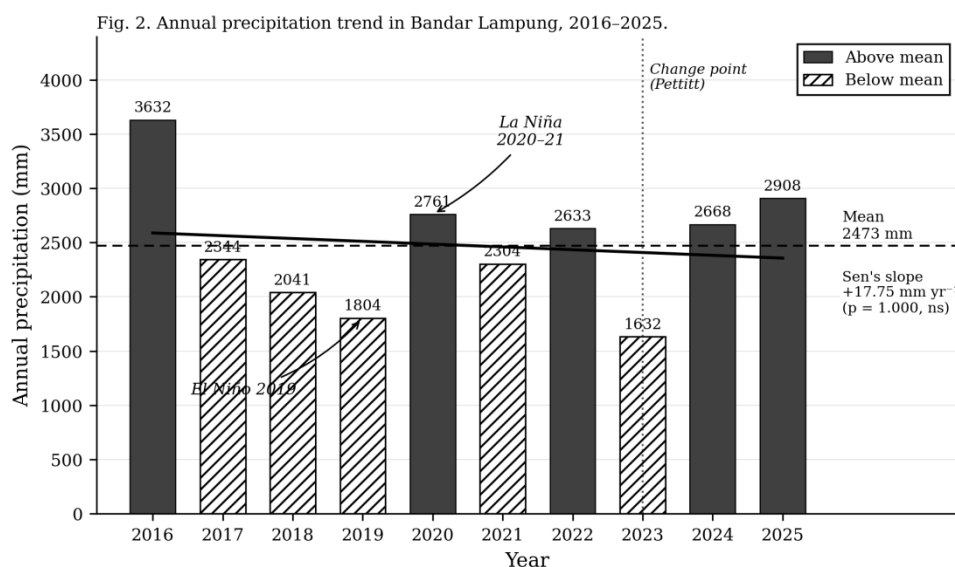


Fig. 1. Annual precipitation trend in Bandar Lampung, 2016–2025. Dark bars: above mean; hatched bars: below mean. Solid line: linear trend (Sen's slope = $+17.75 \text{ mm yr}^{-1}$, $p = 1.000$, ns). Vertical dotted line: Pettitt change point (2023).

Precipitation trend and change-point analysis

Mann-Kendall analysis of the *annual* precipitation series yielded $S = 1.0$, $Z = 0.000$, and $p = 1.000$, indicating no statistically significant trend at $\alpha = 0.05$. The Sen's slope of $+17.75 \text{ mm yr}^{-1}$ represents a marginal, statistically non-meaningful upward tendency. The absence of a systematic trend is consistent with Ariska et al. (2024) for Indonesia including Sumatra, who reported that interannual rainfall variability is dominated by ENSO- and IOD-related ocean-atmosphere dynamics rather than a decadal trend signal. The practical implication for flood risk management is important: flood hazard in Bandar Lampung is not driven by a gradually increasing precipitation



trend but rather by extreme interannual variability that cannot be predicted from linear trend extrapolation. The annual precipitation dynamics are illustrated in Fig. 1.

The Pettitt test identified 2023 as a structural change point ($K_{\max} = 10.0$; $p \approx 1.000$). The raw asymptotic approximation returned $p = 1.159$, which exceeds the valid $[0, 1]$ range for a p -value; following standard practice for this approximation at small n , the value was capped at its theoretical maximum ($p = 1.000$), consistent with the non-significant Mann-Kendall result above. Although not statistically significant, likely due to the limited series length ($n = 10$), the mean difference before and after 2023 (~ 394 mm) reflects the transition from La Niña dominance (2020–2022) to a strong El Niño (2023). Pettitt (1979) and Mallakpour and Villarini (2016) caution that non-significant change points in short series may still be hydrologically meaningful when accompanied by a substantial shift in the mean.

At the *monthly* scale (Table 2), no month showed a statistically significant trend. January had the strongest positive tendency ($Z = +1.073$; $\beta = +10.79 \text{ mm yr}^{-1}$), suggesting potential intensification of early wet-season rainfall with implications for flood risk. Conversely, October had the strongest downward tendency ($Z = -0.716$; $\beta = -10.62 \text{ mm yr}^{-1}$), effectively extending the period of agricultural water stress. Although none exceeded the significance threshold, these monthly trend directions align with the "seasonal amplification" pattern projected by global climate models for Sumatra under increasing greenhouse gas concentrations (Kurniadi et al., 2024).

Table 2. Mann–Kendall trend test and Sen's slope estimator for monthly precipitation, Bandar Lampung, 2016–2025.

Month	n	S	Z	p-value	Trend	Sig.	Sen's β (mm yr ⁻¹)
Jan	10	+13.0	+1.073	0.283	Upward	ns	+10.79
Feb	10	−19.0	−1.610	0.107	Downward	ns	−8.93
Mar	10	−1.0	0.000	1.000	Downward	ns	−0.40
Apr	10	−9.0	−0.716	0.474	Downward	ns	−8.80
May	10	−9.0	−0.716	0.474	Downward	ns	−4.47
Jun	10	+13.0	+1.073	0.283	Upward	ns	+1.02
Jul	10	−1.0	0.000	1.000	Downward	ns	−0.70
Aug	10	+1.0	0.000	1.000	Upward	ns	+1.90
Sep	10	−5.0	−0.358	0.721	Downward	ns	−1.92
Oct	10	−9.0	−0.716	0.474	Downward	ns	−10.62
Nov	10	+1.0	0.000	1.000	Upward	ns	+5.13



Month	n	S	Z	p-value	Trend	Sig.	Sen's β (mm yr ⁻¹)
Dec	10	-1.0	0.000	1.000	Downward	ns	-6.77

S, Mann–Kendall statistic; *Z*, standardised test statistic; *ns*, not significant ($p > 0.05$). Sen's slope (β) estimated following Sen (1968).

Water balance and flood risk assessment

Annual PET was 1,641.5 mm, computed with heat index $I = 150.78$ and exponent $\alpha = 3.76$. The monthly water balance (Table 3; Fig. 2) reveals a clear seasonal dichotomy: on a net basis (mean surplus minus mean deficit), Bandar Lampung experiences a net water surplus from January to July and from November to December, and a net water deficit from August to October, with the largest absolute monthly deficit occurring in October (35.8 mm). Because Surplus and Deficit are computed independently for each calendar month across the ten study years and then averaged, several months (notably July, November and December) show a small residual mean deficit alongside a larger mean surplus — reflecting years in which that month fell on the dry side of the water balance even though the ten-year average is surplus-dominant; this is why Table 3 reports a non-zero Deficit value for those months even though their net Status is Surplus. From a flood risk perspective, the mean cumulative annual surplus of 938.2 mm, with January contributing the largest monthly surplus (171.4 mm), represents a substantial proxy indicator of surface runoff and inundation potential. Sugiarti and Ajrina (2025) and Ward et al. (2017) emphasise that water surplus exceeding drainage system capacity is a primary driver of urban flooding in Indonesian and Southeast Asian cities.

Interannual variation in water surplus is large (Fig. 3b): the La Niña year 2016 recorded a cumulative annual surplus of 1,990 mm without any deficit, whereas 2019 generated only 637 mm surplus but incurred a deficit of 467 mm. The near-threefold difference in surplus between these two years illustrates why major flood events in Bandar Lampung are strongly correlated with La Niña phases (Qian et al., 2010). In 2025, the annual surplus reached 1,244 mm, the second highest on record, consistent with intensified wet-season rainfall widely reported by local communities and media during the 2025/2026 rainy season. This pattern confirms that ENSO variability, rather than any linear trend, is the dominant driver of flood risk in Bandar Lampung over short to medium timescales.



Table 3. Mean monthly water balance for Bandar Lampung, 2016–2025 (Thornthwaite–Mather method).

Month	$\bar{T}$ (°C)	PET (mm)	P (mm)	Surplus (mm)	AET (mm)	Deficit (mm)	Status
Jan	26.21	129.70	301.1	171.4	129.7	0.0	Surplus
Feb	26.21	117.11	268.3	151.2	117.1	0.0	Surplus
Mar	26.59	139.13	281.2	142.1	139.1	0.0	Surplus
Apr	26.80	139.98	251.3	111.3	140.0	0.0	Surplus
May	27.07	151.30	203.9	55.6	151.3	0.0	Surplus
Jun	26.62	137.54	168.9	32.4	137.5	0.0	Surplus
Jul	26.45	138.74	134.2	24.8	129.0	9.8	Surplus
Aug	26.51	138.67	100.0	1.4	118.9	19.8	Deficit
Sep	26.60	134.80	129.9	17.3	103.3	31.5	Deficit
Oct	26.95	145.08	141.8	35.7	109.3	35.8	Deficit
Nov	26.77	135.84	233.6	73.3	125.2	10.7	Surplus
Dec	26.48	133.63	258.6	121.7	129.5	4.1	Surplus
Total/Mean	26.61	1,641.5	2,472.8	938.2	1,529.9	111.7	—

$\bar{T}$, mean air temperature; PET, potential evapotranspiration (Thornthwaite, 1948); P, monthly precipitation; AET, actual evapotranspiration. FC = 150 mm; WP = 75 mm; AWC = 75 mm.

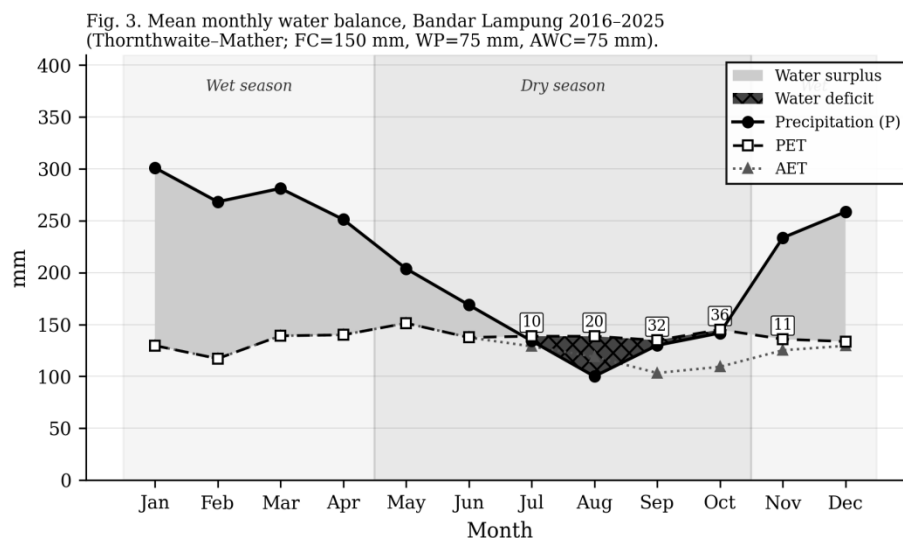


Fig. 2. Mean monthly water balance of Bandar Lampung, 2016–2025. Light-grey area: water surplus ($P > PET$); dark-grey area: water deficit ($P < PET$). Numbers above deficit months indicate mean monthly deficit magnitude (mm).

**Crop water stress assessment (CWRSI)**

Fig. 3a and Table 4 present mean monthly and annual CWRSI for 2016–2025. CWRSI values of 1.000 (optimal) from January to June indicate that actual evapotranspiration was fully satisfied during the core wet season. Values decline in July (0.929) through the dry season, reaching a minimum in October (0.753), before recovering to a still-optimal but sub-unity 0.922 in November and 0.969 in December — reflecting the small residual multi-year mean deficit noted for those two months in Table 3. The dry-season minimum in October (0.753) falls within the *mild stress* category according to FAO classification (Allen et al., 1998). The agronomically critical threshold of $CWRSI < 0.70$ (Steduto et al., 2012) was not exceeded on average, but individual El Niño years tell a markedly different story.

Interannual CWRSI variability was substantial (Table 4). In 2019, CWRSI dropped to a minimum of 0.164, representing severe stress persisting for five consecutive months (June–October), with a cumulative annual deficit of 467 mm. A similarly severe episode occurred in 2023 (minimum CWRSI = 0.168, three months). Water stress of this intensity in tropical food crops such as maize, cassava, and peri-urban vegetables may cause substantial yield losses, depending on crop species and growth stage, with reductions of up to 20–50% reported for some crops under comparable deficit levels (Doorenbos and Kassam, 1979); similarly severe dry-season soil-water depletion has constrained cropping windows for annual crops on comparable Indonesian drylands (Zuhdi and Indarwati, 2024). This underscores the critical need for supplemental irrigation systems and adaptive water management strategies in Bandar Lampung's peri-urban agricultural areas.

Fig. 4. (a) Mean monthly Crop Water Requirement Satisfaction Index (CWRSI); (b) Annual water surplus and deficit, Bandar Lampung 2016–2025.

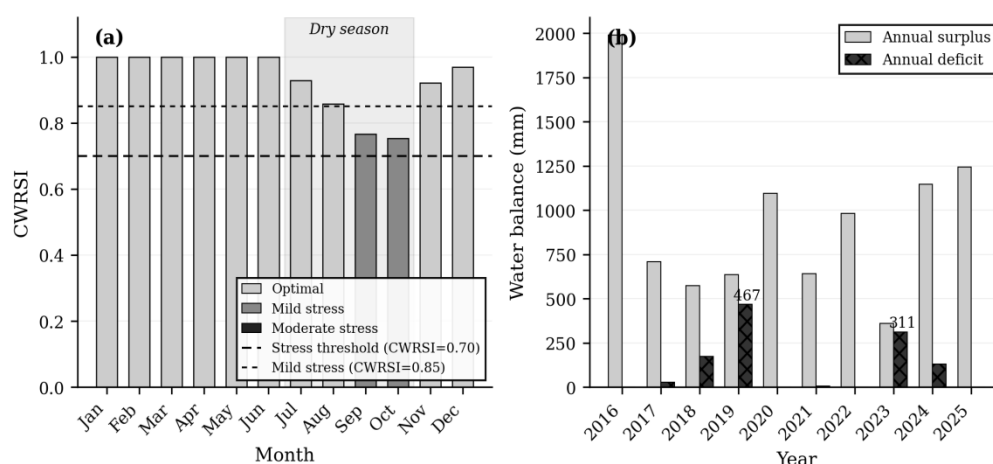




Fig. 3. (a) Mean monthly CWRSI for Bandar Lampung, 2016–2025. Thresholds: dashed line = significant stress (CWRSI = 0.70); dotted line = mild stress (CWRSI = 0.85). (b) Annual water surplus and deficit (mm), 2016–2025.

Table 4. Annual crop water stress summary, Bandar Lampung, 2016–2025.

Year	Surplus (mm)	Deficit (mm)	Stress months (CWRSI<0.70)	Min CWRSI	Stress period	Stress category
2016	1,990	0	0	1.000	—	None
2017	708	28	0	0.789	July	Mild (1 month)
2018	574	174	2	0.535	Aug–Sep	Moderate (2 months)
2019	637	467	5	0.164	Jun–Oct	Severe (5 months)
2020	1,097	0	0	1.000	—	None
2021	641	5	0	0.961	—	None
2022	983	0	0	1.000	—	None
2023	360	311	3	0.168	Aug–Oct	Severe (3 months)
2024	1,147	130	2	0.527	Aug–Sep	Moderate (2 months)
2025	1,244	0	0	1.000	—	None
Mean	938	112	1.2	0.814	—	—

CWRSI = AET/PET. Stress categories after FAO (Allen et al., 1998): Severe < 0.50; Moderate 0.50–0.70; Mild 0.70–0.85; Optimal ≥ 0.85 .

Climate projections and implications for flood risk and agriculture

Ensemble projections for 2026–2030 indicate a relatively stable annual precipitation total of 2,300–2,365 mm (Table 5; Fig. 4a). However, CMIP6 scenario corrections reveal a progressively sharper seasonal redistribution, consistent with the "wet-get-wetter, dry-get-drier" mechanism described by Held and Soden (2006). Under RCP 8.5, the CMIP6 monthly anomaly correction itself adds +5–7% in wet-season months and –6–8% in dry-season months on top of the underlying ensemble trend, with the correction's weight growing from 60% in 2026 to 100% in 2030. Because this anomaly combines with the ensemble's own month-specific trend, the total projected change relative to the historical mean varies considerably by month — for example, +40.4% in January but only –2.4% in July by 2030 — rather than falling uniformly within the +5–



7%/-6-8% range. This pattern simultaneously raises flood risk during the wet season and deepens agricultural water stress during the dry season.

From a flood risk perspective, January precipitation under the scenario-corrected RCP 8.5 projection is projected to rise from the historical mean of 301.1 mm to approximately 422.7 mm by 2030 (+40.4%), substantially increasing monthly water surplus as a proxy for inundation risk. Combined with projected increases in daily rainfall intensity reported by IPCC AR6 for Sumatra, the frequency of flash floods in the city's river catchments is expected to increase. Ward et al. (2017) estimated that under RCP 8.5, flood frequency in coastal tropical cities of Southeast Asia could increase 2-4 fold relative to the historical baseline by mid-century.

From an agricultural perspective, October, already the month with the largest mean water deficit (35.8 mm), is projected to receive only approximately 55.1 mm of precipitation by 2030 under the scenario-corrected RCP 8.5 projection, far below the PET of 145 mm. The projected October CWSI for 2030 reaches 0.40 (severe stress, Fig. 4b), compared with the historical mean of 0.753, representing a near-threefold deterioration in crop water satisfaction. This has serious implications for short-season food crops grown during the dry season in peri-urban Bandar Lampung, particularly maize, cassava, and vegetables that enter critical growth stages in October. These projections reinforce the need for drought-tolerant varieties and water balance-based irrigation scheduling as recommended by Steduto et al. (2012) and FAO (Allen et al., 1998).

Table 5. Monthly precipitation projection for Bandar Lampung, 2026-2030 (mm), Ensemble baseline before CMIP6 scenario correction.

Month	Hist. 2016-25	2026	2027	2028	2029	2030
Jan	301.1	366.8	374.8	382.8	390.8	398.8
Feb	268.3	229.1	222.7	216.4	210.0	203.7
Mar	281.2	267.7	265.1	262.5	260.0	257.4
Apr	251.3	190.9	182.8	174.6	166.4	158.3
May	203.9	193.1	191.4	189.6	187.8	186.1
Jun	168.9	184.4	186.3	188.2	190.1	192.0
Jul	134.2	137.7	138.8	140.0	141.2	142.4
Aug	100.0	97.5	97.5	97.5	97.6	97.6
Sep	129.9	90.8	86.3	81.8	77.2	72.7
Oct	141.8	81.8	74.6	67.4	60.2	53.0
Nov	233.6	234.9	235.2	235.5	235.8	236.2



Month	Hist. 2016–25	2026	2027	2028	2029	2030
Dec	258.6	290.4	293.3	296.2	299.2	302.1
Annual	2,472.8	2,365	2,349	2,332	2,316	2,300

Ensemble = Linear Regression (35%) + Holt Exponential Smoothing (30%) + 3-year Moving Average (35%), uncorrected for scenario-specific CMIP6 anomalies. RCP 4.5 applies a smaller monthly anomaly correction (wet-season +2–3%, dry-season –2–4%) and RCP 8.5 a larger correction (wet-season +5–7%, dry-season –6–8%), after Kurniadi et al. (2024) and IPCC AR6 (2023) for the Sumatra region; annual totals under each scenario are 2,373–2,314 mm (RCP 4.5) and 2,386–2,335 mm (RCP 8.5) for 2026–2030, compared with 2,365–2,300 mm for the uncorrected Ensemble. Hist., historical.

Fig. 5. (a) Annual precipitation projections 2026–2030 (Ensemble, RCP 4.5, RCP 8.5); (b) Projected CWRSI for 2030 vs. historical mean (2016–2025).

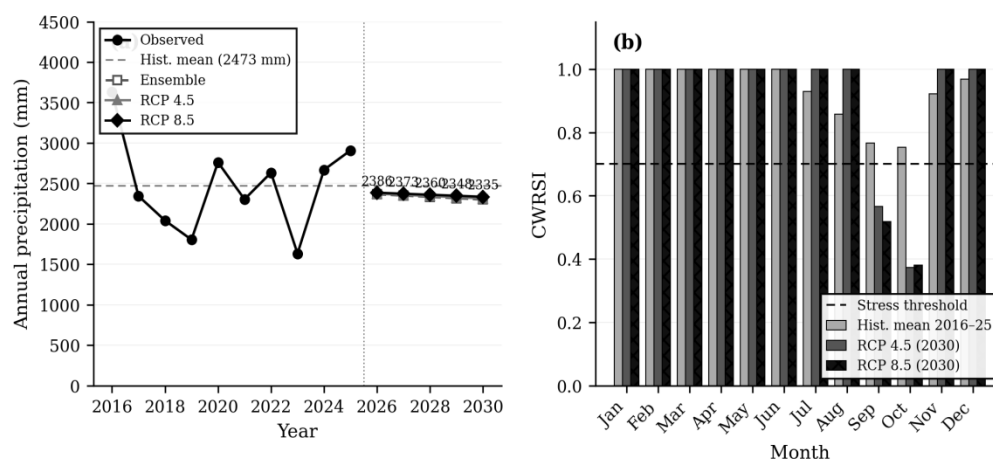


Fig. 4. (a) Annual precipitation projections for 2026–2030 under Ensemble, RCP 4.5, and RCP 8.5 scenarios, with the observed 2016–2025 series for reference. (b) Projected CWRSI for 2030 under RCP 4.5 and RCP 8.5 compared with the 2016–2025 historical mean. Dashed line: significant stress threshold (CWRSI = 0.70).

Integrated implications for urban water management

The synthesis of findings makes clear that hydroclimatological hazards in Bandar Lampung are non-stationary and dominated by ENSO variability rather than gradual long-term trends. The practical implication is that flood mitigation strategies should prioritise capacity for extreme event response, particularly during La Niña phases, rather than simply upgrading drainage capacity for average conditions. ENSO-informed early warning systems, such as those developed



in Thailand and Vietnam (Singhrattna et al., 2005), warrant consideration as a core component of the city's flood management system.

On the agricultural side, the 4–6 month period of water stress per year at varying intensities calls for an adaptive crop calendar grounded in water balance data. Based on the monthly water balance and CWRSI pattern alone, late April appears as a tentative candidate planting window for short-duration crops (< 90 days), potentially allowing harvest before the peak dry-season stress in August–September; however, this water-balance-based indication has not been validated against crop-specific water requirements (Kc), phenological growth stages, or field trials, and should be treated as a preliminary hypothesis for further agronomic testing rather than a planting recommendation. Planting in May–June appears comparatively more precarious in the same water-balance analysis: CWRSI appears optimal at planting but declines sharply as crops would enter generative phases in July–August, potentially exposing them to unanticipated stress. Because these inferences rest on aggregate water balance and CWRSI data rather than a full crop-calendar analysis incorporating Kc and growth-stage sensitivity, they are offered as a starting point for the Bandar Lampung City Agriculture Office to investigate further rather than a directly implementable recommendation.

Facing RCP 8.5 projections of amplified seasonal contrasts, a wetter wet season and a drier dry season, adaptive strategies must address the dual risk of flooding and drought simultaneously rather than in isolation. Green-blue infrastructure (GBI), which stores surplus water during wet periods and provides reserves during dry periods, is the most contextually appropriate solution, as recommended in recent reviews of urban flood mitigation in Indonesian cities (Sugiarti and Ajrina, 2025). The quantitative outputs of this study, including monthly surplus and deficit values, historical and projected CWRSI, and scenario comparisons, provide the concrete design parameters needed to size and plan such infrastructure in Bandar Lampung.

4. CONCLUSIONS

No statistically significant annual precipitation trend was detected over 2016–2025 ($Z = 0.000$; $p = 1.000$; Sen's slope = $+17.75 \text{ mm yr}^{-1}$), confirming that flood risk in Bandar Lampung is not driven by long-term precipitation increase but by extreme interannual variability linked to ENSO (CV = 22.4%), with La Niña years generating annual water surpluses of up to 1,990 mm, associated with a higher modelled flood risk. Thornthwaite–Mather water balance modelling revealed a clear seasonal dichotomy between net surplus (January–July and November–December;



peak January: 171.4 mm) and net deficit (August–October; largest monthly deficit in October: 35.8 mm), with cumulative dry-season deficit averaging 97.1 mm yr⁻¹ and ranging from zero during La Niña years to 467 mm during the strong El Niño of 2019. This deficit was captured by CWRSI values averaging 0.753–0.929 during the dry season under normal conditions, but falling to 0.164–0.168 for 3–5 consecutive months during El Niño years 2019 and 2023, representing severe crop water stress with potential yield penalties of 20–50%.

Scenario-corrected RCP 8.5 projections indicate a strengthening of seasonal contrasts through 2026–2030: the CMIP6 anomaly correction alone adds +5–7% to wet-season months and –6–8% to dry-season months, and combined with the underlying ensemble trend this yields a January 2030 precipitation of 422.7 mm (+40.4% versus the historical mean), intensifying flood risk, while October 2030 falls to approximately 55.1 mm, deepening agricultural water stress, with October CWRSI projected at approximately 0.40 by 2030, roughly three times worse than the historical mean. Collectively, these findings provide a directly applicable quantitative foundation for developing ENSO-informed flood early warning systems, designing adaptive water balance-based crop calendars, and planning green-blue infrastructure capable of mitigating the dual risks of flooding and agricultural drought in Bandar Lampung.

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