ZIBELINE INTERNATIONAL™ PUBLISHING

ISSN: 2521-294X (Online)
ISSN: 2521-2931 (Print)
CODEN: MJSAEJ

Malaysian Journal of Sustainable Agriculture (MJSA)

DOI: http://doi.org/10.26480/mjsa.02.2026.46.52

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RESEARCH ARTICLE

COMPARISON OF REFERENCE EVAPOTRANSPIRATION ESTIMATES IN BORNEO FOR IRRIGATION MANAGEMENT IN BRUNEI

Siti Nurzattey Amirah binti Fadilah, Mohamed Mujithaba Mohamed Najim*, Hassan Ammouneh, Syahirah binti Haji Shahlehi, Ahmed Osumanu Haruna

Faculty of Agriculture, Universiti Islam Sultan Sharif Ali, Kampus Sinaut, Tutong TB1741 Brunei Darussalam
****Corresponding Author Email: najim.mujithaba@unissa.edu.bn***

ARTICLE DETAILS

Article History:

Received 27 February 2026
Revised 20 March 2026
Accepted 25 March 2026
Available online 06 April 2026

ABSTRACT

CROPWAT-CLIMWAT recommended Labuan weather station as a climatic proxy for estimating reference evapotranspiration (ET_o) and crop water requirements in Brunei Darussalam. Labuan is an island hence this data might not provide better estimations of evapotranspiration to the Bruneian conditions. This study evaluates the suitability of Labuan weather data for estimating reference evapotranspiration (ET_o) in Brunei. Long-term meteorological data from Labuan and 11 other stations across Borneo were compared with data from two Bruneian stations, Pekan Tutong and Sinaut. Statistical analyses, including t-tests of monthly temperature, humidity, wind speed, sunshine hours, and derived ET_o, revealed that Labuan exhibits a distinctly moderated maritime climate, with significant differences ($p < 0.05$) in key drivers of evapotranspiration compared to the Bruneian sites. Labuan's monthly ET_o systematically underestimates Bruneian ET_o, with deviations exceeding 14% during critical irrigation periods. No single external Borneo station in the CLIMWAT database provided a statistically suitable substitute for the sites in Brunei. It is found that geographic proximity does not guarantee climatic homogeneity for energy-driven variables like ET_o, as local topography and continentality create distinct microclimates. It is concluded that the use of Labuan data to estimate $ET_o$and then irrigation planning for Brunei either over or underestimate those hence it is recommended to use local meteorological data to the Bruneian conditions.

KEYWORDS

Borneo Island, CLIMWAT, CROPWAT, Irrigation Planning, Water Management

1. INTRODUCTION

The water-intensive agricultural sector is compelled to become accustomed with the changes while halting the progressively heightening consequences of climate change, securing steady food supply for the masses (Dar et al., 2024; Rede et al., 2025). It is crucial to ensure that enough water is supplied to the crop to produce the optimum yield, while conserving the water resources as well as preventing leaching (Lu et al., 2021; Rogovska et al., 2023). The practice of irrigation scheduling is vital, yet when not practiced efficiently results in either over irrigation or under irrigation (Umutoni and Samadi, 2024; Bwambale et al., 2022). To schedule irrigation effectively, the crop water requirement and irrigation water requirement must be obtained (Saggi and Jain, 2022). Crop water requirement refers to the amount of water required by the plant to grow optimally, considering all the factors contributing to water loss such as evapotranspiration and percolation. Irrigation water requirement on the other hand also considers the amount of effective rainfall (Pereira et al., 2015).

Precise irrigation planning and management have become important to achieve sustainability in agriculture (FAO, 2017). This need has become essential in an era where we face increased scarcity in water under climate change (IPCC, 2022). Food and Agriculture Organization (FAO) has developed integrated tools, CROPWAT and CLIMWAT software systems, which are globally recognized as standards for calculating crop water requirements, irrigation scheduling, and assessing agricultural water use under rainfed and irrigated conditions (FAO, 2025; Smith, 1992).

The Food and Agriculture Organization of the United Nations (FAO) has developed a computer program as well as a climatic database with over 5,000 weather stations globally, which are CROPWAT and CLIMAT, respectively purposed to calculate the water and irrigation required for a variety of crops cultivated in different regions, according to the weather, climatic conditions, and soil characteristics (Allen et al., 1998). The weather data provided on CLIMWAT include the average, maximum and minimum daily temperature, the relative humidity, the windspeed, sunshine hours, as well as total and effective rainfall. CROPWAT utilized the Penman-Monteith method, using all the data mentioned except for the rainfall data, to calculate the reference crop evapotranspiration of crops. In addition, it also provides crop coefficient values of different crops at different growth stages. The reference crop evapotranspiration (ET_o) value is essential to find the crop water requirement, as a big portion of water loss is contributed by evapotranspiration. Obtaining crop evapotranspiration value is challenging for normal farmers, hence for agricultural use, the reference crop evapotranspiration values can be used with crop coefficient values. The Penman-Monteith method estimates the water loss from the surface of a hypothetical grass with a height of 0.12 m, hence providing no validity when used on its own (Vozhehova et al., 2018). The crop coefficient values are influenced by the characteristics of the crop at different stages of growth, as well as marginally by the climate. The concept of crop coefficients was introduced in 1968 to ease the determination of water requirement of a crop even when cultivated in a foreign new climate and condition (Jensen, 1968). CROPWAT and CLIMWAT facilitate an easy and reliable approach to calculate the ET_o.

Quick Response Code	Access this article online	
	Website: www.mjsa.com.my	**DOI:** 10.26480/mjsa.01.2026.46.52

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The climatic data of Brunei however is not provided in the CLIMWAT database, and the weather data from the nearest regional station, which is Labuan, Malaysia is suggested. Borneo is huge with differing climate zones, influenced by the location, topography, in addition to the direction of the wind. A study defined the climate zones of Borneo based on cluster analysis as dry and hot (DH), wet and hot (WH), wet (W), as well as wet and cold (WC) by (Sa'adi et al., 2021). These are characterized based on temperature, rainfall, seasonality, as well as the duration of the monsoon. The climatic data from a different location might not be comparable to the actual site, hence affecting the accuracy of ET_o, crop water requirement and irrigation water requirement estimations. Further, Labuan is an island, and transitions from coastal to interior regions in a tropical big island like Borneo significantly alter the agro-meteorological conditions. Such alterations affect temperature, humidity, and spatial and seasonal distribution of rainfall (Kumagai et al., 2013). Coastal regions are under strong maritime influence while inland zones experience greater diurnal changes in weather conditions. Hence, this study was done with the aim of comparing the CLIMWAT data recommended for Brunei with data from Brunei and other surrounding weather stations from Borneo Island. Further, it was aimed to compare calculated $ET_o$for Brunei data, Labuan data and other weather stations in Borneo Island and to recommend the best weather station that fits the Bruneian conditions.

2. Materials And Methods

2.1 Description of study area

This study uses FAO provided long term climatic data from 12 weather stations from Labuan, Sarawak, Sabah, and Kalimantan from Borneo Island (Figure 1). In addition, climatic data from Pekan Tutong station and climatic data from the weather station from the Faculty of Agriculture, Universiti Islam Sultan Sharif Ali, Sinaut were also used. All these stations are from lowland (less than 50m above mean sea level) or located in coastal zones. All the stations exhibit tropical rainforest (Af) climates under Köppen–Geiger classification (Beck et al., 2018), that characterizes year-round average high temperatures around 26–27 °C (Pekan Tutong and Sinaut: mean ~ 28–29 °C), high relative humidity of ≈ 80–90%) and annual rainfalls of 2000–3800 mm. Based on the WMO (2018), data from weather stations are assumed as representative of conditions within a ~15-km radius. Hence, spatial interpolation or extrapolation needs caution, especially in regions with different topography such as uplands or land covers such as interior forests (Daly et al., 2002).

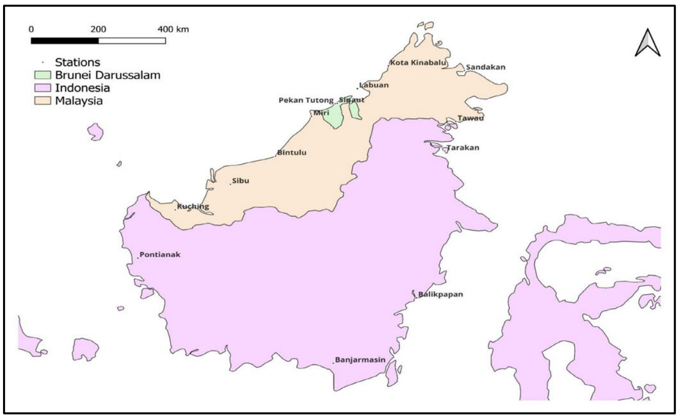

Figure 1: Location map of the study weather stations

2.2 Data collection

Meteorological data for the 12 stations from Sabah, Sarawak and Labuan of Malaysia and from Kalimantan were collected from the CLIMWAT 2.0 software (Allen et al., 1998). The extracted data includes maximum and minimum temperature (°C), relative humidity (%), sunshine hours (h) or solar radiation (MJ/m^2/d), wind speed (km/d) and rainfall (mm). Data for the Pekan Tutong was obtained from the Meteorological Department of Brunei, and data for the Sinaut station was collected from the weather station at the Faculty of Agriculture, Sinaut of the Universiti Islam Sultan Sharif Ali, Brunei.

2.3 CROPWAT and CLIMWAT models

CROPWAT uses soil, crop, and climatic data to model the soil-water balance (Allen et al., 1998). It calculates reference crop evapotranspiration (ET_o) using FAO Penman-Monteith method (Eq. 1), which is combined with the crop coefficient (Kc) (Eq. 2). The model calculates crop evapotranspiration for standard conditions. Crop coefficients that vary with the crop type and growth stages are considered by the software to calculate the crop water requirements. CROPWAT simulates soil moisture depletion based on ETc, rainfall and irrigation supplied. Based on different criteria, CROPWAT allows the user to develop different irrigation schedules and irrigation requirements.

$$ET_o = \frac{0.408\Delta(Rn-G)+\frac{900}{T+273}u_2(e_s-e_a)}{\Delta+\gamma(1+0.3442)} \text{ ……… Eq.} \quad (1)$$

$ET_o$is the reference evapotranspiration (mm/day), T is the mean daily air temperature (∘ C) at 2 m height, u_2 is the wind speed at 2 m height (ms^{-1}), and e_s and e_a are the saturation and actual vapor pressure (kPa), Rn is the net radiation, G is the soil heat flux, Δ is the slope of the relationship between saturation vapor pressure and air temperature, and γ is psychometric constant.

$$ETc = ET_o * Kc \text{ ….. Eq.} \quad (2)$$

CLIMWAT is a database that supports the CROPWAT model with the weather data needed for the simulations. CLIMWAT contains long-term climatic parameters for more than 5000 meteorological stations worldwide.

2.4 Statistical Analysis

Statistical analysis was conducted to evaluate the climatic similarity between the weather stations and evaluate the suitability of the CROPWAT recommended Labuan for application in Brunei. All analyses were performed using GraphPad Prism software (version 10.1.2) and Microsoft Excel. Independent two-sample t-tests (assuming unequal variances) were applied to test for significant differences between station pairs using monthly data series for each variable. A p-value threshold of 0.05 was used to determine statistical significance.

3. Results

3.1 Study Sites

All the study sites are located on Borneo Island. Pekan Tutong (4.58 N, 114.68 E) and Sinaut (4.81 N, 114.70 E) are located in Tutong district, Brunei Darussalam. Miri (4.33 N, 113.98 E) is located roughly 80 km to the southwest of Brunei. Bintulu (3.20 N, 113.03 E), Sibu (2.33 N, 111.83 E), and Kuching (1.48 N, 110.33 E) are farther southwest along the coast, at distances of approximately 250 km, 400 km, and 600 km from Pekan Tutong and Sinaut, respectively. Labuan island (5.30 N, 115.25 E) is located on Northern Borneo, about 100 km away. Kota Kinabalu (5.93 N, 116.05 E), Sandakan (5.90 N, 118.06 E), and Tawau (4.26 N, 117.88 E) are situated 200 km, 400 km, and 350 km from Brunei. Tarakan (3.33 N, 117.56 E), which is an island, is situated across the Brunei Bay at roughly 350 km to the southeast. Balikpapan (1.26 S, 116.90 E), Pontianak (0.15 S, 109.40 E), and Banjarmasin (3.43 S, 114.75 E), are the most remote, with straight-line distances exceeding 700 km, 800 km, and 900 km, respectively, located far to the south and southeast. Some stations are located near the coastal area, which include Labuan, Tarakan, Sibu, Sandakan, Balikpapan, Miri, Tawau, and Kota Kinabalu.

3.2 Comparison of the long-term weather parameters

Table 1 shows that Sinaut has a high average minimum temperature (27.1°C) and low average maximum temperature (28.1°C) compared to other stations considered in the study. The average diurnal temperature variation in Sinaut is around 1.0°C. The average minimum temperature in Pekan Tutong is lower (24.6°C) but the average maximum temperature is higher (31.8°C). The diurnal variation in temperature is around 7.2°C. The average minimum temperature in Labuan is 24.6°C, while the maximum temperature is 31.0°C, with a diurnal variation of about 6.4°C. The statistical data from Table 2 shows that there are no stations included in the study with similar average minimum and maximum temperature as Sinaut, while in Table 3 Pekan Tutong displays statistical similarity to Sandakan. The annual average relative humidity in Labuan is 95%, which is significantly higher than the average relative humidity in Sinaut (91%) and Pekan Tutong (81%). Table 2 shows that the relative humidity in Sinaut is more similar to Sandakan (90%). Meanwhile, the annual relative humidity of Kota Kinabalu (82%), Banjarmasin (81%), and Balikpapan (84%), are statistically closer to the relative humidity in Pekan Tutong. The wind speed data for the stations in Borneo Island and the two Bruneian stations also show significant spatial heterogeneity. The annual average wind speed in Labuan is 148km/day, which is remarkably lower from the wind speeds recorded in Sinaut (166km/day), meanwhile Pekan Tutong recorded 102km/day, which is much lower than Labuan. Kota Kinabalu (172km/day), Sandakan (163km/day), and Tarakan (154km/day) exhibit annual averages which are closer to Sinaut. Meanwhile, the only station with a statistically similar wind speed as Pekan Tutong is Kuching (110km/day). As shown in Table 1, the annual average sunshine duration in Labuan is 6.3 hours/day, and it is statistically similar to Sinaut's average (6.8 hours/day). The annual average sunshine hours in Pekan Tutong are lower (5.4 hours/day), showing similarity to stations in the Western Borneo, which are Kuching (5.1 hours/day), Sibu (5.6 hours/day), and Bintulu (5.9 hours/day).

3.3 Comparison of the monthly reference evapotranspiration

The mean annual ET_o values for Sinaut, Pekan Tutong, and Labuan are 3.82, 3.83, and 3.67mm/day, respectively, and all are considered statistically similar. The difference in the annual ET_o of Labuan and Sinaut is 0.14mm/day, and except for in April, May, and November, the monthly ET_o in Sinaut is usually higher. Based on figure 2, the biggest difference between the ET_o is recorded in September, where Labuan underestimated Sinaut's ET_o by 0.5mm/day. The ET_o of the two stations are the most similar in November, where the ET_o of Labuan and Sinaut are 3.45 and 3.43mm/day, respectively. On the other hand, the annual ET_o of Labuan underestimates the annual ET_o of Tutong by 0.15mm/day. Figure 3 displays that the monthly ET_o of Labuan is also usually lower, except for in June-August. In June and July, the ET_o in Labuan even surpassed the ET_o of Pekan Tutong by 0.22mm/day and 0.28mm/day, respectively. In February and March, the ET_o difference is over 0.6mm/day, whereas in August, the ET_o of the two stations are the most similar. Further, figure 4 exhibits remarkable difference between the monthly of the two stations in Brunei. The annual ET_o of Pekan Tutong is only 0.01mm/day higher than Sinaut, however the differences in the monthly ET_o mostly exceed 0.3mm/day, especially in July where the ET_o in Sinaut is 0.72mm/day higher than the ET_o in Pekan Tutong. The monthly ET_o are the most similar in October, where the ET_o in Tutong is 0.12mm/day higher.

Table 1: The annual weather parameters for all the stations

Stations	Minimum Temperature (◦C)	Maximum Temperature (◦C)	Relative Humidity (%)	Windspeed (km/hour)	Sunshine hours (hour)
Kuching	22.9	31.4	97	110	5.1
Labuan	24.6	31.0	95	148	6.3
Sibu	22.5	32.1	87	71	5.6
Bintulu	23.4	30.8	87	78	5.9
Sandakan	23.2	31.1	90	163	6.4
Balikpapan	23.0	29.3	84	69	6.6
Sinaut	27.1	28.1	91	166	6.8
Pekan Tutong	24.6	31.8	81	102	5.4
Miri	23.3	30.7	86	146	6.5
Pontianak	23.8	31.6	88	69	6.6
Banjarmasin	23.3	31.4	81	73	6.8
Tawau	22.9	31.8	85	135	6.7
KK	23.4	30.9	82	172	6.7
Tarakan	21.9	32.1	83	154	7

Table 2: The statistical analysis of weather parameters between Sinaut and other stations

Comparison	p-value				
	Minimum temperature	Maximum Temperature	Relative Humidity	Wind speed	Sunshine Hours
Sinaut vs Tutong	<0.05	<0.05	<0.05	<0.05	<0.05
Sinaut vs Kuching	<0.05	<0.05	<0.05	<0.05	<0.05
Sinaut vs Sibu	<0.05	<0.05	<0.05	<0.05	<0.05
Sinaut vs Bintulu	<0.05	<0.05	<0.05	<0.05	<0.05
Sinaut vs Miri	<0.05	<0.05	<0.05	<0.05	0.1867
Sinaut vs Labuan	<0.05	<0.05	<0.05	0.2147	0.2960
Sinaut vs Kota Kinabalu	<0.05	<0.05	<0.05	0.4614	0.5308
Sinaut vs Sandakan	<0.05	<0.05	0.2902	0.8889	0.1963
Sinaut vs Tawau	<0.05	<0.05	<0.05	<0.05	0.6509
Sinaut vs Pontianak	<0.05	<0.05	<0.05	<0.05	0.4413
Sinaut vs Banjarmasin	<0.05	<0.05	<0.05	<0.05	0.8919
Sinaut vs Balikpapan	<0.05	<0.05	<0.05	<0.05	0.4217
Sinaut vs Tarakan	<0.05	<0.05	<0.05	0.3922	0.7262

Table 3: The statistical analysis of weather parameters between Pekan Tutong and other stations

Comparison	p-value				
	Minimum temperature	**Maximum Temperature**	**Relative Humidity**	**Wind speed**	**Sunshine Hours**
Pekan Tutong vs Kuching	<0.05	<0.05	<0.05	<0.05	<0.05
Pekan Tutong vs Sibu	<0.05	<0.05	<0.05	<0.05	<0.05
Pekan Tutong vs Bintulu	<0.05	<0.05	<0.05	<0.05	<0.05
Pekan Tutong vs Miri	<0.05	<0.05	<0.05	0.0092	0.1867
Pekan Tutong vs Labuan	<0.05	<0.05	<0.05	0.2147	0.2960
Pekan Tutong vs Kota Kinabalu	<0.05	<0.05	<0.05	0.4614	0.5308
Pekan Tutong vs Sandakan	<0.05	<0.05	0.2902	0.8889	0.1963
Pekan Tutong vs Tawau	<0.05	<0.05	<0.05	<0.05	0.6509
Pekan Tutong vs Pontianak	<0.05	<0.05	<0.05	<0.05	0.4413
Pekan Tutong vs Banjarmasin	<0.05	<0.05	<0.05	<0.05	0.8919
Pekan Tutong vs Balikpapan	<0.05	<0.05	<0.05	<0.05	0.4217
Pekan Tutong vs Tarakan	<0.05	<0.05	<0.05	0.3922	0.7262

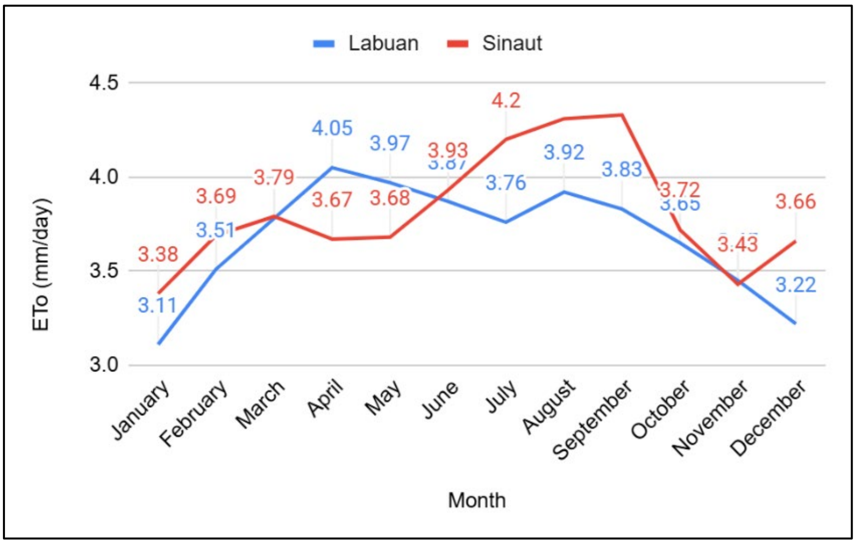

Figure 2: Monthly ET_o deviation between Labuan and Sinaut

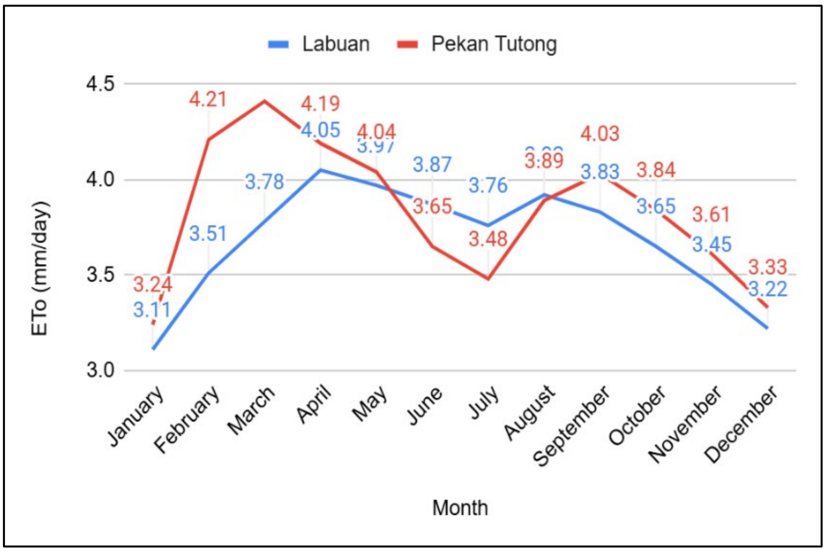

Figure 3: Monthly ET_o deviation between Labuan and Pekan Tutong

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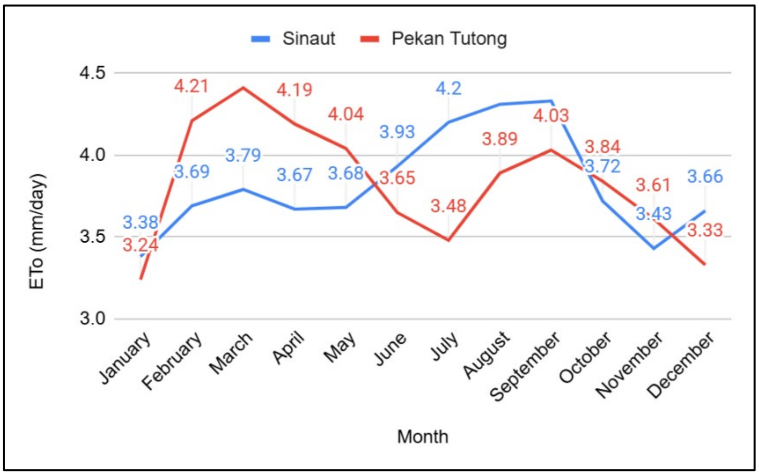

Figure 4: Monthly ET_o deviation between Sinaut and Pekan Tutong.

4. Discussions

Borneo Island has a humid tropical climate however, the sites show regional and monthly variations in the meteorological features (Kumagai et al., 2005). The sites in the Western and Southeastern part (Sibu, Bintulu, Miri, Pontianak, Banjarmasin, and Pekan Tutong) receive relatively lower rainfalls during December-March, where the Northeast monsoon occurs, and this period is relatively dry compared to other periods. The Southwest monsoon period from June-August receives the least amount of rainfall, but the sites do not experience droughts. The Eastern and Northern coastal parts of Borneo are directly exposed to northeasterly winds, which results in heavy monthly rainfalls from December to February. Southwest monsoon from June to September brings lower monthly rainfalls. As a study stated that Pontianak in the southwest exhibits a dual-peak pattern of rainfall, while Sandakan and Tawau in eastern Borneo show a stronger correlation with the northeast monsoon (Tangang et al., 2017; As-syakur et al., 2016). According to southern and southeastern Borneo experiences a more distinct dry season, however, the northern coastal areas such as Kota Kinabalu and Labuan receive localized convective showers, keeping rainfall above 150mm (Aldrian and Susanto, 2003). Sinaut is located inland and experiences the general weather pattern of the western Borneo, but has a slightly less pronounced northeast monsoon peak due to the sheltering by interior highlands.

Meteorological stations in equatorial regions often exhibit broad climatic homogeneity due to consistent solar radiation, and the recommendation to use Labuan in CROPWAT for Brunei was a pragmatic and a data-availability-driven guideline for regional assessments. However, local factors such as continentality, exposure, and land atmosphere interactions create distinct microclimates that alter the surface energy balance (Fisher et al., 2017). Thereby, inaccuracies in any of these inputs will certainly provide significant errors in irrigation scheduling and water management (Allen et al., 1998).

The results display the similarity between the average minimum temperature in Labuan and Pekan Tutong, which is stark in comparison to the higher minimum temperature in Sinaut. However, Sinaut has a lower average minimum temperature, followed by Labuan and Pekan Tutong consecutively. The higher minimum and lower maximum temperature in Sinaut result in low average diurnal variation, which indicates a moderate and stable microclimate due to the sheltered inland position where the daytime heating and night-time cooling is moderated (Bridgewater and Harper, 2020). Pekan Tutong exhibits a coastal-inland hybrid profile, with moderate minimum but a high average maximum temperature (Chang et al., 2005). However, the specific monthly progression of temperature in Pekan Tutong is unique to Bruneian climatic conditions. Labuan on the other hand, recorded a moderate minimum temperature and high maximum temperature, generating a higher diurnal variation. This is also seen in other Southern coastal stations, which are Pontianak and Banjarmasin. Coastal inland sites in Borneo show greater daily temperature variability which is mainly due to maritime and continental influences (McGregor and Nieuwolt, 1998). More or less steady warmth with low variability in temperature is a characteristic of a localized microclimate influenced by terrain, or vegetation (Yamanaka, 2016). According to daytime heating regimes are different in semi-inland areas. This variation is due to stronger maritime influence and not influenced by topographical shelter (Kumagai et al., 2005). The difference between the minimum average temperature in Labuan and Sinaut represent opposite ends of the maritime-continental spectrum. Temperature variability directly influences the estimation of evapotranspiration by the Penman-Monteith equation, therefore using the temperature profile from Labuan for Brunei would evidently underestimate the reference evapotranspiration.

Additionally, the result for the relative humidity also shows that Labuan is more humid than both Bruneian locations, especially Pekan Tutong, which is notably drier. The distinctly higher and more stable humidity in Labuan is a result of the dominant sea-breeze circulations and more moisture advection (Yamanaka, 2016; Chang et al., 2005). Labuan data, if used in CROPWAT modeling, would overestimate humidity by 4-14% for Sinaut and Pekan Tutong, which will affect evapotranspiration estimations and irrigation requirements in CROPWAT. Sandakan may offer a more balanced humidity profile to Sinaut; and Kota Kinabalu, Banjarmasin, and Balikpapan for Pekan Tutong. However localized calibration is needed to avoid overestimation of moisture conditions. The wind speed data of Labuan and Sinaut is considered statistically similar, which are comparable to other coastal regions that are subjected to similar maritime forcing, such as Kota Kinabalu, Sandakan, and Tarakan. Higher wind speeds in Sinaut could be due to greater exposure or local circulation patterns. On the other hand, the lower wind speed in Pekan Tutong is manifested by sheltering, due to the variability in terrain; a common phenomenon in inland tropical valleys that causes surface roughness and obstructions that reduce near-surface wind-flow (Barman et al., 2021). The topographic and land cover factors strongly regulate near-surface wind speeds, especially in tropical regions with complex terrain (Yamanaka et al., 2018; Yamanaka, 2016). In terms of the annual average, the wind speed in Kota Kinabalu, Tarakan, and Sandakan are closer to Sinaut, while for Pekan Tutong, the wind speed in Kuching shows closer proximity. However, not a single station adequately replicates the monthly progression and magnitude for both the Bruneian sites. Consequently, Labuan wind speed is also not a good representation of the Bruneian sites and is unsuitable to estimate evapotranspiration in CROPWAT.

Further, the data shows Pekan Tutong receives significantly lower annual sunshine hours compared to Labuan and Sinaut. The inland position and elevation of Sinaut reduced the cloud cover relative to coastal Labuan, contrarily, a sheltered valley at Pekan Tutong enhanced cloud persistence (Yamanaka, 2016). Despite the similarity in the annual sunshine hours between Labuan and Pekan Tutong, Labuan is still unsuited to represent the sunshine duration in Brunei due to the differences in the monthly variation. Coastal sites such as Miri, Sandakan, Tawau, Pontianak, and Balikpapan show a similar sunshine profile as Labuan. This is because maritime influences smoothen the seasonal extremes of these coastal sites. However, such a pattern is not observable at the more continental inland sites in Brunei. The monthly progression of sunshine hours in Kuching, Sibu, Bintulu are also not comparable to Pekan Tutong. The variation in sunshine hours is due to the high spatial heterogeneity in solar radiation across the maritime continent, due to complex land-sea-atmosphere interactions and topographic modulation of cloudiness (Chang et al., 2005). Therefore, usage of sunshine hours from Labuan or any other Borneo stations in CLIMWAT data base, for the estimation of ET_o and water requirements in Brunei would introduce systematic bias.

It is evident from the analysis above, that Labuan data underestimates ET_o values if used to represent Sinaut and Pekan Tutong, especially during peak seasons, where a notably sharper seasonal amplitude is displayed. The sites considered in the study share a similar equatorial monsoon climate, however, local microclimatic or exposure factors influence the evapotranspiration regimes. Tutong is susceptible to stronger inland heating, while Sinaut is influenced by specific local wind patterns. The small Labuan island is subjected to higher humidity, and more consistent sea breeze. The stronger maritime influence moderates the weather slightly more compared to the mainland coastal locations. Mainland coastal and inland sites experience slightly higher diurnal temperature ranges, and lower afternoon humidity, which promote higher evaporative demand (Linacre, 1992). Pekan Tutong records peak ET_o in February-March period, due to the exposure to dry, northeasterly winds, which is at the tail end of the Northeast monsoon. Further, the local terrain modifies the winds. In an analysis, it clarified the sensitivity of the near-near surface wind speed, a key component of the Penman-Monteith equation, to local terrain (McVicar et al., 2012). Sharp ET_o peak in March in Pekan Tutong could be linked to localized adiabatic warming or enhanced solar exposure during the late Northeast monsoon period, when drier continental air masses influence inland areas more than the maritime conditions in Labuan (Chang et al., 2006). Therefore, using Labuan data without any adjustment would underestimate ET_o in the two Bruneian sites, especially during the high-demand periods critical for irrigation planning.

The proximity of a site does not guarantee climatic homogeneity for energy-driven variables like ET_o as the results evidently displayed the difference in climatic conditions of the west coast of Borneo (Freund et al., 2020, McVicar et al., 2012). Locally estimated ET_o values are essential for rigorous scientific research, water resource management, or precision agricultural planning. Non-local metereological data can introduce substantial errors in water requirement estimates and irrigation scheduling (Pereira et al., 2015). Based on the above analysis, it is clear that no single station included in CLIMWAT from the Borneo Island provides a reasonable estimation of ET_o for the two Bruneian sites considered in this study. Further, the two Bruneian stations also show notable differences from each other. The extreme peak of ET_o in Pekan Tutong highlights the significant micro-scale variability. Therefore, no external sites seem suitable to estimate ET_o, and thereby water requirements of crops. Hence, the more appropriate approach for Brunei would be to use locally available data from different sites in the CROPWAT to estimate crop water requirements. If data for local sites are incomplete or not available, the best option to follow is to either go for spatial interpolation considering distance-weighter average of Labuan, Miri, and possibly Bintulu, or develop a localized regression model using the surrounding stations to predict Bruneian ET_o, rather than direct substitution. The two approaches need further research, which is not reported here as it is beyond the scope of this work.

5. Conclusion

A comparative analysis of meteorological parameters and estimated reference evapotranspiration (ET_o) was conducted among Sinaut and Pekan Tutong, Brunei; the recommended station for Brunei, Labuan; and other eleven stations across Borneo Island. The analysis proves Labuan to be an incompatible climatic proxy for Brunei to estimate ET_o and crop water requirements. All stations share the predominant humid tropical macro-climate of Borneo Island, with significant microclimatic differences among the sites. Strong maritime influence in Labuan creates a moderate climate with higher humidity, lower wind speeds during key periods, and a lowered seasonal ET_o compared to the mainland Bruneian sites. Monthly discrepancies in ET_o exceed 14% during critical high-demand periods. The differences in ET_o are driven by the discripancies in temperature, relative humidity, wind speed, and sunshine hours. Furthermore, no Borneo station included in the CLIMWAT database provides a reliable substitute for Bruneian conditions. Additionally, the differences between Sinaut and Tutong validate the substantial micro-scale variability within Brunei, emphasizing dominant local conditions. This verifies the inaccuracy of non-local data substitution in irrigation scheduling and sustainable water resource planning in the case of Brunei. Findings of this research strongly recommend using locally observed meteorological data in CROPWAT applications for irrigation planning and water management. The CROPWAT recommendation for Brunei, therefore, should be revised to reflect this need.

Declaration Of Competing Interest

The authors declare that there is no competing interest that influence any work in this paper.

Acknowledgements

The authors acknowledge the Research Management Centre, Universiti Islam Sultan Sharif Ali (UNISSA) for providing the Research Grant under the Title: Determination of Crop Evapotranspiration and Crop Water Requirement of Three Major Paddy Varieties (Titih, Sembada and MRQ76) Cultivated in Brunei Darussalam (UNISSA/PPP/CRP0033-2024/2026) to accomplish this research outcome.

AI Usage Statement

The authors acknowledge that no Generative AI tools were involved in the process of developing the manuscript.

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