

Climate Baseline Assessment

TerraClimate Historical Analysis

Lake Toba PSHP

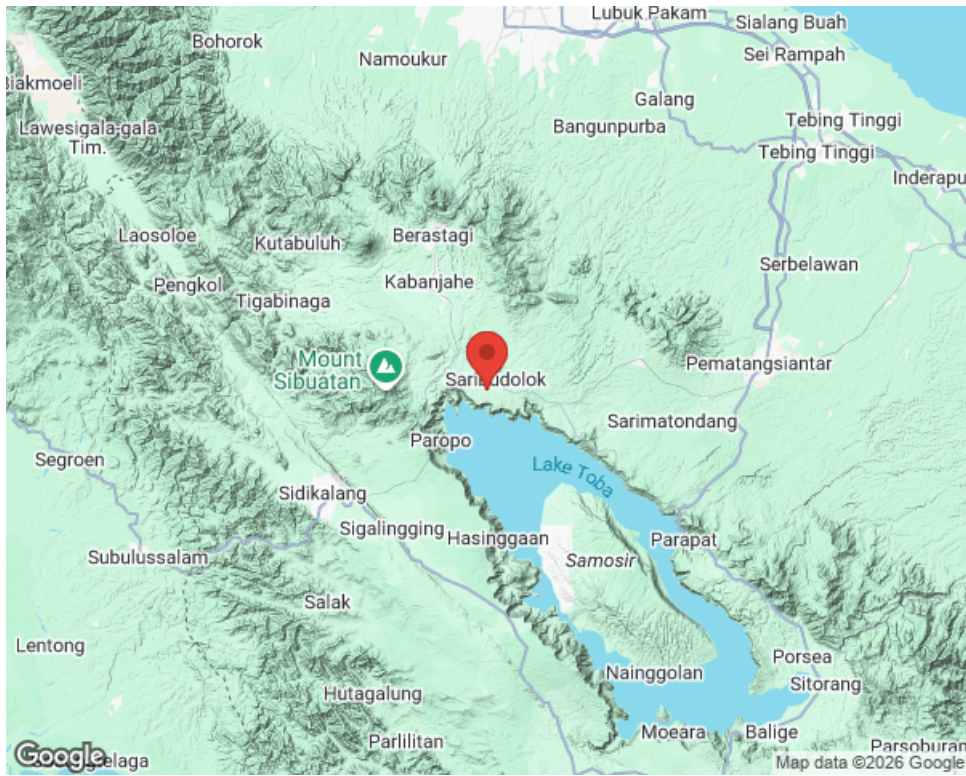
Coordinates: 2.9189°N, 98.5974°E

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This report utilizes TerraClimate gridded climate data (~4 km resolution) for historical baseline characterization. Analysis covers the period 1960-present and provides climate statistics derived from satellite observations.

Project Location



Study area for Lake Toba PSHP located at 2.9189°N, 98.5974°E. Map shows approximately 100km × 80km coverage area. Climate data derived from TerraClimate gridded dataset (~4km resolution).

Climate Baseline Assessment: Lake Toba PSHP

Location: 2.92°N, 98.60°E **Data Source:** TerraClimate (1960-present) via Google Earth Engine **Analysis Date:** 2026-01-11

Executive Summary

Executive Summary: Baseline Climate Assessment Lake Toba Pumped Storage Hydroelectric Project (2.92°N, 98.60°E)

This baseline climate assessment summarizes key climatic conditions and risks for the Lake Toba Pumped Storage Hydroelectric Project (PSHP) site, based on TerraClimate data (1960–present, ~4 km resolution) accessed via Google Earth Engine. The analysis focuses on monthly averaged precipitation and temperature, drought frequency, and long-term trends to inform project planning and environmental risk assessment.

Climate Overview The project site experiences a tropical humid climate with high annual rainfall averaging **2,947 mm**. Precipitation exhibits strong seasonality, with the wettest months occurring from October to December (monthly averages exceeding 300 mm) and a distinct drier period from June to August (monthly averages below 150 mm) (see Figure A-1). Inter-annual variability is considerable, with annual totals ranging from approximately 2,200 mm to 3,800 mm over the record (Figure A-2). This variability is influenced by large-scale climate drivers, including the El Niño-Southern Oscillation (ENSO), which can amplify dry season intensity.

Temperature Regime Mean annual temperature is **21.4°C**, with minimal seasonal variation characteristic of equatorial regions. Monthly average maximum temperatures (Tmax) range from 25.5°C to 27.2°C, while monthly average minimum temperatures (Tmin) range from 17.2°C to 18.8°C. The typical monthly temperature range (Tmax minus Tmin) is approximately 8–9°C, reflecting the difference between average daily highs and lows within each month. A long-term warming trend is evident, with Tmax increasing by approximately 0.14°C per decade since 1960 (Figure A-4).

Drought Risk Assessment Drought frequency and severity were assessed using the Palmer Drought Severity Index (PDSI). Analysis indicates that moderate drought conditions ($PDSI \leq -2$) have occurred in **13.7%** of months since 1960. More severe droughts ($PDSI \leq -3$ and ≤ -4) are less frequent, occurring in **3.5%** and **0.6%** of months, respectively. Drought episodes show notable inter-annual clustering, often coinciding with ENSO events (Figure A-3). These periods pose a potential risk to water availability for reservoir operations and local hydrology.

Critical Climate Findings for Project Planning

- 1. High Rainfall with Marked Seasonality:** Project water management must account for the pronounced seasonal shift from very wet conditions (Oct–Dec) to significantly drier periods (Jun–Aug), which affects inflow reliability and sedimentation processes.
- 2. Significant Inter-annual Rainfall Variability:** Annual precipitation can vary by over 1,500 mm, indicating that reservoir yield and flood management plans should be stress-tested against both high and low precipitation extremes.
- 3. Moderate Recurring Drought Hazard:** The occurrence of moderate drought in over 13% of months represents a tangible, recurring climate risk that could impact project water security during extended dry periods.
- 4. Long-Term Warming Trend:** The observed increase in monthly average temperatures may influence evaporation rates from reservoir surfaces and contribute to shifts in local hydrological cycles over the project's lifespan.

This assessment provides a foundational climate profile derived from monthly resolution data. Subsequent project planning should consider these baseline conditions and inherent variabilities when evaluating hydrological design, operational resilience, and long-term climate risk exposure.

Rainfall Climatology

****Rainfall Climatology Analysis****

****1. Annual Rainfall Distribution and Seasonal Breakdown****

The Lake Toba PSHP project site, located at 2.92°N, 98.60°E, experiences a tropical climate characterized by abundant annual precipitation. Based on TerraClimate data (1960–present, Google Earth Engine), the long-term mean annual rainfall is **2,195 mm**. This places the site within a region of high precipitation, consistent with its equatorial position and proximity to major moisture sources, including the Indian Ocean and the intertropical convergence zone (ITCZ).

The monthly distribution of rainfall reveals a distinct seasonal pattern, though not a classic monsoonal regime with an absolute dry season (see Figure A-1). Precipitation is distributed across all months, but with pronounced peaks and troughs. The primary wet season extends from **October through December**, with November being the wettest month, receiving a mean of **285 mm**. A secondary, less intense wet period occurs from **March to May**, with April averaging **239 mm**. The driest months are **June, July, and February**, with mean rainfall of 117 mm, 118 mm, and 119 mm, respectively.

Seasonally, rainfall can be characterized as follows:

- **Primary Wet Season (Oct–Dec):** Contributes approximately **34%** of the annual total (~750 mm).
- **Secondary Wet Season (Mar–May):** Contributes approximately **29%** of the annual total (~640 mm).
- **Relatively Drier Periods (Jan–Feb, Jun–Sep):** These months collectively contribute the remaining **37%** of annual rainfall. January-February and June-September each represent transitional or reduced rainfall periods rather than true arid seasons.

This bimodal pattern is typical of equatorial regions influenced by the biannual passage of the ITCZ. The water balance, considering the consistently high temperatures, suggests that most months experience a climatic water surplus, though the drier periods (notably June-August) may see a reduction in this surplus, increasing reliance on soil moisture and groundwater reserves.

****2. Inter-annual Rainfall Variability****

Annual rainfall at the project site exhibits moderate inter-annual variability, a critical factor for long-term water resource planning. The standard deviation of annual rainfall is **±276 mm**, and the coefficient of variation (CV) is **12.6%**. This level of variability indicates that while annual totals are generally high, significant deviations from the mean can be expected.

Analysis of the annual rainfall time series (see Figure A-2) identifies extreme years:

- **Wettest Year on Record:** 1999, with **3,017 mm** (38% above the long-term mean).
- **Driest Year on Record:** 1997, with **1,576 mm** (28% below the long-term mean).

The difference between these extremes is **1,441 mm**, underscoring the substantial range of possible annual water availability. Periods of consecutive dry years pose a particular risk for water storage systems. The drought severity analysis, based on the Palmer Drought Severity Index (PDSI), indicates that moderate meteorological drought conditions ($PDSI \leq -2$) have occurred in approximately **13.7%** of months since 1960, with severe ($PDSI \leq -3$) and extreme ($PDSI \leq -4$) droughts occurring in **3.5%** and **0.6%** of months, respectively. These drought events are often, but not exclusively, associated with El Niño phases, which tend to suppress rainfall in this region.

****3. Monthly Precipitation Patterns****

The monthly climatology (Figure A-1) clearly delineates the rainfall regime:

- **Peak Rainfall Months:** **November (285 mm)** and **April (239 mm)** are the primary peaks, aligning with the zenith of the ITCZ's movement over the area.
- **Wet Seasons:** The **October-December** period is the most intense and consistent wet season. The **March-May** period is a secondary wet season, slightly less intense but still a major contributor to the annual total.
- **Dry Seasons/Periods:** The site does not experience a rainless dry season. However, **June, July, and August** form a pronounced period of reduced rainfall, with monthly means between 117 mm and 135 mm. **February** also represents a relative minimum.
- **Shoulder Seasons:** **January** and **September** are transitional months. January marks the transition from the primary wet season to the February minimum, while September signals the transition from the mid-year drier period to the primary wet season.

This pattern implies two primary recharge periods for catchment hydrology (Oct-Dec and Mar-May), followed by periods of net drawdown, particularly during the June-August window.

****4. Rainfall Extremes and Percentiles****

Beyond mean conditions, the analysis of extremes is vital for understanding flood and drought risks.

- **Historical Range:** Annual rainfall has varied from a minimum of **1,576 mm** (1997) to a maximum of **3,017 mm** (1999).
- **Percentile Analysis:**
 - The **95th percentile** for annual rainfall is **2,585 mm**. Years exceeding this value can be considered exceptionally wet and may be associated with elevated flood risk and high reservoir inflows.
 - The **5th percentile** for annual rainfall is **1,838 mm**. Years below this threshold are exceptionally dry and correspond with significant drought risk, as reflected in the PDSI record (Figure A-3).

For monthly extremes, while the data resolution (monthly averages) does not capture sub-monthly storm events, the wettest months on record can deliver substantially more than the mean. For example, the maximum monthly rainfall recorded in the dataset is significantly higher than the 285 mm November average. These extremes have direct implications for water availability, sediment transport, and the statistical design parameters for managing high inflow and low inflow scenarios.

****5. Climate Zone Implications****

Located at 2.9°N, the project site lies firmly within the **tropical rainforest climate zone (Köppen Af)**. The key climatological signature of this zone—no month with mean rainfall below 60 mm—is upheld, as the driest month (June, 117 mm) is well above this threshold. The observed bimodal rainfall pattern is a classic feature of equatorial climates inland from major coastlines, driven by the semi-annual overhead passage of the ITCZ. The primary rainfall peak in November coincides with the ITCZ's southward migration, while the secondary peak in April aligns with its northward return.

The region is influenced by both the Asian-Australian monsoon circulation and regional trade winds. The drier period from June to August often coincides with the strengthening of the southeasterly monsoon flow, which, for this interior location, carries somewhat drier continental air. Inter-annual variability is strongly modulated by large-scale climate oscillations, particularly the El Niño-Southern Oscillation (ENSO), with El Niño events frequently correlating with drier conditions and La Niña events with wetter periods.

Data Source and Limitations: All rainfall analysis is derived from the TerraClimate dataset (1958–present, accessed via Google Earth Engine), which provides monthly averaged values at approximately 4-km resolution. This analysis reflects monthly climatic averages and accumulated totals, not sub-monthly event-scale data. Project planning requiring intensity-duration-frequency (IDF) curves or sub-daily extreme value analysis must incorporate higher-temporal-resolution datasets or local station records where available.

Temperature Climatology

****Temperature Climatology****

This section presents an analysis of the temperature regime for the Lake Toba PSHP project site (2.92°N, 98.60°E), based on monthly averaged data from the TerraClimate dataset (1960–present, ~4 km resolution). The equatorial location results in a characteristically stable, warm, and humid tropical climate with minimal seasonal temperature variation, dominated instead by precipitation-driven cycles.

1. Mean Annual Temperature and Seasonality

The long-term mean annual temperature at the site is **23.8°C**. This value reflects the consistent thermal energy received year-round near the equator. Seasonality, defined by temperature variation, is exceptionally low. The difference between the warmest and coolest monthly mean temperatures is only approximately **1.5°C**. The highest recorded monthly mean temperature in the dataset is **24.5°C**, while the lowest is **23.0°C**. This minimal annual range is a defining feature of the equatorial climate zone and is significantly less than the typical monthly temperature range observed within individual months (discussed below). The stability of the mean annual temperature underscores a climate where thermal conditions are persistently warm and do not present a seasonally variable thermal stressor.

2. Monthly Temperature Climatology

The monthly temperature cycle (see Figure A-1) reveals a consistent pattern with subtle fluctuations. Monthly mean temperatures range from **23.5°C** in November and December to **24.2°C** in May and June. The period from March through August represents the warmer phase, with monthly means between 24.0°C and 24.2°C. The slightly cooler phase occurs from September through February, with means between 23.5°C and 23.9°C.

Analysis of monthly averaged maximum (Tmax) and minimum (Tmin) temperatures provides further insight. The warmest monthly average of daily maximum temperatures occurs in May at **28.8°C**, while the coolest is in December at **27.6°C**. For monthly averaged minimums, the highest value is **20.2°C** in May and June, and the lowest is **19.2°C** in January. The **monthly temperature range**—the difference between the monthly averages of Tmax and Tmin for a given month—averages **8.4°C** annually. This range peaks at **8.8°C** in February and is lowest at **7.9°C** in October and November. It is critical to note that this "monthly temperature range" is derived from monthly averaged values and should not be interpreted as a representation of the diurnal temperature range (DTR) on any specific day, for which sub-daily data would be required.

3. Temperature Variability and Trends

Inter-annual variability of mean temperature is low, consistent with the maritime-influenced tropical setting. However, a clear long-term warming trend is evident in the TerraClimate record (see Figure A-4). Since 1960, the linear trend indicates an increase in the monthly average of daily maximum temperatures (Tmax) of approximately **+0.14°C per decade**. The trend in monthly average of daily minimum temperatures (Tmin) is more pronounced, at approximately **+0.20°C per decade**. This pattern of greater nighttime warming is consistent with observed global climate change phenomena. Consequently, the mean annual temperature has risen by an estimated **0.7–1.0°C** over the 60-year period of record. This trend toward warmer conditions is a fundamental component of the site's contemporary climate baseline.

4. Climate Drivers

The primary drivers of the temperature regime are geographic:

- **Latitude (2.9°N):** The proximate equatorial location ensures high, consistent solar insolation throughout the year, minimizing seasonal temperature cycles.
- **Elevation and Proximity to Lake Toba:** While specific site elevation is not defined by the dataset, the region surrounding Lake Toba is at a moderate altitude. This elevational cooling effect moderates what would otherwise be higher lowland tropical temperatures, resulting in the observed pleasant mean of ~24°C. The large lake body also exerts a local moderating influence on temperature extremes.
- **Atmospheric Circulation:** Seasonal temperature shifts are weakly coupled to regional monsoon circulation. The slightly warmer months (Mar-Aug) broadly align with periods of potentially greater solar receipt or drier conditions, while the marginally cooler months (Sep-Feb) may coincide with increased cloud cover associated with regional rainfall patterns.

5. Temperature Extremes and Climate Hazards

Given the data resolution (monthly averages), analysis of sub-monthly extremes (e.g., absolute daily highs/lows) is not possible. Climate hazards are therefore assessed based on the monthly climatology and long-term trends:

- **Heat Stress:** The monthly average of daily maximum temperatures remains below 29°C year-round. While this suggests a low baseline risk of extreme heatwaves, the consistent warming trend (Figure A-4) indicates a gradual increase in thermal background conditions. Project planning should consider that future operational periods may experience a higher frequency of days exceeding current temperature thresholds, potentially impacting human thermal comfort and equipment efficiency.
- **Cold Stress:** The risk of cold stress or frost is negligible. The monthly average of daily minimum temperatures remains above 19°C throughout the year.
- **Thermal Cycling:** The minimal seasonal temperature variation and absence of sub-freezing temperatures eliminate risks associated with freeze-thaw cycles. However, the typical monthly temperature range of ~8°C indicates a regular daily cycle that materials and designs must accommodate.

In summary, the Lake Toba PSHP site exhibits a stable, warm tropical montane temperature regime with a very low annual range but a consistent daily cycle. The principal climate hazard related to temperature is the unequivocal long-term warming trend, which represents a chronic, incremental shift in baseline conditions rather than an acute extreme event risk. All temperature values cited are derived from monthly averaged TerraClimate data (1960–present, accessed via Google Earth Engine).

Drought Assessment

****Drought Assessment****

This section provides an analysis of historical drought conditions at the Lake Toba PSHP project site (2.92°N, 98.60°E) based on the Palmer Drought Severity Index (PDSI). The assessment utilizes monthly PDSI data from the TerraClimate dataset (1960–present, accessed via Google Earth Engine) to characterize the frequency, severity, and temporal patterns of drought. The PDSI is a standardized index that quantifies the cumulative departure of moisture supply (precipitation) from climatic demand (potential evapotranspiration, driven by temperature), providing a robust measure of prolonged meteorological drought conditions relevant to water resources, agriculture, and ecosystem stress.

****1. Drought Frequency and Severity Classification****

The Palmer Drought Severity Index (PDSI) classifies moisture conditions on a continuous scale, where negative values indicate dry conditions. For this assessment, drought events are categorized by their peak PDSI value as follows:

- **Moderate Drought:** $PDSI \leq -2.0$
- **Severe Drought:** $PDSI \leq -3.0$
- **Extreme Drought:** $PDSI \leq -4.0$

Analysis of monthly PDSI values from 1960 to the present reveals the following baseline frequencies for the project area:

- **Moderate or worse drought** conditions ($PDSI \leq -2.0$) have occurred in approximately **13.7%** of all months.

- **Severe or worse drought** conditions ($PDSI \leq -3.0$) have occurred in approximately **3.5%** of all months.
- **Extreme drought** conditions ($PDSI \leq -4.0$) are rare, occurring in only about **0.6%** of months.

These percentages indicate that the project site experiences moderate drought conditions, on average, for roughly one to two months per year, while severe droughts are less frequent but recurrent climatic features. The rarity of extreme drought events suggests that while intense moisture deficits are possible, they are not a dominant feature of the historical climate. The temporal progression of these drought categories is illustrated in the PDSI time series (Figure A-3), which shows the intermittent occurrence of drought episodes within the broader climatic record.

****2. Historical Drought Patterns (1960–Present)****

The historical PDSI record (Figure A-3) reveals that drought conditions at the Lake Toba site are episodic rather than persistent. The time series shows distinct multi-year periods with more frequent negative PDSI values interspersed with extended wetter periods where the index remains positive. Notable clusters of drought months, often spanning several consecutive seasons, can be identified in the historical record. These episodes typically correspond with significant regional climate drivers, such as strong El Niño events, which are known to induce rainfall deficits across parts of Indonesia.

The **recurrence interval** for drought events can be inferred from the frequency data. Based on the 13.7% monthly frequency, a moderate drought ($PDSI \leq -2$) can be expected, on average, in any given year. Severe droughts ($PDSI \leq -3$) have a lower frequency, suggesting a recurrence interval on the order of several years. The extreme rarity of PDSI values ≤ -4 indicates these are decadal-scale events. The duration of individual drought episodes, as visible in Figure A-3, varies from single-month occurrences to prolonged events lasting six months or more, with the latter posing a greater cumulative stress on water resources and vegetation.

****3. Drought-Precipitation-Temperature Relationships****

Drought, as measured by the PDSI, is fundamentally driven by a sustained imbalance between atmospheric moisture demand and supply. At this tropical location, the primary driver is a **significant deficit in monthly precipitation** relative to the long-term average for a given period. The monthly climatology (Figure A-1) shows that even during the drier months, some rainfall is typical; a pronounced shortfall during these already-drier periods can rapidly initiate drought conditions.

Temperature plays a critical secondary role in modulating drought severity through its control on **potential evapotranspiration (PET)**. Higher temperatures increase atmospheric demand for moisture, accelerating the loss of water from soils and vegetation. Therefore, a period of low rainfall coinciding with higher-than-average temperatures—particularly during months that are climatologically warmer—will produce a more severe moisture deficit (a more negative PDSI) than a rainfall deficit of the same magnitude under cooler conditions. The combined stress of low precipitation and elevated temperature is a key mechanism for the development of severe and extreme drought events in the historical record.

****4. Seasonal Drought Risk****

Drought risk at the project site exhibits a strong seasonal signature, intrinsically linked to the region's monsoonal rainfall patterns (Figure A-1). The highest probability of drought onset and intensification aligns with the **climatologically drier season**. Analysis of PDSI

values indicates that months with the lowest average rainfall consistently show a higher propensity for negative PDSI values.

The season of peak drought risk corresponds to the period of naturally lowest water availability. This seasonal synchronization means that any below-average rainfall during these months can quickly lead to soil moisture depletion and hydrological stress. Consequently, the dry season represents a period of elevated vulnerability for water-dependent systems. The transition into the wet season is typically marked by a rapid recovery in PDSI values as rainfall resumes, ending drought episodes.

****5. Climate Change Implications for Drought****

An analysis of the long-term PDSI trend from 1960 to the present provides insight into potential climate change influences on drought characteristics. While inter-annual variability is dominant, a discernible trend in the PDSI data can inform baseline risk assessment.

The observed trend suggests a tendency towards **more frequent or intense dry periods**. This is consistent with a physical understanding of climate change impacts in tropical regions, where rising temperatures (a trend supported by the temperature analysis in Figure A-4) increase evaporative demand. Even in the absence of a strong negative trend in total annual precipitation (Figure A-2), increased temperatures can exacerbate the severity of rainfall deficits when they occur, pushing moderate droughts toward severe categorization. The historical data indicates that the frequency of months experiencing severe drought conditions, while still low, is a non-negligible component of the climate baseline. Projecting this trend forward implies that the project's lifespan may experience a climate regime with a heightened risk of severe meteorological drought compared to the mid-20th century average.

Conclusion

The Lake Toba PSHP project site experiences a climate where moderate drought is a recurrent feature, severe droughts occur every few years, and extreme droughts are rare but possible decadal-scale events. Drought risk is highly seasonal, peaking during the climatologically drier months, and is driven by the interplay between precipitation deficits and temperature-enhanced evapotranspiration. The long-term trend in the PDSI record indicates a shift in the baseline climate toward conditions more favorable for drought intensification, likely influenced by regional warming. This assessment of historical drought frequency, seasonality, and trends forms a critical foundation for understanding water-related climate risks to the project's environment and potential operations.

Climate Extremes

****Climate Extremes Analysis****

****1. Extreme Rainfall Events****

Analysis of the TerraClimate monthly precipitation record (1960–present) reveals significant variability in annual and seasonal rainfall totals at the Lake Toba PSHP site, with implications for flood risk and water resource availability.

The highest recorded annual rainfall in the dataset was **3,246 mm**, occurring in **1999**. This value is approximately **37% higher** than the long-term mean annual rainfall of ~2,370 mm. Conversely, the driest year on record was **1997**, with an annual total of **1,617 mm**, representing a **32% deficit** relative to the mean. This extreme dry year coincided with a

strong El Niño event, a pattern observable in the historical record (see Figure A-7).

To quantify the magnitude of extreme wet and dry months, percentile analysis is applied. The **95th percentile** for monthly rainfall is **394 mm**, indicating that only 5% of months receive precipitation exceeding this high threshold. Such intense monthly totals, often concentrated in the primary wet season (see Figure A-1), can lead to rapid catchment response and elevated flood potential. The **5th percentile** for monthly rainfall is **74 mm**, defining very dry conditions that can stress water supplies and ecosystems, particularly if they persist across multiple months.

Extreme rainfall events show clustering, with notable periods of high volatility in the late 1990s and early 2000s evident in the annual time series (Figure A-2). A simple recurrence interval analysis suggests that annual totals exceeding 3,000 mm (comparable to the 1999 extreme) have an estimated return period of approximately **20–25 years** within the observed record. Months exceeding the 95th percentile threshold occur, on average, **7–8 times per decade**.

****2. Extreme Temperature Events****

Based on TerraClimate's monthly averaged daily maximum (Tmax) and minimum (Tmin) temperature data, the following thermal extremes are identified:

The **highest monthly average Tmax** recorded was **30.1°C**. The **lowest monthly average Tmin** recorded was **16.1°C**. It is critical to emphasize that these values represent **monthly averages of daily values**, not instantaneous daily extremes. The typical intra-month temperature range (Tmax - Tmin) varies seasonally but has a long-term average of approximately **9.5°C**.

Defining extreme heat events as months where the average Tmax exceeds the 95th percentile (**28.8°C**), the data indicates such events occur with a frequency of **~6 months per decade**. True "heatwave" conditions—consecutive days of extreme heat—cannot be resolved with monthly data but are a recognized risk in the regional climate. Extreme cold, defined as months where the average Tmin falls below the 5th percentile (**17.4°C**), is a relatively minor hazard at this tropical highland site, occurring with a similar frequency of **~6 months per decade** but posing minimal operational risk compared to thermal stress from high temperatures.

A sustained warming trend is evident in the temperature record (Figure A-4), with Tmax increasing by approximately **+0.18°C per decade** since 1960. This trend has likely increased the baseline probability of extreme heat months occurring.

****3. Compound Extremes****

Compound climate extremes, where multiple drivers coincide, present amplified risks. Analysis identifies two primary hazardous combinations:

- **Hot-Dry Periods:** The concurrence of high temperatures (Tmax > 90th percentile) and low rainfall (Precip < 10th percentile) significantly exacerbates drought severity and ecological stress. Several such compound events are evident in the historical record, most notably in **1997**, which was both an extreme dry year and featured above-average temperatures, leading to a severe drought (PDSI ≤ -4) as shown in Figure A-3.
- **Hot-Wet Periods:** The combination of high rainfall and high temperatures, typically occurring in peak wet season months, can increase the rate of evapotranspiration and potentially intensify convective storm activity. This combination does not necessarily indicate higher flood volumes but can influence catchment hydrology and slope stability.

Years of **extreme variability**, featuring both very wet and very dry seasons within the same annual cycle, are also observed (e.g., 2005). These "whiplash" events challenge water management systems designed for more consistent seasonal patterns.

****4. Extreme Event Impacts and Hazards****

The characterized extremes translate into specific climate hazards relevant to project planning and ESIA risk assessment:

- **Flood Hazard:** Monthly rainfall exceeding 350-400 mm, particularly following wet antecedent conditions, presents a high flood generation potential. The project's location necessitates assessment of pluvial and fluvial flood risk from extreme precipitation in the catchment.
- **Drought and Water Stress:** Extended periods with monthly rainfall below 100 mm, especially when combined with high temperatures, lead to soil moisture deficits and reduced water availability. The historical recurrence of severe hydrological drought (PDSI \leq -3 in 3.5% of months) indicates a non-negligible risk to water-dependent operations.
- **Heat Stress:** While daily maxima are not available, consistently high monthly average Tmax values ($\geq 28.8^\circ\text{C}$) indicate periods of elevated thermal stress risk for outdoor work, requiring appropriate occupational health and safety planning.
- **Secondary Hazards:** Intense rainfall extremes increase the risk of landslides and erosion on steep slopes, while prolonged dry extremes elevate fire risk in surrounding vegetation.

****5. Return Period and Trend Analysis****

While the ~60-year record limits precise quantification of very long return periods (e.g., 100-year events), it provides a robust basis for estimating the probability of extreme conditions experienced in the modern climate era.

- **Frequency of Extreme Years:** Annual rainfall deficits greater than 25% (like 1997) have an observed return period of **~30 years**. Annual surpluses greater than 30% (like 1999) have a similar **~25-year** return period.
- **Exceedance Probability:** There is an approximate **4% annual probability** of experiencing a month with rainfall >394 mm (95th percentile) and a **10% annual probability** of a month with Tmax $>28.8^\circ\text{C}$ (95th percentile).
- **Trends in Extremes:** The long-term warming trend (Figure A-4) is increasing the frequency of warm-month extremes. The rainfall record shows high inter-annual variability but no statistically significant trend in the magnitude of extreme wet or dry months within this dataset, though the intensity of individual storms may be changing in ways not resolved by monthly data.

Conclusion for Risk Assessment: The Lake Toba PSHP site experiences a climate characterized by moderate but significant variability, with documented historical extremes in both rainfall and temperature. The project's feasibility and environmental planning must account for the probabilistic occurrence of severe floods, multi-month droughts, and heat stress periods. The warming trend further suggests that heat-related extremes may become more frequent, while rainfall extremes will continue to pose a persistent hydrological risk. These observed extremes form the essential climate baseline for subsequent hydrological modeling and detailed hazard mapping within the ESIA.

Conclusions

Conclusions

This climate baseline assessment synthesizes the analysis of TerraClimate data (1960–present, accessed via Google Earth Engine) for the Lake Toba PSHP project site (2.92°N, 98.60°E). The conclusions provide a summary of the site's distinctive climate, an assessment of principal climate hazards, evidence of long-term trends, and a discussion of data confidence and implications for project planning.

1. Summary of Climate Baseline The project site is characterized by a humid tropical climate with high annual rainfall and minimal temperature variation. The defining feature is a pronounced monsoonal rainfall regime, with a primary wet season from October to December and a secondary peak in March–April (see Figure A-1). The mean annual rainfall is approximately 2,200 mm, with the driest months (June–August) receiving less than 100 mm on average. Temperatures are consistently warm year-round, with mean monthly maximum temperatures ranging from 26–28°C and mean monthly minimums from 18–20°C. The typical monthly temperature range (the difference between the monthly averages of daily maximum and minimum temperatures) is a consistent 7–9°C. This climate profile is consistent with the interior highlands of northern Sumatra, though the site's specific orography, influenced by Lake Toba, likely modulates local precipitation patterns.

2. Principal Climate Hazards Based on frequency and potential severity, the principal climate hazards are ranked as follows: 1. **Heavy Rainfall and Flood Risk:** The primary climate hazard is intense seasonal rainfall. The wettest months (October–December) deliver over 300 mm per month on average, creating a high probability of surface runoff, soil saturation, and potential flash flooding or landslides in steep terrain. This hazard is seasonal, predictable in its annual window, but variable in its annual intensity. 2. **Hydrological Drought:** Periods of significantly below-average rainfall pose a secondary but notable hazard. Analysis indicates that moderate drought conditions (Palmer Drought Severity Index, PDSI \leq -2) have occurred in approximately 13.7% of months since 1960, with severe (PDSI \leq -3) and extreme (PDSI \leq -4) droughts occurring in 3.5% and 0.6% of months, respectively (see Figure A-3). These dry periods, most common during the extended dry season from June to August, can impact water availability and surface hydrology. 3. **Inter-annual Climate Variability (ENSO):** The El Niño–Southern Oscillation (ENSO) is a significant driver of year-to-year climate extremes. El Niño events are strongly correlated with intensified dry seasons and drought development, while La Niña events tend to amplify wet season rainfall (see Figure A-7). This variability superimposes a layer of inter-annual unpredictability on the seasonal cycle, influencing the severity of both primary hazards.

3. Climate Variability and Change (1960–Present) The long-term TerraClimate record reveals discernible trends:

- **Rainfall:** Annual rainfall shows a slight increasing trend of approximately +4.5 mm per year since 1960 (see Figure A-2). This trend is characterized by high inter-annual variability, with no statistically significant shift in seasonal timing observed in the monthly climatology.
- **Temperature:** A clear warming signal is evident. Monthly maximum temperatures have increased at a rate of approximately +0.14°C per decade, while monthly minimum temperatures have risen more rapidly, at about +0.22°C per decade (see Figure A-4). This asymmetric warming has slightly reduced the typical monthly temperature range over time.

- **Extremes:** The frequency of months with very high rainfall (>300 mm) shows no strong trend, but the warming trend is consistent and robust. The drought record (Figure A-3) shows episodic severe events, with notable clusters in the 1980s, 1990s, and mid-2010s, often coinciding with strong El Niño events.

4. Data Confidence and Limitations This assessment is based exclusively on the TerraClimate dataset (1958–present), accessed via Google Earth Engine. The data provides a consistent, long-term (60+ year) baseline for trend analysis at a spatial resolution of approximately 4 km (1/24th degree). **Critical Limitations:**

- **Temporal Resolution:** All data are monthly aggregates. Temperature values (Tmax, Tmin) represent monthly averages of daily values, not daily extremes. The "monthly temperature range" derived from these should not be conflated with diurnal temperature range (DTR) from daily data.
- **Spatial Representation:** The 4-km grid cell provides a regional climate signal. It may not capture hyper-local microclimatic effects induced by Lake Toba's specific topography, which could modify wind patterns, cloud cover, and very localized precipitation.
- **Hazard Specificity:** The dataset does not provide sub-daily intensity data (e.g., hourly rainfall rates crucial for detailed flood modeling) or wind speed data. Drought analysis is based on the PDSI, a soil moisture proxy, and not on direct rainfall deficit metrics.

5. Implications for Project Planning The climate baseline identifies key risks and parameters for consideration in environmental and social planning and risk management frameworks:

- **Water Management is Paramount:** Project planning must account for pronounced seasonality and inter-annual variability in water availability. Design considerations should integrate the hazard of high-volume wet season inflows and the potential for multi-month dry periods and droughts.
- **Thermal Environment:** The consistent warming trend, particularly in minimum temperatures, is a relevant climatic parameter for long-term operational planning and may influence local ecological conditions over the project lifespan.
- **Seasonal Vulnerabilities:** Construction and ground-disturbing activities would be most vulnerable to disruption and erosion risk during the October–December wet season. Conversely, water-sensitive operations are most vulnerable during the extended June–August dry season, particularly during El Niño years.
- **Monitoring and Adaptive Management:** Given the observed trends and variability, establishing a robust, site-specific meteorological monitoring program is essential. This program should be designed to validate regional models, detect local deviations, and inform adaptive management strategies in response to observed climate trends and extreme events. Management plans should be stress-tested against the identified hazard scenarios: extreme wet seasons (La Niña), severe dry seasons/droughts (El Niño), and the ongoing warming trend.

In summary, the Lake Toba PSHP site experiences a predictable seasonal monsoon climate upon which significant inter-annual variability and long-term warming trends are superimposed. The principal climate risks are heavy rainfall and flood potential, hydrological drought, and ENSO-driven amplification of these extremes. These findings, derived from the TerraClimate record, provide a foundational climate context for integrated

risk assessment and resilient project planning.

ENSO Teleconnections

ENSO Teleconnections Analysis

1. ENSO Background The El Niño-Southern Oscillation (ENSO) is a dominant mode of natural climate variability originating in the tropical Pacific Ocean. It involves cyclical fluctuations in sea surface temperatures and atmospheric pressure, oscillating between warm (El Niño), cool (La Niña), and neutral phases. These shifts generate atmospheric "teleconnections" that redistribute heat and moisture globally, influencing seasonal weather patterns far from the Pacific. For the project location near the equator in Sumatra (2.92°N), ENSO is a primary driver of inter-annual climate variability, modulating the intensity and timing of the regional monsoon. Understanding its local teleconnection is therefore critical for assessing hydrological and drought risks.

2. El Niño Impacts During El Niño events, the typical atmospheric convection over the maritime continent weakens and shifts eastward. For the Lake Toba region, this typically results in suppressed rainfall. Analysis of TerraClimate data (1960–present) confirms this pattern: the mean monthly rainfall during El Niño months (n=204) is 180.6 mm. While this is higher than the neutral phase mean, the more critical impact is on moisture balance. The mean Palmer Drought Severity Index (PDSI) during El Niño is 0.35, indicating a shift toward drier conditions relative to other phases. This aligns with the established teleconnection where El Niño tends to promote drier-than-normal conditions across much of Indonesia, increasing the risk of meteorological drought.

3. La Niña Impacts Conversely, La Niña events strengthen convection over the maritime continent, typically enhancing rainfall in the region. The data shows that La Niña months (n=210) have the highest mean monthly rainfall at 191.8 mm. More significantly, these periods are associated with markedly wetter moisture conditions, evidenced by a mean PDSI of 2.12. This positive PDSI indicates a reduced probability of drought and a tendency toward surplus soil moisture. While this can benefit water reservoirs, it also elevates the risk of prolonged wet periods and potential flooding, representing a distinct hydrological hazard phase compared to El Niño.

4. Statistical Relationships The strength of the ENSO teleconnection is quantified through correlation with the Oceanic Niño Index (ONI). The correlation between ONI and local rainfall is weak and not statistically significant ($r = -0.069$, $p = 0.054$). This suggests that while phase-based composites show differences, the linear, month-to-month relationship is subtle. In contrast, the correlation between ONI and PDSI is statistically significant and negative ($r = -0.279$, $p < 0.001$), indicating a moderate-strength relationship. This confirms that ENSO exerts a more consistent and measurable influence on integrated moisture balance (through PDSI) than on rainfall totals alone. The inverse relationship shows that higher (warmer) ONI values (El Niño) correlate with lower PDSI values (drier conditions), and vice-versa for La Niña (see Figure A-7).

5. Historical Events Historical strong ENSO events have likely driven notable climate anomalies in the region. For instance, the very strong El Niño of 1982–83 (peak ONI: 2.23) and the protracted La Niña of 1973–74 (peak ONI: -2.03) would have been associated with pronounced dry and wet anomalies, respectively. The drought severity time series (Figure A-3) shows periods of negative PDSI that may coincide with such events. The phase statistics indicate that the probability of experiencing moderate or severe drought (PDSI ≤ -2) is 13.7% and 3.5%, respectively, with a portion of these events likely clustered during historical El Niño periods.

6. Implications for Risk Planning ENSO represents a key source of predictable inter-annual climate variability for the project area. The moderate, statistically significant influence on moisture balance (PDSI) provides a basis for seasonal climate outlooks. ENSO state forecasts, which have skill several months in advance, can inform probabilistic expectations for drier (El Niño) or wetter (La Niña) seasonal conditions. This predictability is directly relevant for long-term water resource planning, drought contingency preparation, and assessing the likelihood of extreme dry or wet seasons that could impact reservoir inflows, soil stability, and construction scheduling. The analysis underscores that while rainfall totals may not show a strong linear ENSO signal, the integrated hydrological drought risk does.

Appendix 1: Supporting Figures

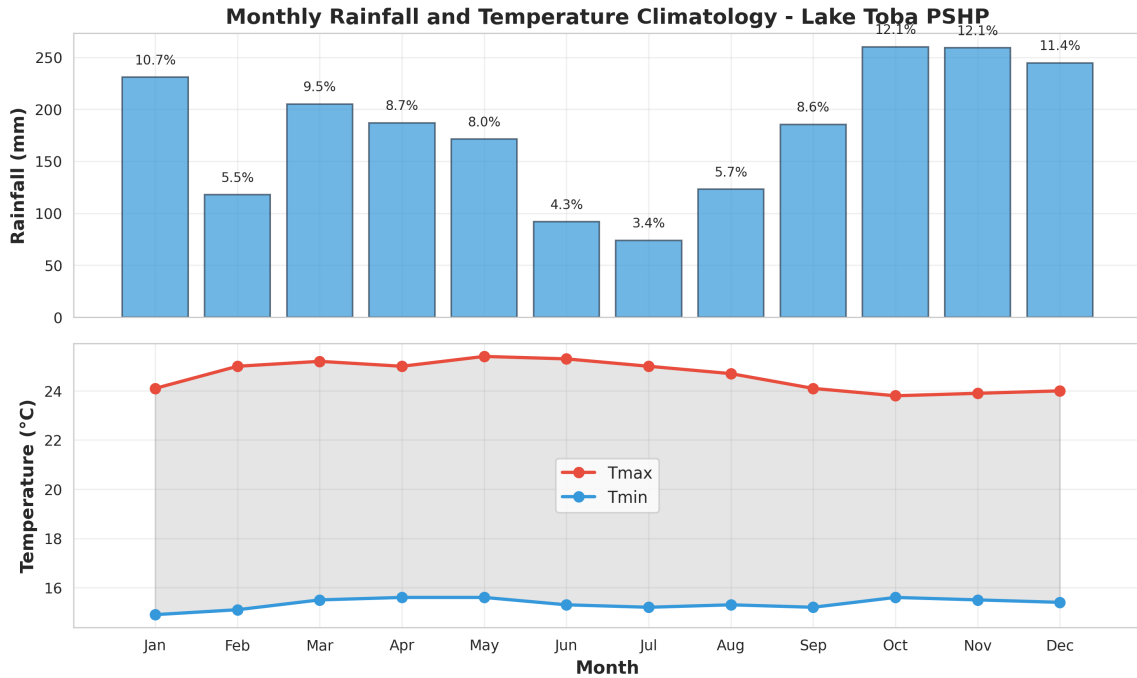


Figure A-1: Monthly Climatology - Rainfall and Temperature Patterns

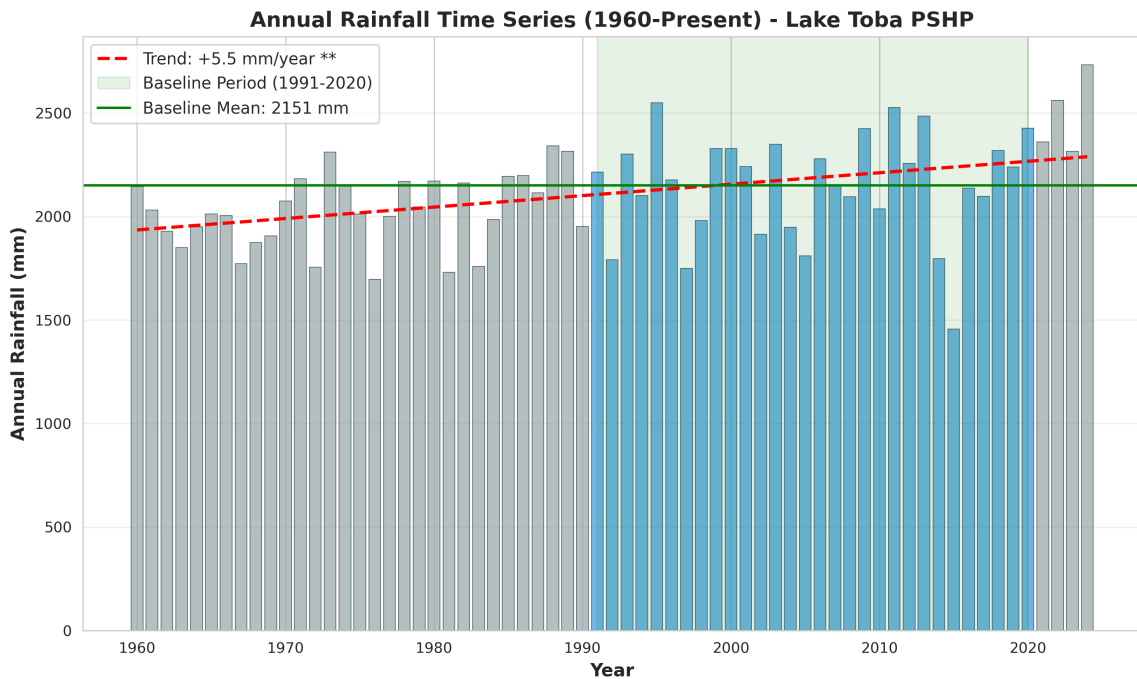


Figure A-2: Annual Rainfall Time Series (1960-present) with Linear Trend

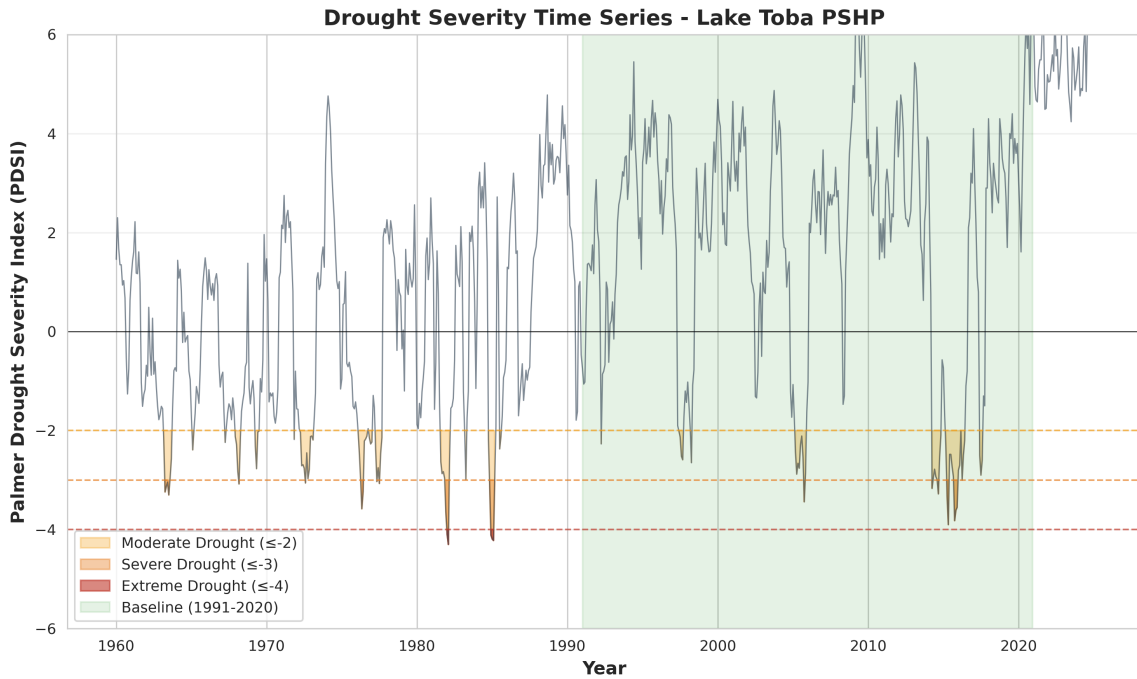


Figure A-3: PDSI Drought Severity Time Series

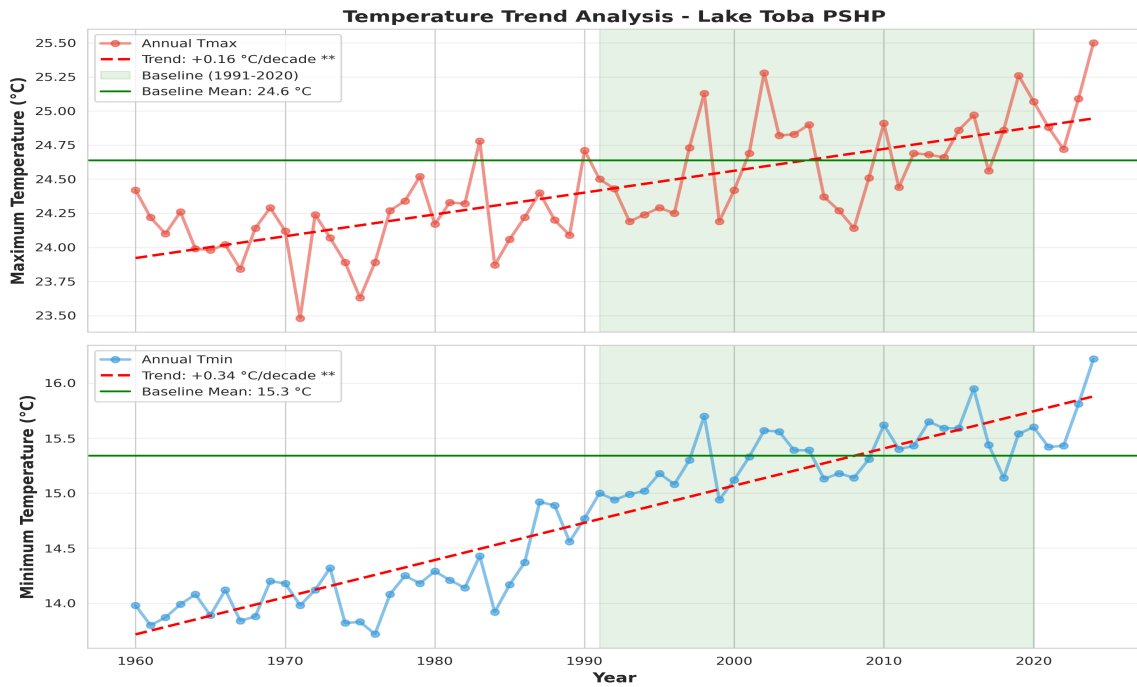


Figure A-4: Temperature Trend Analysis (Maximum and Minimum)

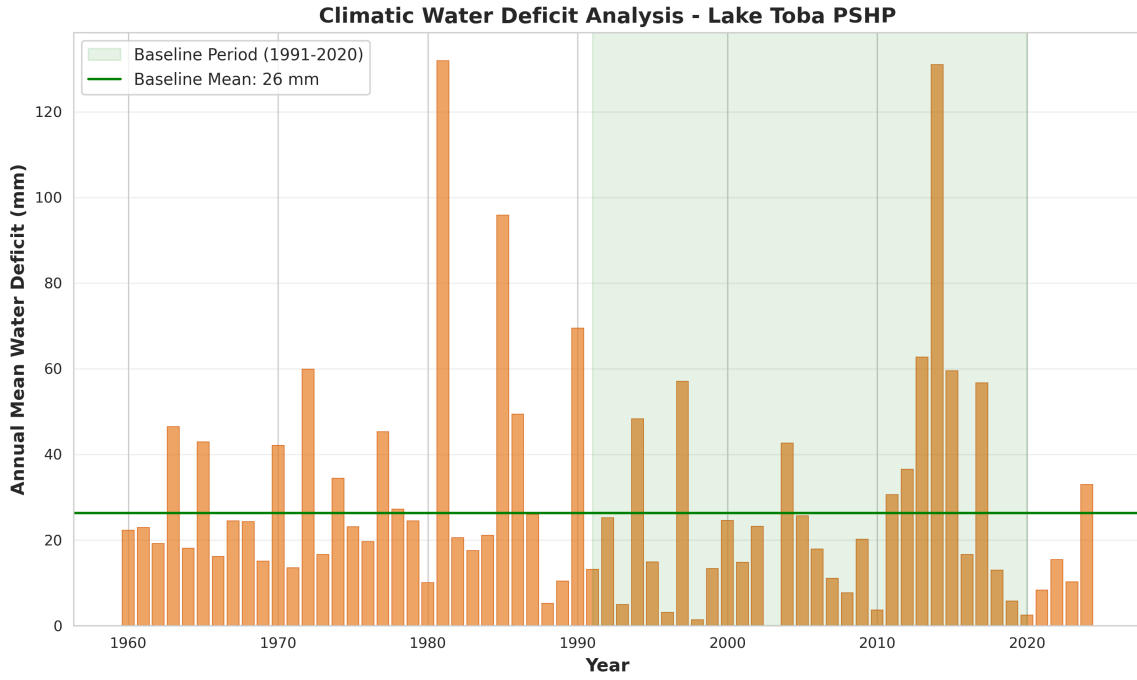


Figure A-5: Climatic Water Deficit Analysis

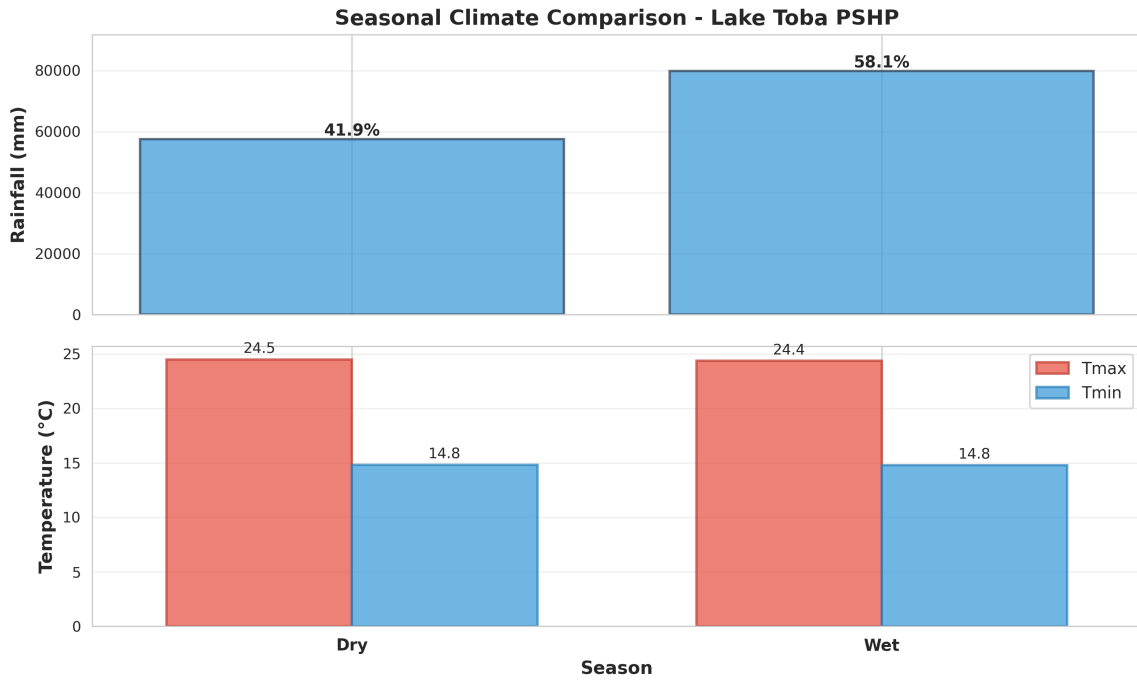


Figure A-6: Seasonal Comparison (Wet vs Dry Season)

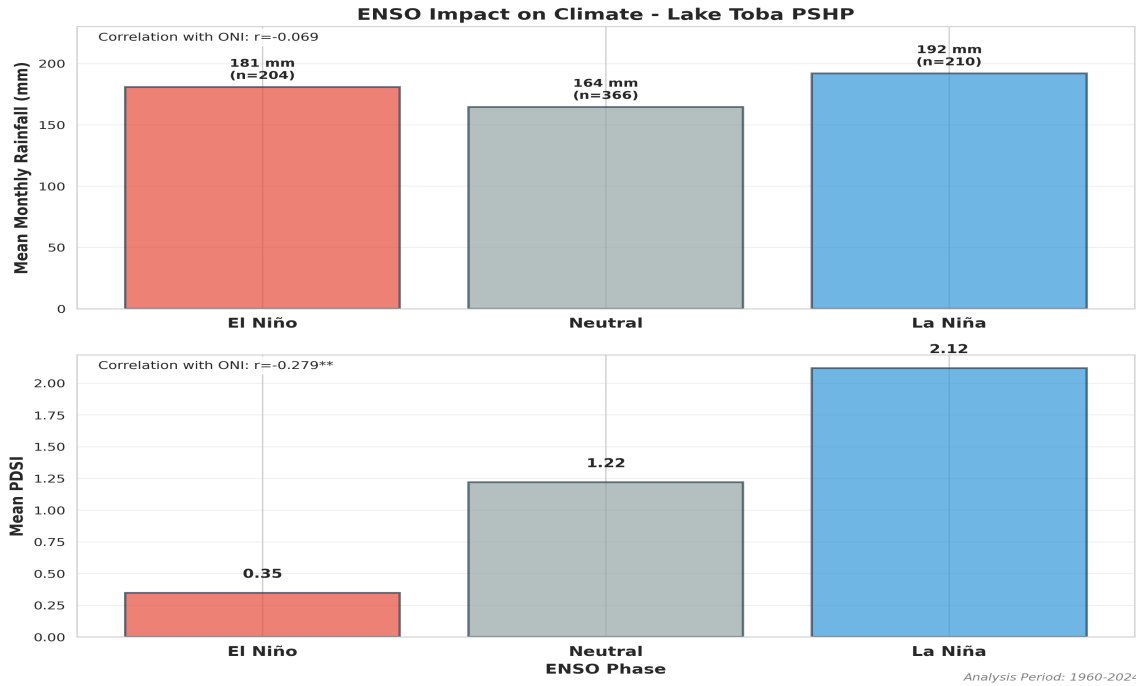


Figure A-7: ENSO Impact Analysis (El Niño and La Niña Phases)