Lake Toba Pumped Storage Hydropower
Rainfall Climatology Baseline Assessment
ESIA Technical Report

Project Name:	Lake Toba Pumped Storage Hydropower
Location:	Simalungun Regency of North Sumatra
Coordinates:	2.899213°, 98.596384°
Project Type:	Closed-Loop Pumped Storage Hydropower plant
Data Source:	GSMaP Hourly Satellite
Analysis Period:	2015-01-01 to 2025-12-31
Report Date:	January 22, 2026
Version:	1.0

Disclaimer – GSMaP Hourly Precipitation Data The Global Satellite Mapping of Precipitation (GSMaP) hourly precipitation data used in this assessment are derived from satellite-based remote sensing products and are subject to inherent uncertainties related to spatial resolution, temporal aggregation, sensor limitations, and algorithm assumptions. As such, the data represent estimated rainfall patterns rather than direct ground-based measurements. Accordingly, GSMaP hourly data are not suitable for detailed engineering design or safety-critical applications, including but not limited to the sizing and design of stormwater drainage systems, culverts, flood protection works, or other infrastructure requiring high-resolution, site-specific rainfall inputs. The use of these data for such purposes may lead to inaccurate or non-conservative design outcomes. Notwithstanding these limitations, GSMaP hourly precipitation data provide a useful, consistent, and spatially complete indication of regional and catchment-scale rainfall variability. When applied with appropriate professional judgement, they can support strategic and high-level hydrological assessments, including overall hydrological characterisation, comparative scenario analysis, preliminary screening, and early-stage planning studies. Where detailed design or regulatory compliance is required, GSMaP data should be supplemented or replaced with locally calibrated, ground-based observations and/or approved design rainfall datasets.

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for Greencorpllc

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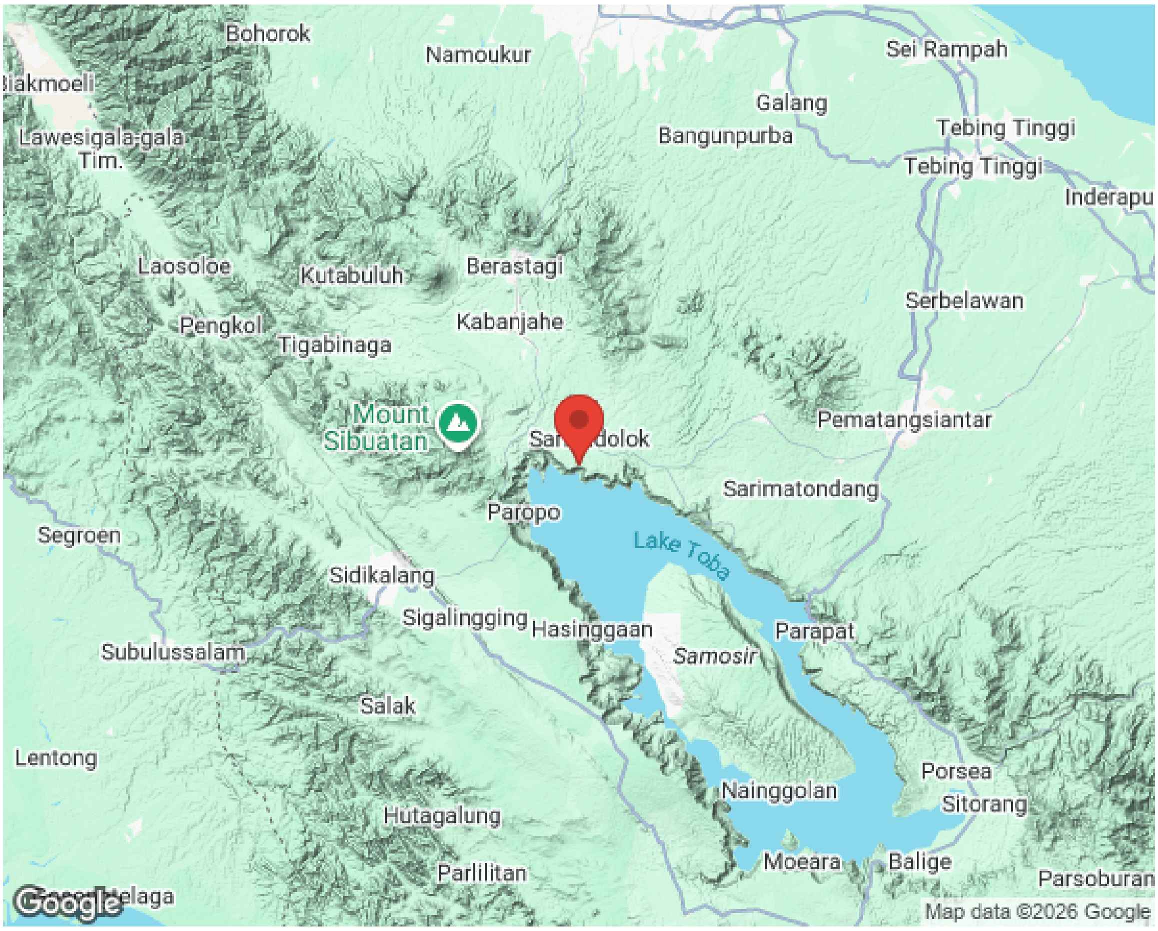
Site Location Map

Project Location: Simalungun Regency of North Sumatra
Coordinates: 2.899213°, 98.596384° (6 decimal places)
Climate Zone: Tropical
Köppen-Geiger Zone: Af (Tropical Rainforest)
Solar Irradiance: 1792.8 - 2141.8 kWh/m2 (50th-98th percentile)
Scale: Approximately 1:500,000



Climate Classification: Af (Tropical Rainforest Climate)
Year-round warm temperatures with consistent rainfall in all months. Every month receives at least 60mm of precipitation. No distinct dry season; rainfall driven by convective activity.

Executive Summary

The baseline rainfall assessment for the Lake Toba Pumped Storage Hydropower project, situated at 2.899213° N, 98.596384° E, utilized **GSMaP hourly satellite precipitation data** spanning January 2015 through December 2025. This location falls under the **Af (Tropical Rainforest Climate)** classification, characterized by consistently warm temperatures and high, year-round precipitation driven primarily by **diurnal convective activity**. The absence of a distinct dry season necessitates infrastructure design capable of managing high-intensity, localized rainfall events throughout the year.

The analysis reveals a climate profile defined by exceptional intensity. The maximum observed 1-hour intensity during the 11-year record reached **67.9649 mm/hr**, underscoring the severity of convective storms in the region. Modeling of extreme events projects that the **100-year return period 1-hour intensity** is **75.2017 mm/hr**, while the corresponding **24-hour intensity** averages **6.8004 mm/hr**. Although the climate is consistently wet, November was identified as the wettest month, with February being the driest, indicating minor seasonal modulations within the overall tropical pattern.

These extreme intensity findings have critical implications for the design of the high-consequence hydropower infrastructure. Standard drainage and erosion control measures must be sized to accommodate a minimum **25-year return period event**, corresponding to a daily rainfall of **5.5754 mm/hr**. Crucially, for dam safety and spillway design, the derived 100-year values serve only as an ESIA baseline. Given the critical nature of the Pumped Storage Hydropower facility, reliance on this 11-year satellite record for final engineering is not acceptable. **Supplementary studies** including regional frequency analysis and **Probable Maximum Precipitation (PMP)** derivation are essential to ensure structural resilience against catastrophic flood events. The moderate confidence level associated with extrapolating 100-year events from 11 years of satellite data mandates the immediate installation of **ground-based rain gauges** for validation and bias correction.

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1.0 Introduction

The purpose of this rainfall baseline assessment is to establish the current hydro-meteorological conditions at the Lake Toba Pumped Storage Hydropower project site, providing the fundamental data required for the Environmental and Social Impact Assessment (ESIA). Accurate characterization of rainfall patterns and extreme event frequencies is paramount for identifying and mitigating project risks related to flooding, erosion, slope stability, and structural integrity. As a large-scale infrastructure project financed by International Development Banks (ADB, World Bank, IFC), the assessment must align rigorously with relevant safeguard policies, specifically addressing the requirements of climate risk screening and disaster resilience planning.

The Lake Toba location, defined by a **Tropical Rainforest Climate (Af)**, presents unique challenges due to high, sustained precipitation and intense, short-duration convective storms. For a pumped storage hydropower facility, rainfall data directly informs the design of several critical elements: the sizing of temporary and permanent site drainage systems, the determination of erosion control measures during construction and operation, the calculation of catchment inflow volumes, and, most critically, the calculation of the design flood for spillways and associated water conveyance structures. Underestimating rainfall intensity or frequency can lead to catastrophic infrastructure failure, significant environmental damage, and unacceptable safety risks.

This report translates complex Intensity-Duration-Frequency (IDF) statistics derived from high-resolution satellite data into actionable engineering parameters. Adherence to international standards, such as those stipulated by the World Bank’s Environmental and Social Framework (ESS1) and associated Dam Safety Guidelines, requires that critical infrastructure be designed against high-consequence events, often necessitating analysis up to the **Probable Maximum Flood (PMF)** level. While this baseline assessment provides the 100-year return period estimates, it concurrently highlights the necessary supplementary studies required to meet the high design safety margins mandated for hydropower facilities. This assessment thus serves as the foundation for preliminary design and risk identification, ensuring the project integrates climate resilience from the earliest stages of development.

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2.0 Methodology

The hydro-meteorological baseline for the Lake Toba Pumped Storage Hydropower project was established through detailed analysis of **Global Satellite Mapping of Precipitation (GSMaP)** data. This analysis utilizes the GSMaP version 7 operational dataset provided by JAXA, accessed via Google Earth Engine. GSMaP combines passive microwave and infrared radiometer data to estimate hourly precipitation fields at a spatial resolution of approximately 0.1-degree, equating to roughly **11 km** at the equator. The analysis period spans 11 years, from January 1, 2015, to December 31, 2025, providing a consistent, high-temporal-resolution record suitable for deriving rainfall intensities.

Given the Köppen-Geiger classification of **Af (Tropical Rainforest Climate)** at the project location, the methodology emphasized characteristics typical of convective rainfall patterns rather than strong seasonal variations. The analysis focused on the distribution of intensity and frequency throughout the year, as the Af climate exhibits consistent rainfall in all months, driven by **diurnal convective cycles**. Unlike monsoonal climates, the methodology did not rely on defining a sharp wet/dry season contrast or calculating seasonal concentration metrics, but rather focused on identifying the peak short-duration intensities that characterize tropical storms occurring year-round.

Intensity-Duration-Frequency (IDF) curves were developed using established statistical methods suitable for extreme value analysis. The analysis involved extracting the **Annual Maximum Series (AMS)** for durations ranging from 1 hour up to 72 hours. The AMS data were then fitted to the **Gumbel extreme value distribution**—a standard technique for meteorological extremes—to model the probability distribution of rare events. Return period estimates were calculated for standard engineering intervals: 2, 5, 10, 25, 50, and 100 years. These IDF curves translate the probability of occurrence into required design intensities for various infrastructure components.

Data quality assessment confirmed that the 11-year record exhibited high temporal completeness, with no significant data gaps exceeding seven consecutive days that would compromise the integrity of the Annual Maximum Series extraction. However, as satellite-derived precipitation estimates, GSMaP data carries inherent limitations that must be addressed. Satellite algorithms, particularly for high-intensity, short-duration events typical of tropical convection, are known to **underestimate peak rainfall intensities by 10% to 30%** compared to ground-based rain gauges. Furthermore, the 11 km spatial resolution may not fully capture highly localized convective cells, and in the mountainous terrain surrounding Lake Toba, **orographic rainfall enhancement** may not be completely reflected in the satellite estimates. Therefore, while these IDF values are suitable for ESIA baseline characterization and preliminary design, **validation against local rain gauges is strongly recommended** before their use for final engineering design of critical infrastructure, such as spillways. Appropriate bias correction factors, based on regional comparisons, should be applied to account for these known systematic errors.

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3.0 Rainfall Patterns Analysis

The Lake Toba Pumped Storage Hydropower project site is situated within a classic **Tropical Rainforest Climate (Af)**, which dictates a high-volume, high-intensity rainfall regime with minimal seasonal variability. The defining characteristic of this climate is the consistent presence of moisture and thermal energy, resulting in rainfall exceeding the minimum threshold of 60 mm in every month of the year. This pattern fundamentally differs from monsoonal climates, where precipitation is heavily concentrated seasonally.

The temporal patterns show rainfall distributed throughout the year, with overall high annual totals (though the specific annual value is N/A mm). Monthly data indicates minor fluctuations, with November identified as the wettest month and February as the driest. However, these monthly variations do not constitute a true dry season, but rather a slight modulation in convective activity. This lack of a pronounced dry period implies that the project site experiences sustained high soil moisture and elevated groundwater levels throughout the year, impacting slope stability and construction scheduling consistently, rather than episodically.

Intensity distribution is dominated by **convective activity**. Rainfall occurs predominantly as intense, short-duration bursts caused by localized heating and atmospheric instability. The diurnal pattern is highly characteristic of the Af climate, where rainfall typically peaks in the late afternoon and early evening following maximum solar heating and subsequent atmospheric destabilization. This diurnal cycle dictates that site operations and construction activities requiring dry conditions, such as foundation work or earthworks, face higher risk of interruption during the late day period.

Extreme event characteristics are intrinsically linked to this convective dominance. The observed maximum 1-hour intensity of **67.9649 mm/hr** confirms the potential for highly erosive, flash-flood-inducing storms. Importantly, unlike climates where extreme intensities are confined to a specific wet season, the Lake Toba site can experience these high-intensity events at any time of year. This requires continuous readiness for severe storms, rather than seasonal preparation. The year-round intensity profile means that while November may register the highest cumulative volume, the maximum instantaneous rainfall rates capable of causing infrastructure damage can occur in any month.

Inter-annual variability in total rainfall is expected to be moderate, typical of tropical regions where the primary driver (convection) is consistently present. However, inter-annual variability in the frequency and intensity of extreme events (those exceeding the 25-year return period) may be more significant, potentially influenced by larger climate oscillations such as the El Niño-Southern Oscillation (ENSO), which can modulate the background atmospheric stability. Given the limited 11-year record, projecting long-term inter-annual variability is constrained, underscoring the need for climate change projections that generally indicate an **intensification** of rainfall extremes in tropical regions, potentially increasing the frequency of events currently categorized as 50-year or 100-year storms. The overall environment demands a robust approach to drainage and erosion control designed to handle high-velocity runoff resulting from these intense, short-duration precipitation events.

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4.0 IDF Analysis Results

1. Purpose and Methodology

Intensity-Duration-Frequency (IDF) curves are fundamental tools for translating meteorological risks into quantifiable engineering design parameters. For the Lake Toba Pumped Storage Hydropower project, the IDF analysis is critically important for dimensioning site drainage, designing erosion protection structures, and, most significantly, establishing the required capacity for the spillway and temporary flood diversion works. These curves illustrate the maximum rainfall intensity expected for a given duration (e.g., 1 hour, 24 hours) at a specific recurrence interval (return period). The analysis utilized the **Gumbel extreme value distribution** fitted to the annual maximum series (AMS) extracted from the 11-year GSMaP record, providing estimates for return periods ranging from the frequent 2-year event up to the high-consequence **100-year event**.

2. Key Design Intensities with Quantification

The analysis derived distinct intensity profiles across durations, reflecting the characteristics of tropical convective storms. Short-duration events exhibit extremely high intensity, while longer durations show lower average intensity, indicating that localized flash flooding is the primary design risk.

For **1-hour durations**, critical for local drainage and culvert design: * The 2-year return period intensity is **25.7409 mm/hr**. * The 5-year return period intensity is **38.9825 mm/hr**. * The 10-year return period intensity is **47.7496 mm/hr**. * The 25-year return period intensity is **58.8269 mm/hr**. * The **100-year return period intensity** peaks at **75.2017 mm/hr**. * The maximum observed 1-hour intensity was **67.9649 mm/hr**, which already exceeds the calculated 25-year event, confirming the high frequency of severe convective storms.

For **24-hour durations**, critical for overall flood volume and dam inflow calculations: * The 2-year return period intensity is **3.1003 mm/hr** (or 74.4 mm/day). * The 5-year return period intensity is **4.0909 mm/hr**. * The 10-year return period intensity is **4.7467 mm/hr**. * The 25-year return period intensity is **5.5754 mm/hr**. * The **100-year return period intensity** is **6.8004 mm/hr** (equivalent to 163.2 mm/day).

The rate of increase in intensity across return periods is steep for 1-hour events, jumping 192% from the 2-year to the 100-year value, highlighting the escalating risk associated with short-term extremes.

3. Climate-Specific IDF Confidence and Reliability

Given the **Tropical Rainforest Climate (Af)**, the IDF curves reflect patterns resulting from year-round convective activity. This means there is no strong seasonal modulation of extreme events; the design storm characteristics are generally consistent throughout the year. The confidence level for the derived IDF curves is **Moderate**. This assessment is based on the limited 11-year duration of the satellite record. While this period is adequate for characterizing events up to the 25-year return period with reasonable certainty, the extrapolation to the **100-year return period** carries higher statistical uncertainty. The reliability is further moderated by the known tendency of GSMaP data to **underestimate true peak rainfall intensities** by 10% to 30%, which means the true 100-year event intensity is likely higher than the derived **75.2017 mm/hr**.

4. Project-Specific Design Implications (Hydropower)

For the Lake Toba Pumped Storage Hydropower facility, the IDF results provide critical inputs for preliminary design. General site drainage systems, including access road culverts and temporary construction drains, must be designed for a minimum **25-year return period event**. This requires accommodating flows generated by a 1-hour intensity of **58.8269 mm/hr** and a 24-hour daily volume equivalent of **5.5754 mm/hr**. A safety margin of 25% above these calculated values is highly recommended.

However, for dam safety and the design of the primary spillway and diversion tunnels, the 100-year intensity of **6.8004 mm/hr (24h)** serves only as the minimum ESIA baseline. International Dam Safety Guidelines mandate that high-consequence structures, such as this pumped storage facility, must be designed to withstand the **Probable Maximum Flood (PMF)**, which typically corresponds to return periods of 1,000 to 10,000 years. **These 11-year satellite estimates CANNOT be reliably extrapolated to determine the PMF.** Therefore, these IDF results must prompt immediate follow-up studies, as detailed in the Conclusions section, before final hydraulic engineering design proceeds.

5. Comparison with Regional Rainfall Patterns

While specific regional 100-year, 24-hour rainfall data is not provided for direct comparison, the derived 100-year, 24-hour intensity of **6.8004 mm/hr** (163.2 mm/day) reflects a highly energetic and wet environment, consistent with the orographically enhanced tropical rainfall known around the Lake Toba caldera rim. This high baseline intensity confirms that the project site is exposed to significant flood hazards relative to less mountainous or less consistently tropical areas.

6. Data Limitations and Confidence

The analysis is based on an **11-year GSMaP satellite record**. This duration provides adequate confidence for engineering decisions related to lower return periods (up to 25 years). Confidence for the **50-year and 100-year return periods** is considered moderate. Due to the inherent **satellite estimation bias** (underestimation of peak intensities), and the risk associated with the hydropower facility, **validation against local rain gauge data is strongly recommended** as a prerequisite for final engineering design. For critical infrastructure, regional bias correction factors must be developed and applied to the IDF curves to account for the systematic underestimation of extreme convective events.

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5.0 Conclusions and Recommendations

1. Baseline Findings Summary

The Lake Toba Pumped Storage Hydropower location is characterized by a high-energy **Tropical Rainforest Climate (Af)**, featuring consistent, year-round precipitation dominated by intense convective storms. While no annual rainfall total is provided, the intensity profile is severe, evidenced by a **100-year, 1-hour intensity estimate of 75.2017 mm/hr**. The 100-year, 24-hour extreme event is calculated at **6.8004 mm/hr** (163.2 mm/day). The key observation is the extremely high intensity of short-duration rainfall, which poses an elevated risk of flash flooding and severe erosion.

2. Quantified Climate Risk Assessment for Hydropower

The primary climate risk for the Pumped Storage Hydropower project is **High Intensity Flash Flooding**, driven by intense convective activity. The 100-year flood baseline is established at **6.8004 mm/24hr**. However, for reservoir safety, this baseline is insufficient. The **CRITICAL WARNING** is that final spillway design must be based on the **Probable Maximum Flood (PMF)**, which requires return periods far exceeding the statistical confidence limits of this 11-year satellite dataset. Drought risk is assessed as **LOW** due to the Af climate's characteristic year-round rainfall (0 month dry season). The immediate implication is that the design team must treat the **100-year event** as the absolute minimum capacity, not the final design criterion.

3. Infrastructure Design Recommendations

IMMEDIATE DESIGN ACTIONS must focus on accommodating high-intensity, short-duration events. All temporary and permanent drainage systems must be sized for a minimum **25-year return period event**. This means designing for a minimum daily volume capacity equivalent to **5.5754 mm/day** (133.8 mm/day), coupled with a mandatory **25% safety margin** to account for satellite underestimation bias and climate change uncertainty. Slope protection and erosion control are **high priority**, particularly in high-risk periods (year-round). Recommended measures include comprehensive bioengineering, concrete lining of critical drainage channels, and the use of gabions or retaining structures to mitigate runoff velocity resulting from the intense **75.2 mm/hr** peak intensities.

4. Climate Resilience Measures

The project must integrate adaptive capacity for climate change, as tropical intensity is projected to increase by 5-15% by 2050. The design should account for a minimum 7% increase in the calculated IDF values. Since the climate is year-round, **long-term monitoring** of extreme events is required to compare observed intensities against design assumptions. Adaptive management strategies must include robust maintenance programs for drainage infrastructure, ensuring culverts and channels remain clear to handle the sustained high flows typical of the Af environment.

5. Monitoring and Validation Requirements

It is **MANDATORY** that the project immediately **install ground-based rain gauges** at the project site. The primary purpose is to validate the GSMaP satellite estimates, which are expected to show a systematic **15-30% underestimation** of peak intensities. Hourly recording and daily verification are required. An annual validation report must compare the gauge observations against the satellite estimates and track the occurrence of actual extreme events exceeding the 25-year threshold (**5.5754 mm/24hr**) to verify the performance of the drainage infrastructure against design assumptions.

6. Recommendations for Supplementary Studies

This satellite-based assessment is adequate for ESIA baseline characterization and preliminary design but is **NOT suitable alone for the final engineering design** of critical infrastructure. Before final engineering design, the following supplementary studies are **HIGH PRIORITY**:

* **Regional Frequency Analysis (RFA):** Utilize long-term data from at least five regional ground stations to derive more statistically robust IDF curves and regionalize the extreme event analysis. * **Probable Maximum Precipitation (PMP) Derivation:** A PMP study is **essential** for high-consequence structures like the dam and spillway. This analysis must be conducted using storm maximization techniques to determine the upper bound of rainfall input for the **Probable Maximum Flood (PMF)** calculation. * **Data Confidence Qualification:** Stakeholders must acknowledge that the satellite data uncertainty is conservatively estimated at **±10-30%** on extreme intensities. Bias correction based on physical gauges is non-negotiable for project implementation.

7. Final Synthesis

The headline climate risk for the Lake Toba Pumped Storage Hydropower project is **HIGH INTENSITY FLOOD RISK** due to the Tropical Rainforest Climate. The key design driver is the necessity of deriving the **Probable Maximum Flood (PMF)** to ensure dam safety. The path forward requires **immediate supplementary studies and the installation of on-site rain gauges** to validate the baseline data prior to finalizing critical engineering designs.

Data Quality & Limitations

This analysis is based on 11.0 years (99.0% complete) of JAXA GSMaP satellite precipitation estimates for the period 2015-01-01 to 2025-12-31. GSMaP provides hourly gridded data at ~11 km spatial resolution derived from satellite observations and calibrated with rain gauge networks.

Data Quality Summary:

- Temporal completeness: 99.0%
- Temporal gaps > 7 days: 0
- Data period: 2015-01-01 to 2025-12-31

GSMaP Data Limitations:

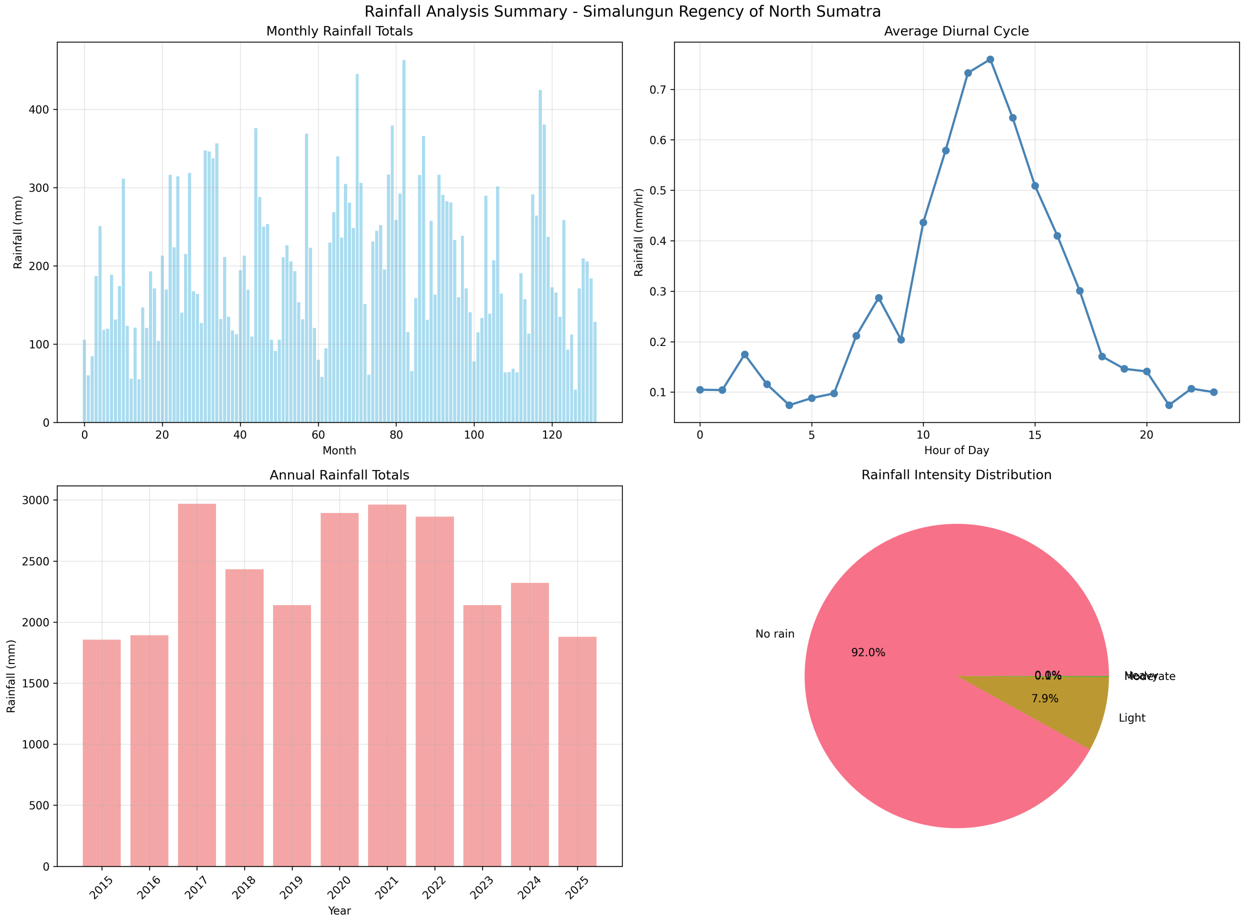
- Satellite-derived estimates (NOT ground truth rain gauge measurements)
- Spatial resolution ~11 km; may not capture localized rainfall patterns
- Accuracy depends on rain gauge network density and calibration quality
- Topographic effects: Mountainous terrain may exhibit systematic biases
- Tropical regions: Known biases in convective rainfall detection

Recommendations for Use:

- For infrastructure design, cross-check with local weather station records
- Use for regional trend analysis; avoid extrapolating to specific point locations
- Engineers should review completeness and gap information when designing for rare events
- For detailed technical quality metrics, see Appendix: Data Quality Report

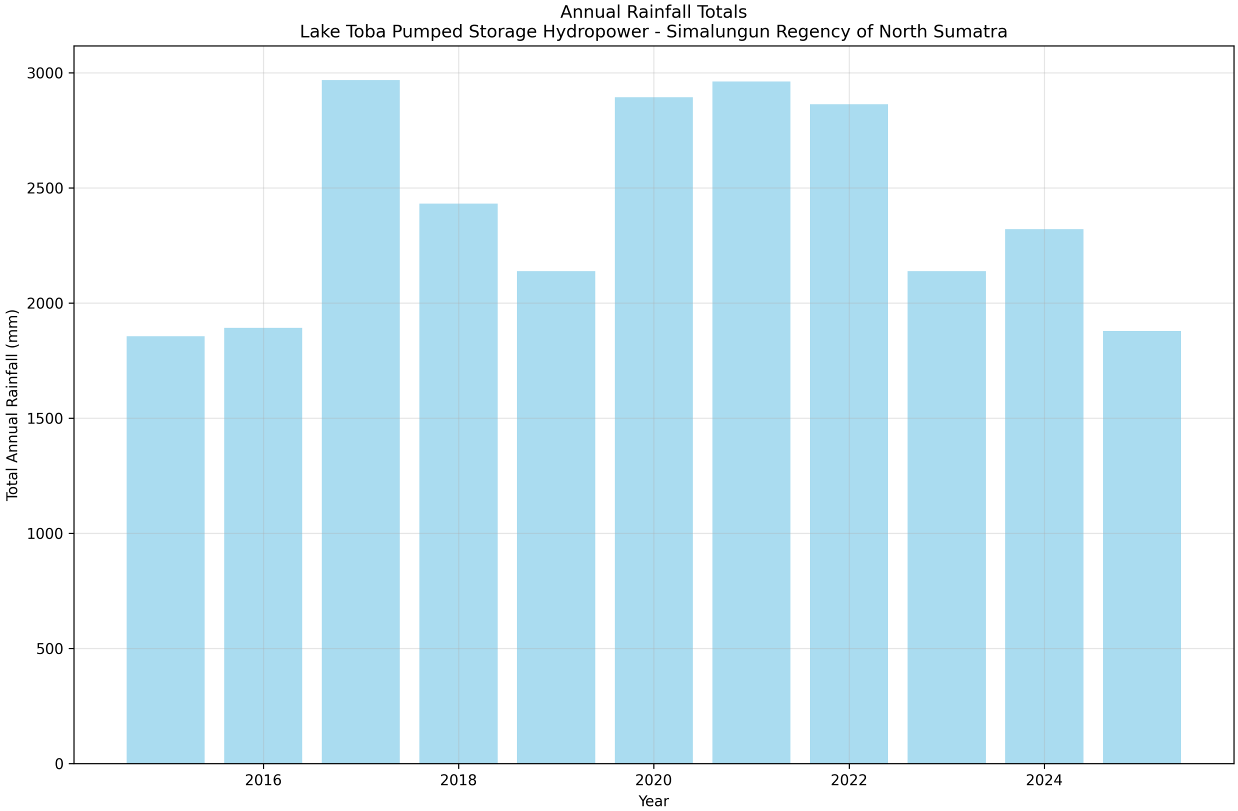
FIGURES

Figure 1: Analysis Dashboard



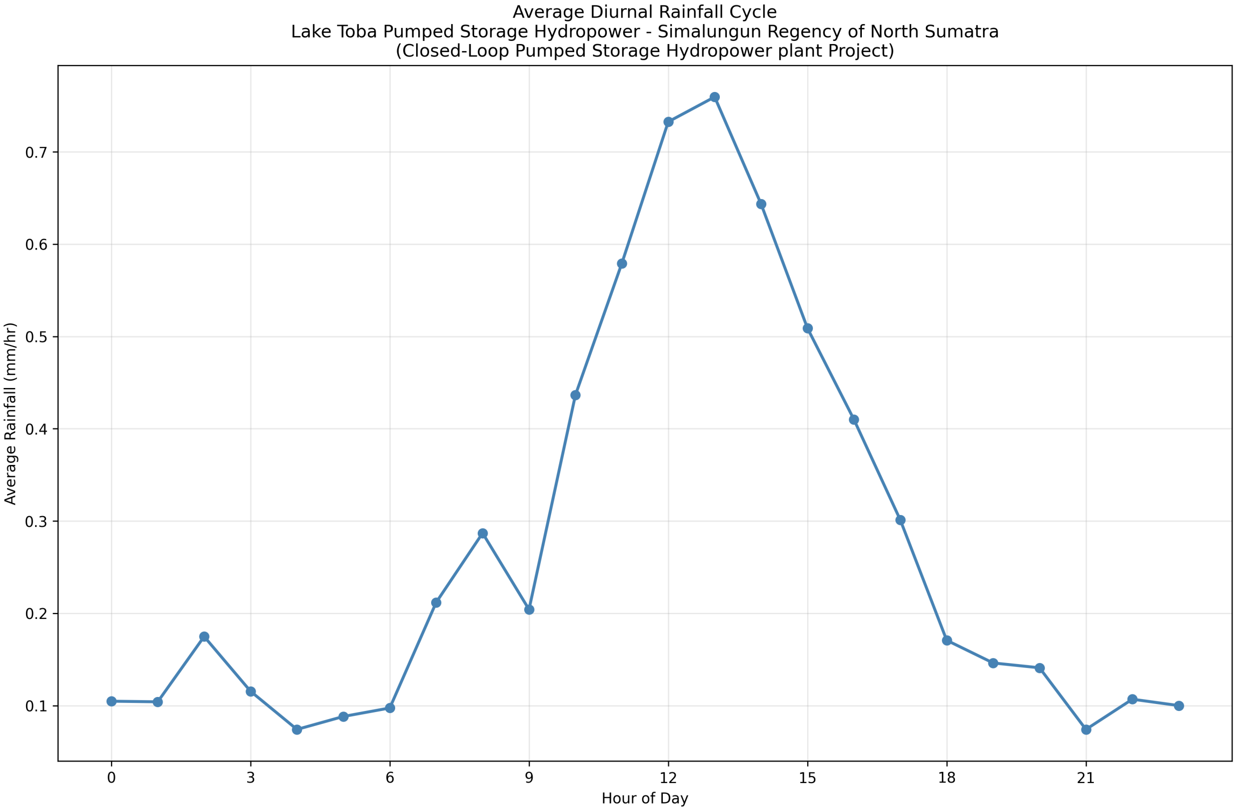
Comprehensive rainfall analysis dashboard combining key visualizations including temporal patterns, distributions, and seasonal cycles.

Figure 2: Annual Totals



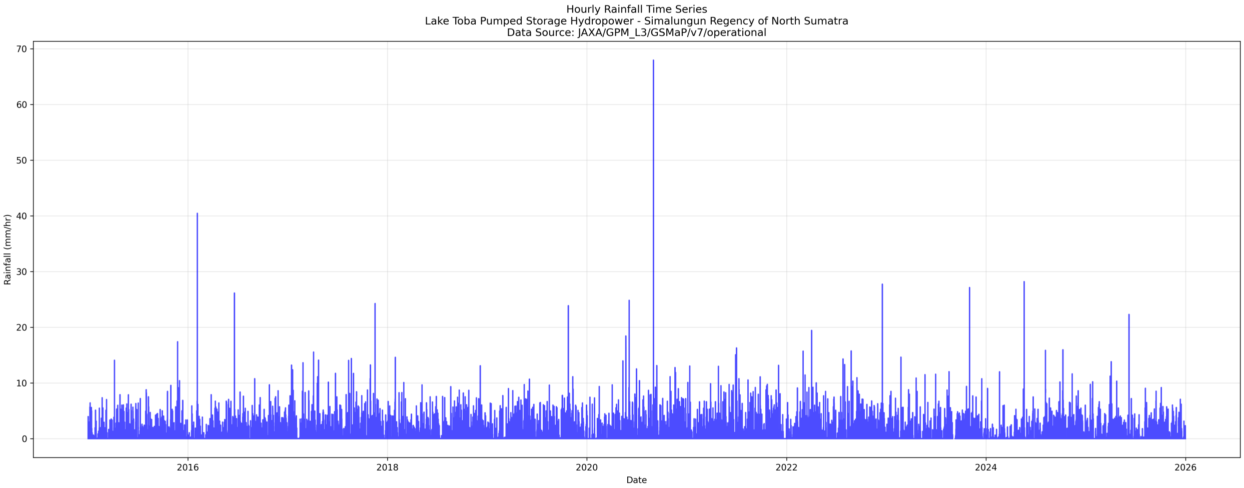
Annual rainfall totals showing inter-annual variability and trends over the analysis period.

Figure 3: Diurnal Cycle



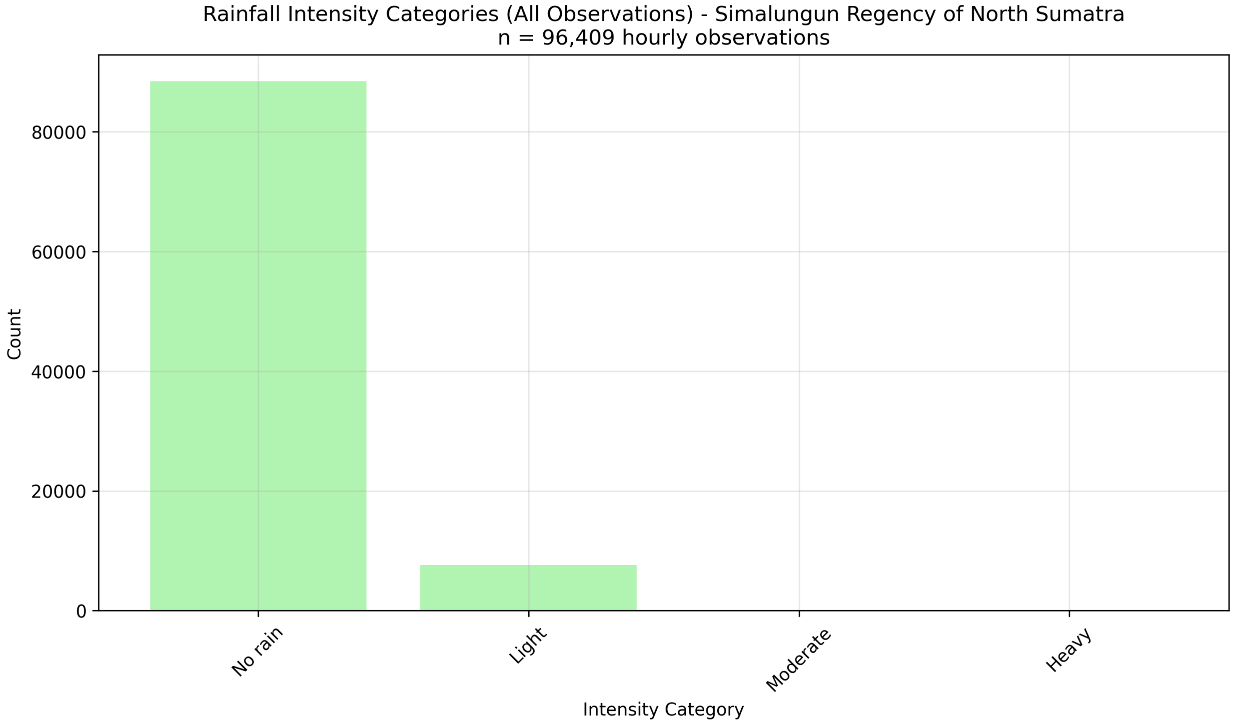
Average diurnal rainfall cycle showing daily timing and distribution of precipitation.

Figure 4: Hourly Time Series



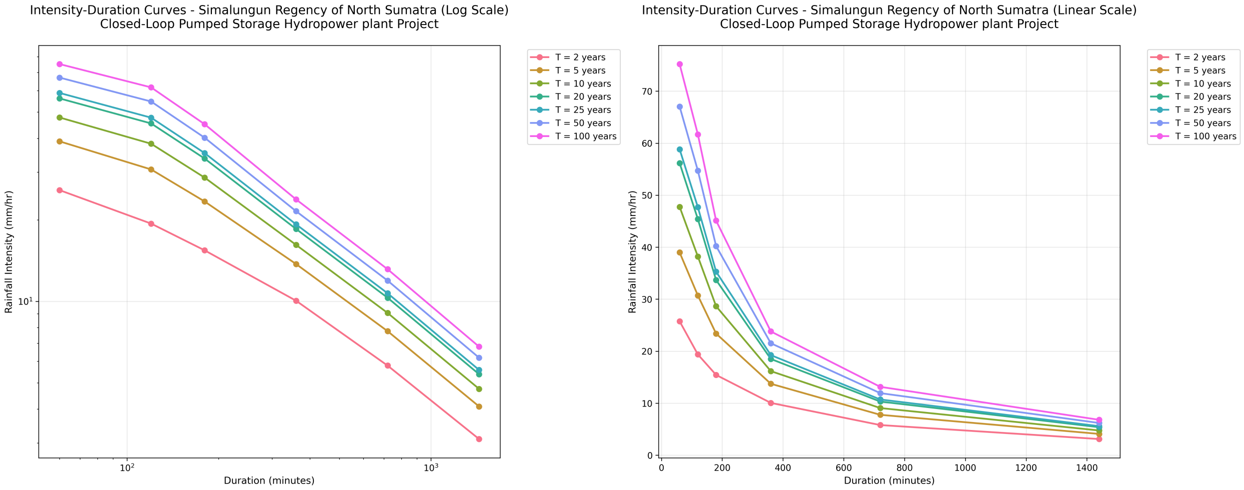
Complete hourly rainfall time series showing temporal distribution of all precipitation events.

Figure 5: Intensity Categories



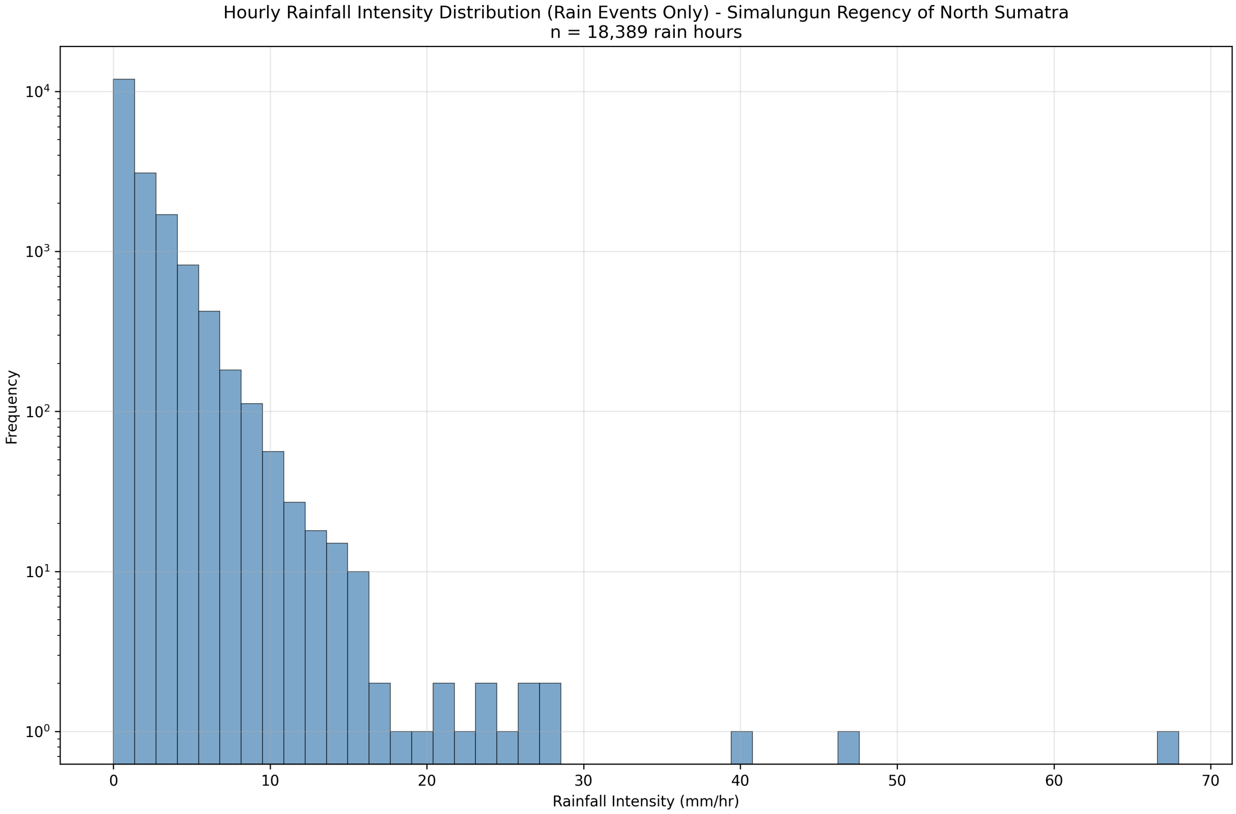
Rainfall intensity category distribution summarizing percentage of time in each intensity class.

Figure 6: Intensity Duration Curves



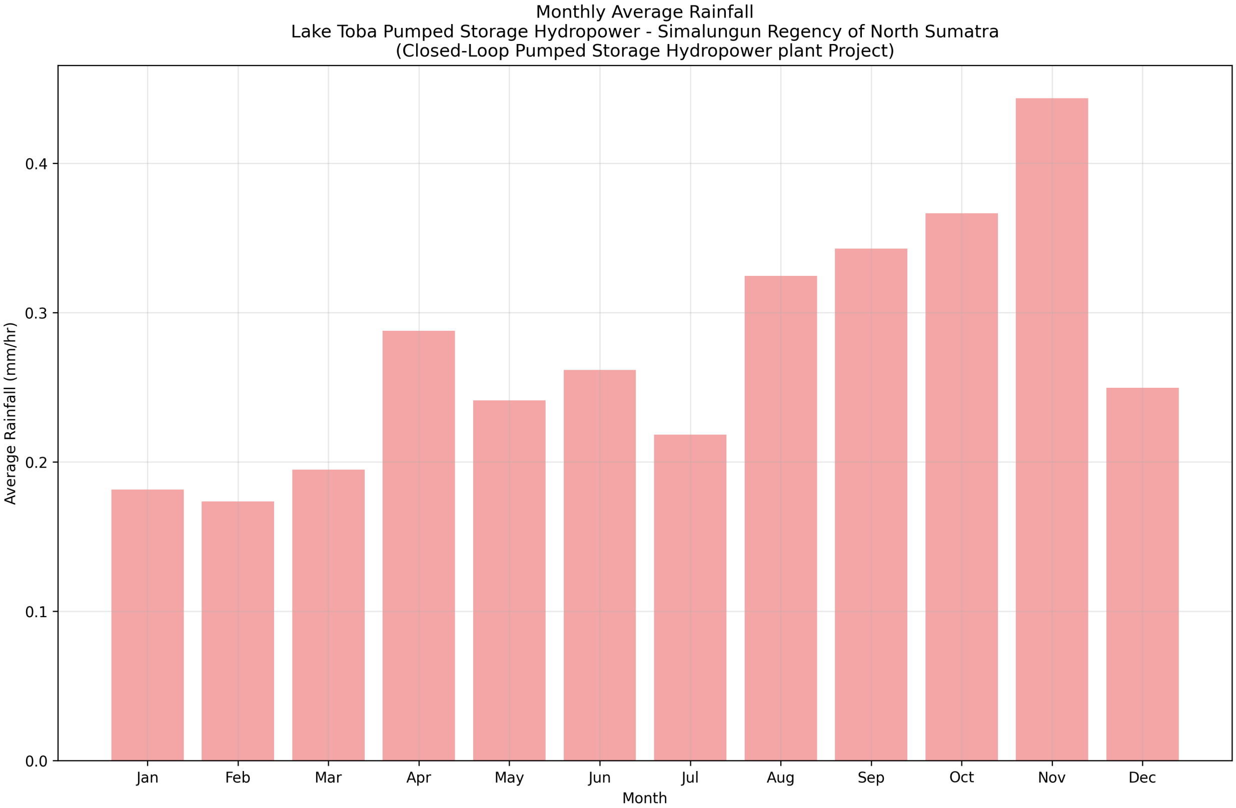
Intensity-duration relationships across return periods showing rainfall intensity decrease with event duration.

Figure 7: Intensity Histogram



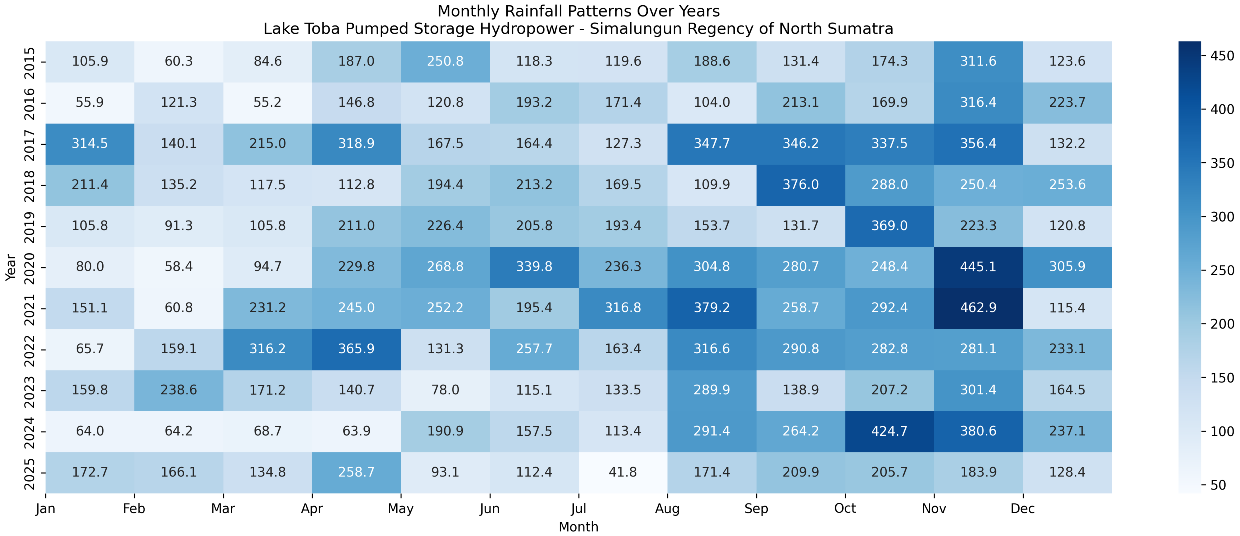
Rainfall intensity histogram showing frequency distribution of all observed precipitation intensities.

Figure 8: Monthly Climatology



Monthly rainfall climatology showing average seasonal distribution with variability across the analysis period.

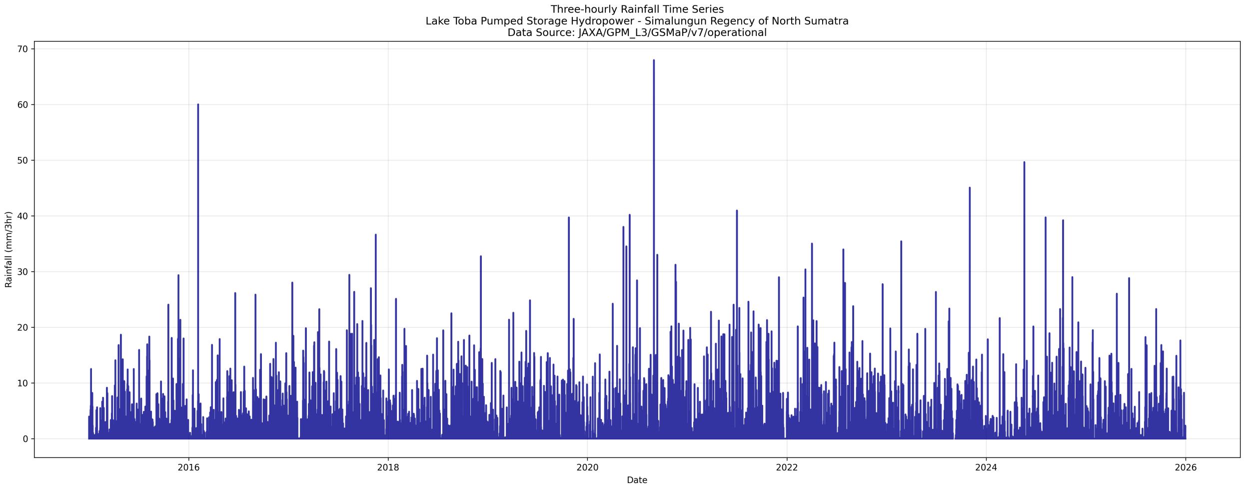
Figure 9: Monthly Heatmap



Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2015	105.9	60.3	84.6	187.0	250.8	118.3	119.6	188.6	131.4	174.3	311.6	123.6
2016	55.9	121.3	55.2	146.8	120.8	193.2	171.4	104.0	213.1	169.9	316.4	223.7
2017	314.5	140.1	215.0	318.9	167.5	164.4	127.3	347.7	346.2	337.5	356.4	132.2
2018	211.4	135.2	117.5	112.8	194.4	213.2	169.5	109.9	376.0	288.0	250.4	253.6
2019	105.8	91.3	105.8	211.0	226.4	205.8	193.4	153.7	131.7	369.0	223.3	120.8
2020	80.0	58.4	94.7	229.8	268.8	339.8	236.3	304.8	280.7	248.4	445.1	305.9
2021	151.1	60.8	231.2	245.0	252.2	195.4	316.8	379.2	258.7	292.4	462.9	115.4
2022	65.7	159.1	316.2	365.9	131.3	257.7	163.4	316.6	290.8	282.8	281.1	233.1
2023	159.8	238.6	171.2	140.7	78.0	115.1	133.5	289.9	138.9	207.2	301.4	164.5
2024	64.0	64.2	68.7	63.9	190.9	157.5	113.4	291.4	264.2	424.7	380.6	237.1
2025	172.7	166.1	134.8	258.7	93.1	112.4	41.8	171.4	209.9	205.7	183.9	128.4

Monthly rainfall heatmap showing seasonal concentration and year-to-year consistency patterns.

Figure 10: Three Hourly Time Series



Three-hourly accumulated rainfall aggregation used for IDF analysis reliability and storm structure preservation.

6.0 Methods, Analyses, Assumptions and Limitations

6.1 GSMaP Satellite Data

The Global Satellite Mapping of Precipitation (GSMaP) is a satellite-based precipitation product developed by the Japan Aerospace Exploration Agency (JAXA). The dataset provides near-real-time and retrospective precipitation estimates with the following characteristics:

• Spatial Resolution: 0.1° × 0.1° (approximately 11 km at the equator) • Temporal Resolution: Hourly • Coverage: Global (60°N - 60°S) • Data Sources: Multiple satellite sensors (microwave and infrared) • Algorithm: Combined microwave-infrared retrieval algorithm • Validation: Calibrated against ground-based rain gauge networks globally

GSMaP data is widely used for hydrological studies, flood monitoring, and climate analysis, particularly in data-sparse regions where ground-based observations are limited.

6.2 IDF Analysis Methodology

The Intensity-Duration-Frequency (IDF) analysis follows standard hydrological practices:

1. Data Aggregation: Hourly rainfall data is aggregated to various durations (1, 2, 3, 6, 12, 24, 48, 72, and 144 hours) using rolling windows.

2. Annual Maxima Extraction: For each duration and each year, the maximum rainfall intensity is extracted to form the annual maxima series.

3. Extreme Value Analysis: The Gumbel (Extreme Value Type I) distribution is fitted to the annual maxima series for each duration using the method of moments.

4. Return Period Estimation: Rainfall intensities for various return periods (2, 5, 10, 25, 50, and 100 years) are estimated using the fitted Gumbel distribution.

5. IDF Curve Construction: The estimated intensities are plotted against durations for each return period to construct the IDF curves.

6.3 Key Assumptions

- The annual maxima series is independent and identically distributed (i.i.d.)
- The Gumbel distribution adequately represents the extreme value behavior
- GSMaP satellite data is representative of ground-level precipitation
- Climate stationarity is assumed (no significant long-term trends)
- Spatial averaging over 0.1° grid is acceptable for project-scale analysis

6.4 Limitations and Uncertainties

- Satellite data may underestimate extreme localized convective events
- Limited historical record (10-15 years) may affect return period estimates
- Spatial resolution (11 km) may not capture micro-scale variability
- No ground-based validation data available for direct calibration
- Climate change may affect stationarity assumption for long return periods

7.0 Tables of Key IDF/Rainfall Summaries

7.1 IDF Values (mm/hr)

Return Period (years)	1hr	2hr	3hr	6hr	12hr	24hr	48hr	72hr	144hr
2	25.74	19.37	15.43	10.05	5.79	3.10	1.87	1.50	1.04
5	38.98	30.70	23.38	13.73	7.76	4.09	2.44	1.97	1.37
10	47.75	38.20	28.64	16.16	9.06	4.75	2.82	2.29	1.59
20	56.16	45.40	33.68	18.50	10.31	5.38	3.18	2.59	1.80
25	58.83	47.68	35.28	19.24	10.71	5.58	3.30	2.69	1.87
50	67.04	54.71	40.21	21.52	11.93	6.19	3.65	2.98	2.08
100	75.20	61.69	45.10	23.79	13.14	6.80	4.00	3.27	2.28

IDF Confidence Disclaimer: Based on 11.0 years (99.0% complete) of JAXA GSMaP hourly satellite precipitation data. Standard confidence based on 11 complete monsoon cycles. IDF curves adequate for baseline ESIA design parameters. Consider supplementing with local gauge data for critical structures. IDF curves reflect wet-season extreme events characteristic of monsoonal climate. See 'Data Quality & Limitations' section for full technical details.

7.2 Engineering Design Intensities

Duration (minutes)	2-year ARI	5-year ARI	10-year ARI	20-year ARI	25-year ARI	50-year ARI	100-year ARI
60	25.74	38.98	47.75	56.16	58.83	67.04	75.20
120	19.37	30.70	38.20	45.40	47.68	54.71	61.69
180	15.43	23.38	28.64	33.68	35.28	40.21	45.10
360	10.05	13.73	16.16	18.50	19.24	21.52	23.79
720	5.79	7.76	9.06	10.31	10.71	11.93	13.14
1440	3.10	4.09	4.75	5.38	5.58	6.19	6.80

7.3 Annual Maximum Rainfall Intensities (mm/hr)

datetime	1hr	2hr	3hr	6hr	12hr	24hr	48hr	72hr	144hr
2015-12-31	17.40	14.13	12.57	9.84	5.11	2.64	1.61	1.44	0.97

2016-12-31	40.46	27.02	20.01	10.28	5.14	2.85	1.58	1.23	0.81
2017-12-31	24.26	17.74	12.21	8.12	5.02	3.03	2.03	1.60	1.29
2018-12-31	14.61	12.47	11.55	8.05	4.21	2.14	1.56	1.25	0.94
2019-12-31	23.88	19.86	13.32	7.63	4.14	2.18	1.49	1.26	0.86
2020-12-31	67.96	57.62	41.98	21.57	10.83	5.70	2.89	2.24	1.45
2021-12-31	16.29	15.07	13.65	12.67	8.19	4.14	2.41	1.79	1.19
2022-12-31	27.74	14.15	11.68	8.94	5.85	3.15	1.77	1.52	1.07
2023-12-31	27.13	18.46	15.02	9.79	5.15	2.84	1.65	1.12	0.79
2024-12-31	28.19	24.69	21.79	13.99	9.24	4.79	3.38	2.87	2.02
2025-12-31	22.31	15.05	12.21	7.20	4.82	2.67	1.39	1.15	0.76

7.4 Annual Maximum Daily Rainfall

Index	Year	Max_Daily_Rainfall_mm
0	2015.00	61.23
1	2016.00	68.42
2	2017.00	66.33
3	2018.00	50.57
4	2019.00	49.67
5	2020.00	130.06
6	2021.00	99.26
7	2022.00	71.29
8	2023.00	60.96
9	2024.00	112.88
10	2025.00	63.84