SURFACE HYDROLOGY BASELINE REPORT

Lake Toba Catchment Area

Subject: Environmental Baseline Characterization for ESIA

Catchment Area: 3,798.53 km^2

Lake Surface Area: 1,135.59 km^2

Analysis Period: 1960-01-01 to 2024-12-31

Framework: IFC Performance Standards (ADB/WB/IFC)

Disclaimer: This report characterizes the baseline surface hydrology using satellite reanalysis data (TerraClimate). It is intended to support the "Physical Environment" section of an ESIA.

Executive Summary

The Surface Hydrology Baseline for Lake Toba reveals a system characterized by its immense scale and unique hydrological dynamics. With a vast volume of 258,913 GL and an average depth of 228.0 m, Lake Toba exhibits a remarkably slow flushing rate, with an approximate residence time of 80 years. Despite an annual catchment yield of 4249.9 GL from its 3,798.53 km^2 catchment area, this inflow is relatively small compared to the lake's massive volume, contributing to its slow flushing nature. Climate trend analysis indicates a statistically significant but weak trend, suggesting no significant long-term climate shift, and thus the historical baseline remains a valid predictor. However, the lake demonstrates moderate vulnerability, experiencing periodic drought events that highlight natural variability in lake levels and seasonal stress on water security. The limnological baseline characterization underscores the unique and sensitive nature of Lake Toba's deep-water environment, which, due to its slow flushing and large volume, is particularly susceptible to cumulative impacts from changes in water quality or external stressors over extended periods.

1. Physical Context

1.1 Geographic Setting

This baseline assessment focuses on the Lake Toba catchment (3,798.53 km²). The lake is a massive volcanic caldera system characterized by extreme depth and volume.

1.2 Morphometric Characteristics

- **Surface Area:** 1,135.59 km²
- **Total Volume:** 258,913 GL (2.59e+11 m³)
- **Average Depth:** 228.0 m
- **Hydraulic Residence Time:** ~0 years

Significance: The long residence time (80 years) indicates a system with very slow water renewal. Pollutants entering the deep water column (hypolimnion) will be retained for decades, making the ecosystem highly sensitive to discharge operations.

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2. Methodology

Data Source: TerraClimate v2.0 (University of Idaho)

Resolution: ~4km Spatial, Monthly Temporal

Variables: Precipitation, Evapotranspiration, Runoff, PDSI, Temperature, Wind Speed.

Method: Time-series analysis of catchment-averaged variables to determine long-term hydrological trends.

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3. Water Balance & Catchment Yield

The water balance of the catchment reveals a moderate surplus of atmospheric inputs over losses. Annually, the catchment receives an average of 180.6 mm/month in precipitation, while experiencing an average evapotranspiration of 89.3 mm/month. This results in a net atmospheric flux where inputs marginally exceed losses by approximately 91.4 mm/month. Seasonally, the Monsoon period (October-April) is characterized by significantly higher precipitation (averaging 216.3 mm/month) and a net flux of 129.7 mm/month, compared to the Dry season (May-September) with lower precipitation (averaging 130.7 mm/month) and a reduced net flux of 37.6 mm/month. The annual catchment yield, representing the total runoff from the catchment, is calculated to be 4249.9 GL. The majority of this yield occurs during the Monsoon season (October-April), contributing approximately 3460.1 GL, while the Dry season (May-September) contributes approximately 789.8 GL. Comparing this annual catchment yield to the total lake volume of 258913.5 GL, it is evident that the catchment's contribution is relatively small, representing approximately 1.64% of the lake's total volume annually. This indicates that the catchment is not a major driver of flushing for the lake. Consequently, the lake's water quality is likely to be more susceptible to the accumulation of pollutants and nutrients, as the rate of water exchange and dilution from catchment runoff is limited. This low flushing rate suggests a longer hydraulic residence time, increasing the potential for internal nutrient cycling and the persistence of water quality issues.

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4. Climate Risk & Hydro-Climatic Variability

The region exhibits notable hydro-climatic variability, marked by 21 recorded drought events occurring at a frequency of approximately 10.90%. These periodic droughts, including the most severe event in 1981-1982 with a minimum PDSI of -4.43, present a risk of ecological drought. Such events can significantly stress littoral zones through reduced water levels, impacting habitat and biodiversity. Despite these recurrent dry spells, a statistically significant but weak long-term wetting trend has been identified, with the Palmer Drought Severity Index (PDSI) increasing by 0.74 per decade. This trend suggests a gradual increase in moisture availability, which could contribute to overall lake level stability over the long term. However, the frequent occurrence of shorter-duration droughts indicates that lake levels remain susceptible to seasonal and inter-annual fluctuations. The climate vulnerability assessment categorizes the region as having moderate vulnerability. While periodic drought events underscore natural variability in lake levels and can induce seasonal stress on water resources, the lack of a significant long-term drying trend suggests that the historical baseline remains a reliable predictor. This implies that while adaptive management for short-term drought impacts is essential, the overall long-term stability of lake levels is not currently under threat from a persistent drying climate.

5. Limnological Stability & Stratification

5.1 Deep Water Characterization

BASELINE CHARACTERIZATION (Lake Toba Specific):

1. MORPHOMETRY & HYDRAULIC RETENTION:

- Surface Area: 1,135 km^2
- Volume: ~259 km^3 (258,913 GL)
- Average Depth: 228 m
- Residence Time: ~80 years

2. PHYSICAL IMPLICATIONS:

- The immense volume and depth (avg 228m) create an exceptionally stable thermal mass.
- A residence time of 80 years classifies the lake as having a "Slow Flushing Rate," meaning pollutants or nutrients retained in the hypolimnion (deep layer) accumulate over decades.
- The lake is likely "Meromictic" or "Oligomictic," meaning the deep waters may rarely or never mix with the surface.

3. STRATIFICATION RISKS:

- Permanent Stratification: The deep water column is likely permanently separated from the surface.
- Anoxia Risk: Due to the lack of mixing and long residence time, deep waters (>100m) are likely oxygen-depleted (Anoxic) and may contain Hydrogen Sulfide (H_2S).
- Surface Hydrology Link: Catchment runoff affects only the surface layer (Epilimnion); it does not flush the deep reservoir.

4. SENSITIVITY:

- The system is highly sensitive to surface pollution because flushing is negligible on human timescales.
- Any withdrawal of water from deep layers risks bringing toxic, anoxic water to the surface.

5.2 Atmospheric Drivers

Trend: ATMOSPHERIC CONDITIONS: Warming trend detected (0.17°C/decade). Persistent atmospheric warming increases stability of the upper water column, potentially reducing mixing frequency.

Surface air temperatures show a trend of 0.17°C/decade.

5.3 Implications for ESIA

The combination of extreme depth (228.0m) and tropical location implies a **Permanently Stratified (Meromictic)** regime. The deep water is likely a nutrient/chemical sink that must not be disturbed.

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6. Integrated Baseline Synthesis

Synthesis of Environmental Baseline: Lake Toba is characterized as a "High Inertia" system due to its immense volume (~259 km^3), significant average depth (228 m), and exceptionally long hydraulic residence time (~80 years). This creates an exceptionally stable thermal mass and a slow flushing rate, meaning changes occur over decades rather than years. While a statistically significant but weak climate trend has been identified, the lake's sheer volume provides a substantial buffer against short-term climatic shocks, making it resilient to rapid fluctuations in water quantity. The primary environmental risk for Lake Toba is not water quantity, but rather water quality, specifically the stability of its stratification. The lake is likely permanently or strongly stratified (Meromictic/Oligomictic), with deep waters (>100m) prone to anoxia and potential hydrogen sulfide accumulation due to the lack of mixing and long retention. Surface hydrology primarily affects only the epilimnion, with negligible flushing of the deep reservoir on human timescales. Consequently, the system is highly sensitive to surface pollution, which can accumulate and degrade water quality without effectively flushing the deep, anoxic layers.

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7. Recommendations for Detailed ESIA

The satellite-based baseline indicates a sensitive, deep-water environment. The following field studies are required to meet IFC PS6 / WB ESS6 standards:

REQUIRED ESIA FIELD STUDIES:

1. Deep Water Profiling (0-250m): Monthly CTD casts to define the thermocline and oxycline.

2. Chemical Baselines: Sampling at 50m intervals for H_2S, NH_4, and heavy metals.

3. Sediment Oxygen Demand: Analysis of deep benthic interactions.

4. Internal Wave (Seiche) Monitoring: Thermistor chains to detect internal basin oscillations.

Appendix 2: Data Source, Methods, and Analytical Techniques

This document provides a detailed description of the data source, methods, and analytical techniques applied in the TerraClimate Hydrology ESIA baseline analysis.

1. Data Source

1.1. TerraClimate Dataset

The primary data source for this analysis is **TerraClimate**, a global high-resolution dataset of monthly climate and climatic water balance variables.

- **Description**: TerraClimate combines high-spatial resolution climatological normals from the WorldClim dataset with time-varying data from CRU Ts4.0 and JRA-55 to produce a comprehensive dataset covering the period from 1958 to the present.
- **Spatial Resolution**: The dataset has a spatial resolution of 1/24th of a degree (approximately 4 kilometers).
- **Temporal Resolution**: The data is provided at a monthly temporal resolution.
- **Access**: The TerraClimate dataset is publicly available on several platforms, including Google Earth Engine, which is used in this analysis. The specific collection ID is `IDAHO_EPSCOR/TERRACLIMATE`.

1.2. Variables Used

The analysis utilizes a subset of the variables available in the TerraClimate dataset. The key variables are:

- **`pr`**: Precipitation (mm)
- **`ro`**: Runoff (mm)
- **`pet`**: Potential Evapotranspiration (mm)
- **`def`**: Climatic water deficit (mm)
- **`pdsi`**: Palmer Drought Severity Index
- **`soil`**: Soil Moisture (mm)
- **`vs`**: Wind Speed (m/s)
- **`tmmx`**: Maximum Temperature (°C)
- **`tmmn`**: Minimum Temperature (°C)

2. Methods and Analytical Techniques

2.1. Data Acquisition and Pre-processing

1. **Area of Interest (AOI)**: The analysis is initiated by providing a GeoJSON file that defines the geographical boundaries of the area of interest. This is typically a catchment area for a lake or reservoir.

2. **Data Retrieval from Google Earth Engine (GEE)**:

* The provided AOI GeoJSON is converted into an `ee.Geometry` object within the GEE environment.

* The TerraClimate `ImageCollection` is filtered to include only the images that fall within the specified date range and intersect with the AOI's bounding box.

3. **Spatial Aggregation**:

* For each monthly image in the filtered collection, a spatial aggregation is performed using the `reduceRegion` function in GEE.

* The `ee.Reducer.mean()` reducer is applied, which calculates the mean value of all the TerraClimate grid cells that fall within the defined AOI polygon.

* This process results in a single, average value for each variable for each month, representing the entire AOI. The aggregation is performed at the native resolution of the TerraClimate dataset (4638 meters).

4. **Data Transformation**:

* The results from GEE are retrieved and parsed into a `pandas` DataFrame.

* Scale factors, as specified in the TerraClimate data catalog, are applied to the raw values to convert them to standard units (e.g., temperature is converted from 0.1 °C to °C).

2.2. Water Balance Analysis

The water balance analysis is performed on the downloaded time-series data to understand the hydrological characteristics of the catchment.

• **Net Atmospheric Flux**: This is calculated as the difference between monthly precipitation (`pr`) and potential evapotranspiration (`pet`). A positive value indicates a water surplus, while a negative value indicates a deficit.

• **Runoff Volume**: The mean runoff in `mm/month` (`ro`) is converted to a volume in Gigalitres (`GL`) by multiplying it by the area of the AOI in square kilometers and a conversion factor (`1 mm * 1 km² = 0.001 GL`).

• **Monthly and Seasonal Statistics**: The time-series data is aggregated to calculate mean monthly and seasonal (monsoon and dry season) statistics for key variables.

• **Catchment Yield and Hydraulic Residence Time**: The total annual runoff volume is calculated to assess the catchment's water yield. This is then used in conjunction with the lake's volume to estimate the hydraulic residence time.

2.3. Climate Risk Analysis

This analysis focuses on evaluating drought and hydro-climatic variability.

• **Drought Event Detection**: Drought events are identified using the Palmer Drought Severity Index (PDSI). A drought is considered to be in effect when the PDSI value falls below a threshold of -2.0. The duration, severity, and impact on runoff are calculated for each event.

• **Climate Trend Analysis**: A linear regression analysis is performed on the PDSI time-series to identify any statistically significant long-term trends (p-value < 0.05). This helps to determine if the region is experiencing a drying or wetting trend.

• **Vulnerability Assessment**: Based on the frequency and severity of drought events and the long-term climate trend, a qualitative assessment of the region's vulnerability to hydro-climatic stress is provided.

2.4. Limnological Stability Analysis

This analysis provides context on the potential for lake stratification based on atmospheric conditions.

• **Atmospheric Conditions**: Monthly mean maximum temperature and wind speed are analyzed to understand the atmospheric drivers that can influence lake stratification.

• **Temperature Trend Analysis**: A linear regression is performed on the maximum temperature time-series to identify any significant warming or cooling trends.

• **Baseline Characterization**: A qualitative characterization of the lake's likely limnological behavior is provided. This is based on the atmospheric analysis, as well as literature-based knowledge of deep tropical lakes and specific data for Lake Toba (e.g., morphometry, residence time).

• **Data Limitations**: It is explicitly stated that this analysis is based on atmospheric data and does not include in-situ measurements of the water column (e.g., thermocline depth, dissolved oxygen profiles). Recommendations for field studies are provided.

2.5. Visualization

A series of charts are generated to visually represent the results of the analysis:

• **Monthly and Seasonal Water Balance**: Bar charts showing the monthly and seasonal distribution of precipitation, evapotranspiration, and runoff.

• **Drought Events Timeline**: A time-series plot of the PDSI, with periods of drought highlighted.

• **Atmospheric Conditions**: A dual-axis plot showing the monthly variation of surface temperature and wind speed.

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8. References

1. Abatzoglou, J.T., et al. (2018). TerraClimate, a high-resolution global dataset. *Scientific Data*.

2. Wetzel, R.G. (2001). *Limnology: Lake and River Ecosystems*.

3. World Bank Group. (2015). *Environmental, Health, and Safety (EHS) Guidelines*.

4. IFC. (2012). *Performance Standard 6: Biodiversity Conservation and Sustainable Management of Living Natural Resources*.

Appendix: Figures

Figure: Climate Risk Drought

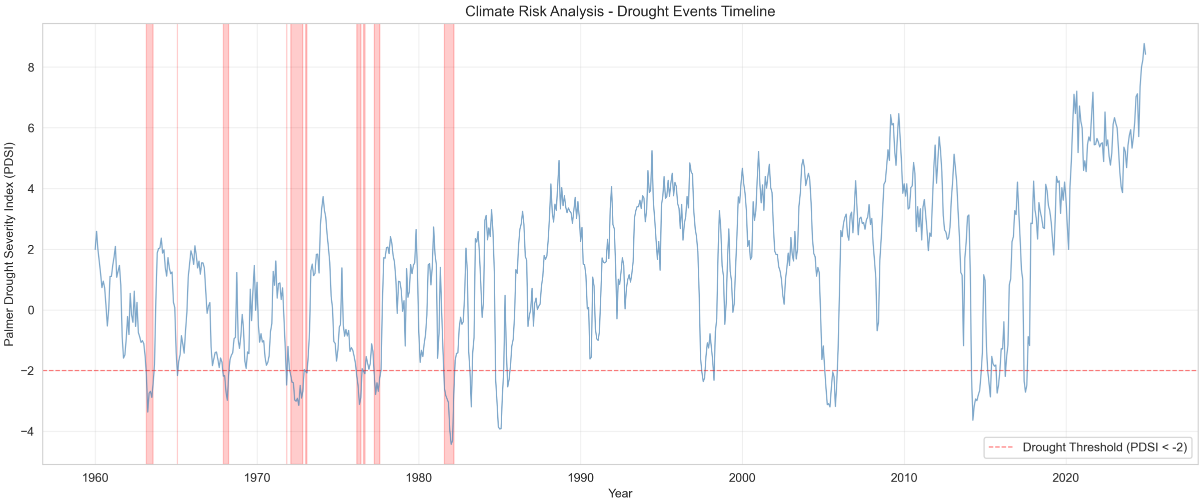

Figure: Limnological Atmospheric Conditions

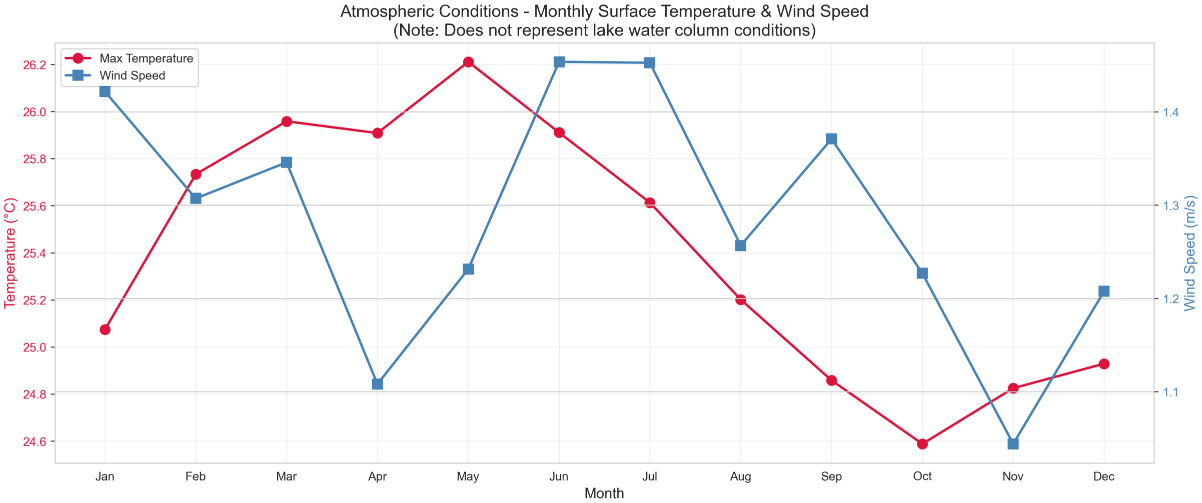

Figure: Water Balance Monthly

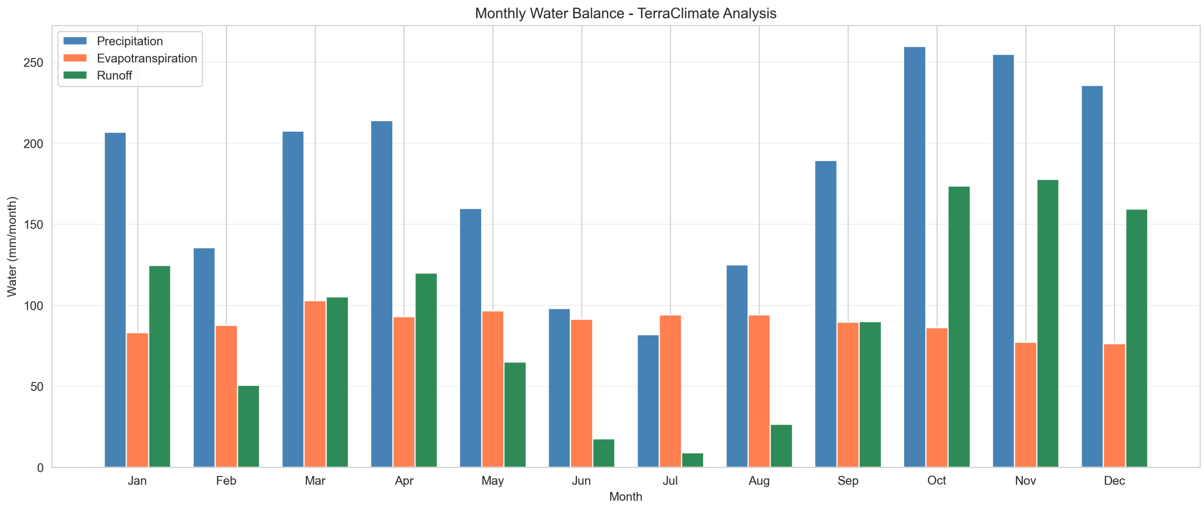

Figure: Water Balance Seasonal