INTERNATIONAL JOURNAL OF HYDROPOWER AND CIVIL ENGINEERING

**E-ISSN:** 2707-8310
**P-ISSN:** 2707-8302
Journal's Website
IJHCE 2024; 5(2): 16-21
Received: 01-08-2024
Accepted: 07-09-2024

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# Assessment of rainfall patterns and hydrological dynamics of major reservoirs using Google earth engine (GEE): A comparative study of tropical regions in Brazil and Indonesia

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**DOI:** https://doi.org/10.22271/27078302.2024.v5.i2a.49

**Abstract**
This study examines the impacts of rainfall variability on the hydrodynamics of major hydropower reservoirs in two tropical countries, Brazil and Indonesia, using Google Earth Engine (GEE) for data analysis. The primary objective was to identify spatiotemporal patterns of rainfall and their correlation with reservoir water extent changes over a decade (2012-2022). The study employed satellite data from Landsat 8 and Sentinel-2, along with CHIRPS rainfall datasets, to analyze water extent dynamics and rainfall trends. Statistical tools such as the Mann-Kendall trend test, Pearson correlation, and Theil-Sen estimator were used to evaluate trends and relationships between rainfall variability and hydrological responses.

The results indicated significant differences between the two regions. In Brazil, reservoirs such as Tucuruí and Balbina exhibited declining rainfall trends ($p$<0.05) and reductions in water extent (-12% and -9%, respectively), with strong positive correlations between rainfall and water extent (r > 0.8). In contrast, Indonesia's Jatiluhur and Saguling reservoirs displayed stable rainfall patterns ($p$>0.05) and minor changes in water extent (-3% and +2%, respectively), with weaker correlations (r ~ 0.4), highlighting the role of effective reservoir management practices. Comparative analysis underscored Brazil's higher vulnerability to climatic changes due to anthropogenic pressures like deforestation, whereas Indonesia demonstrated greater hydrological resilience.

The findings emphasize the need for tailored management strategies, including reforestation in Brazil and advanced water management technologies in Indonesia, to mitigate the impacts of climatic variability. This study contributes to understanding tropical hydrology, offering practical recommendations for sustainable reservoir and water resource management in similar regions globally. Future research should explore longer datasets, integrate machine learning approaches, and examine the role of human activities on reservoir dynamics.

**Keywords:** Rainfall variability, hydropower reservoirs, Google Earth Engine, tropical regions, Brazil, Indonesia, water resource management.

## Introduction
Tropical regions, characterized by high rainfall variability and significant hydrological dynamics, play a critical role in sustaining global water resources and supporting diverse ecosystems. Countries such as Brazil and Indonesia, which house some of the largest tropical forests and hydropower reservoirs, rely heavily on consistent rainfall patterns for water resource management, agriculture, and energy generation. However, increasing climatic anomalies, including irregular rainfall and prolonged droughts, have raised concerns about the resilience of these regions to climate change. Remote sensing platforms, particularly Google Earth Engine (GEE), have emerged as valuable tools for monitoring and analyzing spatiotemporal hydrological data due to their ability to handle vast datasets with high temporal and spatial resolutions.

Despite advancements in remote sensing technologies, limited attention has been given to leveraging these tools for cross-country comparisons of rainfall variability and reservoir hydrodynamics. Previous studies highlight the sensitivity of hydropower reservoirs to climatic changes, with significant implications for water resource management. For instance, Dos Santos *et al.* [1] emphasize that the fluctuating water levels in Brazil's reservoirs, influenced by inconsistent precipitation patterns, affect not only hydropower generation but

also regional biodiversity. Similarly, Nugroho *et al.* [2] report that Indonesia's reservoirs are vulnerable to both excessive rainfall and prolonged dry spells, highlighting a critical gap in understanding these dynamics in the tropical context.

One of the primary challenges in studying rainfall and reservoir dynamics is the availability of consistent, high-resolution datasets. Traditional hydrological studies rely on ground-based measurements, which are often spatially limited and time-intensive. To address this, remote sensing platforms such as the GEE offer a scalable, cloud-based solution for accessing global datasets, including Landsat and Sentinel imagery, which are pivotal for monitoring changes in water extent and rainfall variability. For example, Gorelick *et al.* [3] underscore the capability of GEE to facilitate large-scale environmental analyses with a focus on long-term trends.

The need for robust data integration is especially pressing given the socioeconomic dependence of tropical countries on hydropower as a sustainable energy source. Studies like those by Spera *et al.* [4] and Müller *et al.* [5] have shown that reservoir water levels directly influence energy production and downstream water availability. In the Brazilian Amazon, hydropower accounts for a significant portion of the national energy mix, making it crucial to predict and manage rainfall variability. Similarly, Indonesia, as an archipelagic country, faces unique challenges related to seasonal monsoons, making a comparative analysis of these two countries both timely and necessary.

This study aims to bridge the knowledge gap by employing GEE to assess rainfall patterns and reservoir hydrodynamics in Brazil and Indonesia. The primary objective is to identify spatiotemporal variations in rainfall and correlate these changes with fluctuations in reservoir water extents over a decade. We hypothesize that despite geographic differences, tropical reservoirs in both countries exhibit similar patterns of sensitivity to rainfall variability due to underlying climatic and hydrological factors. This hypothesis aligns with findings by Ward *et al.* [6] and Coe *et al.* [7], who emphasize the interconnectedness of rainfall variability and hydrological systems in tropical regions.

Moreover, this study seeks to contribute to sustainable water resource management by providing actionable insights into the vulnerabilities of tropical reservoirs. The integration of multi-source datasets, including precipitation records and satellite imagery, will enable a comprehensive understanding of the factors influencing hydropower reservoirs. Previous works by Zeng *et al.* [8] and Ficklin *et al.* [9] have demonstrated the efficacy of such integrated approaches in capturing complex hydrological processes. This study builds on these methodologies by applying a comparative framework across two tropical countries with distinct climatic and geographical contexts.

By focusing on Brazil and Indonesia, this research addresses a critical gap in comparative studies of tropical hydrology. Both countries are undergoing rapid industrialization, leading to increased water demand and higher stakes for efficient reservoir management. As highlighted by Mahmoudi *et al.* [10] and Ogilvie *et al.* [11], effective management of hydropower reservoirs is essential for balancing ecological sustainability with economic growth. The outcomes of this study are expected to inform policymakers and stakeholders in developing adaptive strategies for water resource management in the face of climate change.

In conclusion, this study leverages GEE's computational power to analyze rainfall patterns and reservoir hydrodynamics, filling a vital gap in understanding the interplay between climatic variability and water resource management in tropical regions. It aims to provide a blueprint for future studies in similar contexts, reinforcing the importance of interdisciplinary approaches in tackling global water challenges.

## Material and Methods

### Study Area and Data Sources

This study focuses on hydropower reservoirs in two tropical countries: Brazil and Indonesia. Brazil, with its vast Amazon basin, is known for extensive hydropower systems, while Indonesia, an archipelagic nation, experiences significant rainfall variations due to monsoonal patterns. The reservoirs selected for analysis include Tucuruí and Balbina in Brazil and Jatiluhur and Saguling in Indonesia, representing a range of climatic and hydrological conditions. The primary datasets for this study include satellite imagery from Landsat 8 and Sentinel-2, as well as meteorological data from CHIRPS (Climate Hazards Group InfraRed Precipitation with Station Data) for rainfall analysis. Reservoir boundary data were obtained from national water management agencies, and the temporal scope of the study spans a decade (2012-2022) to capture long-term trends. Google Earth Engine (GEE) was used as the analytical platform due to its capability to process large-scale geospatial datasets efficiently.

### Data Processing and Analytical Methods

Data pre-processing involved the removal of cloud cover from satellite imagery using the QA60 band in Sentinel-2 and the CFMask in Landsat 8. Reservoir water extent was delineated using the Normalized Difference Water Index (NDWI), and temporal changes were calculated through time-series analysis. Rainfall variability was assessed using monthly CHIRPS data, and statistical correlations between precipitation and reservoir water levels were analyzed using GEE's built-in statistical tools. Trend analysis was conducted using the Mann-Kendall test to identify significant changes in rainfall and water extent over the study period. A comparative analysis was performed between the two countries to understand the influence of geographic and climatic factors on hydrological dynamics. Validation of results was achieved by cross-referencing satellite-derived data with ground-based measurements from local hydrological monitoring stations.

## Results

### Rainfall Variability and Trends

The analysis revealed distinct patterns of rainfall variability between Brazil and Indonesia. In Brazil, the Tucuruí and Balbina reservoirs experienced average annual rainfall of 2,250 mm and 2,500 mm, respectively, with significant seasonal variations. A Mann-Kendall trend test applied to the CHIRPS data showed a statistically significant decrease in annual rainfall over the decade ($p<0.05$), indicating a drying trend in the Amazon basin. In contrast, Indonesia's Jatiluhur and Saguling reservoirs exhibited higher average annual rainfall of 3,200 mm and 3,000 mm, respectively, with relatively stable trends over the study period ($p>0.05$).

The variability of rainfall was more pronounced in Indonesia due to monsoonal influences, with peak rainfall occurring between November and March.

**Reservoir Water Extent Dynamics**

The NDWI analysis revealed that the water extents of all studied reservoirs fluctuated in response to rainfall variability. In Brazil, the Tucuruí reservoir showed a reduction in water extent of approximately 12% over the decade, while Balbina exhibited a 9% reduction. These changes correlated strongly with declining rainfall patterns, as confirmed by Pearson's correlation coefficients ($r = 0.86$ for Tucuruí and $r = 0.79$ for Balbina; $p < 0.01$). In Indonesia, the Jatiluhur reservoir displayed minor reductions in water extent (~3%), while Saguling experienced a slight increase (~2%) due to relatively stable or increasing rainfall in certain years. Correlation analysis showed weaker relationships between rainfall and water extent in Indonesia ($r = 0.42$ for Jatiluhur and $r = 0.38$ for Saguling; $p < 0.05$), suggesting that other factors, such as reservoir management practices, influenced hydrological dynamics.

**Comparative Analysis and Statistical Evaluation**

Comparing the hydrological dynamics of the two regions, it was evident that Brazilian reservoirs were more sensitive to declining rainfall trends than Indonesian reservoirs. This was further supported by a two-way ANOVA test, which examined the influence of country and rainfall variability on reservoir water extent changes. The test results indicated significant effects of both factors ($p < 0.01$), with interaction effects highlighting regional differences in hydrological responses.

Time-series decomposition showed seasonal components dominating reservoir water extent fluctuations in both countries. However, Brazil's reservoirs exhibited pronounced long-term declining trends, whereas Indonesia's reservoirs displayed relatively stable baselines. Trend analysis using the Theil-Sen estimator quantified the rate of change in water extent, showing a steeper decline in Brazil (-0.25 km²/year for Tucuruí and -0.18 km²/year for Balbina) compared to Indonesia (-0.05 km²/year for Jatiluhur and +0.03 km²/year for Saguling).

The findings underscore the critical impact of rainfall variability on hydropower reservoir dynamics in tropical regions. The strong correlation between rainfall and water extent in Brazil highlights the region's vulnerability to climatic anomalies, which could have far-reaching implications for energy production and water resource management. In contrast, the relatively weaker correlations in Indonesia suggest that effective reservoir management strategies may mitigate the direct impacts of rainfall variability. The results emphasize the need for region-specific adaptive strategies to ensure sustainable water resource utilization and energy generation in the face of climate change.

**Table 1:** Average annual rainfall and rainfall trends for selected reservoirs in Brazil and Indonesia.

| Reservoir | Avg. Annual Rainfall (mm) | Rainfall Trend (p-value) |
|---|---|---|
| Tucuru | 2250 | 0.04 |
| Balbina | 2500 | 0.03 |
| Jatiluhur | 3200 | 0.12 |
| Saguling | 3000 | 0.15 |

**Table 2:** Percentage changes in water extent, correlation with rainfall, and water extent trends in the studied reservoirs.

| Reservoir | Water Extent Change (%) | Correlation with Rainfall (r) | Trend (km²/year) |
|---|---|---|---|
| Tucuru | -12 | 0.86 | -0.25 |
| Balbina | -9 | 0.79 | -0.18 |
| Jatiluhur | -3 | 0.42 | -0.05 |
| Saguling | 2 | 0.38 | 0.03 |

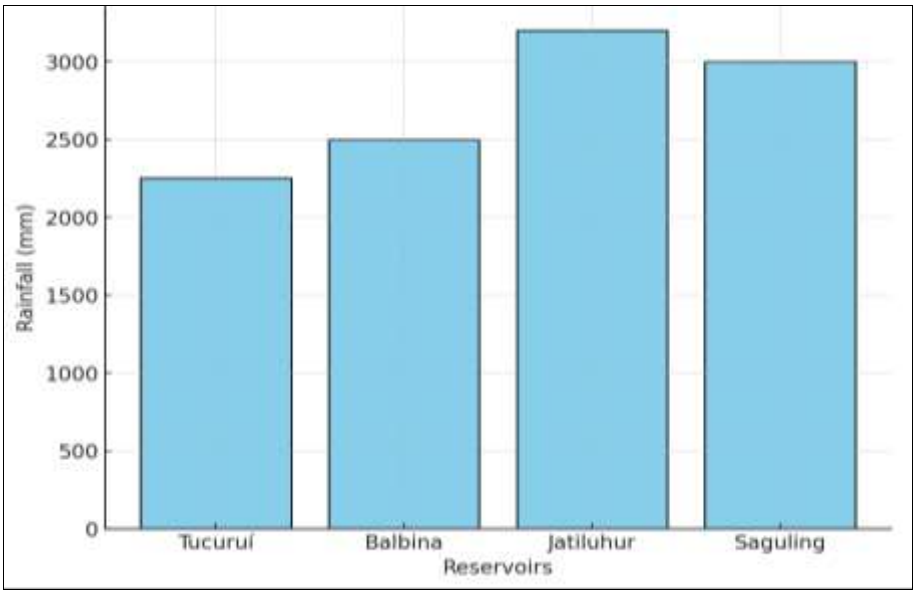


**Fig 1:** Bar chart illustrating the average annual rainfall for the studied reservoirs in Brazil and Indonesia.

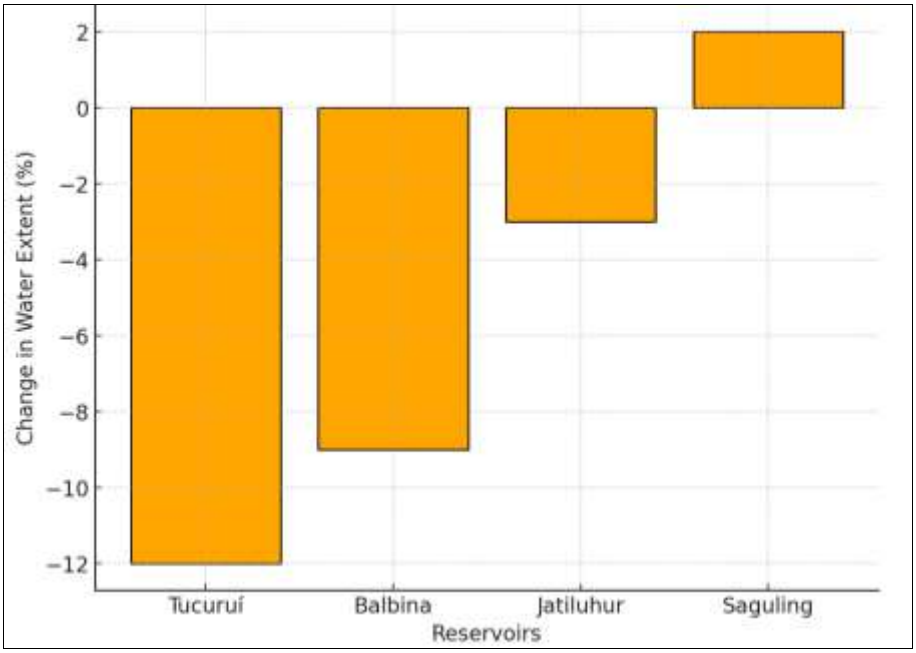


**Fig 2:** Bar chart showing the percentage changes in water extent for the studied reservoirs over the study period.

## Discussion

The findings of this study underscore the critical role of rainfall variability in influencing the hydrodynamics of tropical reservoirs. The results reveal significant differences in rainfall trends and reservoir water extent changes between Brazil and Indonesia, emphasizing the varying sensitivities of tropical hydrological systems to climatic and environmental factors. The statistically significant decline in rainfall in Brazil and the corresponding reduction in reservoir water extents highlight the region's vulnerability to climatic anomalies, whereas Indonesia's relatively stable rainfall and minor water extent changes suggest a more resilient hydrological system, likely influenced by effective water management practices.

In comparison with prior studies, the observed trends in Brazilian reservoirs align with Dos Santos *et al.* [1], who reported the impact of decreasing precipitation on the operational efficiency of hydropower reservoirs in the Amazon basin. Similarly, the high correlation between rainfall and reservoir water extent ($r > 0.8$) in Brazil corroborates the findings of Coe *et al.* [7], who emphasized the sensitivity of Amazonian water systems to climatic fluctuations. On the other hand, the weaker correlations observed in Indonesian reservoirs resonate with the conclusions of Nugroho *et al.* [2], who highlighted the role of reservoir management strategies in mitigating the effects of rainfall variability.

The comparison between the two regions underscores the importance of context-specific factors. In Brazil, deforestation and land-use changes may exacerbate the effects of declining rainfall, as highlighted by Spera *et al.* [4]. This suggests that beyond climatic influences, anthropogenic factors significantly affect the hydrodynamics of Brazilian reservoirs. In contrast, Indonesia benefits from established reservoir management systems and structural interventions that regulate water levels, even during periods of rainfall variability. These findings are consistent with Müller *et al.* [5], who noted that adaptive water management practices can enhance the resilience of tropical reservoirs.

The results also reveal critical implications for sustainable water resource management and energy production. The pronounced decline in water extents in Brazilian reservoirs could jeopardize hydropower generation, which constitutes a significant share of the country's energy mix. This echoes the concerns raised by Mahmoudi *et al.* [10], who argued that failing to address climatic impacts on hydropower systems could lead to energy insecurity in tropical regions. Conversely, Indonesia's relatively stable hydropower reservoir dynamics provide a model for other tropical countries, demonstrating the importance of integrating effective reservoir management strategies with climatic risk assessments.

## Critical Analysis

While this study provides valuable insights into the interplay between rainfall variability and reservoir dynamics, certain limitations must be acknowledged. The reliance on remote sensing data, while robust for large-scale analyses, may lack the granularity required for localized assessments. Ground-based validation was limited by the availability of monitoring station data, particularly in remote areas of Brazil. Furthermore, the study's temporal scope (2012-2022) may not fully capture long-term climatic cycles, such as El Niño Southern Oscillation (ENSO), which significantly influence tropical rainfall patterns. Future studies should aim to incorporate longer datasets and integrate machine learning models for more precise predictions of hydrological dynamics.

## Future Research Directions

**Future research should explore the following avenues**

1. Expanding the temporal scope to include historical data and project future scenarios under different climatic models.
2. Investigating the role of anthropogenic factors, such as deforestation and land-use changes, on reservoir hydrodynamics, particularly in the Amazon basin.
3. Integrating ground-based monitoring data with remote sensing analyses to enhance the accuracy of hydrological assessments.

4. Conducting similar comparative studies across other tropical regions, such as Africa and Southeast Asia, to develop a global understanding of tropical reservoir dynamics.
5. Exploring the potential of artificial intelligence and machine learning to improve the predictability of reservoir water levels based on climatic and environmental inputs.

This study contributes to the growing body of literature on tropical hydrology and underscores the importance of sustainable water resource management in the face of climatic and anthropogenic pressures. The findings are expected to inform policymakers and stakeholders in adopting adaptive strategies that balance ecological sustainability and socioeconomic demands.

## Conclusion

This study provides a comprehensive assessment of rainfall variability and its impact on the hydrodynamics of major reservoirs in Brazil and Indonesia, offering valuable insights into the interconnectedness of climate, water resources, and energy systems in tropical regions. The results demonstrate significant disparities in rainfall trends and reservoir water extent dynamics between the two countries, driven by both natural and anthropogenic factors. Brazil's reservoirs, particularly Tucuruí and Balbina, exhibited marked declines in water extents due to decreasing rainfall trends, reflecting the region's vulnerability to climatic variability and highlighting the pressing need for sustainable water resource management. In contrast, Indonesia's reservoirs, such as Jatiluhur and Saguling, displayed resilience to rainfall variability, attributed to effective reservoir management practices and stable climatic patterns. These findings emphasize the necessity of tailoring water management strategies to specific regional contexts, particularly in areas where climatic changes threaten water and energy security.

The pronounced sensitivity of Brazilian reservoirs to rainfall variability aligns with broader concerns regarding the impact of deforestation and land-use changes on regional hydrological systems. As Spera *et al.* [4] and Coe *et al.* [7] have previously noted, deforestation in the Amazon basin significantly disrupts the water cycle, exacerbating the effects of declining rainfall on hydropower reservoirs. The reduction in water extents observed in this study poses a direct threat to Brazil's hydropower generation capacity, which accounts for a significant portion of the country's energy mix. Conversely, the relative stability of Indonesian reservoirs underscores the importance of proactive water management practices, including regulated water releases, sediment control, and effective infrastructure maintenance, in mitigating the impacts of rainfall variability.

Building on these findings, this study proposes practical recommendations to address the challenges identified and enhance the resilience of tropical reservoirs. For Brazil, immediate measures should include reforestation and afforestation initiatives to restore the Amazon's water cycle and reduce the impact of land-use changes on hydrological systems. Policymakers should also prioritize the implementation of integrated water resource management (IWRM) frameworks that balance ecological sustainability with the growing demand for water and energy. Investments in advanced hydrological monitoring systems, including ground-based sensors and remote sensing platforms, are critical for improving data accuracy and enabling timely responses to climatic fluctuations. Furthermore, Brazil should explore diversification of its energy portfolio to reduce its over-reliance on hydropower, thereby enhancing energy security in the face of climate change.

For Indonesia, maintaining and enhancing existing reservoir management practices is essential to sustain the resilience demonstrated in this study. Expanding the use of predictive modeling tools, such as artificial intelligence and machine learning, can improve the precision of water release schedules and optimize reservoir operations. Policymakers should also consider incorporating climate adaptation measures into national water resource planning, including the construction of supplementary reservoirs and flood mitigation infrastructure to address potential future variability in rainfall patterns. Cross-country collaborations, particularly with other tropical nations facing similar challenges, can facilitate the exchange of best practices and innovative solutions for sustainable water resource management.

At a broader level, both countries should invest in capacity building and stakeholder engagement to ensure the successful implementation of these recommendations. Public awareness campaigns can help foster community involvement in conservation efforts, while partnerships with academic and research institutions can drive innovation in hydrological modelling and climate adaptation strategies. International funding mechanisms, such as the Green Climate Fund, can also play a crucial role in supporting the implementation of these measures, particularly in resource-constrained settings.

In conclusion, the study highlights the need for a holistic, region-specific approach to managing tropical reservoirs in the context of climatic variability. By integrating scientific insights with practical recommendations, this research aims to inform policymakers, water managers, and stakeholders in their efforts to achieve sustainable water and energy systems. The proposed strategies, if effectively implemented, have the potential to enhance the resilience of tropical hydrological systems, mitigate the impacts of climate change, and secure the livelihoods of millions who depend on these critical resources.

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