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The Impact of El Niño on The Incoming Flow Rate of The Saguling Hydroelectric Power Plant (PLTA) for Operational Sustainability

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Abstract. This study investigates the impact of El Niño on the inflow dynamics of the Saguling Hydroelectric Power Plant (PLTA), located in West Bandung, West Java, Indonesia, within the upper Citarum River Basin. The plant plays a crucial role in the Java-Bali electricity grid. The research is based primarily on 39 years (1986–2024) of hydrometeorological data (monthly rainfall and reservoir inflow) provided by PT PLN Indonesia Power UBP Saguling, along with Oceanic Niño Index (ONI) data. The objective is to assess the influence of El Niño–Southern Oscillation (ENSO) events on water availability and operational sustainability. Statistical analysis reveals a significant inverse correlation between ONI and rainfall ($r = -0.41$), and ONI and inflow ($r = -0.45$). El Niño years show a 50–60% reduction in inflow and rainfall during dry months, while La Niña years exhibit a 20–30% increase. Wavelet transform analysis identifies dominant periodicities in the 2–4 year range across all variables, confirming ENSO's cyclical impact. The findings highlight the vulnerability of hydropower to climate variability and underscore the importance of integrating ENSO-based climate forecasts into adaptive reservoir and energy management planning.

Keywords: *climate variability, el niño, hydropower, inflow discharge, la niña, reservoir management, saguling, wavelet analysis.*

1 Introduction

Indonesia, as an archipelagic country situated along the equator, experiences two dominant seasons: the rainy and dry seasons. Rainfall plays a pivotal role in shaping the tropical climate, significantly influencing ecological and socioeconomic systems as discussed by Nieuwolt in [1]. However, the timing, duration, and intensity of these seasons are not uniform across regions or years. This variability is largely driven by global climatic phenomena, particularly the El Niño–Southern Oscillation (ENSO), which affects atmospheric circulation and rainfall distribution patterns in Indonesia, as noted by Tjasyono, *et al*. in [2].

ENSO represents an irregular interaction pattern between oceanic and atmospheric systems across the equatorial Pacific Ocean, leading to significant deviations from typical climate behavior, as described by Iskandar, *et al*. in [3]. El Niño, a notable phase of ENSO, is characterized by an increase in sea surface temperatures in the Niño 3.4 region of ≥0.5°C for at least three consecutive months (NOAA). In Indonesia, El Niño events often coincide with prolonged and intensified dry seasons, resulting in diminished rainfall and increased risk of droughts, as explained by Ropelewski, *et al*. in [4]. These climatic anomalies have far-reaching impacts, threatening key sectors such as agriculture, fisheries, and especially energy security.

The rising electricity demand in West Java, driven by population and industrial growth, has exceeded local energy resources. The Ministry of Energy and Mineral Resources [5] identifies West Java as an electricity-critical zone. To address this, hydropower—especially the Saguling Hydroelectric Power Plant (PLTA Saguling)—plays a key role in providing reliable, sustainable energy. Located in West Bandung, PLTA Saguling contributes around 700 MW to the Java-Bali grid, about 2.5% of its total 27,700 MW capacity, according to Sidqi [6]. Since its operation began in 1985, the plant has depended on a reservoir with 611 million m^3 of effective storage. Consistent inflow is needed to maintain its minimum discharge for peak electricity demand. However, as noted by Khalawi, *et al*. [7], its performance is highly sensitive to hydrological changes, making it vulnerable to climate anomalies like El Niño, which can reduce inflows and impact power generation.

Previous studies have demonstrated that rainfall patterns directly influence reservoir inflow patterns, thereby affecting hydroelectric output, as noted by Thattai, *et al*. [8]. Ward, *et al*. [9] further emphasized that during El Niño events, suppressed rainfall reduces river discharge and reservoir inflows, ultimately diminishing electricity generation capacity. This is particularly relevant for the Saguling Reservoir, which depends on the upper Citarum River Basin for its water supply. A key empirical study by Hutagalung [10] examined 40 years of rainfall and discharge data from 23 rainfall stations and 4 hydrological stations within the Citarum watershed. The study found that during El Niño events, rainfall in the upstream region decreased by 48.5%, and by 47.4% in the midstream area, significantly reducing river inflows. Conversely, La Niña conditions increased rainfall by 11.7% and 22% in those same regions, respectively. These results confirm a strong ENSO–rainfall–streamflow linkage in the Saguling hydrological system, underscoring the plant's vulnerability to interannual climate variability. Moreover, the study highlighted that the most significant impacts occurred during the dry season, reinforcing the need for integrating ENSO-based forecasting and hydrological modeling into reservoir management to ensure the operational sustainability of PLTA Saguling.

This study explores how El Niño affects reservoir inflow at the Saguling Hydropower Plant and what it means for the plant's long-term operations. While previous research, like Hutagalung [10], showed that El Niño reduces rainfall and river flow in the upper Citarum Basin, the specific impact on Saguling's operations is still not well understood. Using 30 years of data (1985–2024) on rainfall, inflow, and ENSO indicators (ONI and SOI), this study aims to measure how much inflow drops during El Niño and identify repeating patterns. Unlike general studies, this research focuses specifically on Saguling to see how climate anomalies affect the timing and volume of inflow needed for power generation. The results will help improve planning and climate risk management in Indonesia's energy sector, especially for adapting hydropower operations to future climate challenges.

2 Method

2.1 Location of Research

This study was conducted in the catchment area of the Saguling Reservoir, located within the Upper Citarum River Basin in West Java, Indonesia, and managed by PT PLN Indonesia Power UBP Saguling (Jl. Komplek PLN, Ciptaraharja, Cipatat, Bandung Barat, Jawa Barat 40554). As a key infrastructure for hydroelectric power generation, the reservoir plays a vital role in supplying electricity to the Java–Bali grid but is highly sensitive to climate variability. The region's rainfall is concentrated during the monsoon season, and its hydrological response to atmospheric disturbances—especially those linked to the El Niño–Southern Oscillation (ENSO)—is central to this investigation. This site was selected due to its strategic energy function and heightened vulnerability to seasonal and interannual climate anomalies.

2.2 Data Sources and Availability

This study uses both primary and secondary data derived from different institutions. The rainfall data were obtained from PT PLN Indonesia Power UBP Saguling, which provides daily rainfall records near the Saguling hydropower reservoir (PLTA Saguling), covering the period from 1985 to 2024. The reservoir inflow data for PLTA Saguling, covering the same period as the rainfall data, were obtained from PT PLN Indonesia Power UBP Saguling. To identify ENSO phases, such as El Niño and La Niña, we used the Oceanic Niño

Index (ONI), an index based on sea surface temperature anomalies in the Niño 3.4 region. The ONI data were obtained from NOAA and cover the same period as the other datasets. El Niño events were identified when the ONI was greater than or equal to +0.5°C for several consecutive overlapping 3-month seasons, while La Niña events were identified when the ONI was less than or equal to −0.5°C for the same duration.

2.3 Quantitative Approach

This study uses a simple quantitative approach to analyze the impact of El Niño events on rainfall and reservoir inflow at PLTA Saguling between 1985 and 2024. Three main steps were followed: wavelet analysis, correlation testing, and climatological classification. First, the influence of El Niño-Southern Oscillation (ENSO) was identified using Wavelet Transform. This method helps detect time-frequency patterns in rainfall data. The wavelet formula used is:

$$\Psi_{a,b}(t) = \frac{1}{\sqrt{a}}\Psi(\frac{t-b}{a})$$

Where a is the scale parameter (dilation), b is the time shift (translation), and Ψ denotes the wavelet function.

Second, Pearson correlation analysis was performed to examine the relationship between MEI (Multivariate ENSO Index), rainfall, and inflow. The correlation coefficient r was calculated using:

$$r = \frac{\sum(xi - x)(yi - y)}{\sqrt{\sum(xi - x)^2 \sum(yi - y)^2}}$$

This tested the strength and direction of the relationship. Correlation values close to +1 or -1 indicate strong relationships.

Third, ENSO phases were classified as El Niño, La Niña, or Neutral using NOAA's MEI criteria. Monthly rainfall and inflow were grouped by these phases and then compared to long-term monthly averages to identify if El Niño years showed below-average conditions. This method helped reveal how El Niño events influence hydrological conditions and the operational reliability of PLTA Saguling.

3 Results and Discussion

3.1 Result

3.1.1 Seasonal and Interannual Patterns of Inflow and Rainfall at Saguling Hydropower Plant

Analysis of 39 years of observational data (1986–2024) on inflow and rainfall at the Saguling reservoir shows strong seasonal patterns influenced by the Indonesian monsoonal cycle. The monthly average inflow reaches its peak in April (~160 m^3/s) due to the culmination of the rainy season, and its lowest in August (~25 m^3/s) during the peak of the dry season. Rainfall exhibits a similar trend, peaking in March (~255 mm/month) and reaching a minimum in August (~30 mm/month).

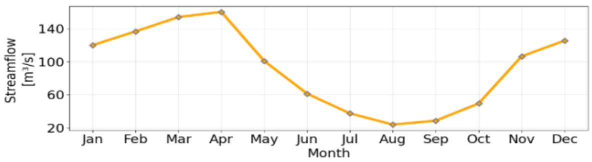

Figure 1 monthly average inflow discharge at the during the period 1986–2024.

This seasonal pattern reflects the area's typical bimodal rainfall, with heavy rain from December to March during the west monsoon and dry conditions from June to September during the southeast monsoon. The close match between rainfall and inflow shows the reservoir responds directly to changes in atmospheric moisture.

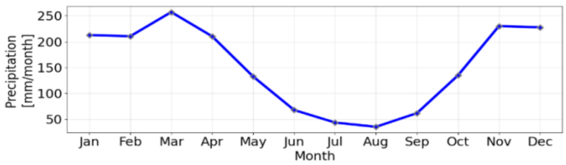

Figure 2 monthly average rainfall at the Saguling catchment area from 1986 to 2024.

These regular seasonal fluctuations are periodically disrupted by interannual climate anomalies particularly those driven by the El Niño–Southern Oscillation (ENSO). The influence of ENSO, especially El Niño events, tends to prolong the dry season, significantly reducing inflow and threatening energy production reliability.

3.1.2 Quantitative Analysis of ENSO’s Influence

3.1.2.1 Correlation Between ONI and Rainfall/Inflow Anomalies

To measure ENSO's impact, Spearman rank correlation was used between the Oceanic Niño Index (ONI) and monthly anomalies of rainfall and inflow, calculated by subtracting long-term monthly averages from observed values. The results showed moderate but significant negative correlations: ONI and inflow ($r = -0.45$, $p < 0.01$), and ONI and rainfall ($r = -0.41$, $p < 0.01$). This indicates that El Niño events usually lead to reduced rainfall and inflow, while La Niña tends to increase both.

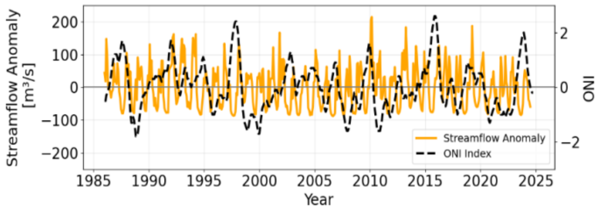

Figure 3 spearman correlation between the ONI and inflow discharge anomalies at the Saguling reservoir.

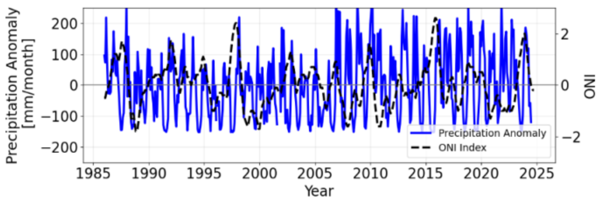

Figure 4 correlation between ONI and monthly rainfall anomalies at the Saguling catchment.

Notably, the lack of perfect linearity suggests additional regional or basin-specific factors may modulate the hydro-climatic response, such as land cover change, soil moisture memory, or intra-seasonal variability. However, the consistent inverse correlation supports the conclusion that ENSO is a primary driver of annual inflow anomalies.

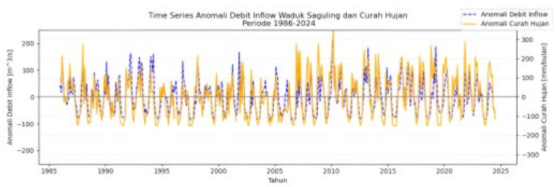

Figure 5 time series of inflow and rainfall anomalies at the Saguling Reservoir from 1986 to 2024.

This figure illustrates the temporal co-variation between inflow anomalies (blue dashed line) and rainfall anomalies (orange solid line) at the Saguling Reservoir over a 39-year period. Both variables are plotted as deviations from their respective long-term monthly climatological means. The synchrony in their trends—especially the drops during El Niño years and surges during La Niña—highlights the direct responsiveness of the reservoir inflow to atmospheric precipitation. This supports the observed statistical correlations (ONI–inflow r = –0.45; ONI–rainfall r = –0.41), confirming ENSO's dominant influence on Saguling's hydroclimate.

3.1.3 Inflow Behavior During ENSO Extremes: Case Study Analysis

3.1.3.1 El Niño 2015: Hydrological Deficit and Operational Risk

The 2015 El Niño, one of the strongest on record with ONI values above +2.0, caused extremely low rainfall in Saguling from May to October, especially in August. This led to a sharp drop in reservoir inflow to just 20–30 m³/s between July and September, well below normal levels. As a result, the reservoir level fell, threatening turbine operation and reducing electricity production. The situation increased the risk of blackouts and forced reliance on fossil-fuel backups, posing a challenge to national energy sustainability goals.

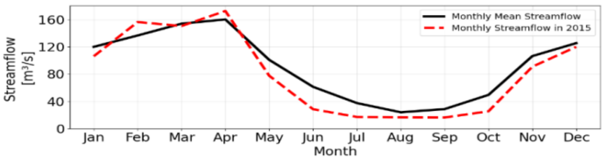

Figure 6 comparison of monthly climatological inflow discharge with actual inflow 2015.

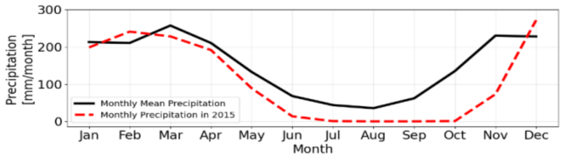

Figure 7 comparison of monthly climatological rainfall with observed rainfall in 2015.

These findings align with regional and global studies that document El Niño-induced droughts across Southeast Asia, typically exacerbated by suppressed convection and displaced Walker circulation.

3.1.3.2 La Niña 2022: Hydrological Surplus and Recovery Potential

In contrast to El Niño, the 2022 La Niña event, with ONI below –0.9, brought much higher rainfall and water inflow to Saguling throughout the year, especially during the rainy and transitional seasons. Inflow reached its highest levels in April (around 185 m^3/s) and December (around 180 m^3/s). Rainfall also rose sharply, going over 300 mm per month in March, October, and December—much higher than the usual average, showing strong recovery potential for the water system. This surplus allowed the reservoir to operate above minimum capacity for longer periods, reducing stress on infrastructure, and creating opportunities for optimal electricity dispatch and strategic water storage.

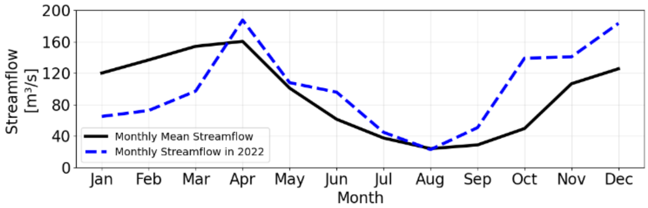

Figure 8 monthly inflow discharge at the Saguling reservoir in 2022.

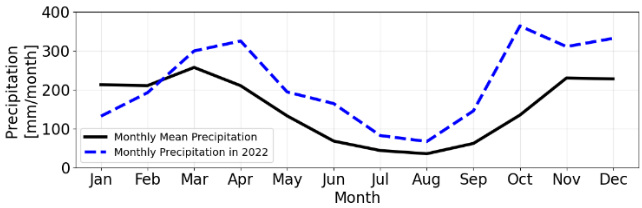

Figure 9 monthly rainfall in 2022.

3.1.4 Synthesis: Climatological Comparison Between ENSO Phases

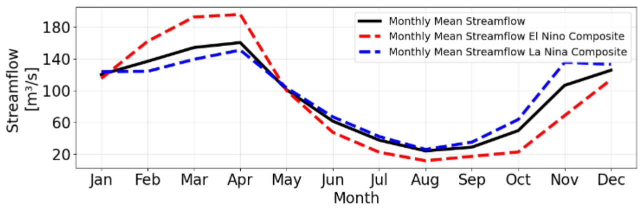

Figure 10 comparative analysis of monthly inflow discharge under three climate phases: climatological average, El Niño, and La Niña, showing significant modulation by ENSO.

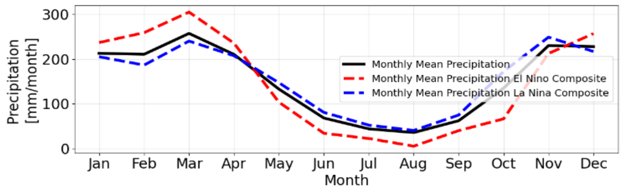

Figure 11 comparison of monthly rainfall patterns during climatological conditions, El Niño, and La Niña years, indicating ENSO-driven precipitation variability.

A comparison of monthly inflow during El Niño (2015), La Niña (2022), and the long-term average (1986–2024) shows clear differences in water availability. El Niño caused inflow to drop by 25–50%, especially from May to September, while La Niña increased inflow by 10–30% during wetter months. These patterns show how strongly ENSO affects regional water resources. For operations, El Niño brings drought risks that require careful water management, while La Niña can lead to excess water, raising concerns about flooding and sedimentation.

3.1.5 Temporal Spectral Analysis Using Wavelet Transform

To explore long-term patterns in ENSO and hydrology, continuous wavelet transform (CWT) was applied to the ONI, rainfall, and inflow time series.

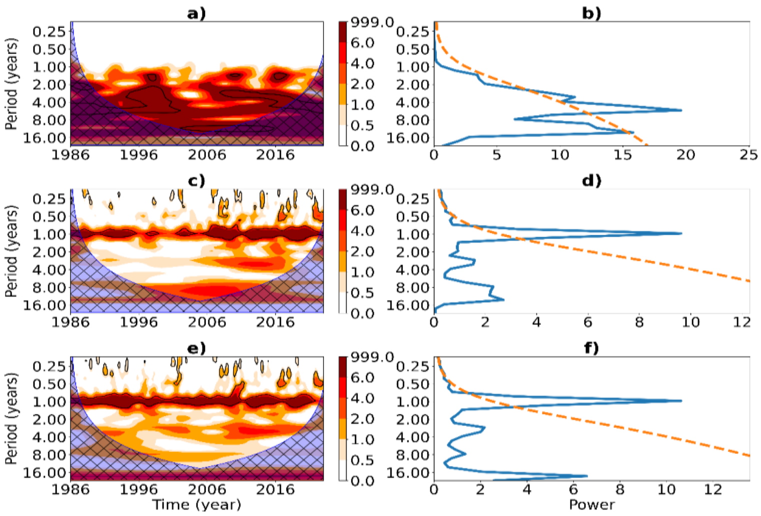

Figure 12 continuous wavelet power spectra and global wavelet spectra for (a–b) ONI, (c–d) rainfall, and (e–f) inflow discharge, showing dominant periodicities in the 2–4 year range associated with ENSO cycles.

3.1.5.1 ONI Spectrum

For the ONI spectrum, the analysis shows strong power at 2–7-year cycles, consistent with typical ENSO behavior. Peaks in power were found around major ENSO events in 1997–1998, 2010, and 2015, showing a clear connection between these events and shifts in oceanic conditions.

3.1.5.2 Rainfall and Inflow Spectrum

Rainfall and inflow patterns at Saguling show a strong connection to ONI cycles, especially within the 2–4-year range. This indicates that ENSO plays a significant role in shaping the hydroclimate of the region. These recurring patterns confirm that inflow and rainfall at Saguling are influenced by the cyclical nature of ENSO events.

3.1.5.3 Global Wavelet Spectra

The global wavelet spectra confirm the consistent high power at 2–4 years for all three variables, reinforcing ENSO's important role in shaping water patterns. The strong connection between ONI and inflow also supports the use of ENSO as a predictive tool for planning water resource management.

3.1.6 Summary of Key Findings

Table 1 shows that the 2015 El Niño caused a 50% drop in rainfall and a 60% drop in inflow, raising operational risk at Saguling. In contrast, the 2022 La Niña increased rainfall by 30% and inflow by 20%, lowering the risk. Correlation values (r = –0.41 for rainfall, –0.45 for inflow) confirm ENSO's strong impact on Saguling's water conditions.

Table 1 Summary of hydrometeorological impacts of El Niño (2015) and La Niña (2022) events on rainfall, inflow, and operational risk at the Saguling Hydroelectric Power Plant, including correlation coefficients (r) indicating the strength of the ENSO influence

Variable	El Niño Impact (2015)	La Niña Impact (2022)	ENSO Link
Rainfall	–50% (Jun–Oct)	+30% (Mar, Oct, Dec)	r = –0.41
Inflow	–60% (Jul–Sep)	+20% (Apr, Dec)	r = –0.45
Operational Risk	High	Low	Strong

3.2 Discussion

3.2.1 ENSO as a Dominant Climate Forcing on Saguling Hydrology

The study confirms that the El Niño–Southern Oscillation (ENSO), particularly the El Niño phase, is a major driver of interannual variability in rainfall and inflow at the Saguling Hydroelectric Power Plant. According to NOAA and as described by Sarachik [11], El Niño disrupts the Walker Circulation, shifting moist air away from the western Pacific and reducing convection over Indonesia, which explains the severe drop in rainfall (~0 mm in mid-2015) and inflow (~25–30 m^3/s) during El Niño years. These findings align with the theoretical model by Tjahjono, *et al*. [12], who reported a 60% correlation between the Southern Oscillation Index (SOI) and rainfall in West Java. This study refines that understanding by showing a Spearman correlation of –0.45 between ONI and inflow, and –0.41 with rainfall, confirming a moderate yet significant negative impact of El Niño on regional water availability.

3.2.2 Mechanisms Linking Rainfall and Reservoir Inflow

Rainfall is the main driver of inflow to the Saguling Reservoir, as supported by Notohadiprawiro [13], who highlighted the reliance of tropical reservoir systems on precipitation, and by Gunawan, *et al*. [14], who showed rainfall's dominant role in seasonal inflow variation in similar hydroelectric contexts. The catchment, located in the highlands of Bandung Raya above 643 meters, has steep slopes and limited vegetation, especially in dry seasons, which increases runoff during rain but also speeds up water loss when rainfall is low.

During El Niño events, reduced rainfall leads to lower inflow, worsened by higher evapotranspiration and reduced soil infiltration, causing streamflow to drop quickly. This pattern is reflected in matching declines in rainfall and inflow during El Niño, and increases during La Niña, highlighting the system's sensitivity to atmospheric changes. Haeruman [15] also noted that steep slopes and fractured geology reduce infiltration and water retention in upland areas like Saguling. These physical traits, combined with ENSO impacts, make the reservoir highly vulnerable to hydroclimatic extremes, emphasizing the need for water management that integrates both climate and land-surface factors.

3.2.3 Implications for Hydropower Generation and Operational Resilience

Hydropower generation at PLTA Saguling depends heavily on consistent inflow, which is driven by rainfall patterns. Arya [8] emphasizes that a plant's efficiency relies on both head and flow rate. During the 2015 El Niño, low inflow fell below operational thresholds, limiting turbine function and reducing electricity output. In contrast, the 2022 La Niña brought increased inflow year-round, creating better operating conditions. However, this surplus also posed challenges, such as heightened flood risks and sedimentation that could stress spillway capacity. These findings reveal Saguling's dual vulnerability (energy shortages during El Niño and overflow or management issues during La Niña) highlighting the need for adaptive planning in both scenarios.

3.2.4 Utility of Wavelet Analysis in Climate-Hydrology Assessment

Wavelet transform analysis confirms that ENSO-related cycles (2–4 years) are consistently present in the rainfall and inflow patterns at Saguling. This method supports earlier statistical results while adding detail on how ENSO impacts vary over time—for example, showing stronger effects during the 1997/98 and 2015/16 El Niño events. By capturing these shifting patterns, wavelet analysis provides a valuable tool for forecasting and reservoir management, especially in responding to non-stationary climate signals that traditional models may overlook.

3.2.5 Policy and Planning Implications

Since ENSO is a recurring and increasingly predictable climatic phenomenon, its integration into water resource and energy planning is not only feasible but urgently required. The findings of this study demonstrate a moderate but statistically significant correlation between El Niño events and reduced inflow to the Saguling Reservoir. As such, predictive ENSO signals (particularly through indices like MEI and ONI) should be formally embedded into the decision-making processes for reservoir operation and energy dispatch.

In alignment with Indonesia's *Rencana Pembangunan Jangka Menengah Nasional (RPJMN) 2020–2024*, which emphasizes climate resilience, energy diversification, and disaster risk reduction [16], ENSO-informed reservoir management directly supports Objective 6.2.1: "Peningkatan Ketahanan Energi Nasional" and Objective 7.2.3: "Pengelolaan Sumber Daya Air Berkelanjutan." On the ministerial level, *Peraturan Menteri PUPR No. 27/PRT/M/2015* concerning dam operation explicitly calls for flexible and adaptive management in response to hydrometeorological extremes [17], making ENSO-based forecasting highly relevant. Furthermore, *Peraturan Presiden No. 60 Tahun 2021* on climate adaptation planning mandates the integration of climate variability indicators including ENSO into national infrastructure and resource planning frameworks [18].

At the regional scale, West Java Province's *RTRW (Rencana Tata Ruang Wilayah)* and *Rencana Aksi Daerah Adaptasi Perubahan Iklim (RAD-API)* emphasize the importance of climate-resilient infrastructure [19][20]. Given the strategic role of the Saguling catchment in supporting the Java–Bali electricity grid, localized implementation of ENSO-based hydrological monitoring could serve as a scalable model for adaptive reservoir operation. This can be realized through the development of scenario-based inflow simulation tools that integrate real-time ENSO indicators, rainfall observations, and land-use data to dynamically adjust storage and release strategies.

The Ministry of Energy and Mineral Resources (ESDM) could require hydropower operators to incorporate seasonal ENSO forecasts—such as those from NOAA—into their RUPTL and annual dispatch planning [21]. This approach would enable early warning-based load adjustments, promote water conservation during El Niño years, and support flood mitigation during La Niña. Integrating ENSO insights into energy planning aligns with Indonesia's commitments to SDG 7, SDG 13, and the Paris Agreement (NDCs). To strengthen long-term resilience at Saguling, it is essential to ensure policy coherence across national and regional frameworks, including the RPJMN and RAD-API.

3.2.6 Limitations and Further Research

Although this study confirms a strong link between ENSO phases and inflow variability at PLTA Saguling, it has several limitations. It focused solely on ENSO, without considering other climate or environmental factors that may influence local weather. Future research should examine multiple interacting variables. Additionally, land-use changes in the Saguling catchment, particularly upstream in Bandung, were not included, even though they affect runoff and infiltration. Incorporating satellite data and land surface models would improve accuracy. The study also analyzed only one reservoir, while Java's power system relies on an interconnected network including Cirata and Jatiluhur, which should be studied together. Finally, applying ENSO forecasts in reservoir management requires stronger institutional coordination, better forecasting tools, and training for dam operators. Future research should address institutional readiness and develop decision support systems to enhance climate-resilient hydropower planning in Indonesia.

4 Conclusion

This study confirms that the El Niño–Southern Oscillation (ENSO) significantly affects the hydrological performance of the Saguling Hydroelectric Power Plant.

Analysis of 39 years of rainfall and inflow data shows that El Niño events cause rainfall and inflow to drop by up to 60%, especially from May to September, posing serious challenges to power generation. In contrast, La Niña increases rainfall and inflow by around 20%, supporting electricity production and reservoir stability. The negative correlations between ONI and both rainfall ($r = -0.41$) and inflow ($r = -0.45$) further validate ENSO's dominant role, while wavelet analysis reveals 2–4 year periodicities tied to ENSO cycles.

These results highlight the vulnerability of hydropower to climate variability and the urgent need to integrate ENSO-based forecasting into reservoir operations and national energy planning. Adaptive measures such as dynamic water regulation, flexible turbine use, and early warning systems for climate extremes are essential for long-term resilience. Future research should consider broader system coordination, land-use changes in the watershed, and the combined effects of other ocean-atmosphere patterns.

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