MORFAI JOURNAL Multidisciplinary Output Research For Actual and International Issue

Multidisciplinary Output Research For Actual and International Issue(MORFAI Journl) ISSN (e): 2808-6635
Volumes 5 No. 2 (2025)

THE IMPACT OF ENSO PHENOMENA ON ELECTRICITY PRODUCTION AT MRICA HYDROELECTRIC POWER PLANT IN CENTRAL JAVA (2013-2023)

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Received	: 18 February 2025	Published	: 26 April 2025
Revised	: 28 February 2025	DOI	: https://doi.org/10.54443/morfai.v5i2.2810
Accepted	: 22 March	Link Publish	: https://radjapublika.com/index.php/MORFAI/article/view/2810

Abstract

This study investigates the impact of the El Niño Southern Oscillation (ENSO) on electricity production at the Mrica Hydroelectric Power Plant (PLTA Mrica) in Central Java from 2013 to 2023. ENSO is global climate phenomenon, influences rainfall and ocean circulation in various regions, including Indonesia. Data on rainfall and river discharge from the Serayu River were analyzed to determine how ENSO affects the operational efficiency of PLTA Mrica. The study reveals that strong El Niño events, such as those in 2015, significantly reduced river discharge, leading to decreased electricity production. Conversely, the La Niña event in 2020 increased river discharge, enhancing electricity production. The findings underscore the critical need for adaptive water resource management and continuous monitoring to optimize electricity generation at PLTA Mrica, particularly in the face of climate variability induced by ENSO. This research contributes to understanding the relationship between climate phenomena and hydroelectric power generation.

Keywords: ***Electricity production, ENSO, Merit order method, Water inflow***

INTRODUCTION

El Niño is a sea surface temperature anomaly phenomenon occurring in the Pacific Ocean, characterized by significant warming in the central and eastern equatorial Pacific (Yoon et al., 2012). This phenomenon can last from several months to over a year. Its impact on global weather systems is widespread, affecting rainfall patterns, temperature, and atmospheric circulation (Aziis et al., 2025). Studying the effects and implications of the El Niño-Southern Oscillation (ENSO) is crucial for enhancing understanding and improving mitigation strategies. ENSO not only affects general weather and climate conditions but also has significant implications for the energy sector, particularly in the operation of power plants. PT PLN (Persero), Indonesia's primary electricity provider, faces challenges in operating power plants efficiently and reliably. The operation of these plants is not only aimed at meeting electricity demands quickly and reliably but must also be efficient to minimize operational costs and reduce the use of fossil fuels. The Meteorology, Climatology, and Geophysics Agency (BMKG) of Central Java has recorded various weather conditions affecting rainfall and the flow of the Serayu River, which is the main water source for the Mrica Hydroelectric Power Plant (PLTA) during the 2013–2023 period (BMKG, 2023). Global climate change and the ENSO phenomenon significantly influence rainfall patterns in Central Java, including the Serayu River Basin (DAS). This phenomenon causes annual fluctuations in rainfall, directly affecting the water inflow of the Serayu River.

One method used to improve the efficiency of power plant operations is the merit order method. This method considers efficiency characteristics at certain loads, operating costs, plant type characteristics, and startup costs (Firmansyah et al., 2022). In the merit order context, hydropower plants (PLTA) are among the most efficient types of power plants due to their relatively low operating costs and non-reliance on fossil fuels. PLTA Mrica, located in Banjarnegara Regency, Central Java, has a capacity of 184.5 MW and an annual electricity production of approximately 564,000 MWh. This plant is one of the primary electricity suppliers in Java, particularly Central Java. To maximize production capacity, several factors must be considered, including machine readiness and the availability of water inflow. Data indicates fluctuations in the capacity factor (CF) trend of PLTA Mrica during the 2013–2022 period. In addition to sediment dredging, the primary factor affecting the CF is water inflow, which is influenced by the wet and dry seasons. This study aims to evaluate whether the ENSO phenomenon significantly impacts electricity production at PLTA Mrica. By understanding the influence of ENSO, better mitigation strategies can be developed to ensure efficient and stable plant operations and reduce reliance on fossil fuel-based power plants.

LITERATURE REVIEW

The El Niño-Southern Oscillation (ENSO) is a climate phenomenon characterized by variations in sea surface temperatures in the Pacific Ocean, which have widespread impacts on global weather patterns, including rainfall, temperature, and atmospheric circulation. The two primary phases of ENSO, El Niño and La Niña, affect climate conditions differently. El Niño is associated with warmer sea surface temperatures and often leads to reduced rainfall in Indonesia, while La Niña is characterized by cooler sea surface temperatures and increased rainfall in the region. These changes in weather patterns directly affect water availability, river flow, and consequently, the operation of hydropower plants (Ramdhan & Afni, 2023).

Hydropower plants, such as PLTA Mrica, rely heavily on consistent water inflow for optimal electricity production. Variations in river discharge caused by ENSO phases can impact the volume of water entering the reservoir, which in turn affects the plant's ability to generate electricity. During El Niño phases, reduced rainfall typically results in lower water levels, leading to a decrease in power generation. Conversely, La Niña brings higher rainfall and increased river discharge, which enhances the plant's electricity production capacity.

In the energy sector, especially in hydropower generation, the ability to manage and mitigate the effects of ENSO is critical for ensuring efficient and stable operations. PT PLN (Persero), as the primary electricity provider in Indonesia, must adapt its operations to respond to these climate-induced changes. By employing strategies such as the merit order method, the company can optimize its plant operations based on efficiency and cost, especially in times of fluctuating water availability due to ENSO. In this study, the theoretical framework revolves around the interaction between climate variability (ENSO) and hydropower production. The ENSO phenomenon serves as an external variable influencing rainfall patterns and river discharge, which are key determinants of hydropower efficiency. Based on this theoretical foundation, the following hypotheses are developed:

a. H1: The El Niño phase significantly reduces water inflow and, consequently, the electricity production at PLTA Mrica.
b. H2: The La Niña phase significantly increases water inflow and enhances electricity production at PLTA Mrica.

These hypotheses will be tested using historical data on water inflow, rainfall, and electricity production at PLTA Mrica over a ten-year period. Statistical analyses will determine whether ENSO phases have a significant impact on hydropower generation, helping to improve operational strategies and mitigate risks associated with climate variability. The Mrica Reservoir has a normal capacity of 157,000,000 m^3, with an active capacity of 47,000,000 m^3 and an inactive capacity of 110,000,000 m^3. The catchment area of the Mrica Reservoir covers 1,022 km^2, with a surface area of 1,250 hectares (Wirjohamidjojo & Swarinoto, 2010). This reservoir, as illustrated in Figure 1, is utilized for the Mrica Hydroelectric Power Plant (PLTA), which is managed by PLN Indonesia Power. The Mrica Hydroelectric Plant is a conventional power plant consisting of three turbines. Its installed capacity is 184.5 MW, with an annual electricity production of approximately 564,000 MWh.

Ensure that the literature review is well-organized, flowing smoothly between topics, and logically leading to your research questions or hypotheses. Proper citations and references are essential to uphold academic integrity and provide credit to original authors.

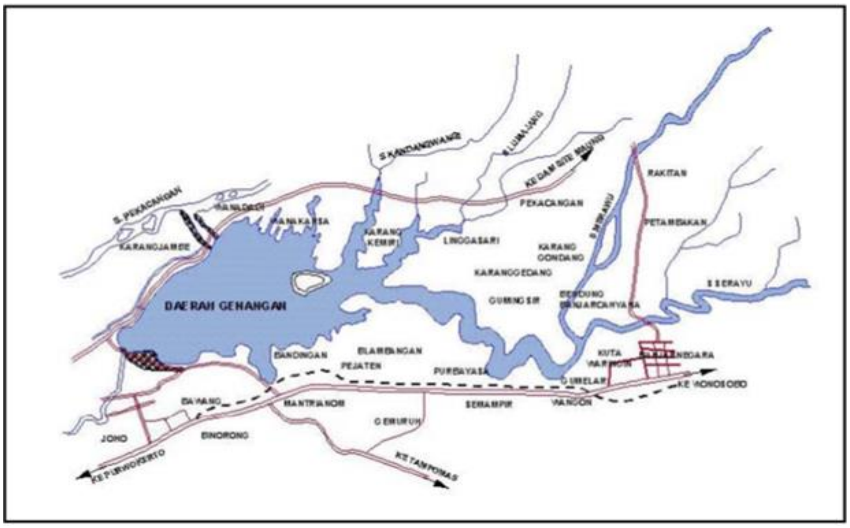

Figure 1: Layout of PB Soedirman Reservoir

This study focuses on analyzing various aspects related to the Mrica Reservoir and the Mrica Hydroelectric Power Plant (PLTA). The scope and limitations of the research are clearly defined to ensure precision and direction. The study will primarily examine the El-Niño Southern Oscillation (ENSO) phenomenon over a 10-year period from 2013 to 2023, specifically evaluating its impact on the water inflow into the Mrica Reservoir. Hydrological and meteorological data, including rainfall, water inflow, and recorded ENSO occurrences during the 2013–2022 period, will form the foundation of this analysis. Statistical methods will be employed to explore the correlation between the ENSO phenomenon, water inflow, and electricity production at the power plant (Chowdhury et al., 2021). Furthermore, the study will focus on measuring and analyzing water inflow into the Mrica Reservoir in relation to rainfall patterns affected by ENSO. A key objective of the research is to determine the relationship between water inflow and electricity production, measured in kilowatt-hours (kWh), at the Mrica Hydroelectric Power Plant.

METHOD

Data Collection

This study utilized a combination of primary and secondary data sources to analyze the impact of ENSO on the kWh production at PLTA Mrica. The primary data included daily water inflow measurements from the Serayu River, obtained from the PLTA Mrica site, and electricity production data provided by PT PLN (Persero). Meteorological data, including rainfall and temperature, were sourced from BMKG (Badan Meteorologi, Klimatologi, dan Geofisika) for the Central Java region. Additionally, we collected Oceanic Niño Index (ONI) data from the National Oceanic and Atmospheric Administration (NOAA) to identify ENSO phases (El Niño and La Niña). Satellite imagery data from the Global Precipitation Measurement (GPM) was also used to verify rainfall patterns and cross-validate ground-level measurements during the study period. The time period for data collection spanned from 2013 to 2023, encompassing multiple El Niño and La Niña phases, which provided a robust dataset for statistical correlation.

Time Series Analysis

The core of the analysis involved time series methods to establish the relationship between ENSO phases and hydrological variables, including water inflow and rainfall. Time series data was collected on a monthly basis for water inflow, rainfall, and electricity production. A time series decomposition technique was applied to separate the long-term trend from seasonal variations and irregular components in the data. The Oceanic Niño Index (ONI) was used to classify each year into different ENSO phases (El Niño, La Niña, or neutral). A classification threshold of ±0.5°C for the Niño 3.4 region was used to categorize the ONI values. El Niño years were identified as those where ONI > +0.5°C, while La Niña years were identified when ONI < -0.5°C.

Time Series Analysis

To determine the relationship between ENSO phases and water inflow, we applied Pearson correlation analysis between ONI values and monthly water inflow data. The correlation coefficient (r) provided an indication of the strength and direction of the relationship.

In addition to correlation analysis, a multiple regression model was developed to quantify the impact of ENSO on electricity production at PLTA Mrica. The independent variables included water inflow, rainfall, and ONI values, while the dependent variable was the monthly kWh production. The regression equation took the form:

$$\text{kWh Production} = \beta 0 + \beta 1\ (\text{River Discharges}) + \beta 2\ (\text{Rainfall}) + \beta 3\ (\text{ONI}) + \in$$

where β0 is the intercept, β1, β2, and β3 are the coefficients representing the effect of each variable on kWh production, and ϵ is the error term.

Hydrological Modeling

A hydrological model was constructed to simulate water inflow into PLTA Mrica based on rainfall data. The model used the hydrological equation:

$$Q = P \times A \times C$$

Where Q is the water inflow (m^3/s), P is precipitation (m), A is the catchment area (km^2), and C is the runoff coefficient, representing the percentage of rainfall that becomes surface runoff. The model was calibrated using observed water inflow data from PLTA Mrica and adjusted for seasonal variations in rainfall due to ENSO phases. To further assess the effect of ENSO on PLTA Mrica's electricity production, a simulation was conducted using the data from extreme ENSO years (2015 for El Niño and 2020 for La Niña). The simulation included inputting the water inflow and rainfall data during these years into the hydrological model to predict the expected impact on electricity production. The results were compared against actual production data to validate the accuracy of the model (Gonzalez-Salazar & Roger Poganietz, 2022).

RESULTS AND DISCUSSION

Water Inflow and Outflow Trends

The analysis of the water inflow and outflow data for PLTA Mrica from 2013 to 2023, as shown in **Table 1**, reveals significant fluctuations over the ten-year period, which are closely tied to ENSO phases. During El Niño years (e.g., 2015 and 2019), the inflow to the reservoir was notably lower (-19.57%) than average due to reduced rainfall in the region. This decrease in inflow led to a corresponding reduction in the outflow, which ultimately limited the power generation capacity of the plant during these periods.

Table 1. Table of Relationship Between ENSO Phase and Average Annual Inflow and Outflow of Mrica Hydroelectric Power Plant

Year	ENSO Phase	Average Inflow (m^3/s)	Average Outflow (m^3/s)
2013	Neutral	77.68	63.24
2014	Neutral	69.48	54.83
2015	El Niño	68.11	59.05
2016	La Niña	109.01	97.19
2017	Neutral	91.94	81.49
2018	La Niña	73.91	57.57
2019	El Niño	62.40	51.56
2020	La Niña	81.17	56.76
2021	Neutral	87.28	80.22
2022	La Niña	94.85	64.00
2023	Neutral	56.74	44.83

In contrast, during La Niña years (e.g., 2016, 2020 and 2022), the inflow to the reservoir increased significantly due to above-average rainfall. The data show that the water inflow during La Niña events was typically 10.6 % higher than the average year. This surge in inflow allowed for greater water availability in the reservoir, resulting in higher outflows and consequently, increased electricity production. The analysis of trends and correlations reveals that during El Niño years, characterized by reduced rainfall, the inflow rates slightly decrease, while outflow management strategies become more conservative to maintain adequate reservoir levels for power generation and other uses. Conversely, during La Niña years, increased rainfall leads to higher inflow and outflow rates, allowing for greater water capture and controlled releases without compromising reservoir levels. In neutral years, the inflow and outflow rates tend to balance around the historical average, reflecting typical hydrological patterns without significant climatic disruptions.

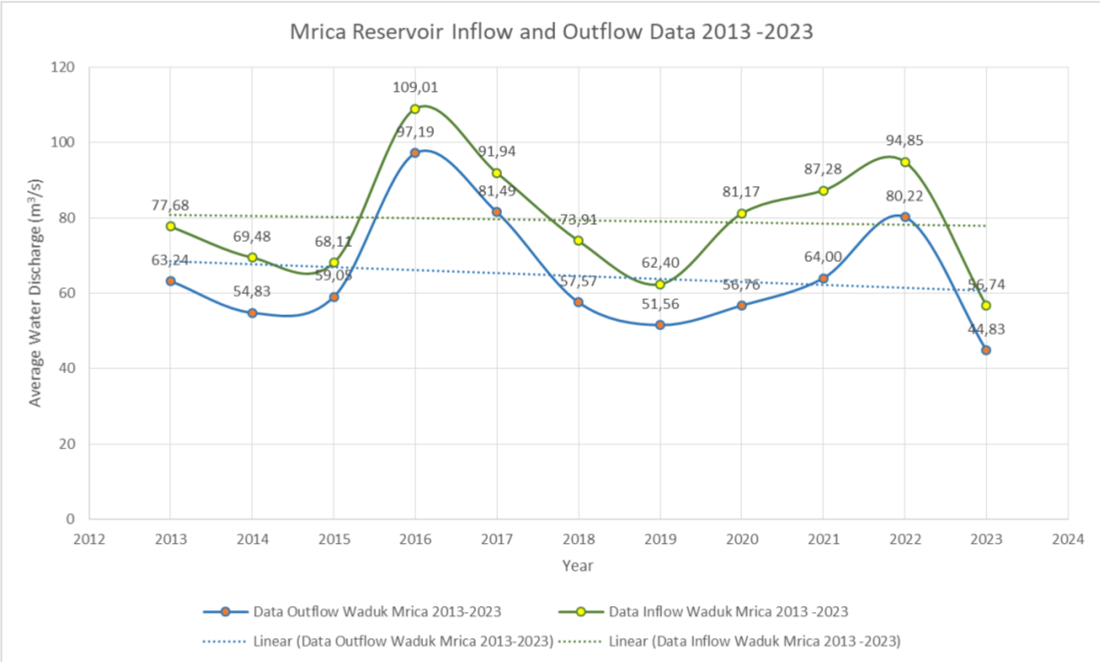

Figure 2: Mrica Reservoir Inflow and Outflow Data 2013 – 2023

Relationship Between Reservoir Elevation and Rainfall Data at Mrica Hydroelectric Power Plant

In the analysis of the hydrological dynamics at the Mrica Hydroelectric Power Plant, rainfall data, sourced from the ERA5 Copernicus dataset, plays a critical role. Figure 3 illustrates the temporal variations in rainfall data, which ERA5 provides as hourly data on a range of atmospheric variables at a high spatial resolution, offering a comprehensive and accurate depiction of weather patterns. This dataset is instrumental in assessing the direct impact of rainfall on the reservoir's water levels. The correlation between rainfall intensities and the corresponding changes in reservoir elevation is vital for understanding water inflow patterns and managing water resources effectively (Harger, 1995). By integrating rainfall data from ERA5 with measurements of reservoir elevation, we can accurately model and predict the hydrological responses of the reservoir to different climatic conditions. This integration is particularly crucial during periods of significant weather anomalies, such as those induced by the El Niño-Southern Oscillation (ENSO) phases, which can dramatically alter rainfall patterns and, consequently, reservoir levels at Mrica.

There are indications of rainfall fluctuations over the period from 2003 to 2023 and elevation data of Mrica Reservoir from 2013 to 2023, with a particular focus on the significant ENSO years of 2015 and 2019. Figure 4 highlights this variability, where in 2015, there was a significant decrease in rainfall. This year was known as a strong El Niño year, which is typically associated with drier conditions in some regions but can also lead to extreme weather conditions including decreased rainfall in other areas. The elevation data shows a decline in 2015, consistent with the reduced rainfall. This decrease might have been compounded by other factors such as increased evaporation due to higher temperatures during El Niño. The year 2019, also marked as an El Niño year, shows a decline in rainfall, evident in the second red box on the graph. This year would typically be dry in regions like Indonesia, and the data displays a decrease in rainfall consistent with the expectations from an El Niño phenomenon. The elevation data also shows a continuous decline from 2019 to 2020, which may reflect the cumulative impact of reduced rainfall during this period, in line with the expectations of El Niño bringing drier conditions.

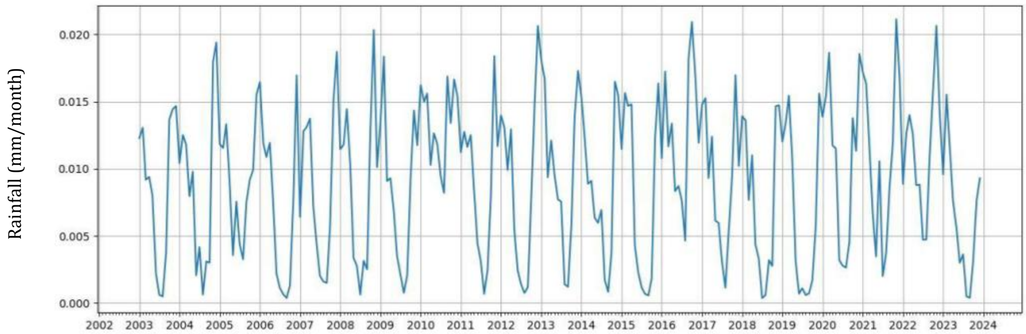

Figure 3: Rainfall Data for the period 2003 - 2023 (20 Years)

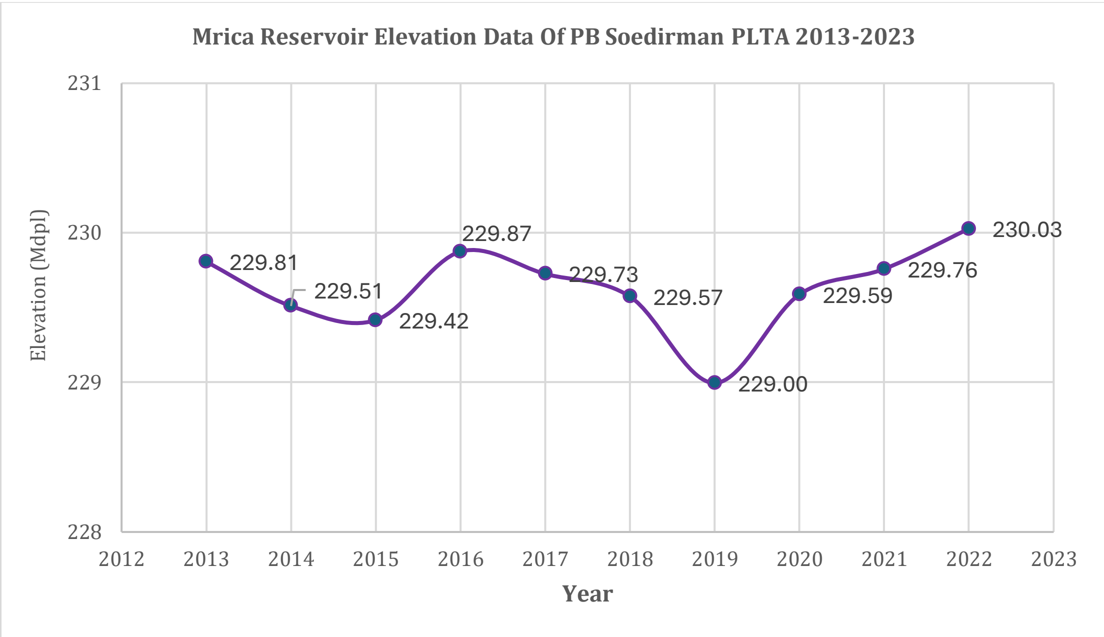

Figure 4: Mrica Reservoir Elevation Data of PB Soedirman PLTA 2013-2023

Results of Water Discharge Data Processing on ENSO and kWh Electricity Production

Sufficient and stable water discharge allows the turbine to operate at optimal capacity. When the water discharge is low, the electricity production capacity can decrease, resulting in less efficient use of resources and potential loss of energy that could be generated (Perdinan et al., 2023). In optimal water discharge conditions, the turbine can operate at maximum efficiency, producing electricity at a lower cost. Electricity production at the Mrica Hydroelectric Power Plant is highly dependent on the availability of water from the Serayu River. When the water discharge is high, the Mrica Hydroelectric Power Plant can produce more electricity to meet the energy needs of the community in Central Java and its surroundings. Conversely, when the water discharge is low, electricity production can decrease, which can result in a deficit in electricity supply and potential power outages. The water discharge at the Mrica Hydroelectric Power Plant is a critical factor affecting the operational efficiency, electricity production, environmental sustainability, and economic impact of the power plant.

Therefore, good management of water resources in the Mrica Reservoir is essential to ensure the continuity and optimization of the Mrica Hydroelectric Power Plant's operations. In this study, we conducted a direct site visit to the Mrica Hydroelectric Power Plant to be able to observe and understand the actual conditions of the Mrica Hydroelectric Power Plant, the Panglima Besar Sudirman Dam (Name of the Mrica Hydroelectric Power Plant Dam), the Serayu River, and obtain direct explanations from the Geotechnical and Reservoir Hydrology (GHW) Team of the Mrica Hydroelectric Power Plant.

In 2015, the kWh sales at the Mrica Hydroelectric Power Plant experienced a significant decline due to the impact of a strong El Niño event. This phenomenon, one of the most intense El Niño events in recorded history, led to a substantial reduction in rainfall across Indonesia, including in the Serayu River Basin, which supplies water to the plant. The decreased rainfall resulted in lower river discharge and reduced water inflow into the reservoir, critically affecting the plant's ability to operate at optimal capacity. **Table 2** illustrates the monthly kWh sales data, highlighting that during key months such as June, July, August, and September 2015, electricity production dropped significantly, with September recording one of the lowest monthly outputs at 2,646,501 kWh. The reduced water availability directly limited turbine operations, highlighting the plant's dependency on stable and sufficient water discharge.

Table 2. Mrica Hydroelectric Power Plant kWh Sales Production Data 2013 – 2023

	2013	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
January	83,064,686	48,618,817	73,905,914	31,578,209	70,443,029	78,132,991	81,036,781	61,124,307
February	63,887,894	28,409,705	72,106,897	43,948,816	83,986,098	85,756,876	70,249,854	62,378,888
March	37,311,159	42,583,238	63,014,312	87,554,012	79,130,013	75,599,427	86,312,570	75,479,224
April	76,954,007	43,386,047	82,914,387	65,844,460	71,871,054	45,299,928	66,165,552	49,046,015
May	40,513,559	32,414,211	41,657,310	69,027,368	31,657,175	23,104,361	29,413,489	46,333,488
June	29,392,023	25,625,584	11,969,625	53,178,715	23,104,361	9,509,459	10,200,378	14,942,164
July	29,600,332	30,916,896	4,010,499	35,416,422	8,880,295	2,610,823	3,122,765	6,456,695
August	11,202,741	18,191,594	4,217,558	22,614,314	9,587,278	1,070,743	116,839	4,504,738
September	9,764,831	5,500,144	2,646,501	59,167,993	12,671,257	6,086,627	3,180,129	9,645,650
October	14,537,761	8,873,437	3,414,004	79,848,191	49,704,343	6,867,190	3,979,324	38,785,091
November	23,830,790	39,093,995	22,858,629	91,257,031	70,684,322	28,225,338	8,126,545	41,431,216
December	64,299,977	94,933,466	54,877,858	81,876,785	64,083,435	66,508,287	32,552,142	11,282,757

This case underscores the vulnerability of hydroelectric power generation to extreme climatic events like El Niño, emphasizing the need for adaptive water resource management and climate-resilient operational strategies to mitigate future risks. The highest electricity production was recorded in 2016, likely influenced by the La Niña phenomenon, which typically increases rainfall and river discharge, supporting optimal operations at the Mrica Hydroelectric Power Plant. In contrast, the lowest average electricity production occurred in 2023, as shown in **Table 2**, potentially due to drought or reduced water discharge, reflecting the influence of climate variability and the need for adaptive strategies in hydropower management.

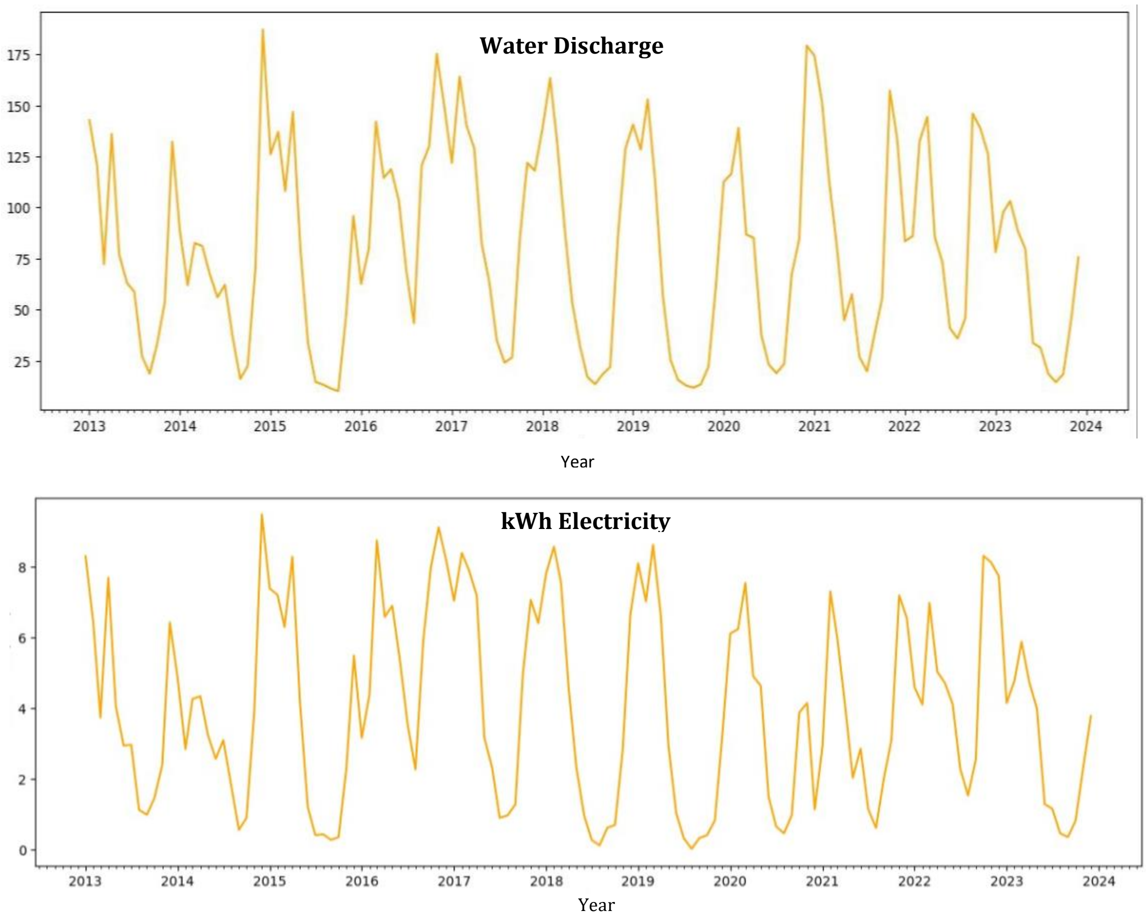

Figure 5. Water Discharge and kWh Electricity Production of Mrica Hydroelectric Power Plant 2013 – 2023

To convert water discharge data into electricity production in kWh for hydropower plants, we need to follow several steps. First, we must understand the relationship between water discharge, potential energy, and kinetic energy produced. Then, we can calculate the energy produced based on the given water discharge data. The potential energy of water falling into the turbine is converted into kinetic energy and finally into electricity. The energy conversion efficiency (η) is usually around 90% or 0.9 for modern hydro turbines. The electrical energy produced (E) in kWh can be calculated from potential energy by considering turbine efficiency. Combine all formulas to get electrical energy from water discharge. Consistent and optimal water discharge is essential to ensure that the turbine can operate at maximum capacity and generate electricity efficiently. Irregular discharge fluctuations can reduce the efficiency of electricity production and affect the stability of the energy supply. Below is shown data on in-situ water discharge and electricity production which researchers took directly from the Mrica hydropower location. ENSO (El Niño-Southern Oscillation) is a climate phenomenon that has a significant influence on rainfall patterns and water discharge in various regions of the world, including Indonesia. ONI (Oceanic Niño Index) is one of the parameters used to measure the El Niño and La Niña phases based on sea surface temperature anomalies in the equatorial Pacific. Changes in the ENSO phase can affect the water discharge entering the hydroelectric power reservoir, which in turn affects electricity production.

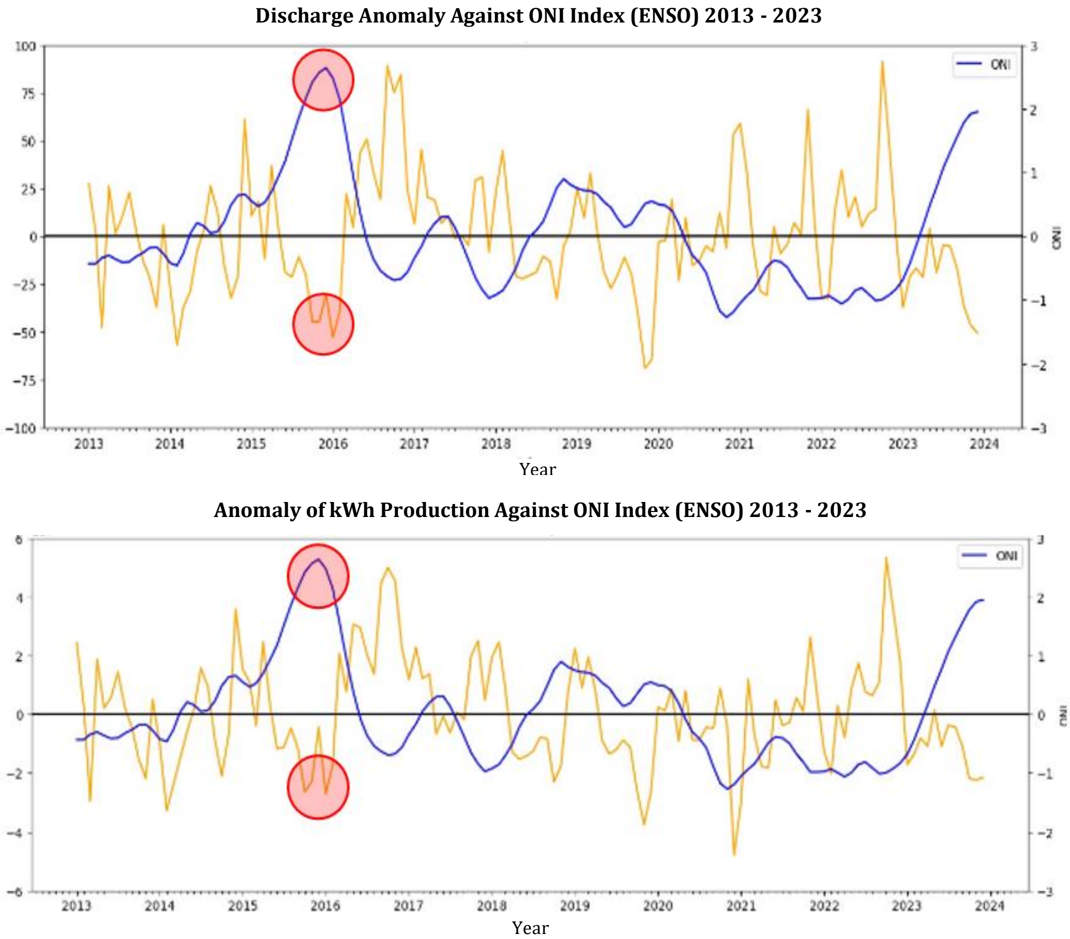

Figure 6. Water Discharge and Electricity Production Anomalies Against ONI Index

Figure 6. showcase the relationship between the Oceanic Niño Index (ONI) and both discharge anomalies and electricity production anomalies from 2013 to 2023. The graphs reveal the impact of ENSO phases on the operational dynamics of the hydroelectric power plant in terms of both water management and electricity generation. The top graph illustrates the fluctuations in discharge anomalies against the ONI index. It is evident from the graph that significant peaks in discharge anomalies correspond with negative phases of the ONI, indicating La Niña events, which are typically associated with increased rainfall and therefore higher water inflow to the reservoir. Notably, the peak around 2016 suggests a significant La Niña effect resulting in increased discharge. Conversely, the troughs, especially around 2015 and 2019, correspond with positive ONI values indicative of El Niño events. These periods show marked reductions in discharge, aligning with the expected decrease in rainfall during El Niño, which subsequently impacts the reservoir's inflow.

The lower graph plots electricity production anomalies against the ONI index over the same period. Similar to the discharge anomalies, electricity production is closely tied to the ONI phases. During La Niña years, as exemplified around 2016, there is a noticeable increase in electricity production, which correlates with higher water availability from increased discharge rates. On the other hand, during El Niño years like 2015 and 2019, there is a significant drop in production, mirroring the reduced discharge and lower water levels in the reservoir. Both graphs clearly demonstrate that ENSO phases significantly influence the operational parameters of hydroelectric power facilities. La Niña phases typically boost both discharge and electricity production due to enhanced water availability, while El Niño phases constrain these activities due to water scarcity. These insights are crucial for predicting and managing the operational capabilities of hydroelectric plants in response to climatic variations.

Annual average discharge offers a comprehensive perspective on river discharge conditions over prolonged periods, which is essential for conducting long-term analyses to discern trends and seasonal patterns in water discharge. Such analyses are crucial for determining the impact of daily discharge on electricity production at Hydroelectric Power Plants (HPPs) and understanding their responses to climatic factors like the El Niño-Southern Oscillation (ENSO). Additionally, this data serves several key functions: it acts as a comparative reference that provides a baseline for comparing fluctuations in daily and monthly discharge; it aids in identifying long-term patterns that could be indicative of climate change or other influential factors affecting water discharge; and it supports operational planning and water management at HPPs by offering essential baseline data for predictive purposes.

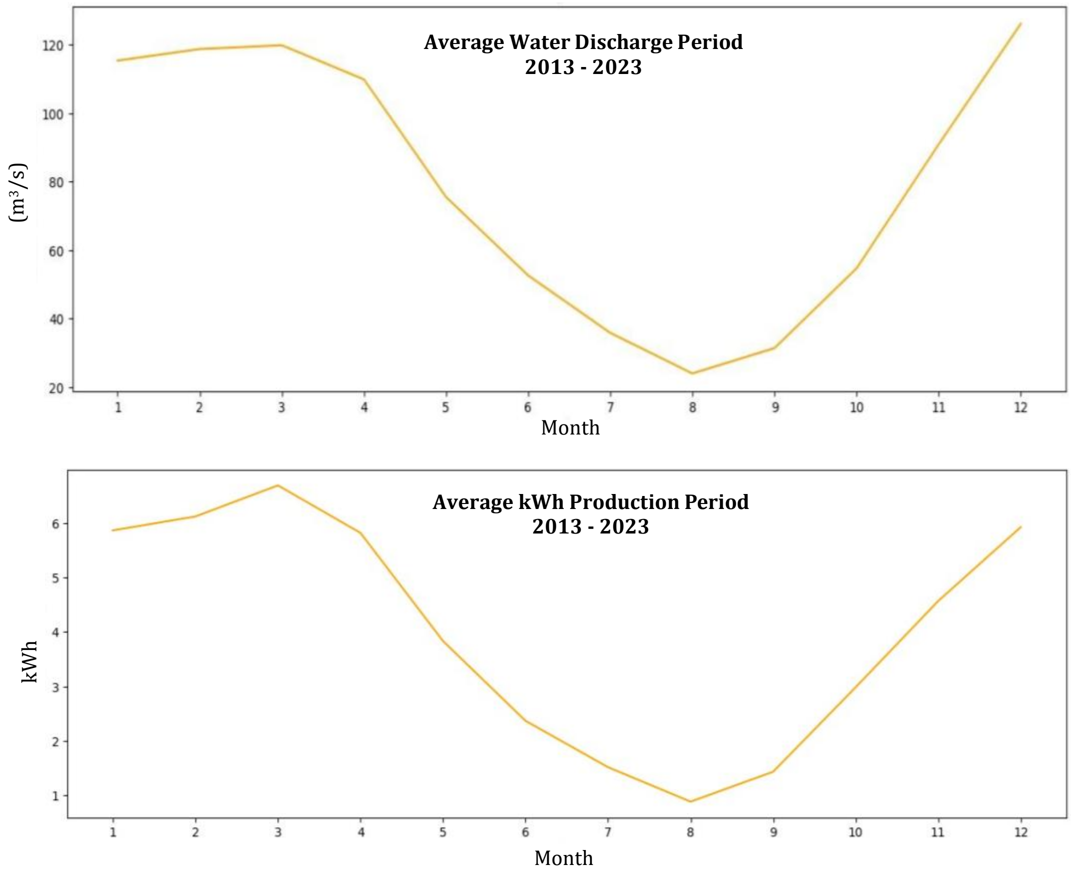

Figure 7. Average Electricity Discharge and kWh Production for the Period 2013-2023

In **Figure 7**, it can be seen that in the JJA season period (June-July-August) in each year from 2013-2023, there was a decrease in water discharge due to the factor of entering the dry season, and began to increase in the transition season in SON (September-October-November). Researchers often choose significant ENSO events such as the 2015 El Niño and 2020 La Niña to study the relationship between water discharge data and ENSO phases due to their large impacts on hydrological patterns, as shown in the time series results in **Figure 6**. This choice is based on several factors: First, the 2015 El Niño was one of the strongest recorded, resulting in significant global weather disruptions, while the 2020 La Niña is noted for its intensity and broad impact on global weather patterns. Second, these events are characterized by rich, well-documented data, allowing for more accurate and in-depth analysis. Third, by analyzing both extreme conditions of ENSO, researchers can understand the full spectrum of its influence on water discharge and electricity production, which is crucial for the operational management of hydroelectric power plants. Fourth, this research is also important in the context of climate change, where understanding the influence of ENSO on hydrological cycles becomes increasingly vital. These studies not only enhance our understanding but also aid in more effective planning and management amidst climate uncertainties.

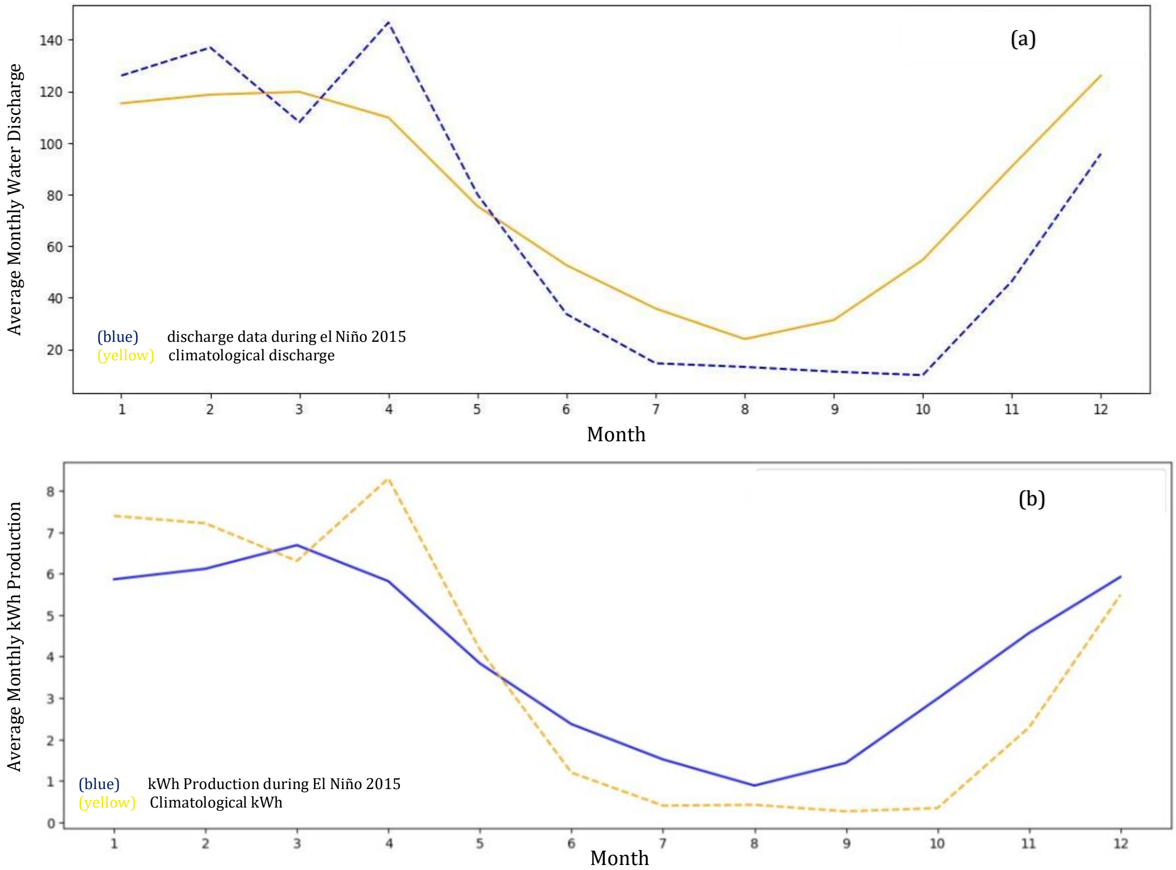

Figure 8. (a) Climatological discharge against discharge during El Niño 2015 & (b) Climatological kWh against kWh Production during El Niño 2015

The year 2015 was a significant period in the context of ENSO because of a strong El Niño, affecting weather patterns and water discharge in various regions, including Indonesia. Water discharge data during the year are important to understand the impact of ENSO on water resources. The context of ENSO in 2015 was the 2015 El Niño which was one of the strongest in history, with the ONI peaking at +2.6°C in November-December 2015. It had a global impact, resulting in extreme weather conditions around the world, including droughts in parts of Southeast Asia and floods in other parts. In **Figure 8**, it can be seen that the discharge data during El Niño in 2015 was lower than the climatological data for the total discharge for the 2013-2023 period and the amount of discharge during the SON season (September-October-November) was lower, indicating that El Niño was strong during that period. However, in March, there was a significant decrease due to the drought anomaly due to rainfall that fluctuated again in April (La Niña) by 0.2. Of course, this is likely due to the influence of annual variability in the Banjarnegara area of East Java, which is not included in the scope of this calculation.

Variability in rainfall patterns and water discharge are critical factors affecting the performance of the Mrica Hydroelectric Power Plant (PLTA). Rainfall in the river basin (DAS) affects the volume of water entering the reservoir, and in turn, the resulting water discharge will determine how much energy the hydroelectric power plant can produce. During the El Niño phase, there is usually a decrease in rainfall in Indonesia, which can cause a decrease in water discharge in watersheds and hydropower reservoirs. Conversely, the La Niña phase often causes an increase in rainfall, which can increase water discharge. In the MAM period (March-April-May) 2015 there was a change in kWh production at Mrica Hydroelectric Power Plant, which was positively correlated with graphic in **Figure 8(b)** Climatological Discharge against discharge during El Niño 2015, where the increase in water discharge in that month had an impact on the increase in kWh Production from Mrica Hydroelectric Power Plant. On the other hand, in the AMJ period (April-May-June) there was a decrease in kWh production from the Mrica Hydroelectric Power Plant which was also influenced by the decrease in water discharge at the Mrica Hydroelectric Power Plant at that time. Next, we will compare it with the La Niña period in 2020, where we know that in 2020 there was a high discharge anomaly. And based on ONI index data for that period, it is true that there was a strong La Niña influence.

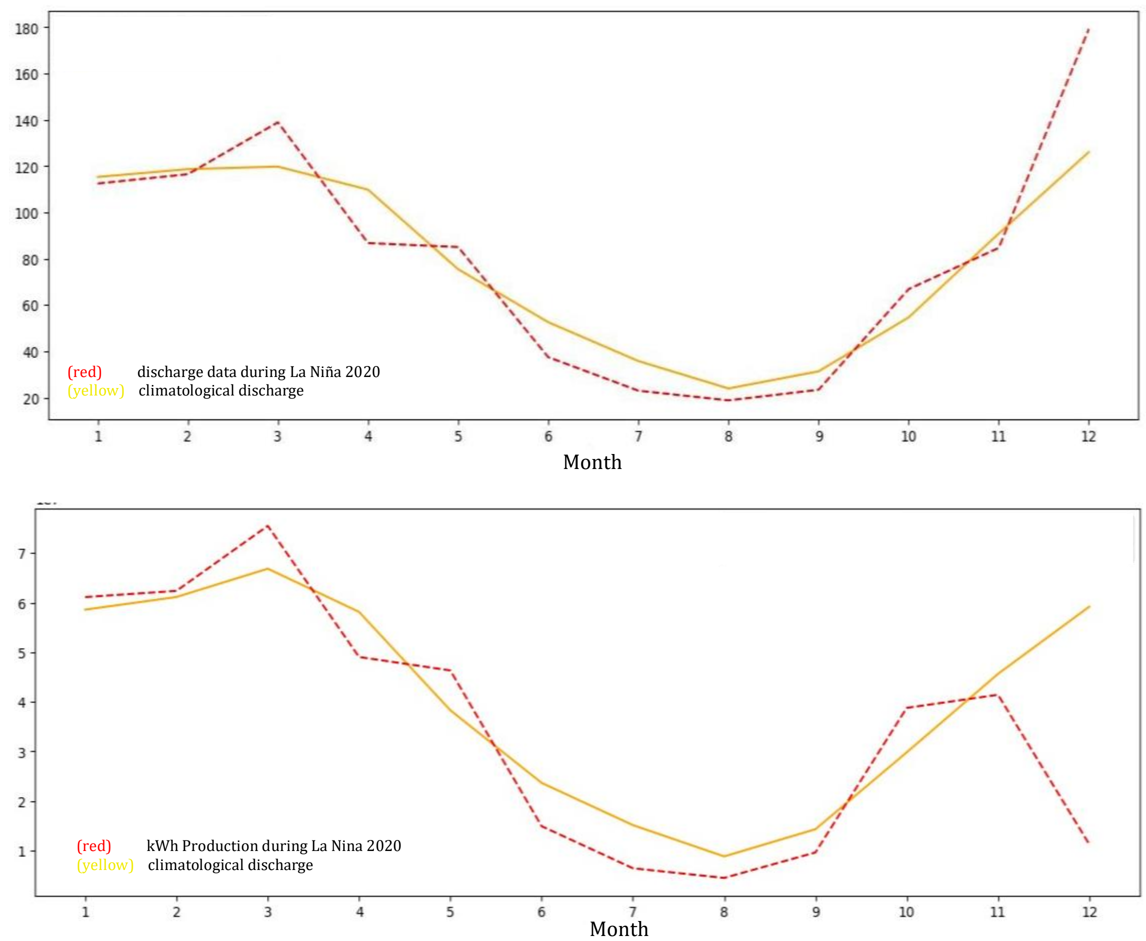

Figure 9. (a) Climatological discharge against discharge during La Niña 2020 & (b) Climatological kWh against kWh Production during La Niña 2020

From **Figure 9(a)**, it is evident that water discharge at the Mrica Hydroelectric Power Plant significantly increased during the MAM (March-April-May) and SON (September-October-November) seasons, with a further rise observed during the DJF (December-January-February) wet season. This spike in water discharge reflects the strong impact of the La Niña 2020 phenomenon, which brought increased rainfall to the Serayu River Basin, the primary water source for the PB Sudirman Reservoir. The elevated water discharge during these periods ensured sufficient water availability for turbine operations, enabling optimal plant performance. The correlation between water discharge and electricity production is clearly illustrated in **Figure 9(b)**. The trend in kWh production closely follows the rise in water discharge, with noticeable increases during the MAM and SON seasons and reaching its peak during the DJF wet season. This demonstrates that the higher water discharge associated with La Niña directly supported the increased electricity production, enabling the turbines to operate at their maximum efficiency. This pattern highlights a strong positive correlation between water discharge and electricity production. Higher water discharge during La Niña, driven by increased rainfall, provides an abundant water supply for turbine operations, resulting in higher electricity output compared to climatological averages. Conversely, during drier periods, such as during El Niño events, reduced water discharge leads to significantly lower electricity production.

The La Niña 2020 event underscores the substantial influence of climatic variability, such as ENSO, on the operations of the Mrica Hydroelectric Power Plant. The significant increase in water discharge during La Niña highlights the importance of adaptive water resource management to optimize electricity production during wet periods. Given the plant's reliance on water from the Serayu River, understanding and leveraging climate variability like La Niña is crucial for maintaining stable electricity production and enhancing operational efficiency. This analysis emphasizes the need for long-term planning and adaptive strategies to manage the impacts of climate variability on hydropower operations.

Results of the Influence of Average Water Discharge Data on Average kWh Production

The research conducted over the period from 2013 to 2023 explores the dynamic relationship between average water discharge and average kWh production in the context of climate change and variability brought about by the El Niño-Southern Oscillation (ENSO) phenomenon (Qian et al., 2010). Over the past decade, significant fluctuations in weather patterns induced by the El Niño and La Niña phases have provided unique opportunities to analyze the direct impacts of hydrological variability on hydroelectric power generation capacity (Rahma & Ludwig, 2024). The focus of this analysis is to identify how variations in water discharge during this period have affected electricity output at hydroelectric power plants, with particular emphasis on the observed variations during years when El Niño and La Niña conditions predominated. The findings from this study are not only crucial for the operational optimization of hydroelectric facilities but also for strategic planning and water resource management in the face of increasingly unpredictable climate changes. To find out the significant effect on climatological water discharge and discharge data during El Niño and La Niña, it can be seen from the **Figure 10** graph. It can be concluded that the effect of active ENSO El Niño on climatological water discharge has a significant effect where during the wet season in DJF (December-January-February) the discharge decreased by an average of approximately 20 m^3/second in January and when La Niña was active there was an increase in discharge in 2020 of 30 m^3/second in the transitional season in November.

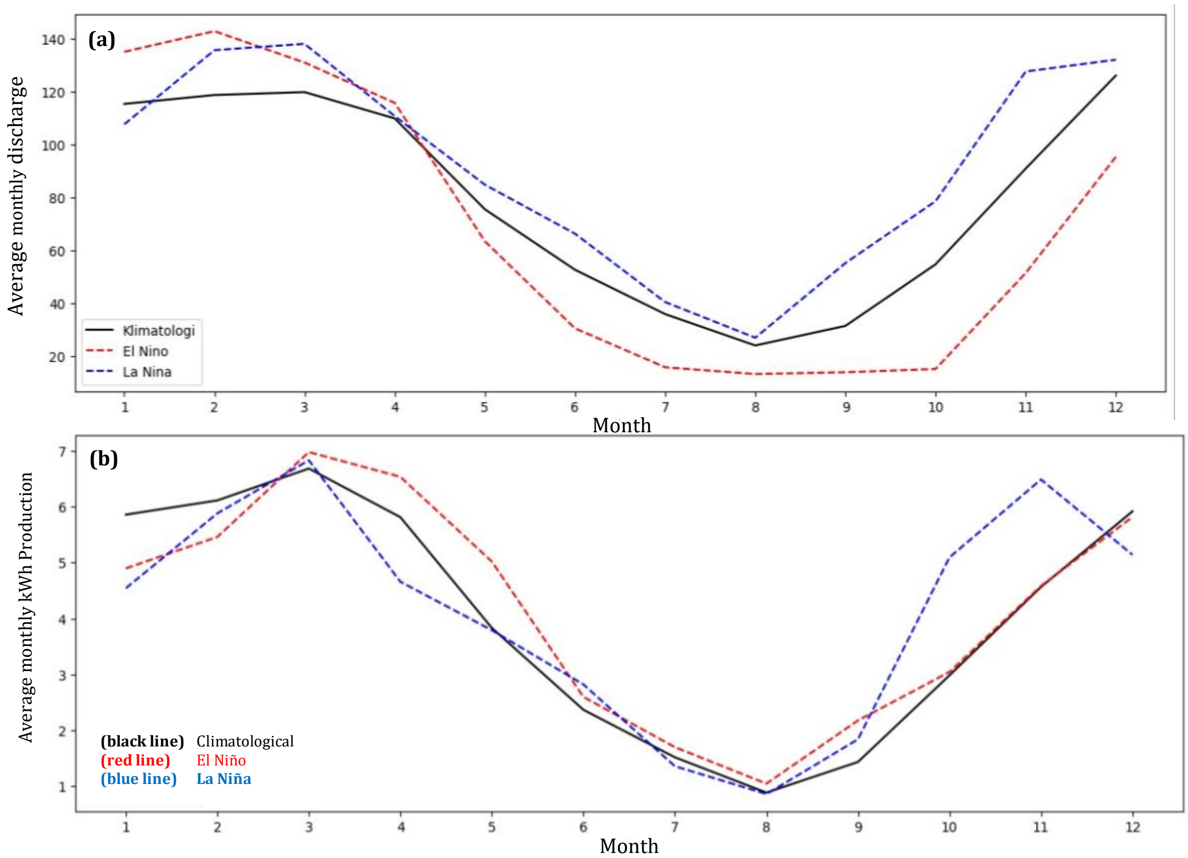

Figure 10. Results of the Influence of Average Water Discharge Data on Average kWh Production in the ENSO Period 2013 - 2023 (10 years)

Figure 10 illustrate the monthly average discharge rates and electricity production across a 10-year span from 2013 to 2023, with specific focus on the typical climatological patterns and the variations caused by the El Niño and La Niña phenomena. These visualizations offer a clear depiction of how these climatic anomalies impact hydroelectric power generation. The climatological average (black line) shows a typical seasonal pattern with peak discharge rates occurring around the beginning and end of the year, and lower rates during the middle months. During El Niño years (red dashed line), the discharge rates are consistently lower than the climatological average throughout the year, especially pronounced from mid-year through the end. This decrease in water inflow during El Niño reflects the drier conditions typically associated with this phase, which limits the water available for generating hydroelectric power. Conversely, during La Niña years (blue dashed line), the discharge rates are noticeably higher than the average, particularly from mid-year onwards. La Niña often brings enhanced rainfall, increasing the river discharge into reservoirs, which boosts the potential for higher electricity production. Similar to the discharge rates, the electricity production follows a seasonal pattern, peaking during the months with higher water availability. Under El Niño conditions, electricity production is significantly reduced (red dashed line) compared to the climatological norm. This is directly correlated with the reduced discharge rates, as less river discharge translates directly into reduced capacity for power generation. During La Niña conditions (blue dashed line), there is a substantial increase in electricity production, aligning with the increased discharge rates seen in the **Figure 10(a)**. The surplus water not only meets the regular demand but allows the plant to operate at or near its maximum capacity, leading to peaks in production during these years.

The data clearly shows that El Niño and La Niña phases have a direct and significant impact on hydroelectric power generation, primarily through their influence on water availability. El Niño typically results in lower water levels and thus reduced power output, while La Niña tends to boost both water levels and electricity production. Understanding these patterns is crucial for effective water resource management and planning in hydroelectric operations, enabling better preparedness and optimization of resources in response to climatic variations. This analysis underscores the importance of integrating climatological data into the operational strategies of hydroelectric facilities to mitigate the impacts of ENSO-related variations and ensure a stable energy supply.

CONCLUSION

The El Niño Southern Oscillation (ENSO) significantly impacted the operational efficiency of the Mrica Hydroelectric Power Plant (PLTA Mrica) in Central Java over the decade from 2013 to 2023. This period, marked by distinct phases of El Niño and La Niña, provided a rich dataset for analyzing how these climatic phenomena affect rainfall, water inflow from the Serayu River, and subsequently, electricity production. The years characterized by El Niño, notably 2015, showed a considerable reduction in water inflow. This reduction was directly linked to decreased rainfall and resulted in lower electricity production at PLTA Mrica. Conversely, 2020's La Niña phase saw increased water inflow, which correlated with higher electricity production. This boost in water availability directly enhanced the power generation capacity of the plant. The variability induced by ENSO has led PLN Indonesia Power, the managing entity of PLTA Mrica, to incorporate ENSO forecasts into their operational strategies. Collaboration with BMKG Jawa Tengah to predict these phenomena helps in preparing and adjusting operational measures in anticipation of the changes in water inflow.

During El Niño years, there is typically a reduction in water discharge due to decreased rainfall, resulting in lower electricity production. The years 2015 and 2019 exemplify this trend, showcasing significant drops in water levels and corresponding reductions in electricity outputs. Conversely, La Niña years, such as 2016 and 2020, experienced increased rainfall, leading to higher water discharges and subsequently enhanced electricity production. The fluctuations in water discharge influenced by ENSO phases present both challenges and opportunities for maintaining consistent electricity output. These variations pose a challenge in ensuring steady electricity production and offer an opportunity to leverage periods of high water availability to maximize power generation. This situation demands flexible and adaptive management strategies to optimally utilize these conditions, addressing shortages during dry periods and enhancing production capacity during wet periods.

The data collected during the ENSO period demonstrates a significant correlation between ENSO phases and fluctuations in water discharge as well as electricity production. During El Niño periods, there tends to be a decrease in water discharge which negatively impacts electricity production, whereas during La Niña, increased water discharge contributes to higher electricity production at the Mrica Hydroelectric Power Plant (HPP). According to the team from the Geotechnical and Hydrology Reservoir (GHR) section of Mrica HPP, PLN Indonesia Power, the operator of the Mrica HPP, has also made ENSO phenomena one of the reference parameters in forecasting kWh sales production. In this effort, PLN Indonesia Power has a collaborative agreement with BMKG Central Java for the prediction of potential ENSO events.

The study underscores the necessity of adaptive management strategies in hydroelectric power generation, particularly in regions prone to significant climatic variations caused by ENSO. It highlights the importance of continuous monitoring and flexible operational planning to optimize electricity production amidst climatic uncertainties. This research not only aids in operational adjustments at PLTA Mrica but also contributes to the broader understanding of the interplay between climate phenomena and renewable energy production. Recommendations to enhance operational resilience and efficiency at the Mrica Hydroelectric Power Plant (PLTA Mrica) and similar facilities that's Invest in advanced forecasting models that integrate meteorological data with hydrological modeling to predict water inflow more accurately. This should include sophisticated ENSO prediction tools that can provide early warnings to help adjust water management strategies proactively.

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