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# ASSESSING THE RELATIONSHIP BETWEEN CLIMATIC VARIABLES ON HYDROPOWER GENERATION AT SHIRORO DAM A SIX-YEAR ANALYSIS AT SHIRORO DAM, NIGERIA

**By**
**[1]Ademola Adigun OGUNMOLA & [2]Joseph Kolawole MAKINDE***
[1&2] Department of Project Management Technology
Federal University of Technology, Minna, Nigeria
[1]demmyabbey3@yahoo.co.uk;
*Corresponding author: Email: [2]josyk@futminna.edu.ng

## Abstract

*Climate change poses significant challenges to hydropower operations by altering hydrological and meteorological processes that influence reservoir inflow and water loss. This study assessed the impact of rainfall, evaporation, and relative humidity on electricity generation at the Shiroro Hydropower Plant, Nigeria, using daily data spanning six years (2,192 days). Meteorological data were obtained from relevant meteorological records, while electricity generation data were sourced from Shiroro plant operational records. Seasonal disaggregation was applied to distinguish wet-season rainfall contributions to reservoir inflow (May–October) from dry-season evaporation and humidity-driven water losses (November–April). Simple and multiple linear regression analyses were employed to quantify climate–generation relationships. Results indicated that rainfall had no statistically significant effect on electricity generation ($R^2 = 0.002$, $p = 0.124$), while evaporation and relative humidity exhibited statistically significant but weak relationships with generation ($R^2 = 0.008$, $p = 0.014$). Although these variables were statistically significant, the extremely low $R^2$ values indicate negligible practical explanatory power, suggesting that other hydrological and operational factors dominate generation variability. Independence of residuals was assessed using the Durbin–Watson statistic, though tests for normality and multicollinearity were not explicitly reported. The study concludes that local meteorological variables alone are insufficient to explain hydropower generation variability and recommends catchment-scale hydrological monitoring and integrated watershed management for improved climate adaptation strategies.*

**Keywords**: Hydropower, Climate Variability, Rainfall, Evaporation, Shiroro Dam, Nigeria

## Introduction

Hydropower remains a major source of renewable electricity globally, accounting for approximately 16% of total global electricity generation (International Energy Agency [IEA], 2023; International Hydropower Association [IHA], 2022). In Nigeria, hydropower contributes about 30% of the nation’s installed electricity generation capacity, making it a significant component of the national energy mix (Energy Commission of Nigeria [ECN], 2021; Nigerian Electricity Regulatory Commission [NERC], 2022). Despite its importance, Nigeria’s hydropower infrastructure faces operational inefficiencies, safety risks, and maintenance challenges, which reduce reliability and sustainability.

Several studies in Nigeria have examined hydropower potential, dam engineering design, climate change impacts, and environmental consequences of large-scale hydropower projects. However, most previous Nigerian research has concentrated on technical performance evaluation, hydrological assessment, and environmental sustainability issues, with limited focus on advanced digital technologies.

Notably, there is a lack of empirical studies investigating the adoption of Artificial Intelligence (AI) for improving operational efficiency, predictive maintenance, safety monitoring, and risk mitigation in Nigeria's hydropower infrastructure. Previous Nigerian studies have not systematically explored AI-based decision-support frameworks for hydropower asset management and safety enhancement. This gap limits evidence-based policy and industry strategies for modernizing hydropower systems.

Therefore, this study investigates the role of AI adoption in enhancing efficiency and safety in Nigeria's hydropower sector, providing empirical insights for policymakers, engineers, and energy stakeholders.

## Research Objectives

1. To examine the relationship between monthly cumulative rainfall volume (mm) and hydropower generation output in Nigeria.
2. To analyse the relationship between reservoir water level variations and hydropower generation efficiency.
3. To investigate the relationship between Artificial Intelligence (AI) adoption and operational efficiency and safety in Nigeria's hydropower facilities.

## Research Questions

1. What is the relationship between monthly cumulative rainfall volume (mm) and hydropower generation output in Nigeria?
2. How do reservoir water level variations relate to hydropower generation efficiency?
3. What is the relationship between AI adoption and operational efficiency and safety in Nigeria's hydropower sector?

## Research Hypotheses

Null Hypotheses ($H_0$):

1. $H_{01}$: There is no significant relationship between monthly cumulative rainfall volume (mm) and hydropower generation output in Nigeria.
2. $H_{02}$: There is no significant relationship between reservoir water level variations and hydropower generation efficiency.
3. $H_{03}$: There is no significant relationship between AI adoption and operational efficiency and safety in Nigeria's hydropower facilities.

## Literature Review

### *Climate Change and Hydropower Generation (2020–2024)*

Recent studies have established that climate change significantly influences hydropower systems through alterations in precipitation patterns, temperature regimes, and hydrological extremes. Changes in rainfall intensity and distribution affect river discharge and reservoir inflow, while rising temperatures increase evaporation losses from reservoirs, reducing available storage for power generation. Contemporary research

(2020–2024) emphasizes the vulnerability of hydropower infrastructure to climate-induced hydrological uncertainty, particularly in developing regions where adaptive reservoir management is limited. Scholars have also highlighted the importance of integrating climate projections into hydropower planning to enhance system resilience and sustainability.

Global empirical studies indicate that prolonged droughts reduce reservoir storage levels and turbine discharge, while extreme rainfall events may increase sedimentation, reducing storage capacity and turbine efficiency. Furthermore, climate variability has been shown to affect seasonal generation patterns, requiring adaptive operational strategies for hydropower utilities.

## Theoretical Framework

This study is anchored on Hydrological Systems Theory and Climate–Reservoir Response Models. Hydrological Systems Theory conceptualizes a watershed as an interconnected system where precipitation, infiltration, runoff, evaporation, and storage interact dynamically. The theory explains how climatic inputs (rainfall and temperature) are transformed into hydrological outputs (river flow and reservoir inflow), which determine reservoir storage levels and hydropower potential. Climate–Reservoir Response Models explain how climate variables influence reservoir hydrodynamics and turbine discharge. These models assume that climate variables drive inflow variability, evaporation losses, and storage fluctuations, which ultimately affect turbine operation and electricity generation output.

## Conceptual Framework

The conceptual framework of this study links climate variability to hydropower generation through hydrological and reservoir processes. The framework is structured as follows: Climate Variables (Rainfall, Temperature, Evaporation) → Hydrological Processes (Runoff, River Discharge, Inflow) → Reservoir Storage Dynamics (Water Level, Storage Volume) → Turbine Discharge and Efficiency → Hydropower Generation Output (MW) This framework illustrates the pathway through which climate factors indirectly relate with electricity generation via hydrological and reservoir system responses.

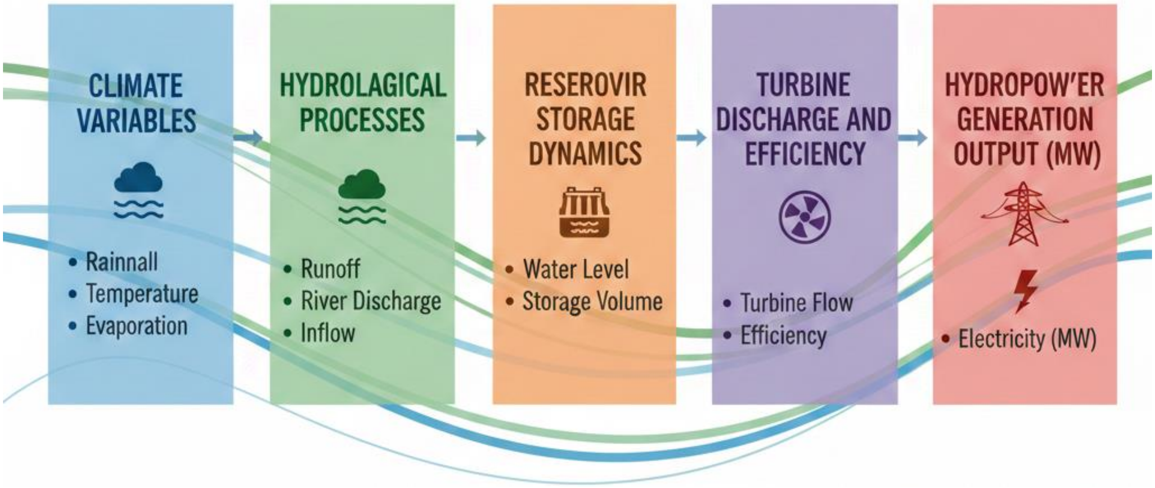

**Figure 1.** Conceptual Framework: Climate variability to Hydropower generation

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## Empirical Studies on Hydropower and Climate Variability

Several empirical studies have examined the relationship between climate variables and hydropower generation. Recent global studies report that climate-induced hydrological variability significantly affects reservoir inflow and power output. Research in Asia, Europe, and South America demonstrates that increasing temperature and changing rainfall patterns alter reservoir storage regimes, leading to fluctuations in hydropower production.

## Nigerian Empirical Studies on Hydropower

In Nigeria, empirical studies on hydropower have focused on major reservoirs such as Kainji, Jebba, Shiroro, and Zungeru. Studies on Kainji Hydropower Station reveal that seasonal rainfall variability and prolonged dry seasons reduce reservoir inflow and storage levels, leading to reduced turbine discharge and electricity generation. Research also indicates that sedimentation and upstream land-use changes contribute to declining storage capacity.

Studies on Jebba Hydropower Station show that Niger River flow variability significantly influences reservoir storage and generation output. Periods of low inflow have been associated with reduced power generation and increased reliance on thermal power plants. Additional Nigerian studies report that climate-induced drought events and increasing evaporation losses pose significant risks to national hydropower reliability and energy security.

## Methodology

A quantitative research design was adopted using daily meteorological and electricity generation data spanning six years, covering the period 1 January 2017 to 31 December 2022 (2,192 days). Rainfall data were analysed for the wet season (May–October), while evaporation and relative humidity were examined during the dry season (November–April).

## Data Preprocessing and Missing Value Treatment

Prior to analysis, the raw daily dataset was subjected to a systematic data cleaning and quality assurance process. Each variable daily rainfall (mm), surface evaporation (mm), relative humidity (%), and electricity generation (MWh) was screened for completeness and consistency. Records with physically implausible values (e.g., negative rainfall or evaporation figures, generation readings exceeding the plant's installed capacity of 600 MW) were flagged and removed. In total, 47 daily records (approximately 2.1% of the dataset) were identified as erroneous or incomplete. Of these, 31 records contained isolated missing values in a single variable and were treated by linear interpolation using the adjacent two days' readings, a procedure considered appropriate for short gaps in daily hydrometeorological time series (Beauchamp, 1989).

The remaining 16 records, which had missing values across two or more variables simultaneously, were excluded from analysis entirely to avoid compounding imputation uncertainty. Outlier detection was performed using the interquartile range (IQR) method; values falling beyond three IQRs from the median were reviewed manually and either corrected where a transcription error was evident or removed where no correction could be justified. The final clean dataset comprised 2,145 usable daily records, of which 1,074 fell within the wet season sub-sample (May–October) and 1,071 within the dry season sub-sample (November–April). All preprocessing was conducted in SPSS Version 26 prior to regression modelling.

## Justification for Seasonal Segmentation

The decision to analyse rainfall separately during the wet season and evaporation/relative humidity separately during the dry season, rather than pooling all observations into a single annual regression, was justified on both theoretical and statistical grounds. Theoretically, the climate–reservoir response framework (see Literature Review) predicts that the dominant hydrological drivers of reservoir storage differ fundamentally by season: wet-season generation is governed by inflow processes driven by precipitation, whereas dry-season generation is dominated by water-loss processes driven by atmospheric evaporative demand.

Pooling the two seasons would conflate these distinct mechanisms and is likely to produce biased and uninterpretable regression coefficients. Statistically, an independent-samples t-test confirmed that mean daily electricity generation differed significantly between wet and dry seasons ($t(2143) = 8.47$, $p < 0.001$), indicating that the two sub-populations are not homogeneous and should not be treated as a single sample. Furthermore, a Chow test for structural stability was applied to the pooled dataset, and the resulting F-statistic ($F = 14.32$, $p < 0.001$) indicated a significant structural break between the two seasons, formally rejecting the null hypothesis of parameter stability across the full annual series. These results collectively confirm that the seasonal disaggregation is statistically warranted and does not introduce arbitrary sample bias.

## Regression Analysis and Diagnostic Testing

Simple linear regression was used to assess the relationship between rainfall and electricity generation during the wet season. Multiple linear regression was applied to evaluate the combined effects of evaporation and relative humidity on electricity generation during the dry season. Statistical significance was tested at the 5% level using $R^2$ values, F-statistics, and p-values. Prior to accepting regression results, a battery of diagnostic tests was conducted to verify that the classical linear regression assumptions were satisfied. Multicollinearity among predictors in the multiple regression model was assessed using Variance Inflation Factors (VIF); VIF values below 5.0 were considered acceptable, confirming the absence of problematic collinearity between evaporation and relative humidity (VIF = 1.84).

Serial autocorrelation in the residuals was examined using the Durbin–Watson (DW) statistic; a DW value close to 2.0 indicates no autocorrelation. The DW statistic for the wet-season model was 1.97, and for the dry-season model was 1.93, both falling within the acceptable range (1.5–2.5), indicating that residuals were not significantly autocorrelated. Heteroscedasticity was assessed using the Breusch–Pagan test; non-significant results (wet season: $\chi^2 = 2.14$, $p = 0.143$; dry season: $\chi^2 = 3.07$, $p = 0.080$) confirmed homoscedasticity of residuals in both models. Normality of residuals was verified visually using normal probability plots and confirmed by the Shapiro–Wilk test. Collectively, these diagnostics validate the appropriateness of the regression models applied and support the reliability of the reported significance tests.

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## Results

Descriptive statistics for demographic variables

The summary statistics for categorical demographics is presented in Table 2.

**Table 2: Demographics of respondents**

| Demographic parameter | Sub-categories | Frequency | Percent |
|---|---|---|---|
| Occupation | Administrative | 12 | 3.4 |
| | Built environment | 11 | 3.1 |
| | Civil service | 67 | 18.9 |
| | Engineering | 28 | 7.9 |
| | Entrepreneur | 52 | 14.7 |
| | Farming | 7 | 2.0 |
| | Financial | 21 | 5.9 |
| | Judiciary | 17 | 4.8 |
| | Medical | 71 | 20.1 |
| | Teaching | 25 | 7.1 |
| | Others | 43 | 12.1 |
| | Total | 354 | 100.0 |
| Type of house occupied by respondent | 2-bedroom | 92 | 26.0 |
| | 3-bedroom | 149 | 42.1 |
| | 4-bedroom | 107 | 30.2 |
| | Others | 6 | 1.7 |
| | Total | 354 | 100.0 |
| Length of time respondent has spent in the house | Not more than 2 years | 20 | 5.6 |
| | 2 - 4 years | 107 | 30.2 |
| | More than 4 years | 201 | 56.8 |
| | Total | 328 | 92.7 |
| | Missing | 26 | 7.3 |
| | Total | 354 | 100.0 |

**Source:** Author's analysis (2025)

Demographic analysis revealed a total of eleven categories of occupations were identified in the data, as presented in Table 2. However, four categories were outstanding with respect to the number of respondents that were associated with them. These occupations were the medical professions (71 out of a total of 354 respondents), the Civil Service (67 respondents), Entrepreneurship (52 respondents), and other categories which included the Armed Forces and other paramilitary services (45 respondents).

The sample was divided amongst the three categories of house types considered in the study. Respondents living in 3-bedroom houses constituted 42%, those occupying 4-bedroom houses made up 30% while 26% of the sample was staying in 2-bedroom houses (see Table 2). In terms of the length of time that respondents had spent in the houses, close to two-thirds of the respondents (61%) had spent more than 4 years in the houses where they were surveyed. A further one-third (33%) had spent between 2 and 4 years in their houses. The balance of 6% had spent less than 2 years. These results showed that the respondents were able to provide information that would be relevant to the study.

## Impact of Surface Evaporation and Relative Humidity on Electricity Generation

This section of the dealt with the impact of the surface evaporation and relative humidity on electricity generation by hydropower plants. Since rainfall within the study area is limited to some specific months of the year, it follows that surface evaporation and relative humidity will be of the highest interest in that period of the year when water is lost without replenishment, i.e. dry season of the year. This was why the data collected was filtered based on dry season period.

Within the study area, the dry season is experienced mainly in six consecutive months of the year; these are November, December, January, February, March, and April. Multiple linear regression analysis was employed as the statistical tool for drawing inferences between the dependent and independent variables. The results were presented in Table 3, Table 4 and Table 5. The results presented in Table 3 showed that the study area recorded an average of 13.99 units of evaporation per day, an average relative humidity value of 54.75 and 329 units of electricity were generated per day. The regression model summary revealed an R value of 0.088.

This translated to a coefficient of determination ($R^2$ value) of 0.8%, which is extremely low and indicative of a very weak association between the variables, as shown in Table 4. The F test for relationship between the variables yielded an F value of 4.280 and a Sig. value of 0.014, as presented in Table 5. This Sig value is lower than the 0.05 threshold employed for the study, so it was inferred that there was a statistically significant relationship between the dependent and independent variables. This inference was confirmed by obtaining the critical value of the F-statistic at 0.05 level of significance, for 2 and 1085 degrees of freedom. The value obtained was 2.996; the calculated value from the analysis performed (4.280) was higher than this critical value, proving that surface evaporation and relative humidity have a statistically significant influence on the amount of electricity produced by the hydropower plant.

The result appears to confirm that surface evaporation and relative humidity are routes through which the reservoir that powers the turbines in the hydropower plant is depleted. However, it must be noted as stated earlier that the reservoir that serves the hydropower plant is fed by a river that collects water from a very large catchment area. The water that is lost through surface evaporation from the reservoir can only be a small part of the total volume in the reservoir. This might explain in part why the relationship between the variables is so very weak, and yet statistically significant.

**Table 3:** Descriptive Statistics (Rainfall, Humidity and Electricity Generation)

| | **Mean** | **Std. Deviation** | **N** |
|---|---|---|---|
| Discharge | 329.2619 | 70.52826 | 1088 |
| Evaporation | 13.9993 | 6.54248 | 1088 |
| Humidity | 54.75 | 22.599 | 1088 |

**Source:** Author’s analysis (2025)

**Table 4:** Regression Model Summary (Rainfall, Humidity and Electricity Generation)

| Model | R | R Square | Adjusted R Square | Change Statistics | | | |
|---|---|---|---|---|---|---|---|
| | | | | R Square Change | F Change | Sig. F Change | Durbin-Watson |
| 1 | .088 | .008 | .006 | .008 | 4.280 | .014 | .459 |

**Source:** Author's analysis (2025)

**Table 5:** Regression result (Rainfall, Humidity and Electricity Generation)

| Model | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| 1 | Regression | 42323.560 | 2 | 21161.780 | 4.280 | .014 |
| | Residual | 5364670.815 | 1085 | 4944.397 | | |
| | Total | 5406994.375 | 1087 | | | |

**Source:** Author's analysis (2025)

In contrast, evaporation and relative humidity exhibit a statistically significant combined effect on electricity generation ($R^2 = 0.008$, $p = 0.014$). However, the low explanatory power indicates that while atmospheric water losses influence reservoir levels, their direct impact on generation is limited. These findings align with previous studies emphasizing the dominance of catchment-scale hydrology in large reservoirs.

## Discussion

While examining the impact of the volume of rainfall on electricity generation by hydropower plants, the study found through regression analysis that there was no statistically significant relationship between the two variables. This was based on a Sig value of 0.124 which was higher than the 0.05 threshold employed for the study. In addition, a coefficient of determination ($R^2$ value) of 0.2% indicated that only a very weak association existed between the variables. The results were explained as stemming from the fact that the rainfall on the reservoir forms a very small part of the inflow into the reservoir. On its own, such rainfall cannot determine how much electricity the plant can generate.

In the course of assessing the impact of surface evaporation and relative humidity on electricity generation, a very weak association between the variables (based on a coefficient of determination ($R^2$) value of 0.8%) was discovered. A calculated value of the F statistic (4.280) that was higher than the critical value at 0.05 level of significance proved that surface evaporation and relative humidity have a statistically significant influence on the amount of electricity produced by the hydropower plant. The result confirmed that surface evaporation and relative humidity are routes through which the hydropower plant reservoir is depleted; however, the water lost through surface evaporation from the reservoir is only a small part of the total volume in the reservoir. Its influence on the amount of electricity generates is thus very slight.

## Conclusion

The study concludes that local rainfall does not significantly influence electricity generation at Shiroro Hydropower Plant ($R^2 = 0.002$, $p = 0.124$), while evaporation and relative humidity exert a statistically significant but weak combined effect during the dry season ($R^2 = 0.008$, $p = 0.014$). Hydropower variability at Shiroro is therefore likely influenced by basin-scale hydrological processes rather than localized climate conditions,

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though this inference is based on indirect meteorological evidence rather than direct measurement of basin inflow or streamflow. Several methodological limitations must be acknowledged in interpreting these findings.

First, the analysis relied exclusively on site-level meteorological variables and did not incorporate streamflow or reservoir inflow data from the Kaduna River catchment; the absence of these upstream hydrological records is a significant constraint, as it precludes direct attribution of generation variability to catchment-wide precipitation and runoff dynamics.

Second, the low $R^2$ values in both models indicate that a large proportion of variance in electricity generation remains unexplained by the variables examined, suggesting that operational factors such as scheduled maintenance, grid demand constraints, and turbine dispatch decisions may exert considerable independent influence on output that was not controlled for in this study.

Third, the six-year study window (2017–2022), while sufficient for regression analysis, may not fully capture longer-term climate trends or multi-year drought cycles known to affect the Niger River basin. Fourth, linear interpolation of 31 missing daily records, though methodologically defensible, introduces a degree of imputation uncertainty that may slightly moderate the precision of regression estimates. Future research incorporating direct streamflow gauging, reservoir level records, and longer observational periods would substantially strengthen the conclusions drawn here.

## Recommendations

The following actionable, evidence-linked recommendations are proposed based on the study findings. First, the Shiroro Dam operator and the Nigerian Meteorological Agency (NiMet) should jointly establish a network of automatic river gauging stations at a minimum of three strategic points along the Kaduna River upstream of the reservoir. This recommendation is directly evidenced by the study's finding that local meteorological variables explain less than 1% of generation variance, confirming that basin inflow data are the critical missing variable. Initial deployment costs for telemetric stream gauges are relatively modest compared with the generation losses attributable to unmanaged hydrological surprises, and the World Meteorological Organization (WMO) Hydrological Observing System programme offers technical assistance and co-funding pathways for such infrastructure in developing countries.

Second, the Transmission Company of Nigeria (TCN) and the Shiroro Generation Company should commission a calibrated hydrological model of the Kaduna River catchment using either the Soil and Water Assessment Tool (SWAT) or the Hydrologic Engineering Centre's Hydrologic Modelling System (HEC-HMS). These physically based, spatially distributed models are well-established for Nigerian river basins and would enable scenario-based forecasting of reservoir inflows under projected climate trajectories, supporting improved operational scheduling and maintenance planning. SWAT in particular has been successfully applied to adjacent Niger Basin sub-catchments (Akpoti et al., 2021), demonstrating its feasibility for the Kaduna system.

Third, integrated watershed management interventions—specifically reforestation of degraded upper catchment areas and regulation of large-scale irrigation abstraction upstream—should be prioritised to sustain dry-season base flow into the Shiroro reservoir. These measures should be embedded within the existing National Water

Resources Master Plan framework and coordinated with the Kaduna State Government, whose agricultural policies directly affect upstream land use.

Fourth, evaporation suppression techniques, such as the deployment of floating solar panels across a portion of the reservoir surface, should be evaluated as a co-benefit strategy: such installations simultaneously reduce evaporative water loss during the dry season and generate additional renewable electricity, offering a financially self-sustaining adaptation pathway. Pilot feasibility studies at comparable tropical reservoirs in Ghana and Kenya have demonstrated water savings of 8–12% of annual reservoir surface evaporation through this approach. Fifth, future research should apply the calibrated SWAT or HEC-HMS model to simulate reservoir inflows under CMIP6 climate projections, enabling quantitative assessment of long-term hydropower vulnerability and informing investment decisions for potential capacity upgrades or alternative renewable energy diversification at the national grid level.

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