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Projected Rainfall Trends and Variability in the Mrica Catchment under the SSP5-8.5 Scenario

Shamsul Hadi[1,2], Muhammad Rais Abdillah[1], Konstan Aftop Anewata Ndruru[1], Wildan Arya Putra[1,2], Farah Rizki Octavia[1,2], Afif Asykar Amir[1,2] & Nurjanna Joko Trilaksono[1]

[1] Earth Sciences Master Program, Faculty of Earth Sciences and Technology, Bandung Institute of Technology, Indonesia
[2] PT PLN (Persero), Indonesia

Email: Shamsul.hadi@pln.co.id

Abstract. This study analyzes changes in rainfall, inflow discharge, and electricity production at PLTA Mrica using historical data (1985–2014) from CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) and six global climate models (GCMs) under CMIP6 (Coupled Model Intercomparison Project Phase 6). Future projections are based on the SSP5-8.5 (*Shared Socioeconomic Pathway 5 – fossil-fueled development*) scenario to represent a worst-case pathway, enabling assessment of maximum potential climate impacts on hydropower reliability [2] scenario for the period 2021–2100. A delta-based statistical downscaling method is applied to produce high-resolution rainfall projections. This method is **deterministic** in nature; it applies a fixed anomaly (delta) between future and historical climatologies onto observed datasets, without simulating transient atmospheric processes as done in prognostic models. It is computationally efficient and widely used for impact studies where capturing long-term mean changes is prioritized over day-to-day weather variability [2][3]. The results indicate an increase in rainfall during the wet season and a significant decline during the dry season, particularly from January to March, with projected rises of up to **+2.5 mm/day,** or approximately **+30–40%, compared** to the historical baseline. Conversely, the dry season (June–September) is projected to experience a **decline of up to 1.5 mm/day**, equivalent to a reduction of **25–40%**, depending on the month and future time slice. Historical data indicate that monthly rainfall of at least **100–120 mm** is generally required to sustain sufficient reservoir inflow for optimal electricity generation at PLTA Mrica, especially during the dry season. Variability in rainfall, particularly prolonged dry spells or delayed wet season onset, can lead to inflow shortages, reducing turbine operation hours and ultimately affecting annual energy output. This study highlights the importance of using climate data such as projected rainfall thresholds and variability to guide reservoir operations, optimize electricity production, and reduce risks during dry periods. Integrating such information supports more adaptive and resilient hydropower planning under future climate uncertainty.

Keywords: *climate change, rainfall, inflow, hydropower*

1 Introduction

The effects of anthropogenic climate change on freshwater availability have become a critical focus in hydrological research over the past few decades [4][2]. To estimate potential future climatic conditions, General Circulation Models (GCMs) are frequently employed due to their ability to simulate global-scale atmospheric and oceanic processes with physical consistency (Flato et al., 2013). These models serve as the foundation for long-term climate projections under various greenhouse gas emission scenarios. However, the relatively coarse spatial resolution of GCM outputs—typically ranging from 100 to 600 kilometers—limits their direct applicability in basin-scale hydrological analyses, where detailed topography and localized weather patterns play a crucial role [1].

To address this scale mismatch, **downscaling techniques** are applied to translate large-scale GCM outputs into finer-resolution climate information suitable for impact studies. These techniques fall into two main categories: **dynamical downscaling**, which uses regional climate models (RCMs) nested within GCMs, and **statistical downscaling**, which uses empirical relationships between large-scale predictors and local-scale climate variables [2]. In this study, a statistical delta method is used to refine monthly precipitation projections over the Mrica catchment, making them more applicable to hydropower operation planning and hydrological risk assessment.

Downscaling methods operate under the premise that regional climate patterns are shaped by both large-scale atmospheric circulation and local geographic features. These techniques fall into two main categories: **dynamic** and **statistical** downscaling. Dynamic downscaling uses Regional Climate Models (RCMs) nested within GCMs, allowing detailed simulation of regional processes and incorporating physical mechanisms influenced by anthropogenic climate change [5]. However, this approach requires substantial computational resources and specialized modeling expertise.

Conversely, **statistical downscaling** establishes empirical relationships between large-scale predictors (e.g., geopotential height, sea surface temperature) and local climate responses such as precipitation or temperature. While more computationally efficient and easier to implement, statistical methods assume that historical relationships between variables remain valid under future climate conditions. Both methods, when based on GCM outputs that include anthropogenic forcings (e.g., SSP scenarios), are capable of reflecting human-induced climate change effects—though the fidelity of their local representation may vary [6][3].

This study applies a statistical downscaling approach to evaluate projected changes in precipitation over the Serayu River Basin using five selected CMIP6 GCMs under the SSP5-8.5 scenario. Among several available pathways in CMIP6, SSP5-8.5 (*Shared Socioeconomic Pathway 5—fossil-fueled development*) was chosen as it represents a high-end emissions scenario with minimal climate mitigation, serving as a worst-case benchmark for stress-testing water resource systems. This approach enables assessment of maximum potential risks to hydropower operations, consistent with practices in climate impact research [7]. [3]. High-resolution observational data from CHIRPS (*Climate Hazards Group InfraRed Precipitation with Station data*) with a spatial resolution of 0.05° (~5 km) serves as the baseline for bias correction and downscaling. CHIRPS was selected due to its long-term coverage (1981–present), fine spatial resolution, and integration of satellite estimates with ground-based station data, making it suitable for data-scarce regions like the Serayu Basin (Funk et al., 2015). While the target area is relatively small, CHIRPS has been widely validated in Indonesia and shows strong consistency with rain gauge observations. For this study, CHIRPS outputs were cross-checked with available BMKG rainfall station data to ensure local representativeness. In contrast, the five CMIP6 GCMs used have native spatial resolutions ranging from 100 to 250 km, which are insufficient to resolve sub-watershed dynamics without downscaling [8]. [3]. The analysis investigates how future rainfall patterns may affect reservoir inflow and hydropower generation at the Mrica Hydropower Plant, Central Java. Changes in rainfall seasonality and increased interannual variability directly influence the volume and timing of reservoir recharge, which are critical for maintaining stable electricity production. The findings are intended to support adaptive water resource planning by informing reservoir operation schedules, optimizing energy dispatch, and mitigating risks of undergeneration during prolonged dry spells. This is particularly important as Indonesia gradually phases out coal-fired power plants under its Long-Term Strategy for Low Carbon and Climate Resilience (Government of Indonesia, 2021), with hydropower positioned as a key pillar in the national *Net Zero Emissions 2060* roadmap [3]. Strengthening the climate resilience of existing hydropower assets is therefore essential to ensure long-term energy security and sustainability.

2 Data and Methods

This study focuses on the Serayu River Basin in Central Java, Indonesia, where the Mrica Hydropower Plant is located. This region is characterized by a monsoonal climate and plays a vital role in supporting local agricultural and energy sectors. The geographic extent of the study area ranges approximately between 7.3°–7.6°S latitude and 109.3°–109.7°E longitude.

The analysis conducted in this research integrates three primary sources of data: observed precipitation and outputs from Global Climate Models (GCMs), such as those provided by the Coupled Model Intercomparison Project Phase 6 (CMIP6), which are widely used to project future climate conditions at global and regional scales [8]. The GCM outputs used in this study were accessed through the Earth System Grid Federation (ESGF) data portal: https://esgf-node.llnl.gov/projects/cmip6, and operational hydropower data from the Mrica plant.

To represent observed rainfall, the *Climate Hazards Group InfraRed Precipitation with Station Data* (CHIRPS) was employed. With a spatial resolution of 0.05° (~5 km), CHIRPS combines satellite imagery and in-situ station data to produce reliable monthly precipitation estimates with broad spatial and temporal [1]. CHIRPS data covering the 1990–2014 period served as the observational baseline for evaluating the performance of climate models and their relevance to hydrological patterns.

Additionally, monthly precipitation outputs from five CMIP6 GCMs were utilized for both historical (1985–2014) and future (2031–2090) climate projections under the SSP5-8.5 scenario, which reflects a high-emission trajectory with limited global cooperation [7]. All GCM outputs were resampled using bilinear interpolation to match the CHIRPS resolution of 0.05° [3]. Based on the distribution across model grids, three ensemble representations were derived: MER-L (lower quartile), MER-M (median), and MER-H (upper quartile), capturing a range of low to high precipitation projections [4].

This study employs a two-step methodology to obtain and analyze high-resolution future precipitation projections: (1) downscaling CMIP6 model outputs using the **delta statistical downscaling method** and (2) conducting a **time-series analysis** to assess climatological patterns and interannual variability [6].

To enhance the spatial resolution of rainfall projections derived from Global Climate Models (GCMs), the **delta statistical downscaling** method is employed. This approach estimates the relative change (delta) between future and historical model outputs, which is then applied to observed precipitation data to generate high-resolution future projections [7].
The delta value is computed for each month using the following equation:

Prior to computation, all GCM outputs are resampled to match the CHIRPS spatial resolution (0.05°) using **Statistic Downscaling Delta**. This ensures spatial consistency across all datasets.

This method is widely recognized for its simplicity, computational efficiency, and its ability to preserve the spatial structure of observed data while incorporating projected climate change signals from GCMs [3].

Following the delta downscaling process, the high-resolution precipitation datasets are further analyzed to assess their temporal characteristics, including climatological behavior and interannual variability. This analysis is essential to understand the potential impacts of climate change on rainfall regimes, particularly for hydrological planning and water resource management [1].

The evaluation is conducted across three representative timeframes:

- **Historical baseline:** 1985–2014
- **Mid-century projection:** 2031–2060
- **End-century projection:** 2061–2090

Three key analytical components are applied as follows:

The annual mean precipitation is calculated for each period to detect long-term trends in rainfall magnitude. This metric provides a baseline for assessing potential increases or decreases in total water availability over time. Consistent with previous studies, changes in annual mean precipitation can significantly influence hydrological processes, reservoir inflow, and hydroelectric energy production [9][10].

A climatological seasonal profile is constructed by averaging monthly precipitation values over each respective period. This analysis enables the identification of shifts in rainfall patterns, such as delayed wet season onset, shortened rainy seasons, or altered peak rainfall months. Detecting such changes is critical for agricultural planning and reservoir operations [10].

To evaluate fluctuations in rainfall from year to year, the standard deviation of annual precipitation totals is calculated. This serves as an indicator of interannual variability, which reflects the stability or instability of climatic conditions over time. High interannual variability suggests increased uncertainty in water availability, which may challenge the reliability of hydropower systems and agricultural productivity [11].

3 Results and Discussion

This subsection analyzes the relationship between rainfall, inflow, and electricity generation at the Mrica hydropower plant using monthly data from 2013–2023. Regression lines indicate a strong positive linear correlation between rainfall and inflow (left), as well as rainfall and electricity production in GWh (right), with coefficients of determination $R^2 = 0.78$ and $R^2 = 0.73$

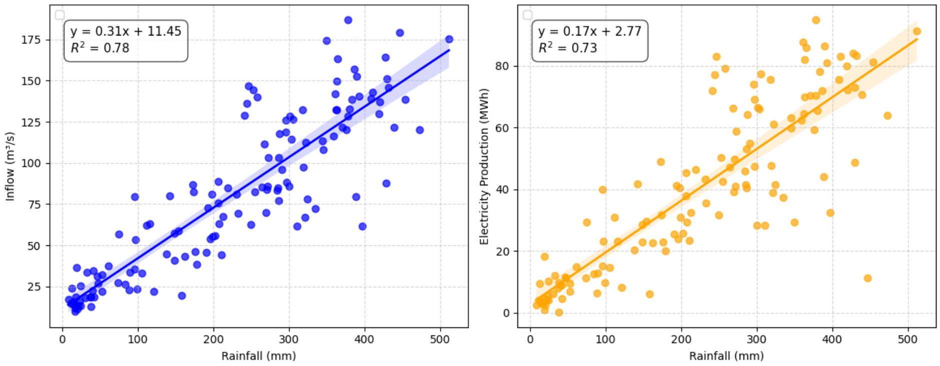


Figure 1 Relationship between Rainfall, Inflow, and Electricity Production at Mrica Hydropower Plant (2013–2023)

Understanding the ability of Global Climate Models (GCMs) to replicate observed rainfall dynamics is crucial before applying them to future projections. In this section, the historical precipitation patterns over the Mrica Watershed are examined through a comparison between CHIRPS observations and outputs from five CMIP6 GCMs, spanning the period 1985–2014.

The seasonal distribution of precipitation is further summarized in Figure 1. Based on CHIRPS observations, the climatological cycle exhibits a characteristic monsoonal pattern. Rainfall reaches its maximum in **December**, tapering off toward the dry season, which spans **June to September**. During this drier phase, mean precipitation drops below **3 mm/day**, with the lowest point in **August**. Shaded bands around the monthly mean illustrate the standard deviation, indicating moderate variability during transition months (April, October) and relatively stable conditions during peak dry periods.

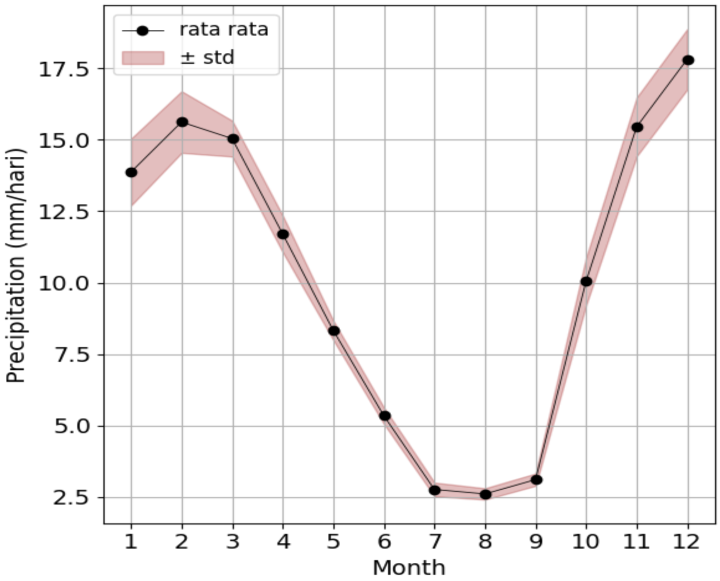
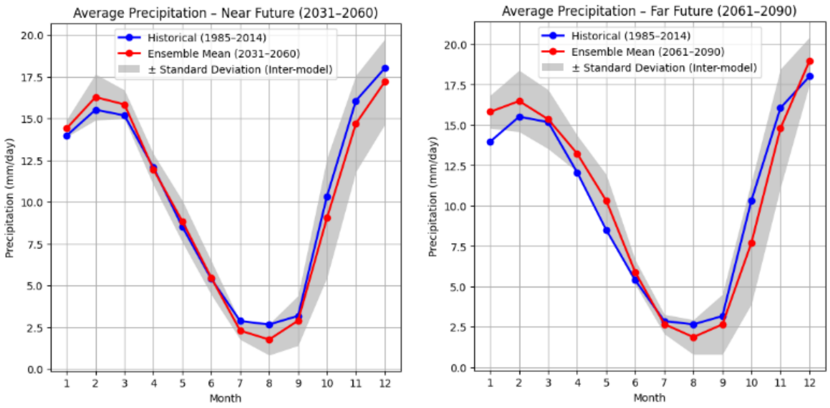


Figure 2 Climatological mean monthly precipitation and standard deviation over the Mrica Watershed (1985–2014).



(a) (b)

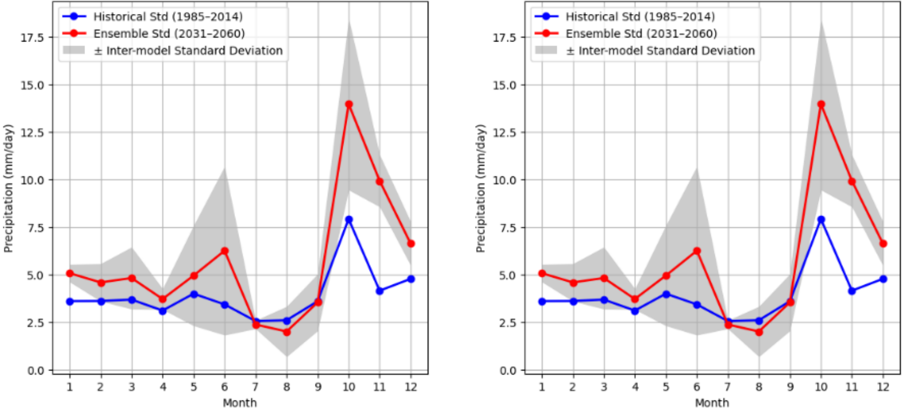
Figure 3 (a) Monthly climatology comparison: historical vs. near future (2031–2060) & (b) historical vs. far future (2061–2090)

Figures 3 assess the month-by-month standard deviation of precipitation over time, representing interannual variability:

- Future projections show **greater variability** across almost all months compared to historical data.

- **October to December** displays the most significant increase in standard deviation, with up to **14 mm/day**, suggesting greater uncertainty in wet-season rainfall intensity and duration.

This could imply increased challenges for water resource planning and hydropower reliability.



(a) (b)

Figure 4 (a) Monthly climatology comparison: historical vs. near future (2031–2060) & (b) historical vs. far future (2061–2090)

Figure 4(a) shows a notable increase in the annual precipitation range (maximum–minimum) in future periods. Compared to the historical baseline, the range expands by **+24.0% during 2031–2060** and **+29.1% during 2061–2090**, indicating greater interannual variability and a higher likelihood of extreme wet or dry years.

Meanwhile, (b) illustrates that the mean annual precipitation increases only slightly—by **+2.6% in the near future** and **+1.6% in the far future**. This suggests a modest rise in overall water availability, but with significantly more uncertainty from year to year. Such a combination of limited increase in total rainfall and heightened variability may complicate reservoir operations at the Mrica hydropower plant, particularly in maintaining consistent inflows for electricity production.

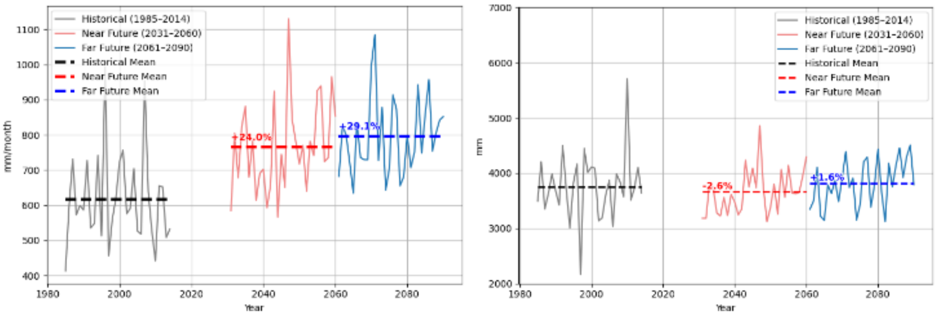


Figure 5 Interannual precipitation range: historical vs. future & Annual precipitation trends across three time periods

The future projections of hydrological conditions and hydropower generation at the Mrica Hydropower Plant (HPP) were analyzed using climate projections under the SSP5-8.5 scenario. The simulations indicate a potential positive impact on both streamflow and electricity production, though with increasing variability across future time slices.

During the near-future period (2031–2060), annual average streamflow is projected to fluctuate between **90 and 140 m³/s**, while in the far-future period (2061–2090), the streamflow remains elevated within **100 to 140 m³/s**, *as shown in Figure 7*. The increase in streamflow reflects a likely intensification of the regional hydrological cycle under projected warming, particularly during wet seasons.

Consequently, hydropower production also exhibits an upward trend. The projected annual electricity generation reaches **approximately 600–850 MWh** in 2031–2060, rising to **650–800 MWh** in 2061–2090, *as illustrated in Figure 8*. Despite these positive trends, inter-annual variability becomes more pronounced in the far-future period, highlighting potential challenges for reservoir operation and energy supply consistency.

Overall, while climate change may bring opportunities for increased hydropower capacity at Mrica HPP, the growing variability underscores the need for adaptive water resource management and more robust climate-resilient operational strategies to maintain reliable power generation in the face of changing climate patterns.

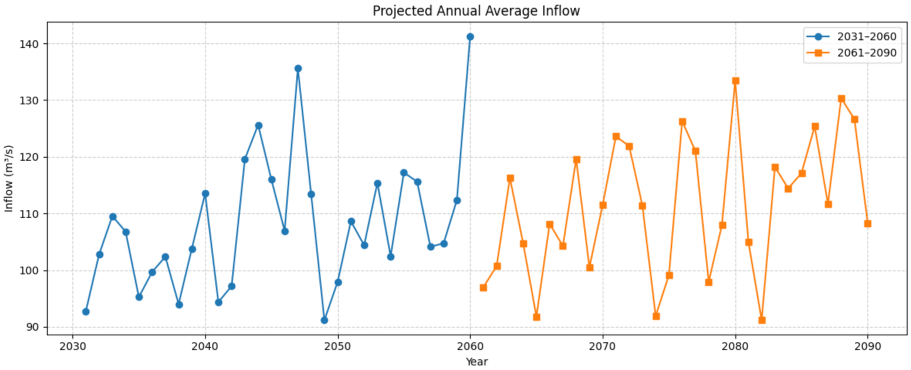


Figure 6 Projected annual streamflow at Mrica under SSP5-8.5.

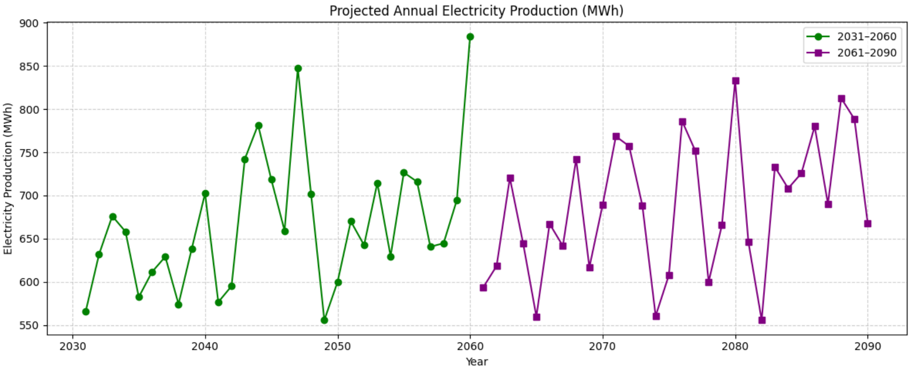


Figure 7 Projected annual hydropower generation at Mrica under SSP5-8.5.

Figure 8 and Figure 9 present the projected monthly climatology for inflow and electricity production at Mrica Hydropower Plant under the SSP5-8.5 scenario, based on two future periods: near-future (2031–2060) and far-future (2061–2090). The projections indicate a consistent seasonal pattern, with peak inflow and electricity generation occurring between January and March, while the lowest values are observed during the dry season (June to September).

The inflow climatology (Figure 8) shows slightly higher values in the far-future period, accompanied by increased inter-annual variability, as reflected by the wider standard deviation bands. A similar trend is observed in electricity production (Figure 9), where electricity generation follows the inflow pattern due to the strong dependence of hydropower output on water availability.

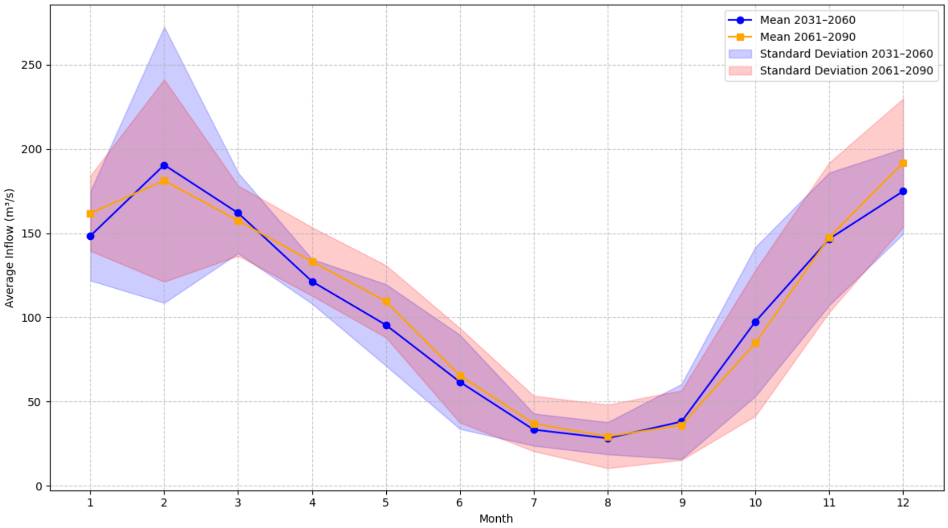


Figure 8 Projected monthly inflow (m^3/s) for 2031–2060 and 2061–2090 (SSP5-8.5).

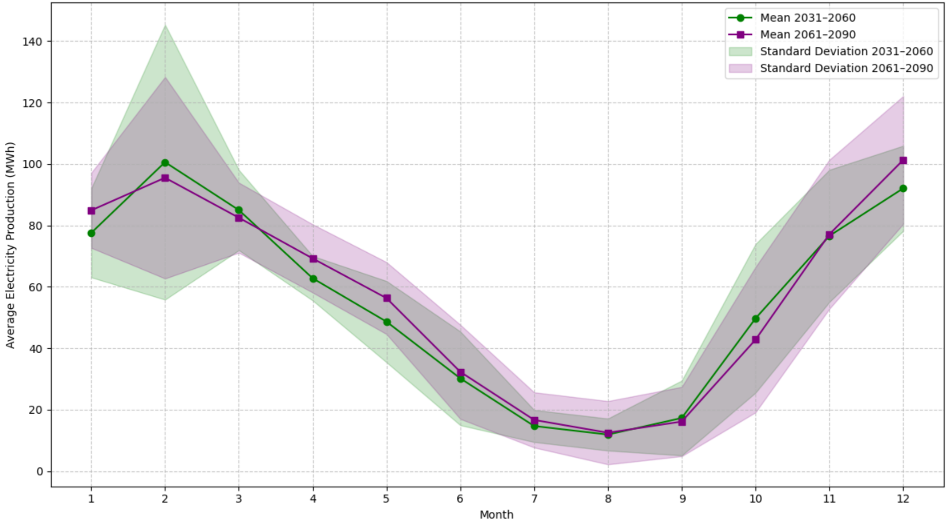


Figure 9 Projected monthly electricity production (MWh) for 2031–2060 and 2061–2090 (SSP5-8.5).

4 Conclusion

Projected changes in precipitation patterns over the Mrica watershed under the SSP5-8.5 scenario reveal not only a moderate increase in long-term average rainfall but also a substantial intensification of both intra-annual and interannual variability. This evolving climate signal presents a significant challenge for water resource and energy management, particularly for hydropower systems like the Mrica reservoir that depend on consistent inflow throughout the year.

Statistical downscaling of five CMIP6 models using the delta method shows that annual precipitation is projected to increase by approximately 24.0% in the near future (2031–2060) and 29.1% in the far future (2061–2090), relative to the 1985–2014 baseline. These results are consistent with broader findings in Southeast Asia as reported [3] [1]. While these increases suggest a marginal improvement in long-term water availability, they are accompanied by greater seasonal compression—where rainfall becomes more concentrated in the early (January–February) and late (November–December) monsoon months, while the dry season (June–September) becomes drier and potentially longer.

Simulated inflow based on regression models indicates that although the average inflow volume increases, the variability grows significantly. Electricity production at Mrica Hydropower Plant may increase slightly in total annual generation—approximately 6.3% in the near future and 9.8% in the far future—yet the number of months experiencing below-average output is projected to rise, particularly from July to September, where generation deficits could exceed 20–25% during dry years. These fluctuations imply that the plant's reliability could be compromised, especially under the far-future climate where back-to-back dry years become more [2] [3]

One of the most critical challenges is the increase in interannual variability. Figures 9 and 10 illustrate wider spreads in inflow and power generation projections, suggesting a growing risk of operational imbalance. Monthly climatology (Figures 11 and 12) reinforces this, with higher uncertainty around peak monsoon periods and deeper deficits in dry months. As a result, planning based solely on annual means would be insufficient for future climate resilience.

The selection of SSP5-8.5 is based on its current relevance for worst-case high-emission scenarios, aligning with studies [4] [5], where continued fossil-fuel dependence results in significant warming and hydroclimatic change. However, comparisons to other pathways (e.g., SSP2-4.5 and SSP3-7.0) in other studies suggest lower, but still significant, levels of variability and risk, underscoring the importance of scenario diversity in long-term infrastructure planning [6].

While the delta statistical downscaling method successfully preserves observed spatial rainfall patterns and enables fast integration with historical baselines, it assumes stationary variability and does not account for daily extremes or convective shifts. This methodological limitation may underestimate the impact of future high-intensity events, such as flash floods or prolonged droughts [7].

In conclusion, while the Mrica watershed is expected to experience higher rainfall and water availability in the future, these benefits are offset by increased climate-induced volatility. Hydropower operations at Mrica will need to transition toward more adaptive, flexible management strategies that account for growing uncertainty in inflow timing and magnitude. The findings underscore the importance of integrating multi-scenario climate projections into hydrological and energy models to assess the long-term performance thresholds of the reservoir system and inform resilient energy policy decisions.

References

[1] Fowler, H.J., Blenkinsop, S. & Tebaldi, C., Linking climate change modelling to impact studies: recent advances in downscaling techniques for hydrological modelling, *International Journal of Climatology*, 27(12), pp. 1547–1578, 2007.

[2] R. L. Wilby and T. M. L. Wigley, *Downscaling general circulation model output: A review of methods and limitations*, Progress in Physical Geography, vol. 21, no. 4, pp. 530–548, 1997.

[3] IPCC, *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 2021.

[4] Z. W. Kundzewicz, L. J. Mata, N. W. Arnell, P. Döll, P. Kabat, B. Jiménez, et al., *"Freshwater resources and their management,"* in *Climate Change 2007: Impacts, Adaptation and Vulnerability*, Cambridge University Press, pp. 173–210, 2007.

[5] F. Giorgi and L. O. Mearns, *"Introduction to special section: Regional Climate Modeling Revisited," Journal of Geophysical Research: Atmospheres*, vol. 104, no. D6, pp. 6335–6352, 1999. doi: 10.1029/98JD02072

[6] D. Maraun, T. R. Osborn, E. Rust, R. Vautard, L. Gudmundsson, and R. Hegerl, *"Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user," Reviews of Geophysics*, vol. 48, no. 3, RG3003, 2010. doi: 10.1029/2009RG000314

[7] B. C. O'Neill, C. Tebaldi, D. Van Vuuren, V. Eyring, P. Friedlingstein, E. Hawkins, et al., *"The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6," Geoscientific Model Development*, vol. 9, no. 9, pp. 3461–3482, 2016. doi: 10.5194/gmd-9-3461-2016

[8] V. Eyring, S. Bony, G. A. Meehl, C. A. Senior, B. Stevens, R. J. Stouffer, and K. E. Taylor, *"Overview of the Coupled Model Intercomparison*

Project Phase 6 (CMIP6) experimental design and organization," Geoscientific Model Development, vol. 9, no. 5, pp. 1937–1958, 2016. doi: 10.5194/gmd-9-1937-2016

[9] X. Zhang, F. Zwiers, G. Li, H. Wan, and A. J. Cannon, *"GCM-based regional projections of precipitation extremes over Canada," Journal of Climate*, vol. 31, no. 17, pp. 6405–6427, 2018. doi: 10.1175/JCLI-D-17-0870.1

[10] C. Li, Y. Zhang, H. Xu, and J. Chen, *"Evaluation of statistical downscaling methods for CMIP6 models: A case study in the Yangtze River Basin," Atmospheric Research*, vol. 272, p. 106146, 2022. doi: 10.1016/j.atmosres.2022.106146

[11] E. Hawkins and R. Sutton, *"The potential to narrow uncertainty in regional climate predictions," Bulletin of the American Meteorological Society*, vol. 90, no. 8, pp. 1095–1107, 2009. doi: 10.1175/2009BAMS2607.1