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Evaluation and Bias Correction of CORDEX-SEA Precipitation for Future Rainfall Projection in the Sutami Reservoir Catchment, Indonesia

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Abstract: This study evaluates the performance of CORDEX-SEA precipitation data and applies bias correction for future rainfall projection in the Sutami Reservoir catchment, Indonesia, which has an important role in irrigation and flood control management. Observed rainfall data for 1995–2024 were compared with CORDEX-SEA outputs under the RCP 4.5 and RCP 8.5 scenarios to assess model performance during the present-day period. The model generally overestimated observed rainfall, with average 10-day rainfall values of 86.09 mm/10-day (RCP 4.5) and 89.49 mm/10-day (RCP 8.5), compared to 56.19 mm/10-day from observations. Bias correction was performed using the Linear Scaling (LS) and Quantile Mapping (QM) methods because of their robustness and effectiveness in reducing systematic bias in precipitation data while preserving the temporal characteristics of climate model outputs. The corrected results showed substantial improvement, with the correlation coefficient increasing to 0.95, Nash–Sutcliffe Efficiency reaching 0.90, RMSE-standard deviation ratio decreasing to 0.32, and Percent Bias reducing to approximately 2–3%. Rainfall projections for 2025–2030 indicate a decreasing rainfall trend under both scenarios. This study demonstrates that LS and QM can effectively improve CORDEX-SEA precipitation data reliability for watershed-scale climate change and water resources assessments in Indonesia.

Keywords: Bias Correction; Climate Change; CORDEX-SEA; Precipitation Projection; Sutami Reservoir.

Introduction

Climate change has emerged as a major challenge for water resources management (Pawitan, 2018). Increasing global temperatures caused by greenhouse gas emissions have altered rainfall patterns, increased the frequency of extreme events, and intensified hydrological variability (Ahmad et al., 2025; Sobkowiak, 2025). Southeast Asia is particularly vulnerable, as recent decades have experienced more frequent extreme rainfall events and prolonged dry periods (Hariadi et al., 2024). In Indonesia, particularly in Sumatra and Java, these changes are indicated by an approximately 40% increase in consecutive dry days and greater extreme rainfall intensity in several regions (Supari et al., 2020). Such variability poses substantial risks to water balance conditions and the sustainability of water resources management (Hanifa & Wiratmo, 2024; Nurjani et al., 2025).

The Sutami Reservoir, located in Malang Regency, East Java, is a multifunctional infrastructure system that plays a strategic role in the Brantas River Basin. The reservoir supports irrigation, hydropower generation, flood control, and raw water supply. Its storage capacity is highly dependent on rainfall and inflow from the surrounding catchment area; therefore, changes in rainfall patterns due to climate change may directly affect water availability and reservoir operational reliability (Sulistyani & Irianto, 2024). Understanding future changes in key climate variables, particularly rainfall, is essential for supporting adaptive and resilient reservoir management under changing climate conditions (Saidah et al., 2023).

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Climate change projections are commonly derived from global and regional climate models. The Coordinated Regional Climate Downscaling Experiment for Southeast Asia (CORDEX-SEA) provides climate projection datasets produced through the dynamical downscaling of Global Climate Models (GCMs) using Regional Climate Models (RCMs) (Hastina et al., 2025; Satria et al., 2025). In this study, CORDEX-SEA data with a spatial resolution of 0.22° (approximately 25 km) were employed because they provide consistent long-term precipitation simulations and complete spatial coverage for the Sutami Reservoir catchment. Although this resolution is relatively coarse for watershed-scale applications, the dataset remains suitable for regional hydrological assessments when combined with appropriate bias correction techniques (Supari et al., 2020; Tangang et al., 2020). CORDEX-SEA datasets have been widely used to investigate climate variability and future climate change across Southeast Asia (Marzuki et al., 2026).

This study utilizes the Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 scenarios to represent intermediate- and high-emission pathways, respectively (Diffenbaugh & Giorgi, 2012; San et al., 2016). The CMIP5-based RCP scenarios were selected because they currently provide the most complete and consistently available CORDEX-SEA datasets for the study area and ensure compatibility between the historical and projection datasets used in this analysis (Baycan & Sonmez, 2025; Mahdaoui et al., 2024). Nevertheless, climate model outputs often exhibit systematic biases relative to local observational data due to limitations in spatial resolution and the representation of atmospheric processes (Yersaw & Chane, 2024). To reduce these discrepancies, various bias correction method have been developed to improve the agreement between model simulations and observations, including the widely applied Linear Scaling (LS) and Quantile Mapping (QM) method (Mendez et al., 2020).

Despite the increasing application of CORDEX-SEA datasets, studies focusing on rainfall bias evaluation and correction at the reservoir catchment scale in Indonesia remain limited. Most previous studies have been conducted at regional or national scales, which may not adequately represent local hydrological variability relevant to reservoir operation and water resources management. Furthermore, only a limited number of studies have integrated climate model evaluation and bias correction within a unified analytical framework for strategic reservoirs in Indonesia. In this study, a 10-day temporal resolution was adopted because it aligns with the operational practices of irrigation management, reservoir operation, and cropping pattern planning commonly implemented by water resources agencies in Indonesia, particularly in East Java.

Based on these gaps, this study aims to evaluate the performance of CORDEX-SEA rainfall data against observations and apply bias correction for the Sutami Reservoir catchment. The novelty of this study lies in: (1) the application of CORDEX-SEA precipitation data at the reservoir catchment scale using a 10-day temporal resolution relevant to operational water management; (2) the integration of model performance evaluation and bias correction using the Linear Scaling (LS) and Quantile Mapping (QM) method within a single analytical framework; and (3) the comparative analysis of rainfall projections under the RCP 4.5 and RCP 8.5 scenarios to support hydrological assessment and reservoir operation planning under climate change conditions.

Method

This research was conducted in the Sutami Reservoir Area located in Karangkates Village, Sumber Pucung District, Malang Regency, East Java, Indonesia at coordinates 08°09′23.24′′- 08°12′24.83′′ S and 112°26′45.42′′ - 112°32′59.26′′ E. This reservoir is located in the Brantas River Basin system and receives flow from a catchment area of approximately 2,050 km². As one of the main reservoirs in the region, the Sutami Reservoir has a strategic function as a multifunctional water resource infrastructure that is used for irrigation, hydroelectric power generation, and flood control. The location map of the Sutami Reservoir is shown in Figure 1.

Research Data

Existing data includes rainfall data from nine rainfall stations (10-day period): Kalipare Station, Poncokusumo Station, Jabung Station, Pagak Station, Tumpukrenteng Station, Kepanjen Station, Tumpang Station, Bululawang Station, and Blambangan Station, covering a 30-year data (1995-2024). Observational data were obtained from Department of Public Works and Water Resources of Malang Regency.

Climate data and projections were obtained from the Coordinated Regional Climate Downscaling Experiment – Southeast Asia (CORDEX-SEA), which provides dynamically downscaled outputs of Global Climate Models (GCMs) using Regional Climate Models (RCMs). The dataset has a spatial resolution of approximately 25 × 25 km and has been widely applied in studies of climate variability and change across Southeast Asia. In this study, climate projections are based on the Representative Concentration Pathways (RCP) scenarios, specifically RCP 4.5 and RCP 8.5 with 10-day period, over a 36-year data comprising a baseline (1995–2024) and a future projection period (2025–2030).

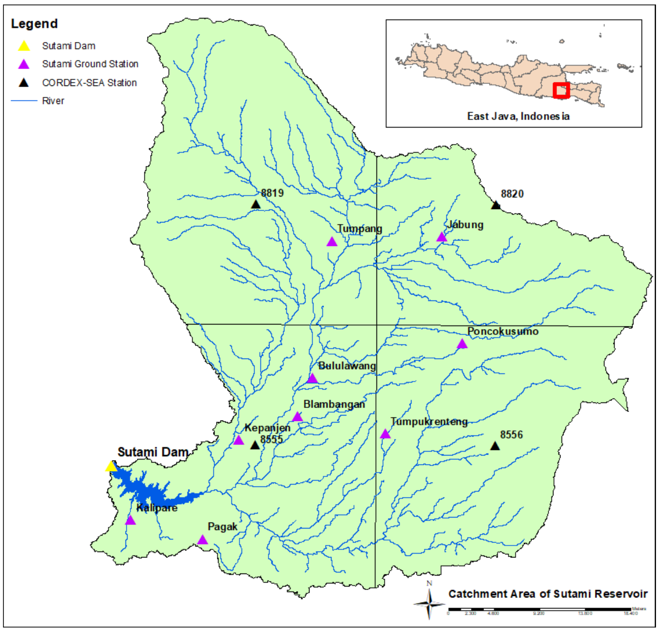

Figure 1. Catchment Area of Sutami Reservoir

Analysis

Prior to the bias correction analysis, areal rainfall over the Sutami Reservoir catchment was estimated using the Thiessen Polygon method to account for the spatial contribution of each rainfall station within the catchment. This method was employed to derive representative catchment-average rainfall values for comparison with the corresponding CORDEX-SEA precipitation data.

Bias Correction

Regional climate model outputs often exhibit systematic deviations from observed data due to limited spatial resolution and uncertainties in representing atmospheric processes. Therefore, prior to their use in hydrological analyses, model outputs require bias correction to align their statistical characteristics with observations (Moya et al., 2024). This step is essential to improve the reliability of climate projections, particularly for hydrological variables such as rainfall, which are critical for water balance assessments in reservoir systems.

In this study, the Linear Scaling (LS) and Quantile Mapping (QM) method was applied to correct biases in the CORDEX-SEA climate projection data. The correction procedure was implemented using Python within the Visual Studio Code (VS Code) environment, where a correction factor was derived by comparing the mean precipitation of the observed data and model outputs during the historical calibration period. The LS and QM method was selected because of its robustness and effectiveness in reducing systematic bias in mean precipitation, and it has been widely applied in hydrological and climate change studies (Azman et al., 2022; Devi et al., 2019; Holthuijzen et al., 2022). Specifically, LS and QM adjusts the mean of simulated data based on the ratio or difference between observed and modeled averages during the calibration period (Mendez et al., 2020).

Although the Linear Scaling (LS) method is effective in reducing systematic bias in mean precipitation and preserving the long-term trends and temporal consistency of climate model outputs, it has limited capability in correcting precipitation variability and the frequency distribution of extreme rainfall events (Tudaji et al., 2025). Therefore, the Quantile Mapping (QM) method was also applied in this study to further adjust the statistical distribution of precipitation by matching the cumulative distribution functions of simulated and observed data, thereby improving the representation of rainfall variability and extreme events (Enayati et al., 2021; Qian & Chang, 2021).

The calculation of bias correction with Linear Scaling (LS) can be seen in equation 1 (Luo et al., 2020).

$$P_{cor\,(10-day)} = P_{raw\,(10-day)} \times \frac{\mu\,(P_{obs\,(10-day)})}{\mu\,(P_{raw\,(10-day)})} \tag{1}$$

where $P_{cor\,(10-day)}$ is the corrected 10-day rainfall, $P_{raw\,(10-day)}$ is the 10-day rainfall from the CORDEX model, $\mu\,(P_{obs\,(10-day)})$ is the existing 10-day rainfall average and $\mu\,(P_{raw\,(10-day)})$ is the 10-day rainfall average from the CORDEX model.

The calculation of bias correction with Quantile Mapping (QM) can be seen in equation 2 (Gudmundsson et al., 2012).

$$P_{corr} = F_{obs}^{-1}(F_{sim}(P_{sim})) \tag{2}$$

where P_{corr} is the corrected data, P_{sim} is the model simulation data, F_{sim} is the cumulative distribution function (CDF) of the simulated data, and F_{obs}^{-1} is the inverse CDF of the observed data.

CORDEX-SEA Data Performance Evaluation

Following bias correction, the data were evaluated to assess the effectiveness of the Linear Scaling (LS) and Quantile Mapping (QM) method in reducing bias and improving the agreement between model outputs and observed climate conditions in the study area. Model performance was assessed using several statistical indicators, including the correlation coefficient (R), Nash–Sutcliffe Efficiency (NSE), the RMSE–standard deviation ratio (RSR), and Percent Bias (PBIAS). These metrics were used to quantify the degree of agreement between simulated and observed data, evaluate the model's ability to reproduce variability, and assess its tendency to overestimate or underestimate observations (Anggraini et al., 2025).

Correlation Coefficient (R)

The correlation coefficient is used to measure the extent of a linear relationship between two variables, whether it is significant or not. In this study, this analysis was used to assess the strength of the linear relationship between existing data and the bias-corrected model data (Mendez et al., 2020). The equation used as shown in equation 3.

$$R = \frac{N\sum_{i=1}^{N} P_i Q_i - \sum_{i=1}^{N} P_i \sum_{i=1}^{N} Q_i}{\sqrt{\sum_{i=1}^{N} P_i^2 - \left(\sum_{i=1}^{N} P_i\right)^2}\sqrt{\sum_{i=1}^{N} Q_i^2 - \left(\sum_{i=1}^{N} Q_i\right)^2}} \tag{3}$$

where Pi is the existing or actual data, Qi is the model data and N is the number of data. The classification of R values can be seen in Table 1 (Moriasi et al., 2007)

Table 1. Classification of Correlation Coefficient (R) values

Value Range	Interpretation
0.80 < R < 1.00	Very Strong
0.60 < R < 0.79	Strong
0.40 < R < 0.59	Medium
0.20 < R < 0.39	Low
0.00 < R < 0.19	Very Low

Nash–Sutcliffe Efficiency (NSE)

The NSE is used to evaluate the accuracy of the correlation between existing data and model data. The closer the result is to 1, the better the interpretation of the NSE value (Nomleni et al., 2021). The equation used is shown in equation 4.

$$NSE = 1 - \frac{\sum_{i=1}^{N} (P_i - Q_i)^2}{\sum_{i=1}^{N} (P_i - \bar{P}_i)^2} \tag{4}$$

where Pi is the existing data, $\bar{P}_i$ is the mean of the existing data, Qi is the model data and N is the number of data. The classification of NSE values can be seen in Table 2 (Moriasi et al., 2007).

Table 2. Classification of Nash–Sutcliffe Efficiency (NSE) values

Value Range	Interpretation
0.75 < NSE ≤ 1.00	Very Good
0.65 < NSE ≤ 0.75	Good
0.50 < NSE ≤ 0.65	Satisfactory
NSE ≤ 0.50	Unsatisfactory

Root Mean Square Error–observation standard deviation ratio (RSR)

RSR standardizes the RMSE using the standard deviation of existing data and incorporates an error index. RSR is calculated using the ratio of RMSE and standard deviation of existing data. The lower the RSR, the lower the RMSE value, thus indicating better model simulation performance (Agaj et al., 2026; Raj et al., 2025). The equation used can be seen in equation 5.

$$RSR = \sqrt{\frac{\sum_{i=1}^{N} (P_i - Q_i)^2}{\sum_{i=1}^{N} (P_i - \bar{P}_i)^2}} \tag{5}$$

where Pi is the existing data, $\bar{P}_i$ is the mean of the existing data, Qi is the model data and N is the number of data. The classification of RSR values can be seen in Table 3 (Moriasi et al., 2007).

Table 3. Classification of RSR values

Value Range	Interpretation
0.00 < RSR ≤ 0.50	Very Good
0.50 < RSR ≤ 0.60	Good
0.60 < RSR ≤ 0.70	Satisfactory
RSR ≥ 0.70	Unsatisfactory

Percent Bias (PBIAS)

PBIAS is used to measure the average tendency of model simulation results to produce higher or lower values compared to observed data, expressed as a percentage (Anindya et al., 2022; Setiyowati et al., 2025). This indicator aims to identify the magnitude of systematic errors generated by the model, as shown in equation 6 (Mendez et al., 2020)..

$$PBIAS = 100 \times \frac{N\sum_{i=1}^{n} (Si - Oi)}{\sum_{i=1}^{n} Oi} \tag{6}$$

where Oi is the existing data at time i, Si is the model data and N is the number of data. The classification of PBIAS values can be seen in Table 4 (Moriasi et al., 2007).

Table 4. Classification of PBIAS values

Value Range	Interpretation
≤ ± 5	Very Good
± 5 ≤ ± 10	Good
± 10 ≤ ± 15	Satisfactory
≥ ± 15	Unsatisfactory

Precipitation Near-term Projection

Rainfall projections for the Sutami Reservoir area for the period 2025–2030 under the RCP 4.5 and RCP 8.5 scenarios were derived from CORDEX-SEA regional climate model outputs.

Following bias correction, the adjusted CORDEX-SEA data—calibrated to reflect local climate characteristics—were used as the basis for generating rainfall projections for the Sutami Reservoir watershed. This adjustment aims to reduce systematic discrepancies between model outputs and observations, thereby providing a more reliable representation of regional hydrometeorological conditions.

Result and Discussion

Simulation Result

Historical Period 1995-2024 Simulation

Rainfall with CORDEX-SEA model outputs under the RCP 4.5 and RCP 8.5 scenarios for the historical period 1995–2024, prior to bias correction. Overall, the model reproduces the general temporal pattern of observed rainfall, particularly the periodic occurrence of peak events, indicating that the seasonal variability is reasonably captured as shown in Figure 2.

However, the model consistently produces higher rainfall values than observations, indicating a positive bias. The mean observed rainfall is 56.19 mm, whereas the simulated means reach 86.09 mm (RCP 4.5) and 89.49 mm (RCP 8.5). This discrepancy confirms that CORDEX-SEA tends to overestimate rainfall relative to actual conditions in the study area.

In addition, the model exhibits greater variability, with more pronounced fluctuations and higher rainfall peaks compared to observations. These amplified extremes suggest that, without adjustment, the model output contains systematic deviations in both magnitude and variability.

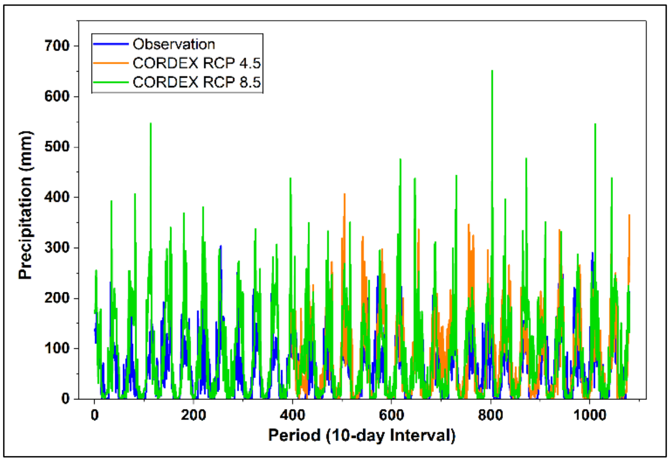

Figure 2. Comparison of observed Precipitation data with CORDEX RCP 4.5 and RCP 8.5 at 10-day intervals (1995-2024)

This finding aligns with previous studies showing that raw rainfall data from RCMs often yields higher estimates than observations, particularly at daily and monthly temporal scales. Therefore, bias correction is necessary (Derdour et al., 2022).

Bias Correction of CORDEX-SEA Precipitation under RCP 4.5 and RCP 8.5

Table 5 presents the performance evaluation of rainfall simulated by the CORDEX-SEA model under the RCP 4.5 and RCP 8.5 scenarios for the historical period 1995–2024, before and after bias correction using the Linear Scaling (LS) and Quantile Mapping (QM) method at a 10-day temporal resolution. Prior to bias correction, the model shows poor agreement with observations. This is reflected in low correlation coefficients (R) (0.51–0.52) and negative Nash–Sutcliffe Efficiency (NSE) values (−0.97 to −1.28), indicating that the model performs worse than the observed mean as a predictor. In addition, RSR values greater than 1 and high Percent Bias (PBIAS) values—53.22% for RCP 4.5 and 59.28% for RCP 8.5—indicate substantial systematic bias, with the model consistently overestimating rainfall relative to observations.

Table 5. Performance Evaluation of CORDEX-SEA RCP 4.5 and RCP 8.5 Data Before and After Bias Correction

Method	Before	Description	After	Description
RCP 4.5				
R	0.52	Medium	0.95	Very Strong
NSE	-0.97	Unsatisfactory	0.90	Very Good
RSR	1.41	Unsatisfactory	0.32	Very Good
PBIAS	53.22 %	Unsatisfactory	2.44%	Very Good
RCP 8.5				
R	0.51	Medium	0.91	Very Strong
NSE	-1.28	Unsatisfactory	0.90	Very Good
RSR	1.51	Unsatisfactory	0.32	Very Good
PBIAS	59.28 %	Unsatisfactory	2.63%	Very Good

After bias correction, model performance improved substantially. The correlation coefficient (R) increased to approximately 0.91-0.95, indicating a very strong linear relationship between simulated and observed data. The Nash–Sutcliffe Efficiency (NSE) also increased to around 0.90, demonstrating a strong ability to reproduce observed rainfall variability. In addition, the RMSE–standard deviation ratio (RSR) decreased to approximately 0.32, indicating reduced simulation error relative to observed variability. The most notable improvement is observed in Percent Bias (PBIAS), which decreased significantly to around 2–3%, suggesting that systematic bias was effectively minimized.

This improvement is further reflected in the mean rainfall values. The observed mean rainfall is 56.19 mm, while the bias-corrected model outputs are 54.82 mm (RCP 4.5) and 54.71 mm (RCP 8.5), closely matching the observations. These results indicate that the applied bias correction method effectively adjusts both the magnitude and distribution of rainfall, making the model outputs more representative of local climate conditions.

As shown in Figure 3, the corrected model outputs more closely follow the temporal variability of observed rainfall, particularly in capturing peak events and low-rainfall periods at the 10-day scale. This demonstrates that bias correction improves not only the mean values but also the representation of temporal variability.

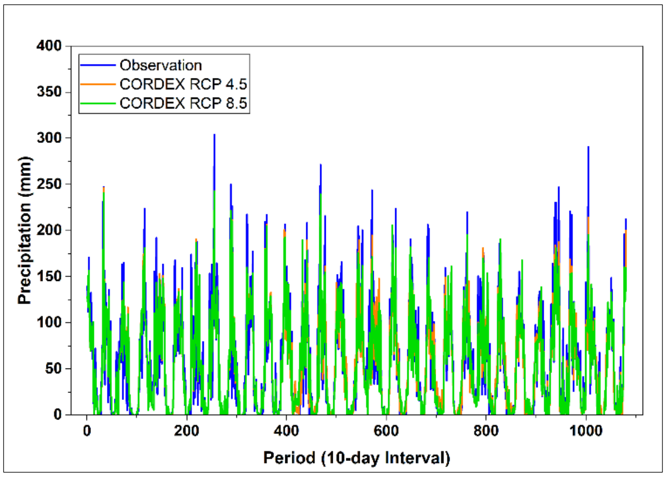

Figure 3. Comparison of observed Precipitation data with CORDEX RCP 4.5 and RCP 8.5 after bias at 10-day intervals (1995-2024)

The results of this study are consistent with previous findings indicating that raw outputs from regional climate models often contain systematic biases in precipitation, necessitating correction prior to their use in hydrological analyses or climate projections. Studies within the CORDEX framework have shown that regional climate model simulations commonly exhibit deviations in both mean values and precipitation intensity. However, model performance can improve substantially following the application of bias correction techniques (Chen et al., 2022; Tieh et al., 2022).

Precipitation Near-term Projection for RCP 4.5 and RCP 8.5 (2025-2030)

Rainfall near-term projections for the Sutami Reservoir watershed were derived from CORDEX-SEA regional climate model outputs for the future period 2025–2030, following bias correction of historical data (1995–2024). This correction aligns model outputs with observed rainfall characteristics, ensuring that the projections more accurately represent local climate conditions. Figure 4 compares 10-day rainfall projections under the RCP 4.5 and RCP 8.5 scenarios. Overall, both scenarios exhibit similar variability patterns, with fluctuations reflecting alternating wet and dry periods. Several rainfall peaks persist in both scenarios, indicating that high-intensity rainfall events may continue to occur in the future.

However, the mean projected rainfall for 2025–2030 shows a decline relative to historical conditions. The average rainfall is 42.72 mm under RCP 4.5 and 43.05 mm under RCP 8.5, both lower than the bias-corrected historical mean of approximately 56 mm. This indicates a decreasing trend in average rainfall.

The difference between scenarios is relatively small, with RCP 8.5 yielding slightly higher values than RCP 4.5. Nevertheless, both scenarios consistently indicate a reduction in mean rainfall, suggesting potential changes in future climate patterns that may affect water availability in the Sutami Reservoir watershed.

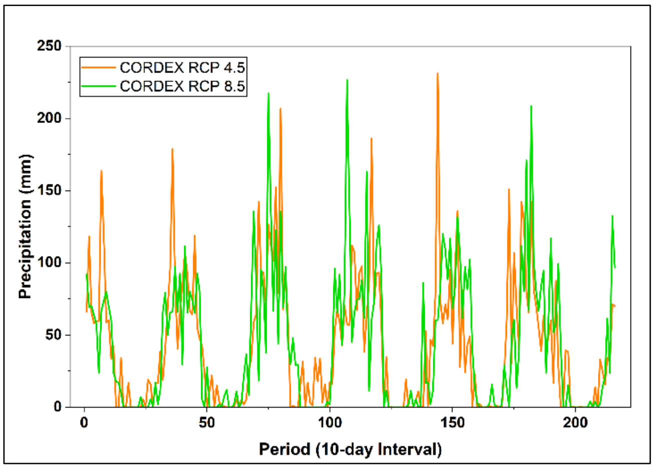

Figure 4. Bias-corrected CORDEX-SEA Precipitation projection results RCP 4.5 and RCP 8.5 (2025–2030).

These results indicate that although rainfall variability still occurs, the tendency for a decrease in the average rainfall value can be an early indication of climate change that has the potential to affect the hydrological dynamics of the study area. The projected decline in mean rainfall is expected to reduce inflow to the Sutami Reservoir, particularly during dry periods, thereby increasing the risk of water balance deficits and compromising the reliability of irrigation supply, raw water provision, and hydropower generation. Despite the overall decline, the persistence of rainfall peaks suggests a more uneven temporal distribution, indicating an increased likelihood of extreme events, such as prolonged droughts and short-duration, high-intensity rainfall, which may lead to higher runoff and elevated local flood risk. This finding is consistent with previous studies in Southeast Asia, which reported that climate change–induced rainfall variability can reduce water availability while increasing flood risk and hydrological extremes, thereby affecting reservoir operation and water resources management (Ly et al., 2023; Yun et al., 2020).

These findings underscore the need for adaptive reservoir management strategies that address reduced water availability while anticipating extremes. Key approaches include optimizing reservoir operation, enhancing irrigation efficiency, and strengthening flood early warning systems. Moreover, bias-corrected CORDEX-SEA projections provide a robust foundation for medium- to long-term water resources planning under climate change uncertainty.

Conclusion

The CORDEX-SEA model outputs exhibit systematic overestimation of observed rainfall during the historical period (1995–2024), with mean precipitation values of 86.09 mm per 10-day period under RCP 4.5 and 89.49 mm per 10-day period under RCP 8.5, compared with 56.19 mm per 10-day period from observations. Following the application of Linear Scaling (LS) and Quantile Mapping (QM) bias correction methods, model performance improved substantially, as demonstrated by strong correlation coefficients (R = 0.91–0.95), high Nash–Sutcliffe Efficiency values (NSE = 0.90), and reduced error metrics (RSR = 0.31; PBIAS ≈ 2–3%). Moreover, the corrected mean rainfall values (54.7–54.8 mm per 10-day period) closely matched the observed precipitation. Near-term projections (2025–2030) suggest a potential decrease in average rainfall to 42.72 mm per 10-day period under RCP 4.5 and 43.05 mm per 10-day period under RCP 8.5. The relatively small difference between the two scenarios is consistent with near-term climate projections, in which scenario divergence is generally not yet pronounced because of the dominant influence of interannual climate variability. These results confirm that CORDEX-SEA outputs contain systematic bias at the catchment scale but can be effectively improved through bias correction techniques. The projected decline of approximately 24% in mean rainfall may pose substantial risks to water availability and the operational reliability of irrigation supply, hydropower generation, and reservoir management in the Sutami Reservoir watershed. This finding underscores the need for adaptive water resources management strategies, including optimization of reservoir operations and revision of the Annual Water Allocation Plan. Furthermore, bias-corrected rainfall projections provide a reliable basis for water balance analysis and future hydrological assessments under changing climate conditions. Future research should consider longer projection horizons, the application of more advanced bias correction methods to better represent extreme events, and integration with hydrological models to evaluate impacts on reservoir inflow, storage dynamics, and flood–drought risk.

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Author Contributions

Conceptualization D.A., S.W., and M.B; methodology D.A and S.W; analysis D.A; writing-original draft preparation D.A; writing-review and editing D.A., S.W., and M.B; visualization D.A.; All authors have read and agreed to the published version of manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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