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Assessing Future Drought Extremes and Their Impact on Hydropower Vulnerability in Sarawak

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Droughts pose a critical threat to water-dependent sectors, particularly hydropower, a vital low-carbon energy source in Sarawak, necessitating an assessment of future drought impacts. Utilising Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) dataset, Standard Precipitation Index at 3 months (SPI-3) was identified as the most representative drought time scale, contributing most to pincipal component 1 (PC1), which explained 73.86% of the total variance. MPI-ESM1-2-HR (CPI = 0.057) and NorESM2-LM (CPI = 0.005), were identified as top-performing based on compromise programming index (CPI) and Fisher-Jenks classification, effectively simulating low rainfall percentiles with Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) below 0.06 across 1st to 15th percentiles. Random Forest (RF) achieved the highest distributional agreement Overlap Coefficient (OVL = 0.83), with reduced Standard Deviation (SD) (55 mm) and near-zero skewness (-0.25), indicating superior bias correction performance. Temporally, drought frequency was projected to decrease by mid-century, then rose again by 2075–2100 to 5,037 moderate, 2,315 severe, and 1,058 extreme events, indicating a mid-century dip followed by a late-century increase. Hydropower vulnerability to drought in Sarawak varies temporally and spatially, with Batang Ai peaking mid-century (vulnerability index 1.00), Bakun and Murum most vulnerable by century's end (indices 1.00 and 0.93), and Baleh consistently least affected (≤0.17).

1. Introduction

Droughts represent one of the most critical climatic stressors affecting water availability in hydropower catchments. Defined as prolonged periods of deficient rainfall relative to the norm, drought events can substantially diminish reservoir inflows, compromising the capacity to generate electricity reliably (Schilstra et al., 2024). In tropical regions like Sarawak, where seasonal rainfall patterns are pronounced, shifts in drought characteristics such as frequency, intensity, and duration may profoundly impact hydropower performance. Recent decades have witnessed an increase in the occurrence of extreme weather events, including droughts, attributed to climate change (Huang et al., 2023). This raises concerns about future water resource sustainability and energy security in hydropower-dependent regions.

Despite the recognized importance of drought impacts on hydropower, there remains a paucity of region-specific studies integrating high-resolution observational data with advanced climate model projections to robustly assess future drought extremes in Sarawak. Previous assessments mainly focused on historical trends using

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station-based climate data, which may lack the spatial resolution needed to capture localized drought extremes critical for hydropower planning and adaptation. Moreover, the evolving nature of climate forcing necessitates the use of the latest generation of climate models, such as those from the Coupled Model Intercomparison Project Phase 6 (CMIP6), which offer improved representation of climate processes and future scenarios under different socioeconomic pathways.

The objectives of this study are to address critical knowledge gaps by presenting a comprehensive assessment of future drought extremes across Sarawak, focusing specifically on districts hosting major hydropower infrastructure. Another key objective is to identify General Circulation Models (GCMs) from the CMIP6 ensemble that can accurately simulate extreme low rainfall conditions, particularly the 1st, 5th, 10th, and 15th percentiles of historical rainfall distributions. To achieve this, gridded-based Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) dataset was used, and three bias-correction method was compared, namely, Quantile Mapping (QM), Random Forest (RF), and Quantile Random Forest (QRF), before ensemble. Delta-based spatial disaggregation was applied to downscale projections under SSP5-8.5, with drought frequency and intensity assessed using SPI classifications for the 21st century. The study aims to provide decision-relevant information for water resource managers and energy planners by quantifying potential impacts on hydropower vulnerability and underscores the urgent need for climate-informed adaptation strategies to enhance the resilience and sustainability of Sarawak's hydropower sector amid increasing climatic uncertainties.

2. Study area

Sarawak, located in the northwestern part of the island of Borneo, is the largest state in Malaysia by land area, covering approximately 124,450 km^2 (Figure 1). It lies between latitudes 0.5°N and 5.5°N and longitudes 109°E and 115°E, sharing international borders with the Indonesian provinces of Kalimantan to the south and Brunei to the north. Sarawak's tropical equatorial climate is influenced by the Intertropical Convergence Zone and monsoon systems, resulting in high annual rainfall (averaging between 3,000 and 4,000 mm) and relatively stable temperatures typically ranging from 23°C to 32°C. The climate and geography contribute to rich biodiversity and complex hydrological patterns, making the state highly sensitive to environmental and climatic changes.

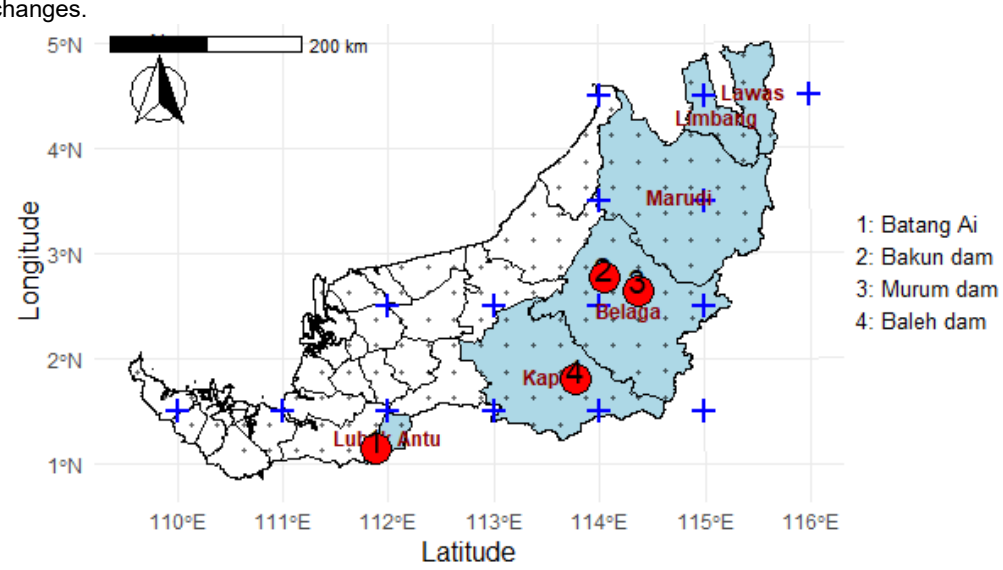

Figure 1: Location of Sarawak showing 159 black dots (0.25° grids) and 15 blue crosses (1°) from CHIRPS. The light blue highlight indicates districts with dam locations, as identified by Alamgir et al. (2020). The number correspond to the main hydropower dam in Sarawak

3. Data

3.1 Climate data

This study utilized 0.25° resolution CHIRPS precipitation data (1981–2014) spanning 159 grid points, providing a validated and reliable baseline for assessing historical drought variability and future climate projections in Southeast Asia (Du et al., 2024). For drought analysis, daily CHIRPS precipitation data were aggregated to monthly totals to calculate the SPI at multiple timescales (1-, 3-, and 6-month), allowing quantification of short to medium-term drought conditions. SPI values classify drought severity as follows: -0.99 to +0.99 indicates

near-normal, -1.0 to -1.49 mild drought, -1.5 to -1.99 moderate drought, and below -2.0 severe to extreme drought. Future climate projections in this study are derived from 23 selected GCMs participating in the CMIP6 as previously identified by Sa'adi et al. (2024). CMIP6 represents the latest generation of climate models that incorporate improved physical processes, higher spatial resolution, and updated greenhouse gas emission scenarios, making them well-suited for regional climate impact assessments. The study focuses on the high-emission SSP5-8.5 scenario, representing a worst-case pathway with ~8.5 W/m² radiative forcing by 2100, to assess upper-bound drought risks and guide risk-averse water and energy planning in Sarawak.

4. Methodology

This study employed a structured and multi-stage methodology to select suitable GCMs and to assess future drought and their potential impact on selected hydropower in Sarawak.

1. A homogeneous 1° grid was initially established by bilinearly interpolating CHIRPS (0.25°) and CMIP6 GCM datasets to enable direct comparison and evaluation.
2. GCMs were then selected based on their skill in reproducing observed rainfall extremes at lower percentiles (1st, 5th, 10th, 15th), using Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) metrics.
3. Models were ranked via a compromise programming index (CPI) aggregated across percentiles, classified with Fisher-Jenks natural breaks, and further validated using probability distribution function (PDFs) and statistical metrics, namely, skewness, kurtosis, and overlap coefficient (OVL).
4. Principal Component Analysis (PCA) was used to identify key SPI timescales (1-, 3-, and 6-month) that can best represent drought variability, guiding drought frequency, and intensity calculations.
5. Top-ranked GCM outputs were bias-corrected using QM, RF, and QRF, with the best-performing method used to produce an RF-driven ensemble for future projections. Finally, delta-based spatial disaggregation was used to downscaled the bias-corrected ensembled GCMs into 0.25° CHIRPS grid to produce a high-resolution future projection.
6. A comprehensive spatiotemporal drought assessment was conducted across Sarawak's by analyzing drought frequency and mapping the mean of the top three maximum intensities, with a hydropower vulnerability index derived from the min–max normalized mean intensity and frequency at each dam's nearest grid point.

5. Results and discussion

5.1 PCA-based evaluation of SPI timescales

The PCA results revealed that the first principal component (PC1) has a standard deviation of 1.4885 and explains 73.86% of the total variance, while the second principal component (PC2) contributes an additional 18.58%, bringing the cumulative variance explained by the first two components to 92.44%. This high cumulative proportion indicates strong collinearity among the three SPI timescales. The variable loadings on PC1 were 0.5309 for SPI-1, 0.6206 for SPI-3, and 0.5771 for SPI-6. Among these, SPI-3 exhibited the highest loading, indicating its dominant contribution to the principal drought signal across scales. This finding suggests that SPI-3 is the most representative timescale, capturing both short- and mid-term drought variability. Therefore, SPI-3 was selected as the optimal index for subsequent spatial mapping analyses, balancing sensitivity to rapid rainfall deficits with the capacity to reflect longer-term hydrological stress.

5.2 Top-performing GCMs

The resulting CPI scores and subset classification using the Fisher-Jenks natural breaks algorithm, grouped the GCMs into nine performance classes (Figure 2). The top-performing model, NorESM2-LM, achieved the lowest CPI (0.0055), with near-zero MAE and RMSE across all percentiles (e.g., MAE1 = 0.0055, RMSE1 = 0.00005), indicating exceptional capability in replicating low-percentile rainfall extremes. It was followed by MPI-ESM1-2-HR (CPI = 0.0572) and NorESM2-MM (CPI = 0.0738), both also showing low MAE and RMSE values across all thresholds (e.g., MPI-ESM1-2-HR: MAE1 = 0.0417, RMSE1 = 0.0026). These two models, were grouped into Class 1, forming the subset of top-performing GCMs. In contrast, models like IPSL-CM6A-LR, INM-CM4-8, and INM-CM5-0 fell into Classes 9, 8, and 7 respectively, with the highest CPI values (e.g., IPSL-CM6A-LR = 2.83) and consistently large MAE and RMSE errors (e.g., all metrics equal to 1.0 for IPSL-CM6A-LR). This ranking framework enabled a robust identification of GCMs most capable of capturing extreme low-rainfall events.

The evaluation of bias correction methods applied to the MPI-ESM1-2-HR (Figure 3a) and NorESM2-LM (Figure 3b) GCMs reveals distinct improvements over raw model outputs in simulating monthly rainfall characteristics (Figure 3). For MPI-ESM1-2-HR, the raw GCM has a mean monthly rainfall of 206 mm (Standard Deviation (SD) 69 mm), negative skewness (-0.64), moderate kurtosis (2.90), and moderate similarity to observations (OVL 0.48). Bias corrections increased mean rainfall to 268–310 mm, improving alignment with observed data. The

RF method performed best, achieving the highest OVL (0.83), reduced SD (55 mm), and more symmetric skewness (-0.25), indicating better rainfall variability representation. QM raised the mean to 310 mm with higher kurtosis (3.14) and positive skewness (0.59), suggesting more extreme events (OVL 0.81). QRF showed moderate improvements with mean 268 mm, SD 59 mm, skewness -0.27, kurtosis 2.29, and OVL 0.73. For NorESM2-LM, the raw model showed a mean monthly rainfall of 264 mm (SD 99 mm), near-neutral skewness (-0.19), kurtosis 2.91, and a strong baseline match with observations (OVL 0.80). Bias corrections improved results, with QM yielding the highest OVL (0.86) and mean rainfall (310 mm) but with increased kurtosis (4.06) and positive skewness (0.66), suggesting overemphasized extremes. RF correction matched QM's mean (310 mm) but reduced variability (SD 55 mm), skewness (-0.27), and kurtosis (2.34), with an OVL of 0.83. QRF showed moderate improvement (mean 269 mm, SD 59 mm, OVL 0.74). Overall, RF best balanced mean accuracy and variability, making it the preferred bias correction for subsequent analyses.

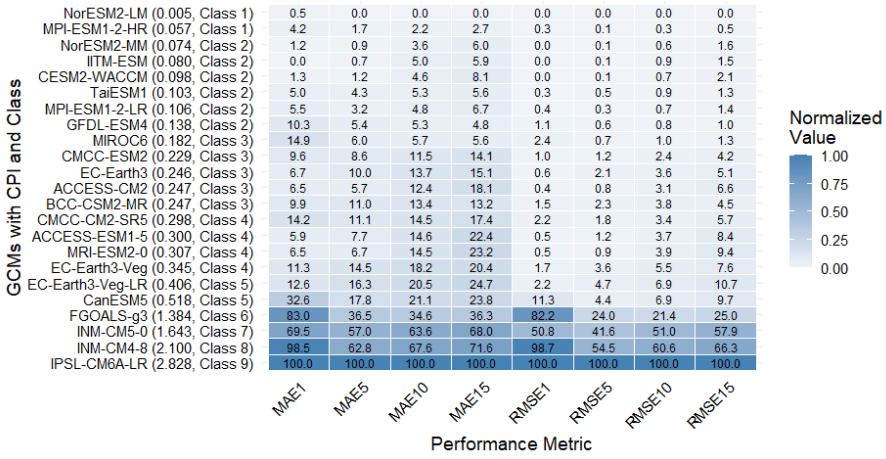

Figure 2: The heatmap illustrates the performance of each GCM using the 1st, 5th, 10th, and 15th percentile values of MAE and RMSE (normalised)

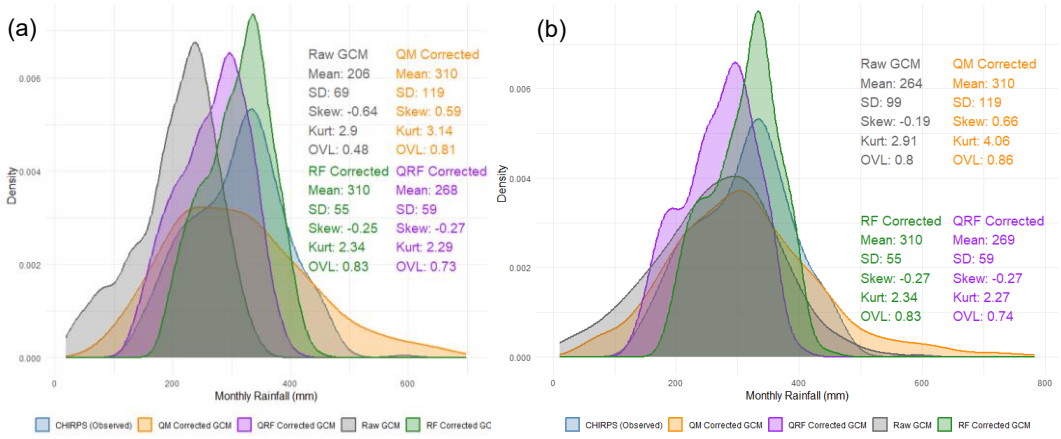

Figure 3: PDFs showing the distribution of monthly rainfall totals from raw, and bias-corrected top-performing GCMs, (a) MPI-ESM1-2-HR and (b) NorESM2-LM, including CHIRPS observations based on QM, RF, and QRF

5.3 Future projection under SSP5-8.5

The temporal analysis of drought frequency across Sarawak reveals notable shifts in drought occurrence intensity from the historical period through to the far-future projection (Figure 4a and 4b), highlighting important implications for regional water resource management and climate resilience planning. During the historical baseline period (1981–2014), moderate drought events were the most frequent, with 6,035 occurrences, followed by severe droughts at 2,603 instances and extreme droughts totaling 1,477. Moving into the near-future period (2025–2049), the frequency of moderate droughts decreases to 4,319 events, with severe droughts slightly reducing to 2,282 occurrences and extreme droughts at 1,152, suggesting a modest decline in overall

drought frequency shortly after the historical baseline. This declining trend continues into the mid-future period (2050–2074), where moderate droughts occur 3,904 times, severe droughts 1,929 times, and extreme droughts reduce further to 927. However, projections for the far-future period (2075–2100) indicate a significant resurgence in drought frequency across all severity classes, with moderate droughts reaching 5,037 occurrences, severe droughts increasing to 2,315, and extreme droughts remaining substantially high at 1,058 events. This non-linear trend implies a complex climatic response, with a temporary mid-century alleviation followed by intensified drought conditions toward the end of the century. The persistence of frequent moderate to severe droughts highlights escalating vulnerability and the urgent need for adaptive water management and drought mitigation tailored to Sarawak's socio-ecological context. This aligns with Turner and Voisin (2022), who demonstrate that climate change–driven droughts can substantially reduce hydropower capacity over decades, thereby exposing power grids to prolonged drying risks, a conclusion supported by numerous global and regional studies. For instance, Samjhana and Manan (2025) highlight that increased drought frequency reduces hydrological discharges and limits water availability during lean seasons, adversely affecting energy generation.

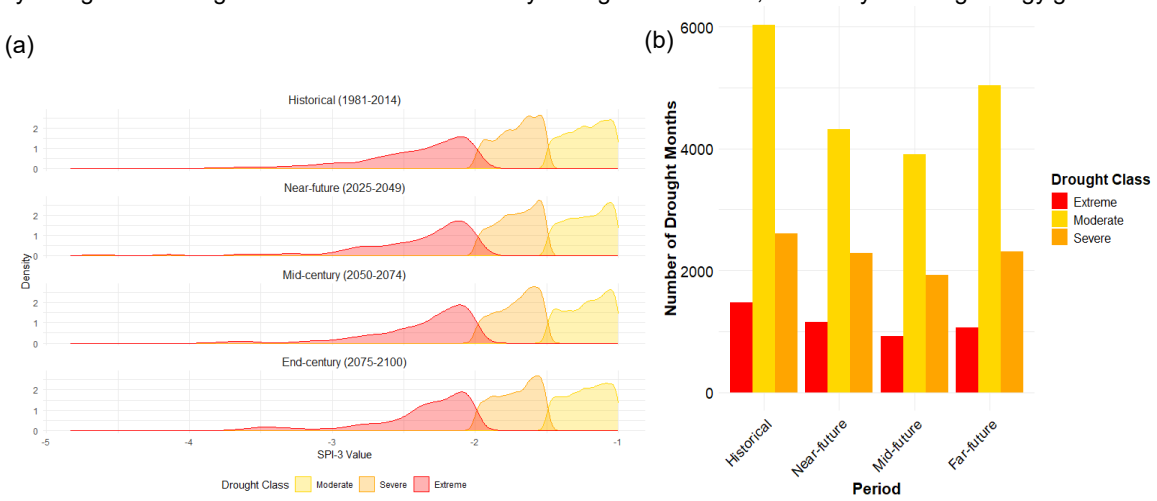

Figure 4: The (a) PDFs and (b) bar plot of SPI-3 values associated with different drought severity classes (Moderate, Severe, Extreme) for Sarawak across

Figure 5 highlights spatial hotspots of drought risk and identifies hydropower infrastructure most vulnerable under future climate conditions. In the near-future period (2025-2049) (Figure 5a), Batang Ai experiences the most severe drought conditions with a maximum intensity of −2.75 and a severe drought frequency of 3 events, resulting in a moderate vulnerability index of 0.50. Bakun and Murum exhibit similar maximum drought intensities (−2.53 and −2.52, respectively) with higher severe drought frequencies (9 events), leading to vulnerability indices of 0.75 for both dams. Baleh records the lowest drought severity (−2.31) and a moderate frequency of 5 events, resulting in the lowest near-future vulnerability index of 0.17. By mid-future period (2050–2074) (Figure 5b), Batang Ai intensifies to −2.90 with a doubled frequency (6 events), and the highest possible vulnerability index (1.00). Baleh follows with −2.62 and 6 events, producing a vulnerability of 0.82, while Bakun and Murum both weaken in maximum intensity (−2.14 and −2.11) and record only 2 severe drought events, yielding the lowest mid-century vulnerability (0.02 and 0.00, respectively). In the far-future period (2075–2100) (Figure 5c), Bakun records the most severe drought intensity (−2.77) and highest frequency (7 events), and a vulnerability index of 1.00. Murum follows closely (−2.74, 7 events), resulting in a vulnerability index of 0.93. In contrast, Batang Ai sees a reduction in drought severity (−2.51) and 5 events, resulting in no vulnerability (0.00), while Baleh shows similar drought intensity (−2.51) and frequency (5 events), producing a near-zero vulnerability index (0.003). These temporal shifts reveal spatially heterogeneous drought risk trajectories, with Batang Ai and Baleh experiencing vulnerability peaks mid-century, while Bakun and Murum become most vulnerable toward the century's end. Previous work by Yusoff et al. (2019) projected increased water availability and hydropower output at Murum Dam, likely driven by extreme rainfall during the wet season; however, this study highlights that drought severity during dry periods may worsen, indicating compounded climate change impacts. Chiew et al. (2013), also reported dams in Sarawak River face reduced storage and altered operations due to decreased discharge and prolonged intervals between high-flow events, reinforcing the "dry gets drier" paradigm.

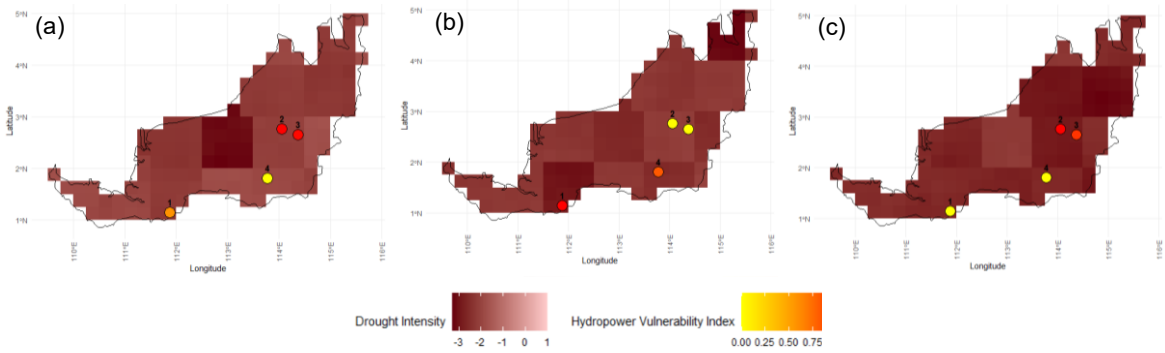

Figure 5: Spatial distribution of mean top three maximum drought intensities (SPI-3) for the projected period across Sarawak, (a) near-future (2025-2049), (b) mid-future (2050-2074), and (c) far-future (2075-2100), overlaid with hydropower dam locations. Circular markers denote hydropower dams, where the fill color intensity corresponds to the calculated hydropower vulnerability index at each dam location

6. Conclusions

This study provides a critical advancement in understanding future drought dynamics within Sarawak's key hydropower catchments by integrating high-resolution observational data with top-performing climate models under a high-emission scenario. The comprehensive assessment of drought frequency, and intensity, reveals escalating risks to hydropower reliability throughout the 21st century, emphasizing the vulnerability of this vital low-carbon energy sector to climate change. The findings offer essential guidance for water resource managers and energy planners to develop proactive, climate-informed adaptation strategies, thereby enhancing the resilience and sustainability of Sarawak's hydropower infrastructure amidst growing climatic uncertainties.

Acknowledgments

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