

Assessment on future rainfall variability for adaptive water resource management in Sabah

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Abstract. Climate is changing at an unprecedented rate, and the increasing demands of the growing population will place further pressures on the climate and environment. Water infrastructures such as water treatment plants often face increased stress during extreme weather events such as heavy rainfall or prolonged drought, disrupting societal needs and prompt urgent upgrades to adapt to the changing climate. The use of climate model projections is increasingly adopted in engineering practices for assessing climate risks and impacts to inform adaptive design and strategy of new infrastructures or upgrades. Using a bias-corrected ensemble member of the fifth phase of the Coupled Model Intercomparison Project (CMIP5) tailored for applications in the water sector, we assessed the variability of projected rainfall from 2021 to 2050 under the moderate warming scenario (RCP 4.5). The findings from this study aim to inform adaptive strategies for upgrading 22 water treatment plants across 18 sites in Sabah, Malaysia, where these plants have experienced numerous disruptions due to high turbidity resulting from heavy rainfall in recent years. The average annual rainfall amount ranges from 1630 mm to 4415 mm, with average total monthly rainfall peaks (>460 mm) in June and August at most sites. The observed shift in June and August is a deviation from historical patterns and is also reflected in the maximum consecutive 1- to 5-day rainfall, ranging from 22 mm to 760 mm across all sites, particularly in the interior and west coast districts. This highlights the need for resilient infrastructure upgrade strategy and adaptive water resource management, such as the introduction of off-site river storage to accommodate the anticipated future rainfall.

1 Introduction

Frequent occurrence of extreme weather events such as extreme rainfall and temperatures has significantly intensified over the recent decade due to climate change

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[1-4]. Climate change also increases the likelihood of compound events, where an extreme event causes other extreme events within a short period of time [1], amplifying the severity of consequences, such as severe flooding. For instance, a storm surge coinciding with a high tide and prolonged heavy rainfall can lead to catastrophic flooding, overwhelming drainage systems as they are unable to cope with the combined influx of water. These consequences significantly disrupt daily life, particularly impacting the reliability of water supply systems [5-6]. Water treatment plants face increased stress during such periods. Intense rainfall events raise water levels in rivers and reservoirs, increasing the risk of overflowing and contribute to widespread flooding. The increased water flow carries high amount of sediment, debris and pollutants, which are difficult to filter and treat effectively, forcing water treatment plants to shut down to prevent damage to equipment and to avoid distributing contaminated water. This shutdown results in a temporary loss of water supply to affected communities, exacerbating the difficulties they face during and after flood events. The situation is compounded when the downtime needed to clean and repair treatment facilities delays the restoration of normal water services. This heightened demand, coupled with a reduced supply, create a critical challenge for water management authorities. In response, there is a growing emphasis on water quality treatment, spill containment and sustainability requirements in water infrastructure design and strategy to better adapt to unprecedented changes in climate [7].

For many years, water infrastructure design has relied on well-established principles grounded in a strong understanding of hydrology and hydraulic design standards. These principles however, relied upon a stationary assumption that the probability distribution of extreme weather events will not change significantly over time [7-9]. In recent decades, it has become increasingly evident that this assumption may no longer hold true in many regions due to the impacts of anthropogenic activities and climate-induced stressors that cause nonstationary conditions to introduce significant variability and unpredictability to the hydrological cycle [2]. Rising global temperatures are driving climate change, disrupting atmospheric dynamics and processes, altering rainfall patterns and increasing the risk of more extreme weather events [10]. These changes are further complicated by other factors such as population growth, evolving attitudes and cultural norms, emerging technologies and other unknowns, which are not captured in historical data [11-14], making reliance on such data inadequate for developing robust and adaptable sustainable water infrastructure design and strategy that are resilient to dynamic changes in the long term.

Adaptive infrastructure planning in a changing climate requires considerable engineering judgement to balance the potential costs of mitigating risks through adaptation against the potential of failure and the level of protection provided by the design [15]. The use of climate model simulations for future climate risk and impact assessment to inform engineering design is increasingly adopted as a scientifically informed strategy for building an economically reasonable and resilient future [15]. In recent decades, climate models have been significantly improved and more outputs have been bias-corrected against observation datasets, making it suitable for use in many

applications [16]. Climate models, at their core, use physically based mathematical equations to represent processes and interactions that drive the Earth's climate [17] beyond those that can be estimated from historical data alone. Global climate models, such as those utilised in the Coupled Model Intercomparison Project (CMIP), adopt a set of greenhouse gas concentration trajectories and socioeconomic conditions with varying mitigation efforts to simulate the potential impacts of different levels of greenhouse gas emissions on global temperatures and climate systems [18-21]. The outputs from these models help policymakers, researchers and planners understand the possible impacts of different scenarios. In this study, a bias-corrected future rainfall dataset from CMIP5, tailored for water sector applications [22], was utilised to assess the variability of future rainfall from 2021 to 2050. The study intends to provide an overview of anticipated future rainfall variability to inform adaptive strategies for upgrading the 22 water treatment plants across 18 sites in Sabah, Malaysia, where water treatment plants in the area have experienced numerous disruptions due to high turbidity resulting from heavy rainfall in recent years.

2 Methodology

2.1 Study area

This study assessed the variability of future rainfall projections for 18 sites in Sabah where 22 water treatment plants encountered frequent downtimes due to rise in turbidity levels exceeding 700-1000 NTU during heavy rainfall events (Fig. 1). The study sites are located in three districts: the West Coast district (Topokon, Pekan Kota Belud, Bayayat, and Bandau); the Interior district (Kg Keningau, Kg Agudon, Kg Bingkor, Sook, Tulid, Pekan Tenom, Senagang, Kg Mosopoh, Beaufort, and Kg Ulau); and the Tawau district (Kalabakan, Merotai, Kg Silabukan, and Kalumpang).

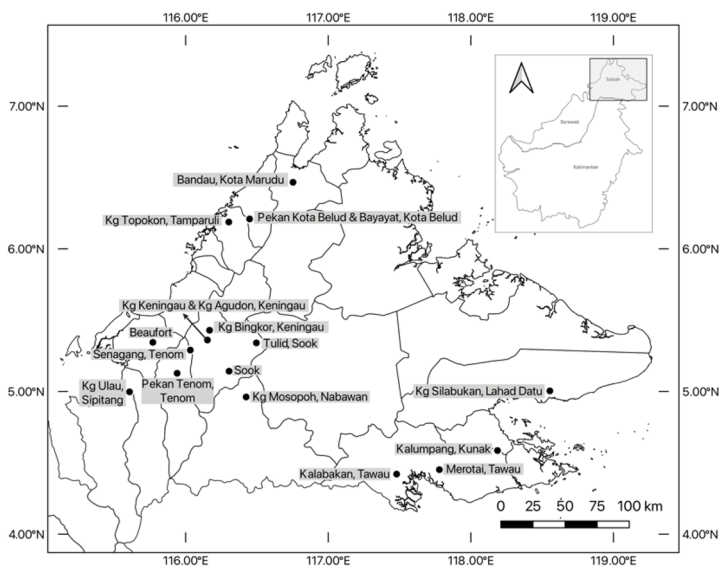


Fig. 1. Map of study area: 18 sites in Sabah where 22 water treatment plants are located.

2.2 Data and methods

The dataset used in this study is derived from an ensemble member of the fifth phase of Coupled Model Intercomparison Project (CMIP5), specifically the HadGEM2-CC-lilp1 model with $0.5^\circ \times 0.5^\circ$ (~50 km x 50 km) grid resolution. This dataset was bias-adjusted by [22] based on [23], and is tailored for applications in the water sector. We investigated the daily rainfall for 18 sites in Sabah under the moderate warming scenario (RCP 4.5) for a period of 30 years from 2021 to 2050. The RCP 4.5 scenario represents an intermediate path where global greenhouse emission stabilise by the mid-21st century and then decline [20-21]. This scenario was selected as it assumes significant mitigation policies are implemented to limit emissions, which aligns with Malaysia's nationally determined contributions to reducing greenhouse gas emissions by mid-21st century [24]. The coordinates of the 18 sites were identified in the climate model grid, and the daily rainfall output from the selected grids were extracted and analysed temporally in terms of average total annual and monthly rainfall. Further analysis on maximum consecutive 1- to 5-day rainfall were conducted for each month, averaged over the 30-year study period, using a sliding window approach. The method involves iterating through each day and computing the rolling sum of 1-, 2-, 3-, 4- and 5-day rainfall over 30 years. The data is then grouped by months and the maximum values for each consecutive day period is determined.

3 Results and discussion

From 2021 to 2050, the average total annual rainfall amount ranges from 1630 mm to 4415 mm (Fig. 2a), with highest peak observed in 2030 and a prolonged period of relatively low rainfall from 2031 to 2041. Consistently high rainfall amount was observed for five sites in the interior district: Kg. Mosopoh, Kg. Ulau, Kalabakan, Senagang and Bandau. On the other hand, Topokon, Kalumpang and Beaufort in the West Coast and interior districts, respectively, are projected to have consistently low rainfall amount. The 30-year future rainfall climatology shows significant variability, with significant dips observed every 3-4 years from 2025 to 2050. Between the dips, rising trends occur within spans of 2-4 years. This high variability is attributed to Sabah's unique position in the Maritime Continent within the ascending regions of the Hadley and Walker circulation. This geographical location exposes Sabah to a range of atmospheric dynamics at the local, regional and global scales, contributing to its high rainfall variability. The diurnal forcing from local land-sea breeze contrasts plays a role in shaping the daily rainfall patterns, while the regional monsoons–Northeast and Southwest monsoons–bring distinct seasonal variations in rainfall. Global phenomena such as El Niño and Southern Oscillation (ENSO), Madden-Julian Oscillation (MJO), Intertropical Convergence Zone (ITCZ), Indian Ocean Dipole (IOD), the Borneo vortex and cold surge further impact the rainfall patterns in Sabah on inter-annual and inter-decadal timescales [25-31].

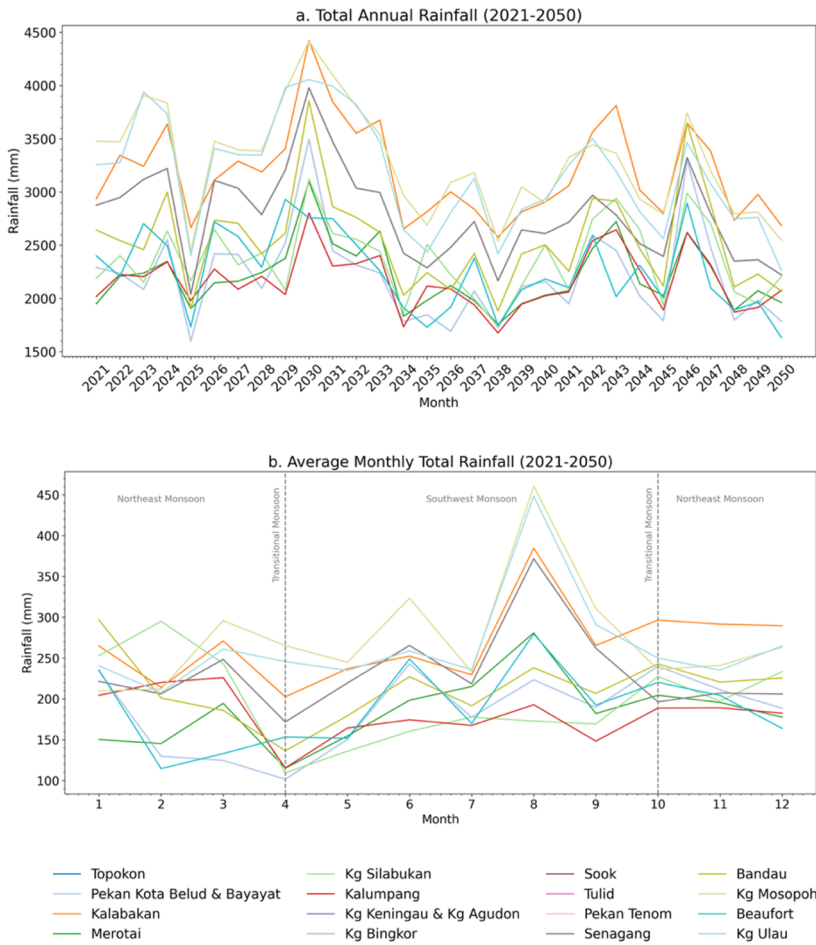


Fig. 2. Time series plots for a. total annual and b. average monthly rainfall from 2021 to 2050 over 18 sites in Sabah.

The average monthly total rainfall is projected to range from 102 mm to 460 mm between 2021 and 2050 (Fig. 2b). The future monthly rainfall pattern is anticipated to deviate from historical patterns, especially with the increased rainfall amount observed in June and August for all sites except Kg Silabukan. This is an emerging pattern as historically, the region tends to experience relatively low rainfall in June to August and higher rainfall in December to February [32]. This shift may indicate a strengthening of Southwest monsoon or shifts in tidal heights, attributed to the warming trends of the global temperatures. However, the specific mechanisms underlying this shift remain uncertain as these effects involves the complex interplay of other meteorological cycles and topographic localities [32], which have yet to be fully studied. This shift is also reflected in the maximum consecutive 1- to 5-day rainfall (Fig. 3). The maximum consecutive 1-day, 2-day, 3-day, 4-day, and 5-day rainfall are projected to range from 22 mm to 760 mm across all sites. In June, sites with higher peaks are concentrated in the interior district (Kg Mosopoh, Beaufort, Bingkor, Kg Ulau, Senangang, Sook, Kg Keningau,

Kg Agudon and Tulid) and the west coast district (Topokon, Pekan Kota Belud, Bayayat and Bandau). In August, higher peaks are observed in both the interior and Tawau (Kalabakan and Merotai) districts. Peaks in maximum consecutive rainfall are also observed for the interior and west coast districts during the transitional monsoon periods in April and October. This highlights the need for critical attention to accommodate the anticipated rainfall. Enhancing the adaptive response of the water treatment plants to the projected rainfall variability requires resilient design and strategic infrastructure upgrades, which typically implies the need for greater redundancy in the design provisions. Engineering solutions, such as off-site river storage, is recommended to manage the increased rainfall volume, serving both as a pre-treatment and flood mitigation measures, thereby reducing stress on the water treatment plants.

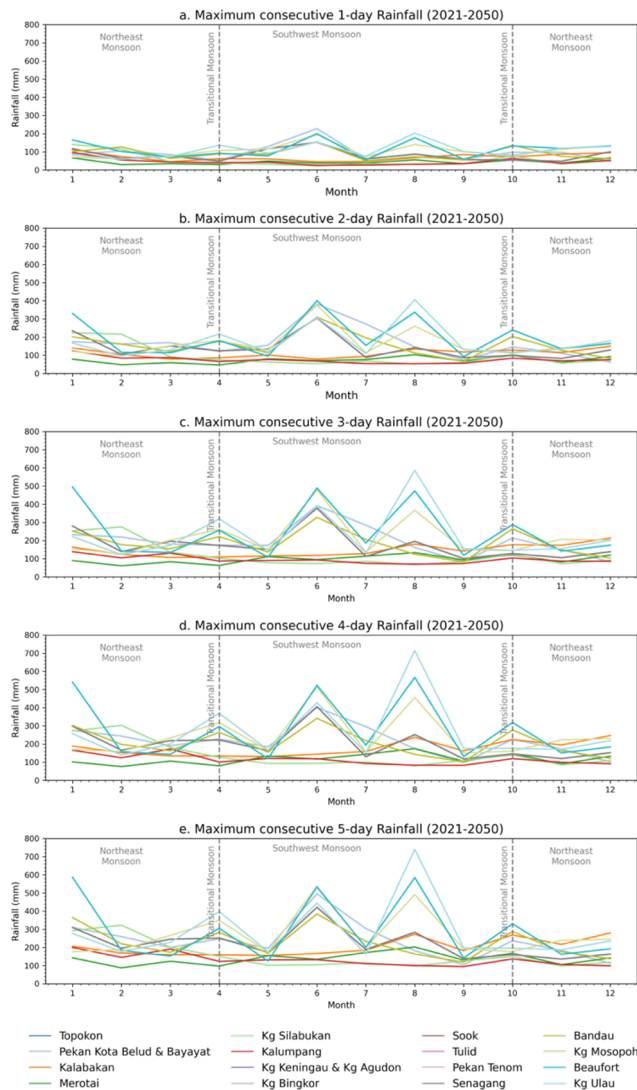


Fig. 2. Monthly time series plots for maximum consecutive a. 1-day, b. 2-day, c. 3-day, d. 4-day, and e. 5-day rainfall averaged between 2021 and 2050 over 18 sites in Sabah.

4 Conclusion

This study is an initial assessment into future rainfall projections derived from a bias-corrected global climate model dataset inform adaptive strategies for upgrading the 22 water treatment plants in the study area. The study reveals significant variability in the future rainfall patterns, particularly the emerging peaks of rainfall in June and August up to 760 mm over a 5-day heavy rainfall period. Engineering solutions, such as off-site river storage is recommended to bolster resilience and ensure consistent performance of the water treatment plants under varying hydroclimate conditions. The underlying mechanisms behind the emerging peaks in June and August is beyond the scope of this study and remain inadequately elucidated in current literature, warranting further investigation. The present study is limited by the use of global climate dataset at lower spatial resolution (~50 x 50 km), which perform better over longer time scales. Although downscaling techniques can be employed to obtain higher-resolution local projections for guiding engineering design and planning, the uncertainty is much larger [33] and entail substantial computational costs, potentially increasing the expenses of the design and planning processes. The advent of artificial intelligence offers promising and powerful tools such as deep learning to process big data with enhanced accuracy and faster processing time, thus reducing costs compared to conventional climate modelling and downscaling. As engineering design and strategy are generally constrained by economic considerations and the need for adequate protection, this approach enables achieving a balance between cost efficiency and the level of protection in infrastructure design and strategy for climate adaptation. We therefore recommend that future studies explore the use of deep learning techniques to optimise analysis processes and address the uncertainties in climate projections to better enhance the resiliency of engineering design and strategy for adaptive water resource management that is capable of withstanding future climate variability and extreme weather events.

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