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Regional Projections of Rainfall Extremes in Sri Lanka: Developing Future IDF Curves Under Climate Change

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Abstract

This study developed future regional Intensity-Duration-Frequency curves for Sri Lanka using climate change scenarios to address the growing need for adaptive infrastructure planning. Rainfall projections were generated with the CNRM-CM6-1 global climate model under Shared Socioeconomic Pathways (SSP) for moderate (SSP2-4.5) and high (SSP5-8.5) emissions. These projections were bias-corrected using a linear scaling method and analyzed across eleven hydro-meteorologically homogeneous regions. IDF curves were constructed for three future periods: near future (2025-2049), middle future (2050-2074), and far future (2075-2099). The results demonstrate significant spatial and temporal variability in rainfall intensity. Change factors were estimated for all regions to quantify deviations from historical baselines, identifying regions 5, 7, and 9 as particularly vulnerable to climate change under both SSPs. For SSP2-4.5, the overall change factor values are 1.73 for the near future, 1.65 for the middle future, and 1.335 for the far future, with an average of 1.57 across all periods. For SSP5-8.5, the values are 1.72 for the near future, 1.70 for the middle future, and 1.82 for the far future, resulting in an average of 1.74. The findings indicate a trend toward more extreme rainfall under both scenarios, with greater intensity and uncertainty under SSP5-8.5. These results underscore the urgent need for region-specific adaptation strategies, improved flood resilience, and the integration of climate projections into national infrastructure planning and disaster risk management.

Keywords

Future regional IDF; climate change; change factor; Shared Socioeconomic Pathways (SSP); Sri Lanka

1. Introduction

Intensity-Duration-Frequency (IDF) curves are essential analytical tools in hydrology and civil engineering [1]. These curves depict the relationship among three key characteristics of precipitation events: intensity, duration, and frequency. Intensity is defined as the volume of rainfall occurring over a specified period, while duration indicates the length of the rainfall event. Frequency describes the occurrence of a particular intensity level within a given timeframe [2-4]. Analysis of these interrelationships provides critical insights for water resource management and infrastructure planning. Historically, IDF curves have been treated as stationary; however, the impacts of climate change necessitate reassessing this assumption, as stationary models do not yield accurate predictions under a changing climate [5]. Therefore, the development of nonstationary (future) IDF curves is essential for estimating the capacity of future hydrological infrastructure to manage stormwater runoff, mitigate flooding and waterlogging in urban areas, and support the assessment and adaptation of existing hydraulic systems affected by climate change [6]. Also, when combined with advanced hydrological modeling techniques, IDF curves facilitate more accurate predictions of flood events, which are fundamental to effective flood forecasting and management strategies [7].

Since the late twentieth century, climate scientists have recognized that climate systems are dynamic rather than static, subject to changes driven by various factors, especially those resulting from human activities [8]. The significant rise in greenhouse gas emissions, primarily driven by industrialization, urbanization, and deforestation, has been a major contributor to these transformations [5]. Countries around the world are experiencing significant changes in their hydrometeorological variables, including altered precipitation patterns, temperature fluctuations, and an increased frequency of extreme weather events [9]. These trends are often associated with the long-term effects of climate change, including changes in rainfall frequency and intensity, prolonged droughts, and more severe flooding [10]. The complex relationship between climate change and hydrometeorology underscores the need for updated IDF curves that reflect ongoing changes in weather patterns, ensuring that infrastructure and water management systems adapt effectively to this evolving landscape [6].

Historically, urban drainage systems and other hydraulic infrastructure have relied on conventional IDF curves for design and operation [11]. In light of the changing climate, the impact of global climate change on regional weather patterns is profound. Variations in temperature and precipitation are expected to significantly alter hydrological cycles, leading to more extreme weather events and modifying historical rainfall patterns previously used to develop traditional IDF curves [12]. Consequently, there is an urgent need to update current IDF curves to more accurately reflect the potential impacts of climate change [13]. Additionally, it is increasingly important to assess the accuracy and uncertainties of the IDF curves used in the design of hydraulic structures and systems, particularly regarding projected short-duration rainfall (hourly or sub-daily) in a changing climate [14]. Therefore, it is imperative to create innovative IDF curves that accurately reflect these climate-induced changes. This adaptation will enhance our preparedness for future disasters by ensuring that urban drainage systems and hydraulic infrastructure are equipped to accommodate anticipated increases in rainfall intensity and frequency [15]. The intensification of extreme precipitation due to climate change has spurred substantial global research aimed at updating traditional IDF curves. Conventional IDF relationships, which are based on historical data, are increasingly viewed as insufficient for estimating future risks, especially in a warming world [12]. The Intergovernmental Panel on Climate Change (IPCC) states with high confidence that climate change is already influencing the frequency and intensity of extreme rainfall events worldwide [16].

Early global-scale research identified trends in extreme precipitation by analyzing reanalysis datasets and observational records to assess future changes [17]. Subsequent studies incorporated climate model projections to develop future IDF curves, thereby enhancing understanding of future extreme precipitation behavior. These studies frequently used downscaling methods to adjust Global Climate Model (GCM) projections, with statistical downscaling being a prevalent approach for bias correction [18, 19].

In Asia, the monsoon-driven climate and the increasing susceptibility to hydrometeorological hazards have heightened interest in future rainfall extremes [20]. Research consistently indicates that the region is expected to see significant rises in both the frequency and intensity of heavy rainfall events, particularly in tropical and subtropical areas [21]. South Asia, predominantly influenced by the Indian summer monsoon, is highly susceptible to climate variability and extreme weather events [22]. There is substantial documentation of increasing trends in intense rainfall events, with studies indicating a shift toward more frequent, shorter-duration, and higher-intensity storms [23]. In India, significant progress has been made in developing future IDF curves. Maity & Maity [24] utilized three climate models from the Coupled Model Intercomparison Project 6 (CMIP6) for three Shared Socioeconomic Pathways (SSPs) to model future IDF curves across India. Ghosh et al. [25] applied bias correction and statistical downscaling techniques to enhance GCM-based projections of rainfall intensity for water infrastructure design. Pakistan and Bangladesh have undertaken similar initiatives, although to a lesser degree. Shah et al. [26] developed IDF relationships for Abbottabad, Pakistan, and investigated the impact of climate variability using wavelet analysis. Despite these advancements, a notable lack of consistent national frameworks remains for formulating future IDF curves across most South Asian countries. Data limitations, non-homogeneous terrain, and uncertainties in monsoon dynamics persist as significant challenges.

Despite growing evidence of shifts in rainfall extremes, comprehensive efforts to develop future IDF curves in Sri Lanka remain limited.

Existing literature demonstrates that, except Sri Lanka, few studies have investigated future IDF curves in Southeast Asian countries. In contrast, India has produced a substantial body of research on the development of future IDF curves. In the Sri Lankan context, existing literature mainly concentrates on historical rainfall analysis and flood vulnerability mapping [27]. Although the latest site-specific and regional IDF curves, developed by Zoysa et al. [28] and Iresh et al. [3], meet the need for updated hydrological design, particularly in urban stormwater systems, these IDF studies have primarily focused on the assumption of stationarity, based on historical observations. However, such approaches no longer provide reliable estimates of design rainfall under a changing climate, where the frequency and magnitude of extreme rainfall events are expected to evolve [16]. Moreover, updated IDF studies have been limited to site-specific or regional-scale analyses and have not developed climate-informed site-specific or regional future IDF relationships using the latest CMIP6 climate projections. Similarly, no systematic methods have been developed for creating spatially distributed, future-oriented IDF curves using robust statistical techniques, such as Regional Frequency Analysis (RFA), combined with bias-corrected high-resolution climate projections. To address these gaps, this study develops regional future IDF curves for Sri Lanka by integrating statistically bias-corrected CMIP6 climate model outputs with RFA for eleven meteorologically homogeneous regions [3]. The meteorologically homogeneous regions developed by Iresh et al. [3] were derived from hourly data from 50 rain gauge stations and daily data from 221 across Sri Lanka, with varying record lengths, typically spanning 1971 to 2020. The eleven regions developed well capture the spatial variation in seasonal and annual rainfall in Sri Lanka [3]. The eleven meteorologically homogeneous regions identified by Iresh et al. [3] were utilized in this study because they were developed using recent datasets and robust analytical methods, such as Ward's Clustering Algorithm, and provide an accurate representation of rainfall variation in Sri Lanka. Regions 1 and 2 belong to the country's wet zone, which receives the highest rainfall, whereas Region 11 belongs to the arid zone. Regions 1 to 11 represent a gradual decrease in intensity and spatial variation in island rainfall.

The study examines the impact of climate change on IDF curves by estimating future IDF curves for two SSPs: SSP2-4.5, which represents moderate carbon emissions, and SSP5-8.5, which represents high carbon emissions, utilizing the CNRM-CM6-1 GCM. Jayaminda et al. [29] identified the high-resolution CNRM-CM6-1 GCM as the most effective for simulating the Sri Lankan climate. Their analysis provided a comprehensive assessment of all CMIP6 GCMs, including ensemble modeling with individual models, and concluded that the CNRM-CM6-1 model was optimal. Based on these findings, the present study utilized outputs from the CNRM-CM6-1 climate model, despite relying on a single model rather than an ensemble modeling approach. The research establishes a foundation for forecasting changes in rainfall intensity and duration, thereby improving planning and decision-making for climate adaptation and resilience strategies. The study significantly contributes to the existing body of literature by providing one of the first nationwide evaluations of future rainfall intensities in Sri Lanka under climate change, with potential implications for infrastructure resilience, flood management, and climate adaptation planning.

2. Study Area

Sri Lanka, the study region, is an island country in the Indian Ocean south of India. The island lies between latitudes 6° and 10° N and longitudes 79.5° and 82° E, as shown in Figure 1. It covers 65,610 km². Sri Lanka's climate is classified as a tropical monsoon, with significant spatial rainfall variability relative to its land area, primarily due to central mountain ranges that intercept northeast and southwest monsoon winds, resulting in orographic rainfall. Furthermore, this orographic effect contributes to convective rainfall during the inter-monsoon periods. Due to spatial variation in rainfall, the country has been classified into three main climatic zones based on mean annual rainfall: wet zone (>2500 mm), intermediate zone (1750-2500 mm), and dry zone (<1750 mm) [30]. The topography of Sri Lanka is classified into three main zones: coastal 0-30 meters Above Mean Sea Level (AMSL), lowland (30-300 AMSL), and central highlands (above 300 AMSL) [30].

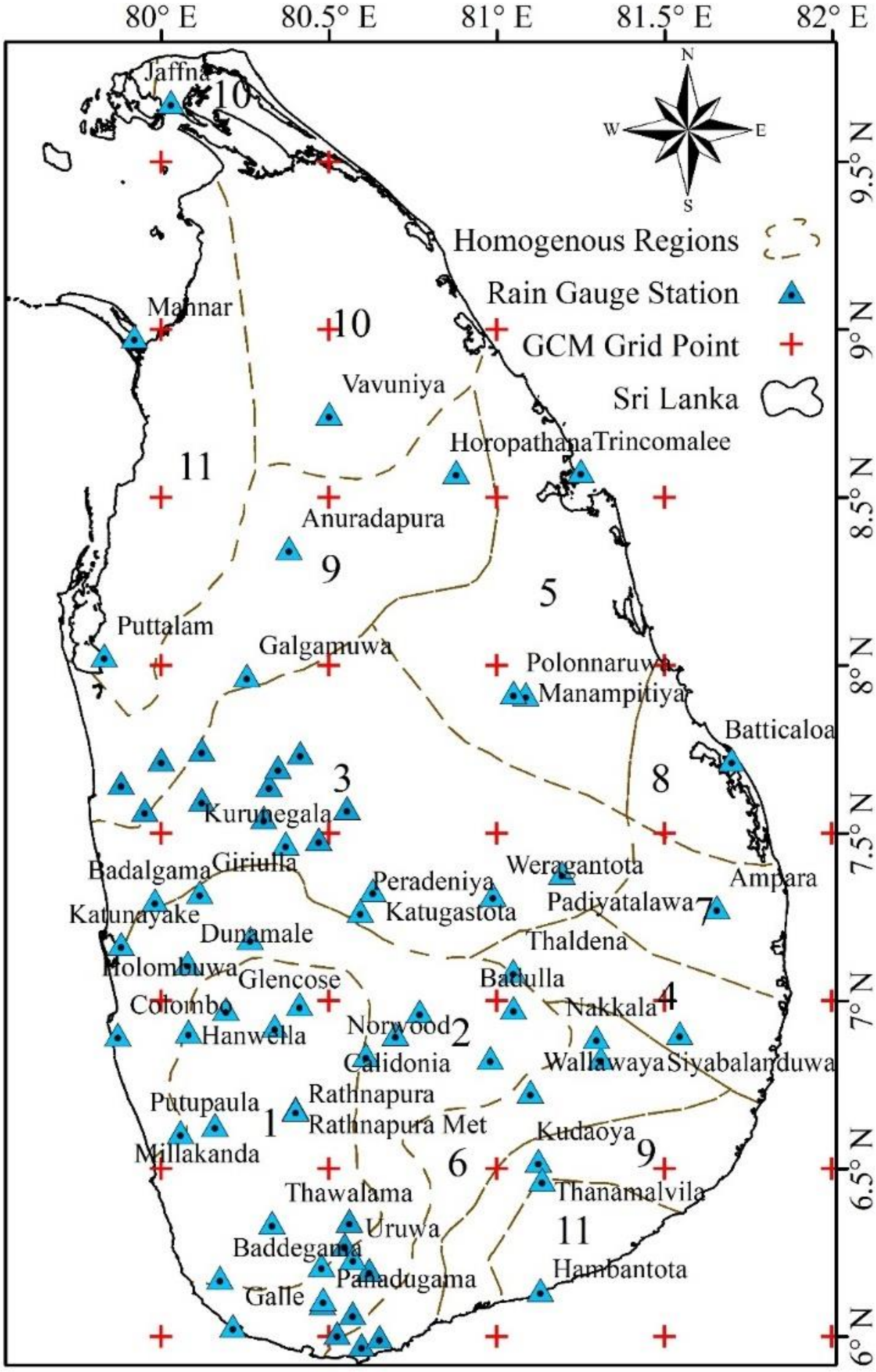

Figure 1 Rain Gauge Distribution, Homogeneous Regions, and the CNRM-CM6-1 GCM Grid Distribution.

3. Data Collection

3.1 Historical Rainfall Data

The study has compiled a comprehensive dataset of long-term, daily rainfall measurements for Sri Lanka. These datasets were derived from 50 hourly rain-gauge recordings distributed across the island. These stations offer a robust representation of climatic variations across different regions. Historical rainfall data, spanning 1975 to 2014, serve as a crucial foundation for estimating the current baseline. This information is essential for understanding and developing an algorithm that employs a statistical linear-scaling bias-correction method to adjust future precipitation. Figure 1 illustrates the locations of 50 stations that provide hourly-recorded data alongside GCM grid points. Initially, data screening was conducted to assess data quality. Data gap identification and screening were performed using visual observation, the T-test, and the F-test. Analysis of 50 hourly rain-gauge recordings from 1975 to 2014 revealed no data gaps, and the F-test and T-test confirmed the stability of the daily time series in terms of variance and mean. The observed data series for each grid point was constructed by integrating spatially distributed observations using the Thiessen polygon method. While the Thyssen polygon method has generally been ineffective for representing precipitation extremes in areas with significant spatial variability, its application in this study mitigates the typical errors associated with the method. To maintain data consistency, only the nearest rain gauges from meteorologically homogeneous regions corresponding to each grid point were selected for grid point data development.

3.2 Future Rainfall Data

This study primarily used daily precipitation outputs from the CMIP6 GCM CNRM-CM6-1 to derive future IDF curves under the carbon-emission scenarios SSP2-4.5 and SSP5-8.5. Daily GCM outputs were selected instead of sub-daily outputs due to the absence of historical sub-daily records necessary for bias correction. To address this limitation, daily GCM outputs were bias-corrected and subsequently converted to sub-daily data using a rainfall disaggregation method. Sub-daily data are essential for IDF curve development because only sub-daily records can capture short-duration extreme rainfall events. In contrast, daily aggregation loses temporal information, which is critical for accurately representing rainfall intensity and analyzing extreme rainfall.

The SSP2-4.5 and SSP5-8.5were selected for this analysis due to their distinct characteristics: SSP2-4.5 represents a moderate mitigation scenario aimed at achieving a radiative forcing of 4.5 Watt/m^2 by the end of the 21st century, whereas SSP5-8.5 aligns with a high emissions scenario, projecting a radiative forcing of 8.5 Watt/m^2 by the same timeframe [20]. Thus, the study addresses both moderate-and high-emission scenarios. This essential dataset is available through the Earth System Grid Federation (ESGF) (https://esgf-metagrid.cloud.dkrz.de) and is presented in the Network Common Data Format (NetCDF). The data were bias-corrected using observations from 50 designated rain gauges, employing the linear scaling bias-correction technique to improve the accuracy of these projections. This straightforward bias-correction method has proven effective and is widely used in studies to refine future climate projections [31]. Subsequently, the bias-corrected future data for the same 50 stations were extracted for further analysis. The data were systematically organized into three distinct future timeframes: the near future (2025-2049), the middle future (2050-2074), and the far future (2075-2099). This categorization facilitates a comprehensive understanding of anticipated changes in precipitation patterns in future periods.

4. Methodology

The future IDF curves for SSP2-4.5 and SSP5-8.5 were developed across three distinct time frames. The methodology for creating these future IDF curves consists of two main steps: first, formulating the future IDF curves, followed by estimating change factors. These change factors are derived by comparing newly developed future IDF curves with IDF curves from the control period, which were created using bias-corrected GCM data from 1975 to 2014. A detailed step-by-step methodology is presented in Figure 2.

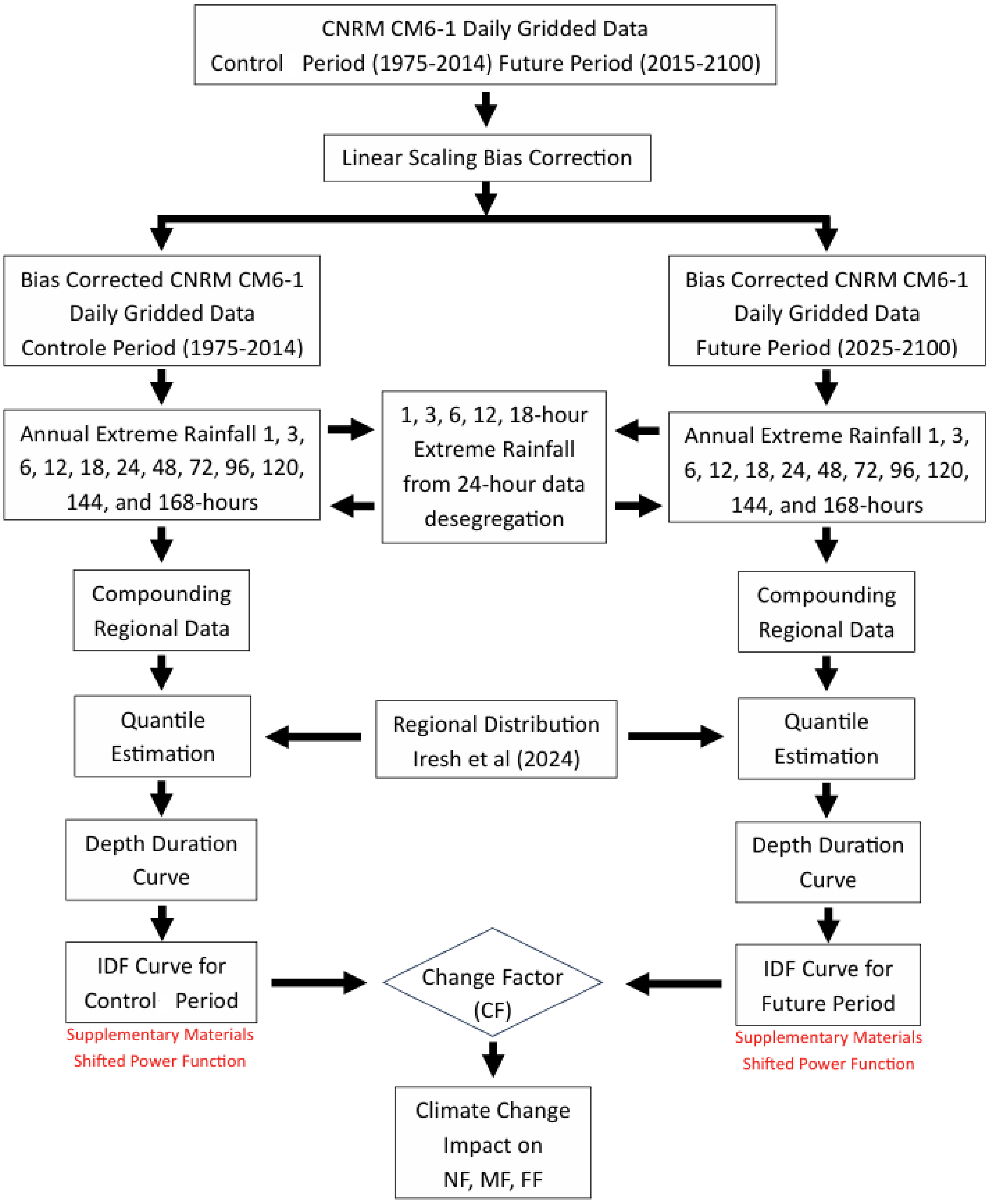

Figure 2 Methodology Schematic Diagram.

4.1 Regional Future IDF Curve Development

The regional future IDF curves were meticulously developed for each meteorologically homogeneous region of Sri Lanka, as classified by Iresh et al. [3]. This process commenced with the bias correction of GCM rainfall data. This model better represents both extreme and normal rainfall events than other CMIP6 models. Hence, the CNRM-CM6-1 model, available in NetCDF format, was the primary GCM utilized in this study. The CNRM-CM6-1 model has a spatial resolution of 50 km with a temporal resolution of 24 hours. The control period spanned 1975-2014, whereas the future period extended from 2015 to 2100. The study investigates two SSPs, SSP2-4.5 and SSP5-8.5, to generate IDF curves. The NetCDF data was processed using the Climate Data Operator (CDO) within the Cygwin environment, which facilitates the execution of Unix commands on Windows systems. CDO, developed by the Max Planck Society, functions as a command-line tool for climate data analysis, making it an invaluable resource for researchers managing large datasets [32]. The linear scaling bias correction technique [33] has been employed to the GCM raw daily data using historical daily data from 50 stations scattered throughout the country, as illustrated in Figure 1. For further details on the linear-scaling statistical bias correction, readers are referred to Iresh et al. [33], as these topics are not addressed in this paper.

The grid-point data were allocated to 50 stations using the Thiessen polygon method, and the station data were compiled into a regional dataset. The observed precipitation patterns at the rain gauge stations were analyzed to construct regional datasets for developing future IDF curves. The hydrometeorological homogeneous regions identified in the current IDF, developed by Iresh et al. [3], served as the basis for aggregating data from each station within those regions. This compounding aimed at creating a coherent, comprehensive regional dataset that accurately reflects expected climatic changes over the defined future periods [2].

Annual maximum rainfall depths for durations of 3, 6, 12, 18, 24, 48, 72, 96, 120, 144, and 168 hours were extracted from bias-corrected future data. Since the temporal resolution of the bias-corrected GCM data was 24 hours, simple scaling can be used to derive hourly intensities from 24-hour data [34]. However, different frequency distributions across 11 regions were employed to develop future IDF curves. Hence, the IMD 1/3rd Rule, as provided by the Indian Meteorological Department, was applied to disaggregate the 24-hour data into 1-, 3-, 6-, 12-, and 18-hour intervals [35]. Further information on the IMD 1/3rd Rule is available in Patel et al. [35]. Sub-daily rainfall intensities derived from daily data are estimates rather than direct representations of future sub-daily processes. The IMD 1/3rd Rule has been widely applied in engineering hydrology to estimate short-duration rainfall depths, particularly in contexts where sub-daily rainfall records are limited. Nevertheless, the use of the IMD 1/3rd Rule is considered appropriate for this study because long-term, spatially consistent sub-daily rainfall observations are not readily available, and no regional rainfall disaggregation method exists for Sri Lanka. In the absence of such a method or sub-daily observations to bias-correct sub-daily GCM rainfall outputs, applying bias correction to daily GCM data using daily observations and subsequently disaggregating daily to sub-daily values with the IMD 1/3rd Rule provides a viable approach for developing regional future IDF curves based on GCM outputs.

The regional distribution parameters identified in the current IDF curves [3] have been utilized to develop a non-linear probability distribution, which serves as the basis for analyzing extreme rainfall patterns and enhancing the reliability of the results. This methodological assumption may introduce uncertainty into future IDF curves, as climate change could alter monsoon circulation, atmospheric moisture, convective activity, and the frequency of extreme weather systems. The present study does not assume that the absolute magnitude of future extreme rainfall will remain stationary. Instead, the historical regional frequency framework serves as the foundation for estimating future rainfall frequency, incorporating projected changes from climate models. This method offers a practical, internally consistent approach to developing future regional IDF curves. The selection of the regional frequency distribution is critical, as it substantially influences the accurate estimation of hydrological quantiles. The regional frequency distribution adopted by Iresh et al. [3] for current climate conditions has also been applied to generate future IDF curves, which subsequently inform further development. This methodology enables the creation of future IDF curves in contexts where sub-daily rainfall records are insufficient. For further details on the regional frequency distribution and the procedure for estimating frequency factors, readers are referred to Iresh et al. [3], as these topics may not be addressed in this paper.

In examining the return period of a given rainfall event (*T*), it was adhered to the principle that this value represents the reciprocal exceedance probability associated with a particular depth. This relationship is mathematically expressed by;

$$T = \frac{1}{1 - F} \tag{1}$$

where *F* is the probability distribution function of depth. The *F* has been estimated for *n* data points and the rank of an event (*r*) by using the plotting position formula [36], i.e.

$$F = \frac{r}{n + 1} \tag{2}$$

Furthermore, depth-duration curves tailored to return periods of 2 to 200 years were constructed. Depth-duration relations were derived from regional compounded rainfall data, using the best-fitting distribution parameters. Finally, future IDF curves were developed by applying the shifted power equation to the depth-duration relationships. The shifted power equation has been identified as the robust equation for developing the present IDF curves [3].

$$I = a \times (D - b)^c \tag{3}$$

where *I* is the intensity in millimeters per hour (mm/hr), *D* is the duration in hours, and *a, b*, and *c* are constants for each curve. Baghirathan and Shaw [2] used a power equation, while Nandalal & Ghnanapala [4] and Ranatunga [37] used a shifted power equation for developing IDF curves. Similarly, the updated IDF curves by Iresh et al. [3] used the shifted power equation with justification. The future IDF curves belonging to three distinct future time frames: the near future (NF) (2025-2049), the middle future (MF) (2050-2074), and the far future (FF) (2075-2099), under two SSPs were developed.

4.2 Estimation of Regional Change Factor

The regional Change Factor (CF) is a dimensionless index that quantifies the impacts of climate change and how these changes might affect rainfall patterns over time [38]. The CF for a specific duration and return period is calculated by comparing projected future rainfall intensities with those of the control period. The objective of CF is to adjust current IDF relationships to account for future changes in rainfall intensity, duration, and frequency due to climate change.

Estimating the regional CF involves analyzing current and future regional IDF curves, which depict the relationship among rainfall intensity, duration, and frequency in specific meteorologically homogeneous regions. The CF is instrumental in assessing climate change impacts by comparing the control period with projected rainfall intensities under various carbon emission scenarios. These change factors modify historical IDF curves for future use in hydrological planning, infrastructure design, and flood risk assessments [39].

$$CF = \frac{I_{future}}{I_{historical}} \tag{4}$$

where I_{future} is the projected rainfall intensity for a given duration and return period under future climate conditions. $I_{historical}$ is the observed historical rainfall intensity for the same duration and return period. The CF can vary across return periods depending on how extreme future rainfall events are projected to be. The CF belongs to three distinct future time frames, each estimated to represent future climate change. Finally, the CF estimates were discussed across three periods to assess the impact of climate change under two SSPs.

5. Results and Discussion

The development of future IDF curves offers valuable insights into extreme rainfall patterns associated with weather events. The analysis examines changes in extreme rainfall across three future time horizons. Notable findings indicate anticipated shifts in rainfall intensity, duration, and frequency. This temporal framework aims to clarify the expected changes in rainfall intensity, accounting for varying durations and frequencies. The key findings from the analysis are discussed as follows.

5.1 Regional Future IDF Curves for Three Time Frames Under SSPs

Regions were meticulously chosen based on the homogeneous characteristics identified during the development of IDF curves for current conditions, as depicted in Iresh et al. [3]. Two distinct carbon--emission scenarios reflect varying levels of greenhouse gas emissions, with SSP2-4.5 indicating a moderate approach and SSP5-8.5 representing a high emission trajectory. Future IDF curves were developed for each SSP across three critical temporal frameworks: the near future (typically the next 24 years), the middle future (approximately 24-49 years), and the far future (beyond 50 years). This temporal stratification provides a comprehensive overview of how anticipated climate change is expected to affect rainfall intensity and patterns over time. These curves were formulated using the shifted power function, as detailed in Equation 3. In this context, Table S1, Table S2, and Table S3 present the projected IDF curves for the near-, middle-, and far-future periods under SSP2-4.5. The tables provide constants for Equation 3, which defines the intensity-duration-frequency curves characterizing 11 regions. These curves illustrate changes in regional precipitation patterns and intensities, offering essential information for urban planning and infrastructure design under the moderate-emission scenario. Table S4, Table S5, and Table S6 also provide the forecasted IDF curves for the near-, middle-, and far-future periods associated with SSP5-8.5. Hence, Tables S1-S6 display the projected IDF curves for 11 regions in Sri Lanka under the

SSP2-4.5 and SSP5-8.5 scenarios. These curves highlight the anticipated variations in rainfall intensity across different return periods (2, 5, 10, 25, 50, 100, and 200 years) and various storm durations. A notable observation is a decreasing rainfall intensity with increasing duration, suggesting that shorter-duration events tend to produce higher intensities. Specifically, regions 4, 7, and 11 exhibit a significant decline in intensity for shorter durations, indicating a higher likelihood of experiencing intense rainfall events. In contrast, regions 8 and 10 exhibit more gradual declines, indicating prolonged periods of lower-intensity rainfall. Meanwhile, regions 1 and 2 demonstrate moderate intensity, placing them in the intermediate category. Furthermore, extreme rainfall, particularly in regions 3, 5, and 6, heightens the risk of flash floods due to increased rainfall intensities, especially at the 100-year return periods. Given their higher projected rainfall changes, regions 3, 5, and 6 need to establish flood mitigation infrastructure. On the other hand, region 11 records the lowest intensity, reflecting its unique hydrological characteristics.

Figure 3 presents the IDF curves for SSP2-4.5 in the near future, providing a concise depiction of 11 regions with moderate climate change impacts. Under the SSP5-8.5 scenario, there is a projected increase in extreme rainfall events. Similar trends of declining intensity with duration and heightened rainfall for higher return periods are anticipated. Regions 4, 10, and 11 face significant increases associated with short-duration heavy rainfall, while regions 8 and 10 could experience riverine flooding and landslides due to prolonged rainfall. Overall, careful planning and resource allocation will be crucial to effectively manage flood risks and strengthening resilience to climate variability in Sri Lanka. A further notable observation is the intersection of IDF curves at certain return periods, particularly at far-future time frames with lower return periods under the SSP5-8.5 scenario. Figure 3 (regions 10 and 11) illustrates this phenomenon. However, the underlying cause of the intersection cannot be determined from the current analysis due to uncertainty in the future IDF curves.

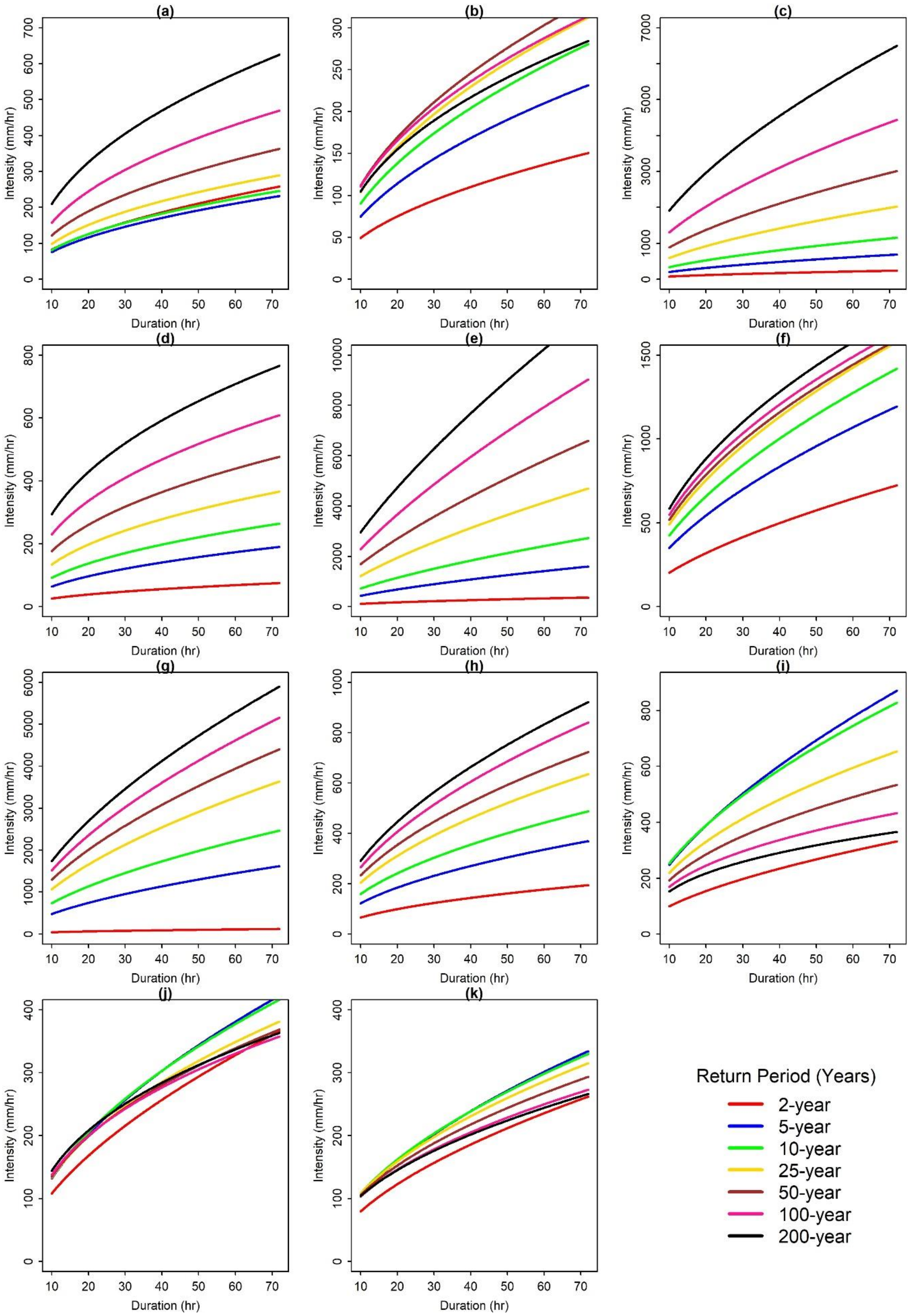

Figure 3 IDF Curves Developed for Regions 1 to 11 (a to k) of the Near Future Time Frame Under SSP2-4.5.

Additionally, these intersections reveal significant uncertainty in climate projections, highlight the limitations of statistical bias correction for extremes, underscore the non-stationary nature of future rainfall patterns, particularly under the SSP5-8.5 scenario, and the complexities involved in downscaling and model resolution. Figure 4 provides a concise comparison of IDF curves for the near future under both current and projected climate conditions in region 5, based on the SSP2-4.5 and SSP5-8.5 scenarios. Notably, for higher return periods, future IDF curves consistently exceed those of the present, indicating increased rainfall intensity across all durations in future climate scenarios. This upward shift is particularly pronounced under SSP5-8.5 and is evident across middle- and far-future time frames, as well as in other regions.

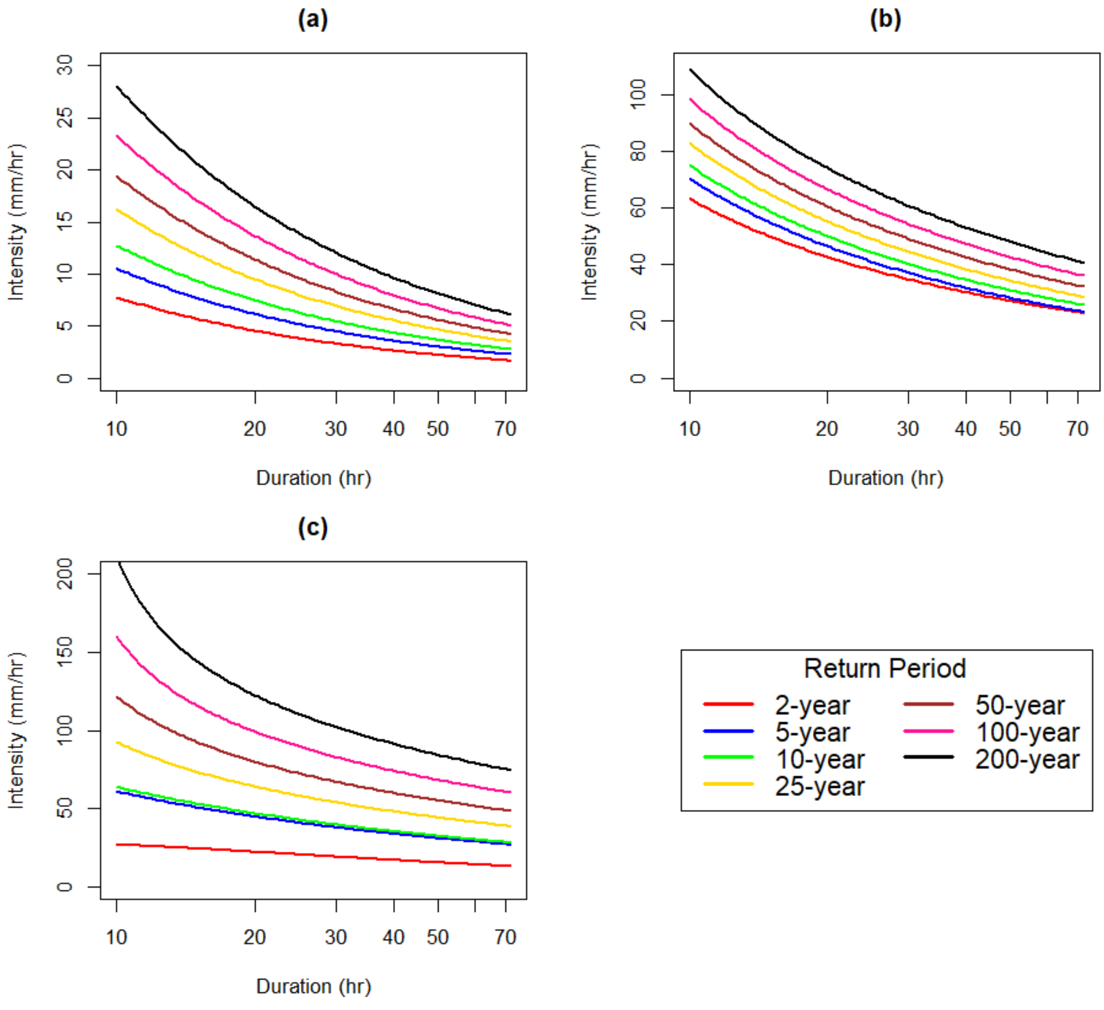

Figure 4 IDF Curve Comparison for Region 1 (a) Current Climate, (b) Near Future, SSP2-4.5, (c) Near Future, SSP5-8.5.

5.2 Uncertainty Associated with Regional Future IDF Curves

Uncertainty in future IDF curves for two carbon emission scenarios and three future time frames arises from GCM selection, statistical bias correction, assumptions about regional frequency distributions, and the temporal resolution of GCM rainfall outputs. These sources of uncertainty influence the translation of climate model projections into future extreme rainfall characteristics. Although the CNRM-CM6-1 model was selected based on explicit analysis [29], projections remain inherently uncertain, particularly when a single GCM is used to represent atmospheric circulation, convection, land-atmosphere interactions, and internal climate variability. Employing a multi-model ensemble would provide a broader representation of climate model uncertainty and could yield more robust estimates of future extremes by accounting for inter-model variability. Therefore, future research should extend the current framework by incorporating multi-model or regional climate model ensembles.

The linear scaling statistical bias correction method was selected based on an explicit analysis by [33] from among five methods: linear scaling, quantile mapping, delta change approach, power transformation, and local intensity scaling. However, the linear-scaling statistical bias-correction method generally assumes stationarity under future warming conditions and may not fully preserve projected changes in rainfall variability or adequately represent changes in extreme precipitation characteristics. This limitation introduces additional uncertainty when interpreting projected future extremes. To address this, future investigations should incorporate multivariate bias-correction approaches to improve the accuracy of reproducing future rainfall extremes.

Furthermore, this study assumes that regional frequency distributions identified from historical records remain applicable for future climate conditions. This assumption represents an important source of uncertainty as climate change may modify not only the magnitude of extreme rainfall but also its statistical characteristics. Consequently, the frequency distribution that adequately represents historical rainfall extremes may not necessarily remain unchanged under future climate conditions.

Moreover, applying future IDF curves to daily or short-term events requires caution, since convective precipitation processes responsible for short-term, high-intensity storms are often not adequately represented in daily GCM outputs. To address this limitation, the IMD $1/3^{rd}$ Rule was employed to convert daily rainfall outputs to sub-daily resolution. However, as this empirical relationship was developed in India, its direct applicability to Sri Lanka may introduce additional uncertainty. Notably, uncertainties tend to increase for shorter durations because the temporal concentration of rainfall within individual storm events is not explicitly captured in daily climate model data. Therefore, future sub-daily IDF estimates should be interpreted as regionalized projections derived from an empirical temporal disaggregation method. The uncertainty associated with these disaggregation techniques and the reliance on daily GCM outputs could be mitigated in future research by deploying automated weather stations and establishing a dense rain-gauge network in Sri Lanka.

Additionally, the future IDF curves developed for the three time frames should be applied to scenarios with return periods not exceeding 30 years, despite their development for periods up to 200 years. Return periods exceeding 30 years provide only general guidance based on statistical extrapolation, which entails considerable uncertainty, and are therefore not recommended for design estimates. The limited occurrence of extreme events introduces both sampling and parameter uncertainty when estimating the upper tail of the selected distribution. While the adopted regional frequency analysis enhances the reliability of extreme rainfall estimation by aggregating data from multiple stations, each GCM grid point typically represents a single region. Consequently, rainfall intensities estimated for higher return periods (>30 years) should be regarded as statistical extrapolations with increased uncertainty rather than precise predictions. Design engineers are encouraged to use these updated IDF curves as indicators of directional change and to incorporate safety margins or adaptive management strategies to address the non-stationarity of extreme rainfall.

5.3 Rainfall Intensity Variability Based on CF

After developing future IDF curves for two distinct SSPs across three projected time frames, the CF was estimated to quantify the variability in anticipated rainfall intensity relative to control-period data (i.e., IDF curves developed for the control period). This CF was assessed for various return periods, carefully tailored to reflect the unique hydrological characteristics and climatological conditions of each region. Figure 5 showcases a series of box plots that visually depict the distribution of CF values across various return periods for each region, effectively highlighting the variability, outliers, and underlying trends associated with the projected changes in rainfall patterns across 11 regions in Sri Lanka under two scenarios: SSP2-4.5 (moderate emissions) and SSP5-8.5 (high emissions). Hence, the analysis demonstrates the differing impacts of climate change across the regions. A comparison of the two SSP scenarios reveals substantial variability in CF values, particularly in regions 5, 7, and 9, which exhibit high CFs and increased projected rainfall to extreme climatic events. Under SSP2-4.5, CF values trend upward, ranging from 0.76 to 4.36, with regions 3, 5, and 7 displaying significant variability. In contrast, Region 1 maintains relatively stable CF values, while Region 5 is projected to experience the most significant increases in CF in the future, indicating severe climate extremes. The CF-based adjustments for regions 3, 4, and 7 should be considered with an understanding of the associated uncertainty. For engineering applications, it is recommended to incorporate safety margins or conduct sensitivity analyses when utilizing these projections. The results for these regions are more appropriate for indicative or planning-level assessments rather than precise design without additional local validation. Despite the variability, median trends across scenarios continue to offer valuable insights into the direction and magnitude of change, consistent with broader regional climate projections.

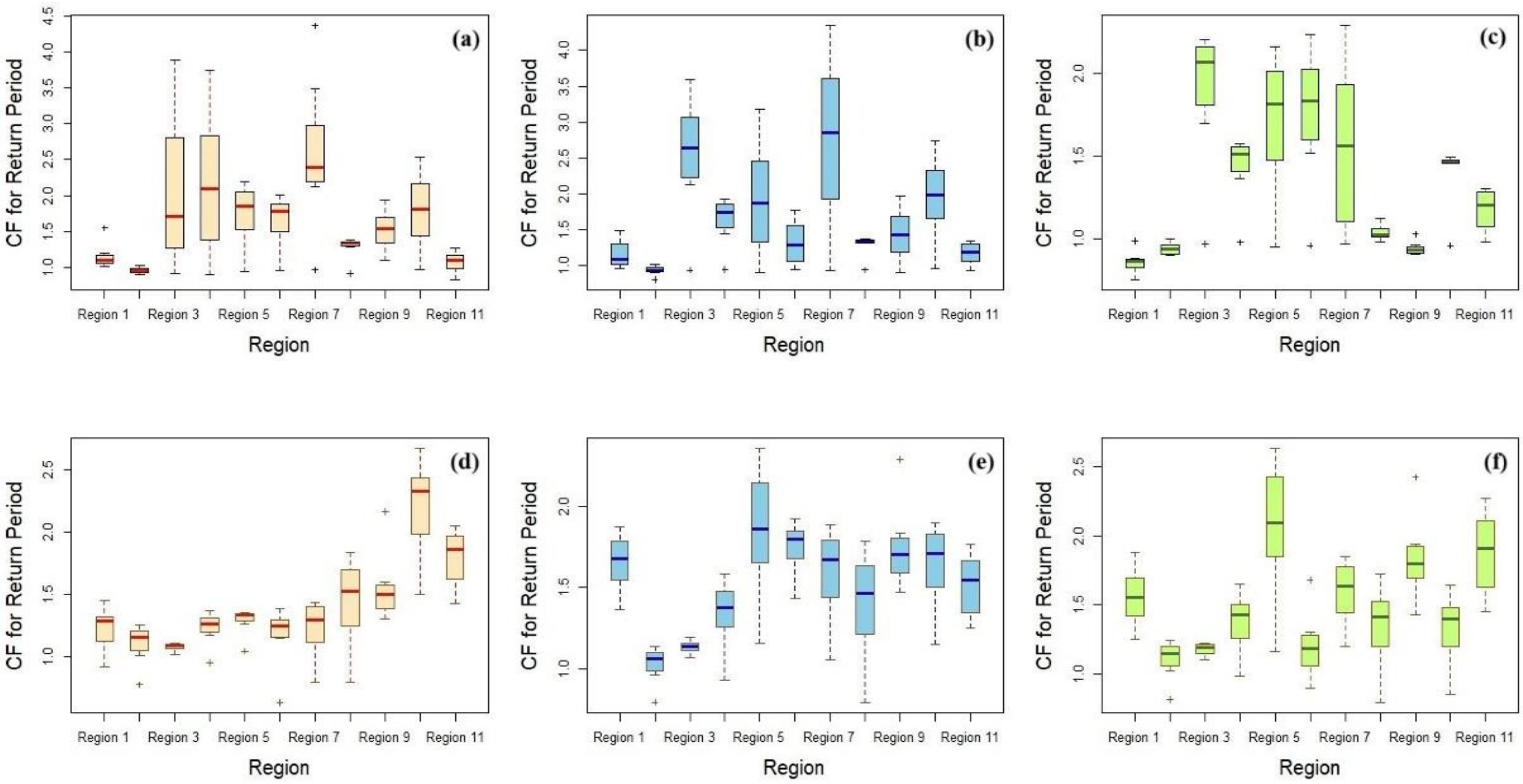

Figure 5 Change Factor variation boxplot for Different Regions with Regions, (a) Near Future, SSP2-4.5, (b) Middle Future, SSP2-4.5, (c) Far Future, SSP2-4.5, (d) Near Future, SSP5-8.5, (e) Middle Future, SSP5-8.5, (f) Far Future, SSP5-8.5.

This study underscores the pronounced sensitivity of regions 5, 7, and 9 to climate change, as evidenced by elevated CF values and increased variability. The SSP5-8.5 scenario reveals significant climate transformations marked by increased variability, frequent outliers, and long-term uncertainty. Elevated CF values may indicate uncertainty in the IDF curve. Consequently, verifying these climate-induced impacts is necessary to support the implementation of adaptive strategies and to mitigate risks in the most affected regions. Figure 6 illustrates changes in CF across different return periods, showing a consistent upward trend under the SSP2-4.5 scenario (Figure 6a), indicating a gradual intensification of extreme events.

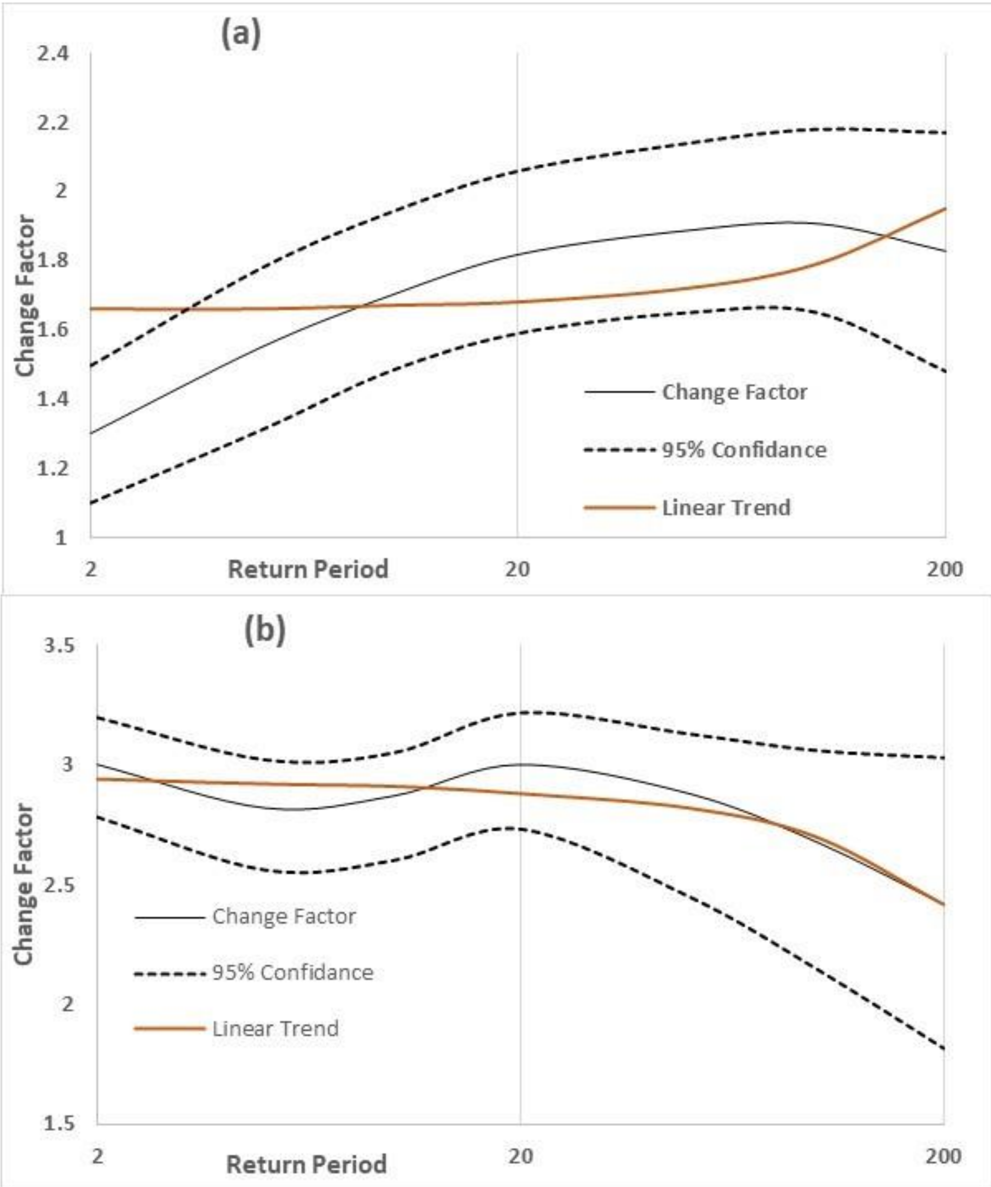

Figure 6 Average CF Variation for Return Periods: (a) SSP2-4.5 and (b) SSP5-8.5 with Confidence Band.

Additionally, Figure 6 shows the variation in the CF at the 95% confidence level, clearly demonstrating a correlation with increasing return periods, ranging from 2 to 200 years. This comprehensive analysis emphasizes the significant implications of climate change on rainfall patterns.

Similarly, it provides crucial insights to inform future water resource management strategies, ensuring resilience and sustainability amid changing climatic conditions. The widening 95% confidence intervals reflect growing uncertainty as projections extend into the future. The regional disparities in CF trends also underscore that geographic variations significantly influence climate impacts.

In contrast, the CF variation under SSP5-8.5 exhibits a more complex, non-linear pattern, featuring initial declines followed by erratic fluctuations, suggesting higher projected variability in the intensity of extreme events (Figure 6b). The broader confidence intervals in this high-emission scenario further accentuate the heightened uncertainty. While the SSP2-4.5 scenario indicates a steady increase in extreme events, SSP5-8.5 reveals greater projected variability. These findings reinforce the need for adaptive strategies to address the risks posed by uncertain climate dynamics, particularly in Sri Lanka's vulnerable regions 5, 7, and 9.

Additionally, CF values are influenced not only by SSPs but also by the statistical and methodological procedures used to derive future IDF curves. In this study, the estimated CFs were conditional on the selected GCM, SSPs, bias-correction method, temporal disaggregation method, probability distribution, and return period. Therefore, CF was interpreted as a conditional estimate of projected rainfall change within the selected modeling framework, rather than as a deterministic climate change factor. Relatively high or low CF values for a specific region or future time frame indicate the projected magnitude of change within this framework. Notably, CF values associated with longer return periods are expected to be more uncertain because they rely on estimates of the upper tail of the extreme rainfall distribution. While the methods employed in this study are well-established, the systematic application of these methods to develop future IDF curves for sub-daily data-scarce regions such as Sri Lanka represents a novel approach that may apply to other regions.

6. Conclusion

Regional future IDF relationships for Sri Lanka were established by integrating bias-corrected future rainfall data with regional frequency analysis. The results demonstrate significant spatial variability in extreme rainfall characteristics across the eleven identified regions. In particular, Regions 5, 7, and 9 exhibit markedly higher rainfall intensities for various return periods, indicating potentially increased flood hazard from extreme precipitation events. The derived IDF parameters provide a consistent regional framework for estimating rainfall intensities over multiple durations and return periods. This framework facilitates the evaluation of hydrological design and flood risk assessment by incorporating uncertainties.

Although this study primarily used daily rainfall forecasts, the resulting future IDF relationships apply to hydraulic design scenarios requiring shorter rainfall durations. Caution is necessary when estimating sub-daily rainfall intensities from these IDF curves, as they are particularly relevant for the design of urban drainage systems, culverts, and other hydraulic structures where short-duration rainfall extremes are critical.

The estimated CF values for two carbon-emission scenarios and three future time frames provide a basis for reviewing existing hydraulic structural designs. However, the future IDF curves and CF estimates should serve as climate-informed or planning-level information, which may be further substantiated through additional engineering assessment, rather than being applied directly as design values.

The results also show that regions with high agricultural productivity, such as the dry-zone districts of Polonnaruwa, Ampara, and Anuradhapura, overlap with areas experiencing high extreme rainfall intensities. The increased likelihood of extreme rainfall events increases the risk of flooding for essential agricultural and infrastructure systems. Furthermore, recently established solar power projects in these districts are likely to be affected by potentially increased flood hazards.

Several limitations are evident in this analysis. The study relies on frequency distributions based on historical rainfall observations, and potential non-stationary climate effects were not explicitly incorporated into the frequency analysis. The limited availability of sub-daily rainfall records also restricts the direct development of high-resolution non-stationary IDF relationships. The use of a single GCM may not capture the full range of spatial patterns in extreme rainfall change, and linear scaling bias correction may be inadequate to address variance, skewness, temporal persistence, or the extreme-rainfall tail. Hence, projected changes in extreme rainfall, IDF curves, and CF can be interpreted as conditional projections rather than definitive increases. Future research should integrate climate model projections with sub-daily rainfall datasets and assess the non-stationary behavior of extreme rainfall under changing climate conditions. Also, Future studies should employ ensemble modeling across multiple GCMs and incorporate dynamic downscaling to capture inter-model variability and reduce dependence on individual model characteristics. These advancements would improve the reliability of rainfall design estimates and support long-term climate adaptation planning. Integrating sub-daily data via dynamic downscaling could further improve the temporal resolution of IDF curves, thereby enhancing their applicability to flood simulation studies. Additionally, future studies on detailed flood simulation or urban drainage design in small catchments should utilize higher-temporal-resolution, downscaled climate data at sub-daily intervals. This approach would improve the representation of short-duration extremes and increase relevance for local hydrologic design. Furthermore, future research may integrate the generated IDF curves with hydrologic or hydraulic models in vulnerable basins to quantify changes in peak discharge, inundation extent, and infrastructure performance under projected climate conditions.

The future regional IDF relationships developed in this study provide a scientific basis for estimating extreme rainfall intensities across Sri Lanka. These relationships are climate-informed, planning-level information for hydrological design, flood risk management, and the development of climate-resilient infrastructure.

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Author Contributions

Iresh-Conceptualization, Analysis, writing, original draft preparation. Athapattu-Supervision, Software. Fernando-Investigation, Visualization, Data curation, Reviewing. Obeysekara-Methodology, Supervision, Validation. Rathnayake-Reviewing and editing.

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Competing Interests

The authors have declared that no competing interests exist.

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Data available on request due to privacy/ethical restrictions.

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Artificial intelligence (AI) tools were used solely for basic grammar correction and language refinement in the preparation of this manuscript. AI tools were NOT used in any research activities. The authors have thoroughly reviewed and edited the AI-assisted text to ensure its accuracy and accept full responsibility for the content of the manuscript.

Additional Materials

The following additional materials are uploaded at the page of this paper.

1. Table S1: IDF Curves Developed for Near Future, SSP2-4.5.
2. Table S2: IDF Curves Developed for Middle Future, SSP2-4.5.
3. Table S3: IDF Curves Developed for Far Future, SSP2-4.5.
4. Table S4: IDF Curves Developed for Near Future, SSP5-8.5.
5. Table S5: IDF Curves Developed for Middle Future, SSP5-8.5.
6. Table S6: IDF Curves Developed for Far Future, SSP5-8.5.

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