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Development of intensity–duration–frequency relationships in Khon Kaen City, Thailand under changing climate using GCMs and a simple scaling method

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ABSTRACT

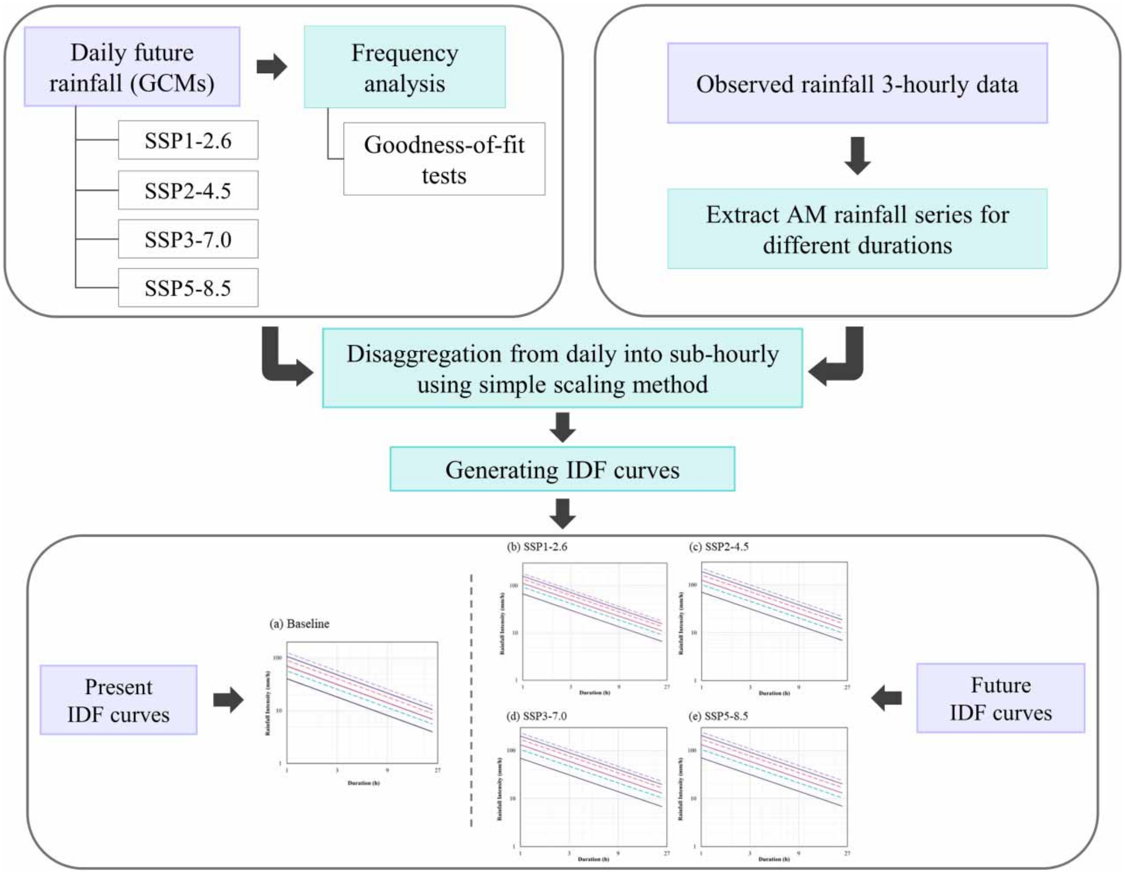
This study analyses the annual maximum (AM) rainfall series (1991–2022) in Khon Kaen City, Thailand. The AM rainfall series ranging from 3 to 24 h was best fitted to the Log-Pearson Type-III distribution. Notably, our findings reveal linear relationships between the moments of rainfall intensities and durations establishing the practicality of the simple scaling method for disaggregating 24-h AM rainfall data. Additionally, the results of this method are influenced by factors such as sample size, rainfall durations and the chosen probability distribution. Comparisons between intensity–duration–frequency (IDF) curves obtained through the simple scaling method and those derived from traditional frequency analysis provide valuable insights. Furthermore, this method was applied to bias-corrected rainfall data of 15 global climate models facilitating the generation of future IDF curves under SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios. Our results highlight that rainfall events in the SSP5-8.5 scenario are projected to exhibit higher intensities emphasizing the need to understand and prepare for increased rainfall extremes in the context of climate change. This research contributes valuable insights into rainfall analysis and prediction techniques, which are crucial for effective water resource management and climate adaptation strategies in the Khon Kaen region.

Key words: climate change projections, CMIP6 GCMs, IDF curves, Log-Pearson Type-III distribution, rainfall extremes, simple scaling

HIGHLIGHTS

- The application of the simple scaling method to disaggregate 24-h annual maximum rainfall series offers a valuable tool for understanding rainfall patterns.
- The application of the simple scaling method to bias-corrected global climate model data highlights its utility for climate change impact assessments.
- This study equips decision-makers with a robust methodology for assessing future rainfall events to mitigate flood and drought risks.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Hydrological characteristics of urban areas have dramatically changed because of rapid urbanization and climate change increasing the risk of urban flooding. Designing stormwater infrastructure for metropolitan areas and comprehending rainfall patterns need the use of intensity–duration–frequency (IDF) curves (Martel *et al.* 2021). However, conventional IDF curves may no longer be accurate due to changing climatic conditions and the complexities of urban development. To overcome this difficulty, it is necessary to incorporate cutting-edge climate projections into the creation of IDF curves. Future climate conditions are forecasted using the most recent generation of climate models as represented by the Coupled Model Intercomparison Project Phase 6 (CMIP6). Therefore, updating IDF curves to reflect the changing rainfall characteristics is predominant to effective urban flood management and resilient urban infrastructure (Kourtis *et al.* 2023).

CMIP6 models from the sixth report of the Intergovernmental Panel on Climate Change (IPCC) combine representative concentration pathways (RCPs) with shared socioeconomic pathways (SSPs) to create more reasonable future scenarios (Crévolin *et al.* 2023). Additionally, CMIP6 endeavours to tackle the concerns identified by CMIP5 such as improving the representation of changes in land use, improving the estimation of radiative and aerosol forcings, as well as reducing systematic errors in process simulations (Eyring *et al.* 2016). Over Southeast Asia, CMIP6 models have been found to replicate precipitation more accurately than their previous versions (Khadka *et al.* 2022). Similar to this, Nooni *et al.* (2023) reported that the majority of CMIP6 global climate models (GCMs) precisely reproduced the spatial variation of precipitation over Africa and the Arabian Peninsula. Additionally, Crévolin *et al.* (2023) found that simulations of CMIP6 in extreme precipitation are closer to the observed datasets than CMIP5 for almost all 30 Canadian cities. To enhance the accuracy of GCM rainfall prediction at regional and local scales, several downscaling tools are available such as Long Ashton Research Station Weather Generator (Semenov & Brooks 1999), hybrid Regional Climate Model–Statistical Downscaling Model scaling (Wilby *et al.* 2023) and stacking ensemble machine learning (Anaraki *et al.* 2023) and scaled distribution mapping (Switanek *et al.* 2017).

In engineering applications, the necessity arises for the use of sub-daily rainfall data to generate IDF curves. Nevertheless, the data typically available from measurement stations and future climate models are mainly detailed on a daily temporal scale. This poses a challenge for the formation of IDF curves, which are essential for designing hydraulic structures and improving flood management for maximum efficiency (Kourtis *et al.* 2023). Sophisticated statistical and hydrological approaches become more important for updating IDF curves. These approaches effectively bridge the gap between the available daily data and the need for shorter-duration data. In a study conducted by Alzahrani *et al.* (2023), various temporal disaggregation methods were compared. These methods consisted of the multiplicative random cascade model, the Hurst–Kolmogorov process, the K-nearest techniques and the Fahad–Ousmane method. The analysis was based on sub-daily simulations using observed daily rainfall data obtained from the South Nation watershed in Canada. The findings of their study suggested that the Fahad–Ousmane method characterised by its simplicity and the steady-state stochastic disaggregation model can yield superior results when compared to more complex alternatives. Adib & Rad (2019) applied a radial base function–artificial neural network to extract climate data using the HadCM3 model. This was done to prepare rainfall data for a 30-year period (2021–2050) based on A1B, B1 and A2 scenarios. Subsequently, the selected network was used to generate IDF curves for the Baghmalek watershed in southwestern Iran. Crévolin *et al.* (2023) applied the quantile–quantile downscaling approach to estimate extreme rainfall values at fine spatiotemporal scales in Canadian cities. Additionally, an alternative simple temporal disaggregation approach introduced by Gupta & Waymire (1990) and widely adopted internationally is known as the simple scaling method. For instance, Maity & Maity (2022) formulated a new set of IDF curves incorporating the influence of climate change impacts across India. This was achieved by integrating the simple scaling method with the generalised extreme value distribution. Similar to this, examples of the use of the simple scaling method for temporal disaggregation can be found in diverse geographical contexts such as Slovakia (Bara *et al.* 2010), Japan (Nhat *et al.* 2008), Iran (Soltani *et al.* 2017) and Thailand (Yamoat *et al.* 2023).

The primary aim of this study is to investigate the scaling property of observed annual maximum (AM) rainfall series across durations ranging from 3 to 24 h at 3-h intervals, and to develop present and future IDF curves. The development of future IDF curves is dependent on the extraction of scaling properties from historically observed rainfall data and the climate projections provided by the CMIP6 models. This constitutes a novel contribution of this study. By incorporating the most recent climate model outputs into the IDF curve generation process, this study seeks to develop a more reliable and adaptable tool for urban planners and engineers. The intention is to ensure that the changing precipitation patterns brought through climate change are appropriately taken into consideration during the design and evaluation of stormwater infrastructure. Ultimately, this study aims to provide a comprehensive and up-to-date framework for integrating urban flood management techniques with the changing climatic conditions, thereby enhancing the sustainability and resilience of urban regions.

2. MATERIALS AND METHODS

To enhance the resilience of IDF relationships, this study incorporates scaling properties of historical rainfall data and projected daily rainfall under four climate change scenarios, namely SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 to develop future IDF curves. The overall methodology framework employed in this study is shown in Figure 1. In the first step, observed rainfall 3-hourly data and projected daily rainfall data were gathered to extract AM rainfall series. The subsequent step involved frequency analysis and the evaluation of probability distribution to identify the most suitable distribution for the AM rainfall series. Finally, the simple scaling method were applied to disaggregate AM daily into sub-hourly intervals for the development of historical and future IDF curves for Khon Kaen City.

2.1. Case study area

This study was conducted in Khon Kaen City located in the northeastern region of Thailand as shown in Figure 2. It spans geographical coordinates between latitudes 16°23′24″ and 16°28′48″ north and longitudes 102°46′12″ and 102°53′24″ east, encompassing a total land area of approximately 75 km^2. The study area includes Khon Kaen Municipality and Banped Sub-district Municipality. Khon Kaen City experiences an annual average rainfall of about 1,250 mm influenced significantly by seasonal monsoonal patterns. Notably, Khon Kaen City has undergone substantial population growth in recent decades resulting in the expansion of residential and commercial zones leading to an increase in impervious surfaces. The proliferation of concrete structures, including housing, roadways and infrastructure, has disrupted natural drainage patterns, thereby increasing the susceptibility to flood events. Given the dynamic nature of urban development and its profound effects on local hydrological dynamics, it becomes necessary to conduct a comprehensive study aimed at the development and

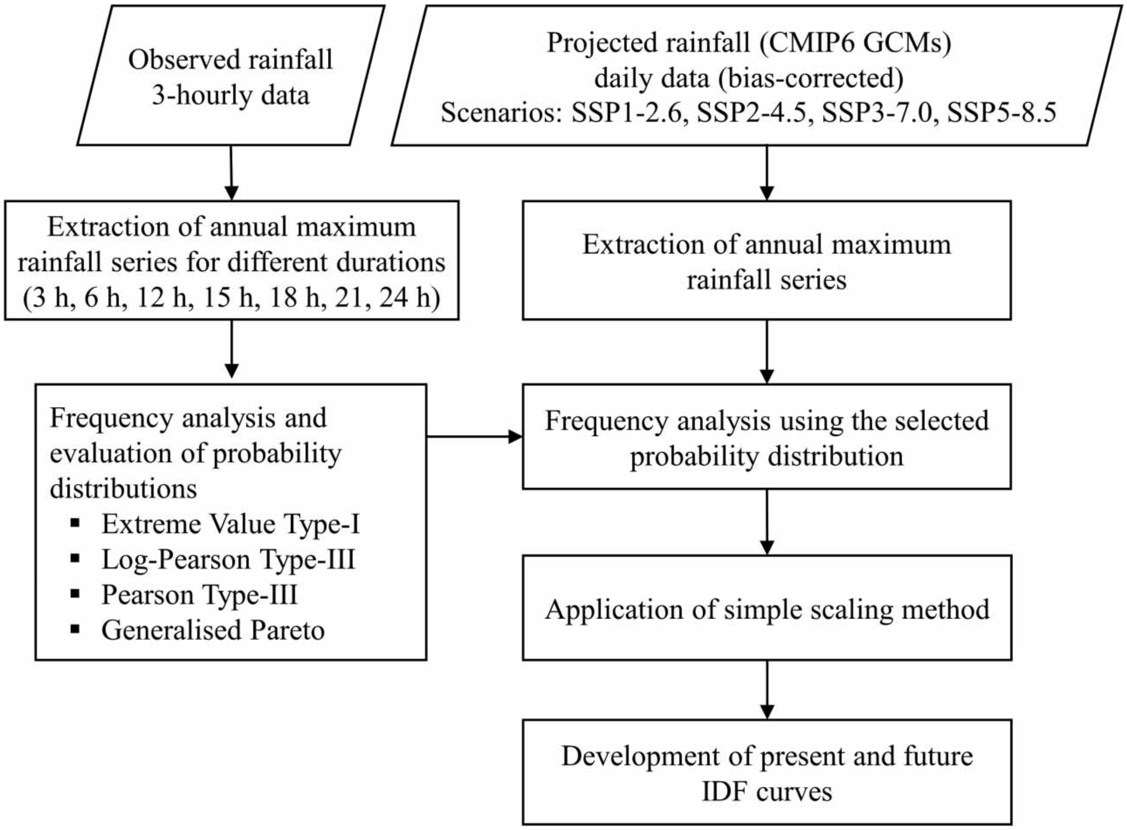


Figure 1 | Overview of the methodology framework adopted in this study.

updating of IDF curves particular to Khon Kaen City. These curves play an important role in guiding urban planners, engineers and policymakers in designing resilient infrastructure and effective flood management strategies.

2.2. Data collection and preliminary data analysis

2.2.1. Observed rainfall data collection and analysis

The ground-based rainfall observation is located at the Khon Kaen meteorological station in Khon Kaen City, Thailand. The station is 187 m above mean sea level and is situated at latitude 16°27′40″ north and longitude 102°47′23″ east. The observed 3-hourly and daily rainfall datasets available cover the period from 1991 to 2022. They were collected from the Thai Meteorological Department. To construct IDF curves, AM rainfall series for various durations are required. Therefore, AM rainfall series over moving windows of 3-, 6-, 9-, 12-, 15-, 18-, 21- and 24-h durations were derived from the observed datasets.

2.2.2. Preliminary analysis of climate model simulations

GCM outputs of CMIP6 are crucial tools for deriving future climate data. Due to their coarse spatial resolutions, GCM outputs often require a downscaling process to make them applicable to the regional and basin scales. Along with the coarse resolution, systematic errors because of various factors such as incomplete representation of physical processes and the inherent limitations of the models must be reduced through bias-correction techniques (Fang *et al.* 2015). Therefore, in this study, the downscaled and bias-corrected outputs of 15 CMIP6 GCMs collected from the Hydro-Informatics Institute (HII) in Thailand were employed. Statistics regarding the annual rainfall data of these 15 CMIP6 GCMs from 1991 to 2014 are presented in Table 1. These downscaled and bias-corrected outputs of the 15 CMIP6 GCMs were derived using observed rainfall data from 1,150 ground-based stations across Thailand and the scaled distribution mapping method (Switanek *et al.* 2017). Simulated rainfall outputs were accessible on a daily basis and at a resolution of 5 km. For this investigation, future simulated rainfall data spanning from 2023 and 2050 under four climate change scenarios, namely SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, were considered for the analysis of future IDF curves.

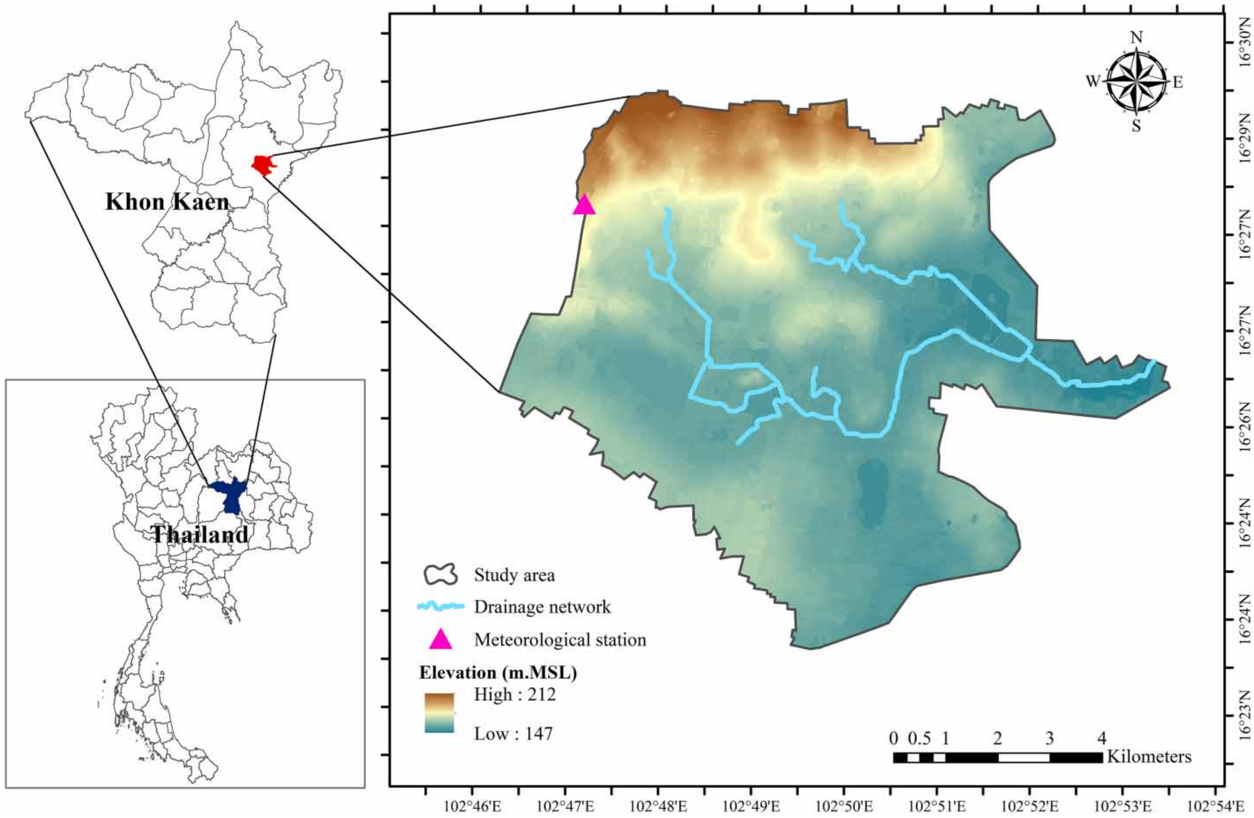


Figure 2 | Case study area: location of the Khon Kaen meteorological station.

Table 1 | Statistics of annual rainfall data observed by the Thai Meteorological Department and based on the bias-corrected CMIP6 GCMs outputs of the HII during 1991 to 2014

Rainfall data	Average (mm)	SD[a] (mm)	CV[b]
Observation	1,228.80	245.90	0.20
GFDL-ESM4	1,202.07	260.21	0.22
CESM2	1,193.26	395.05	0.33
CanESM5	1,236.58	336.34	0.27
ACCESS-ESM1-5	1,211.09	334.96	0.28
BCC-CSM2-MR	1,303.49	322.69	0.25
CMCC-ESM2	1,248.03	222.02	0.18
EC-Earth3	1,236.01	295.53	0.24
FGOAL-g3_MIP	1,174.78	358.26	0.30
IPSL-CM6A-LR	1,203.58	241.40	0.20
MIROC6	1,223.25	261.99	0.21
MPI-ESM1-2-HR	1,230.03	261.35	0.21
MPI-ESM1-2-LR	1,225.60	241.25	0.20
MPI-ESM2-0	1,310.72	268.27	0.20
NorESM2-LM	1,210.35	312.33	0.26
NorESM2-MM	1,289.16	305.71	0.24

[a] Standard deviation.

[b] Coefficient of variation.

SSP1-2.6, which is SSP1 + RCP2.6, represents an optimistic path towards sustainability and climate action with a low level of greenhouse gas emission. SSP2-4.5, which is SSP2 + RCP4.5, represents a future characterised by moderate population growth, intermediate levels of economic development and efforts to mitigate climate change. SSP3-7.0, which is SSP3 + RCP7.0, is considered a realistic worst-case scenario characterised by regional rivalry and limited global cooperation. SSP5-8.5, which is SSP5 + RCP8.5, represents a future with high population growth, high energy demand and limited climate change mitigation efforts (IPCC 2023). In this study, these scenarios were chosen because they capture a range of future climate conditions enabling a more comprehensive assessment of potential changes in design storm frequencies under diverse climate scenarios.

In addition, the evaluation of the bias-corrected CMIP6 GCM rainfall data was executed by appraising a specific statistical index, the correlation coefficient (r). This coefficient was computed from the comparison between the monthly mean rainfall series observed and those that had undergone correction. Afterwards, the bias-corrected CMIP6 GCM rainfall data that exhibited the higher r value were identified as the most suitable CMIP6 GCM and were consequently chosen for subsequent analyses.

2.3. Frequency analysis of annual maximum rainfall series

Frequency analysis of rainfall is important for understanding the variability of rainfall. In this study, the AM rainfall series for 3-, 6-, 9-, 12-, 15-, 18-, 21- and 24-h durations were fitted to four probability distributions, namely, Gumbel or Extreme Value Type-I (EV1), Log-Pearson Type-III (LP3), Pearson Type-III (P3) and Generalised Pareto (GP). The distribution fitting was performed by using the Bulleting 17B method implemented in the Hydrologic Engineering Center's Statistical Software Package.

The outcomes of fitting the distributions were evaluated using the Kolmogorov–Smirnov (KS) and Chi-squared tests. The KS test is a non-parametric technique for verifying the equivalence of two continuous probability distributions. The KS test operates by identifying the maximum difference between the empirical distribution function of the data and the cumulative distribution of the proposed distribution. This difference is indicated by the KS statistic, which is defined as:

$$\mathrm{KS} = \max|F_E(x) - F_O(x)| \tag{1}$$

where $F_E(x)$ is the empirical distribution function of the observed data and $F_O(x)$ is the cumulative distribution function (CDF) of the proposed distribution (Justel *et al.* 1997).

The Chi-squared test is used to determine whether the probability distribution of a variable is different from an expected distribution. The Chi-squared statistic is computed as follows:

$$\chi^2 = \sum \frac{(O_j - E_j)^2}{E_j} \tag{2}$$

where O_j represents the observed frequency for class j and E_j represents the expected frequency for class j.

After the computation of KS and Chi-squared statistics, they were compared with the critical values at the significant level of 0.05 as per the KS and Chi-squared statistical tables. If the KS and Chi-squared statistics were less than or equal to the critical values, the distribution is considered appropriate for frequency analysis. Subsequently, the four probability distributions were ranked according to the KS and Chi-squared statistics. The lower these statistics, the more suitable the probability distribution is considered for the AM rainfall series. Finally, the best-fit distribution was chosen based on this ranking and was then used for the scaling analysis and IDF generation.

2.4. Scaling analysis of rainfall intensities

This study employed the simple scaling method as proposed by Gupta & Waymire (1990) to derive updated rainfall intensities for different durations based on the outcomes of GCMs. The simple scaling method is a widely used approach that transforms daily IDF relationships to sub-daily ones (Yu *et al.* 2004). This method involves scaling the rainfall intensities over various timescales using scaling factors obtained from observed historical data. The basic equation of the simple scaling method can be expressed as follows:

$$I_d \overset{\mathrm{dist}}{=} \lambda^{-K} I_D \tag{3}$$

where I_d and I_D are AM rainfall intensity series for rainfall duration d and D, respectively; the equality $\overset{\text{dist}}{=}$ means that the probability distributions in both sides of the equation are identical; λ represents a scale factor, which is the ratio d/D, and K denotes a scaling parameter. The property of the scaling relation is usually denoted as 'simple scaling in the strict sense' (Gupta & Waymire 1990). It also implies that the moments of any order are scale-invariance. Thus, these statistical moments can be expressed as the following relationship (Menabde *et al.* 1999; Nhat *et al.* 2008):

$$E[I_d^q] = \lambda^{-K(q)} E[I_D^q] \tag{4}$$

where $E[]$ is the expected values operator and $K(q)$ denotes the scaling exponent function of order q. The scaling parameter K can be estimated from the slope of the linear regression relationships between the log-transformed values of the moments $E[]$ and scale factor λ for various orders of moments. If the scaling exponents and the corresponding order of moments have a linear relationship, it implies that K is a constant and the random variable I_d exhibits the property of simple scaling (Menabde *et al.* 1999).

According to the principle of the simple scaling method, the AM rainfall intensities for different durations can be fitted to a CDF and its parameters of the fitted CDF are related to each other by a scale ratio (Menabde *et al.* 1999; Yu *et al.* 2004; Maity & Maity 2022). As a result, the IDF formula can be derived from scaling invariance of rainfall (Nhat *et al.* 2008). The scaling relation is given as follows:

$$I_{d,T} = (d/D)^{-K} I_{D,T} \tag{5}$$

where T is the return period; $I_{d,T}$ represents the AM rainfall intensity series for the duration d (h) and the return period T (year); $I_{D,T}$ represents the AM rainfall intensity series for the duration D (that is, 24 h) and the return period T (year); K denotes the scaling exponent.

In the practice of the simple scaling method, the EV1 distribution is typically applied (Bara *et al.* 2010; Yamoat *et al.* 2023); however, in this study, the simple scaling method was used with the distribution that was determined to be most suitable during the evaluation based on the KS and Chi-squared tests. Consequently, the AM rainfall intensity series spanning various durations (3, 6, 9, 12, 15, 18, 21 and 24 h) were fitted with the selected distribution. The corresponding distribution parameters were determined by using the method of moments. IDF curves were constructed through this conventional frequency analysis procedure using the selected distribution. Simultaneously, additional IDF curves were derived by means of the simple scaling of the 24-h AM rainfall intensity series. To assess the effectiveness and suitability of the simple scaling method, an observation of the scaling behaviour was conducted, and a comparative analysis among these IDF curves was carried out.

2.5. Development of future IDF curves

In the previous section, current IDF curves were produced using the simple scaling method. For the formulation of IDF curves under the projected scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5), the 24-h AM rainfall series from 2023 to 2050 were extracted from the bias-corrected rainfall data of CMIP6 GCM, which was determined to be most suitable based on the observed rainfall data. These 24-h AM rainfall series were fitted to the selected distribution. Following this, the 24-h AM rainfall series of various return periods (2, 5, 10, 25, 50 and 100 years) were disaggregated into durations of 3, 6, 9, 12, 15, 18, 21 and 24 h using the simple scaling method. As a result, future IDF curves for the four projected scenarios were generated.

3. RESULTS AND DISCUSSION

3.1. Selection of climate model outputs

The bias-corrected rainfall data from the 15 CMIP6 GCMs covering the years 1991 to 2014 were compared on a monthly basis with the rainfall data observed at the Khon Kaen meteorological station. These comparisons were evaluated using the application of the correlation coefficient (r). Figure 3 shows the assessment results for the bias-corrected rainfall data from the GCMs. The top five GCMs with corresponding r values of 0.6313, 0.6080, 0.6030, 0.5980 and 0.5809 were BCC-CSM2-MR, NorESM2-MM, EC-Earth3, CMCC-ESM2 and MPI-ESM1-2-LR. As a result, BCC-CSM2-MR was chosen to create future IDF curves since it had the highest r value and was considered to be the appropriate GCM for the observed

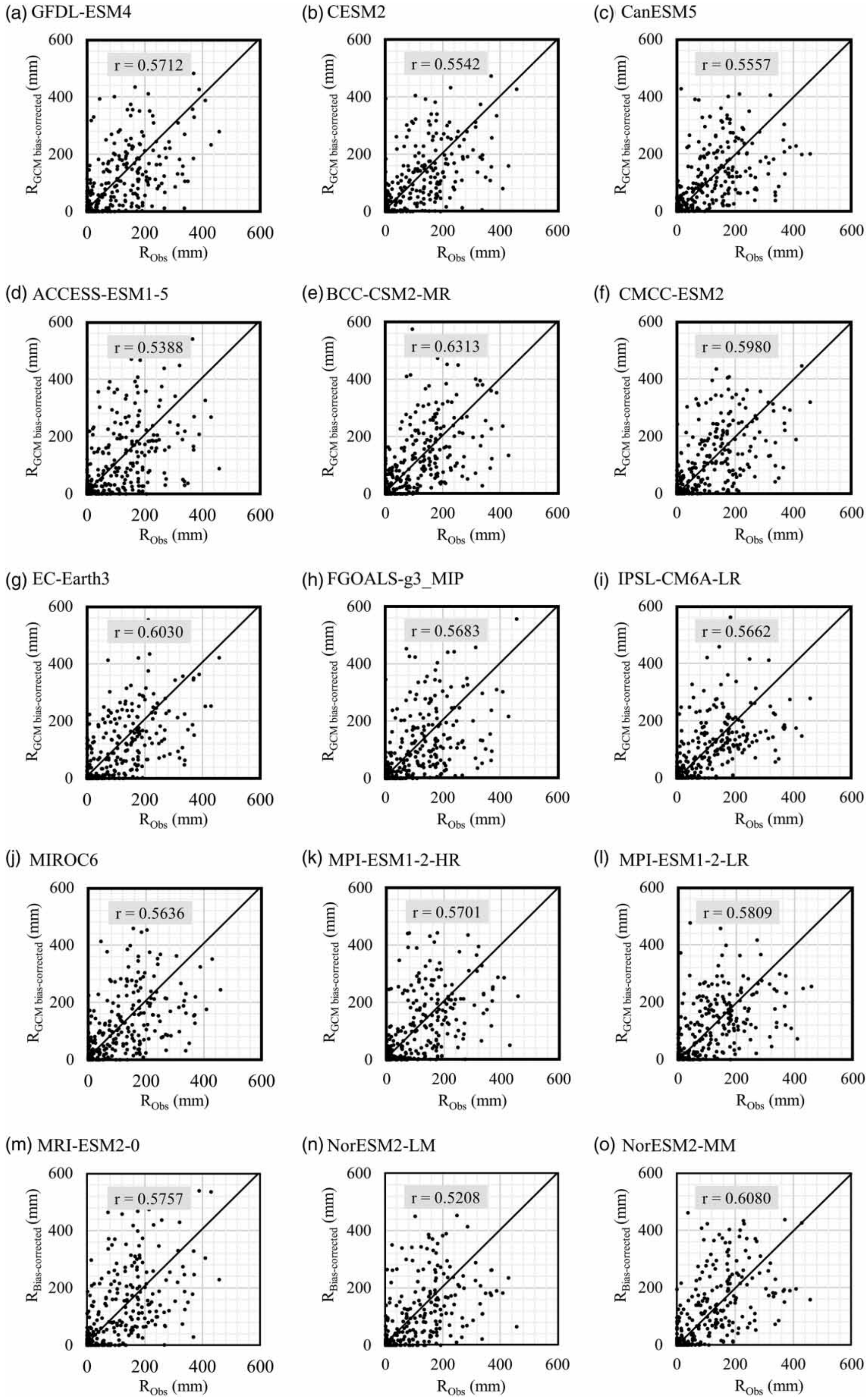


Figure 3 | Comparisons between observed rainfall and bias-corrected rainfall data from 15 HII GCMs.

rainfall data of the station. These findings align with outcomes from previous studies. For example, Khadka *et al.* (2022) identified the top five CMIP6 GCMs in descending order as EC-Earth3-CC, NorESM2-MM, EC-Earth3, TaiESM1 and HadGEM3-GC31-MM. Their findings were based on the comparisons between CMIP6 GCMs and ERA5 datasets. Pimonsree *et al.* (2023) reported that the simulated rainfall datasets of EC-Earth family have a high value of spatial correlation coefficient with rainfall data observed over Thailand sourced from the Global Precipitation Climatology Centre. Similarly, Liang-Liang *et al.* (2022) highlighted the satisfactory performance of MPI-ESM1-2-XR in simulating rainfall datasets across Central Asia evidenced by an r value of 0.72. According to this analysis, it is noted that CMIP6 GCMs performance in rainfall simulation in different regions can be varied.

3.2. Evaluation of probability distributions

The AM rainfall series for 3-, 6-, 9-, 12-, 15-, 18-, 21- and 24-h durations extracted from the Khon Kaen meteorological station were subjected to testing with four probability distributions. These probability distributions were evaluated based on the KS and Chi-squared tests for goodness of fit. A summary of the ranking of the probability distributions, according to the goodness-of-fit tests, is presented in Table 2. As observed, LP3 was identified as the best fit for the AM rainfall series across nearly all rainfall durations. Consequently, the LP3 distribution was selected for further investigation.

3.3. Application and validation of the simple scaling method

The AM rainfall series at different durations (3, 6, 9, 12, 15, 18, 21 and 24 h) were fitted to the LP3 distribution. The relationships between the log-transformed values of the moments based on the LP3 distribution and rainfall durations for various orders of moments at the Khon Kaen meteorological station are shown in Figure 4. Evidently, the relationships have a linear pattern for durations between 3 and 24 h. The strength of these correlations quantified by coefficients of determination (R^2) ranges from 0.9990 to 0.9996. The observed linearity of moments in the present study aligns with findings from prior investigations. For instance, Nhat *et al.* (2008) reported comparable linearity in rainfall data from Japan. Similar findings were made by Bara *et al.* (2010) in Slovakia, Wilby *et al.* (2023) in Uganda and Kenya, and Soltani *et al.* (2017) in southwest Iran.

Figure 5 shows the relationship between the scaling exponent function $K(q)$ and the order-q moments for the Khon Kaen meteorological station. The slope of this relationship is the scaling parameter K, which has a value of 0.7286 for the station. This outcome contrasts with the findings of Yamoat *et al.* (2023) who determined the scaling parameter for the station to be 0.699. This inconsistency may be due to several factors. First, the variance in the sample size differs. Second, the disparity in rainfall durations is used in the simple scaling analysis. Lastly, the choice of the probability distribution for the analysis can influence the results. The current study employed the LP3 distribution, while Yamoat *et al.* (2023) used the EV1 distribution. Upon applying the simple scaling method, it was noted that the outcomes were sensitive to the sample size, the range of rainfall durations and the selected probability distribution for the analysis. In addition, the relationship between the scaling exponent function and the order-q moments was linearly related with an R^2 value of 0.9999. This substantiates the applicability of the simple scaling method for the estimation of short-term rainfall intensities based on the existing 24-h AM rainfall

Table 2 | Summary of the ranking of probability distributions for the AM rainfall series for 3-, 6-, 9-, 12-, 15-, 18-, 21- and 24-h durations at the Khon Kaen meteorological station

	Probability distribution ranked based on the KS test				**Probability distribution ranked based on the Chi-squared test**			
Duration	**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**	**Rank 1**	**Rank 2**	**Rank 3**	**Rank 4**
3 h	GP	P3	LP3	EV1	EV1	LP3	P3	GP
6 h	GP	P3	LP3	EV1	P3	GP	LP3	EV1
9 h	P3	LP3	GP	EV1	GP	LP3	P3	EV1
12 h	LP3	EV1	P3	GP	LP3	GP	P3	EV1
15 h	LP3	GP	P3	EV1	LP3	GP	P3	EV1
18 h	LP3	GP	P3	EV1	P3	LP3	GP	EV1
21 h	LP3	GP	P3	EV1	LP3	GP	EV1	P3
24 h	LP3	GP	P3	EV1	LP3	GP	EV1	P3

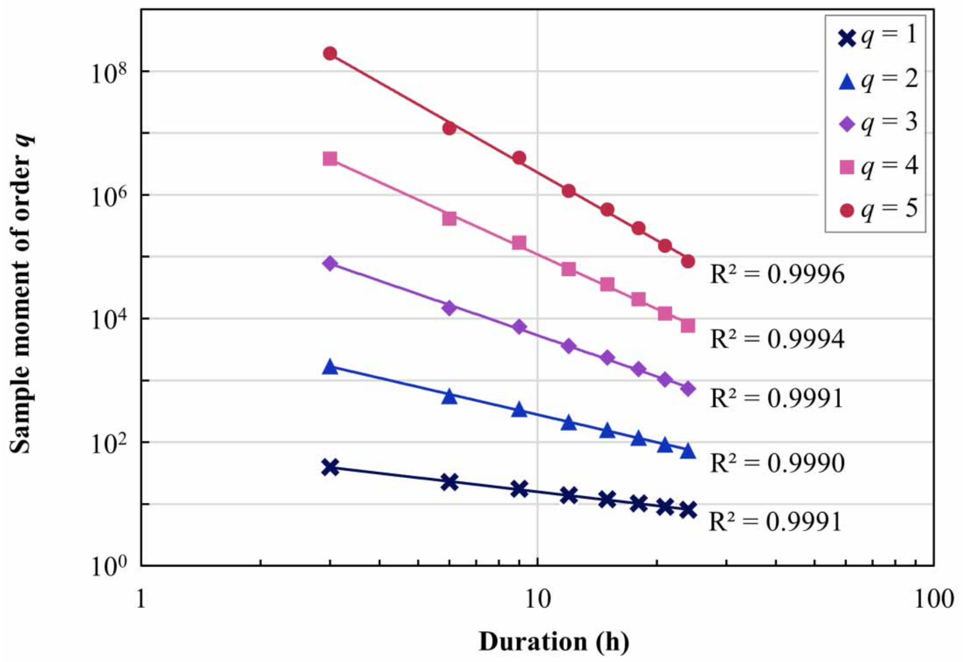


Figure 4 | Relationships between moments of rainfall intensities and durations from 3 to 24 h at the Khon Kaen meteorological station.

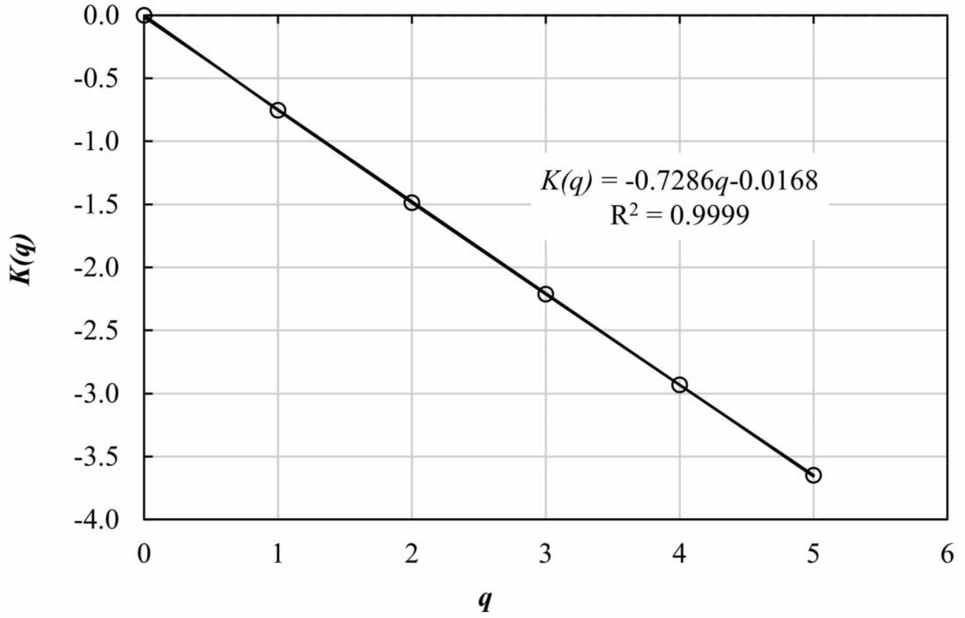


Figure 5 | Relationship between the scaling exponent function $K(q)$ and the order-q moments for the Khon Kaen meteorological station.

series at this station. These findings are in alignment with prior research on the temporal disaggregation of daily rainfall series, which has underscored the utility of the simple scaling method (e.g., Bara *et al.* 2010; Soltani *et al.* 2017).

Figure 6 presents the IDF curves generated by applying the simple scaling to the 24-h AM rainfall intensity series obtained from the Khon Kaen meteorological station. These derived IDF values were subsequently compared with AM rainfall intensities computed through the conventional frequency analysis procedure using the LP3 distribution across different durations

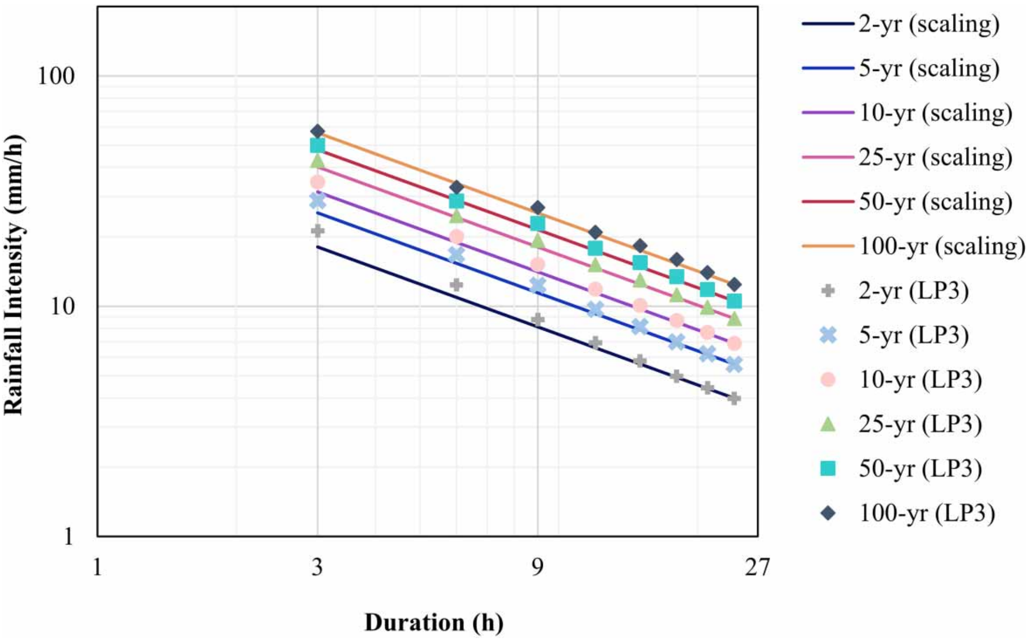


Figure 6 | Comparison of the IDF relationships of durations from 3 to 24 h derived from the scaling model and those with the conventional frequency analysis of the LP3 distribution.

(3, 6, 9, 12, 15, 18, 21, and 24 h). The comparative analysis results revealed a remarkably high level of agreement, as denoted by an R^2 value of 0.9950. This confirms the appropriateness and accuracy of the simple scaling method for the estimation of short-term rainfall intensities drawing upon the existing 24-h AM rainfall series recorded at this meteorological station.

3.4. Development of future IDF curves

Figure 7 illustrates the future IDF curves for each return period spanning 2, 5, 10, 25, 50 and 100 years. These IDF curves were constructed using the 24-h AM rainfall intensity series of observed data and rainfall projections from the BCC-CSM2-MR model under the four climate change scenarios. The future IDF curves were derived from the simple scaling method, which was applied to disaggregate the AM daily rainfall projections. When comparing the future IDF curves with the present ones, it is observed that intensities increase under climate change for most of the rainfall durations. The rainfall intensity of SSP5-8.5 is higher than the other scenarios. The observation of increasing rainfall intensity due to change in climate aligns with findings from previous studies (e.g., Maity & Maity 2022; Wilby *et al.* 2023).

The findings of this study may be somewhat limited by the simulated rainfall of GCMs as the selection of GCMs was grounded on the monthly analysis between the observed rainfall data and the bias-corrected rainfall data of the GCMs. Despite the GCM being deemed suitable for simulating monthly rainfall, it may fall short in accurately representing extreme daily rainfall events. These findings underscore the importance of considering the uncertainties of GCMs in predicting daily rainfall. Therefore, it is recommended to consider multiple GCMs to establish the upper and lower boundaries of the results. Moreover, future research could investigate downscaling and bias-correction methods for modelling and predicting extreme rainfall events under climate change conditions.

4. CONCLUSIONS

In the pursuit of developing comprehension of rainfall characteristics within the context of climate change, this study has adopted a comprehensive approach consisting of data analysis, statistical methodologies and climate modelling. The investigation mainly focused on the analysis of AM rainfall series with a particular emphasis on disaggregating 24-h AM rainfall data recorded at the Khon Kaen meteorological station spanning from 1991 to 2022. The application of the simple scaling method yielded valuable insights into the temporal distribution of rainfall intensities. An inherent advantage of this method lies in its capability to estimate design values of rainfall intensities across various durations using the often readily available daily

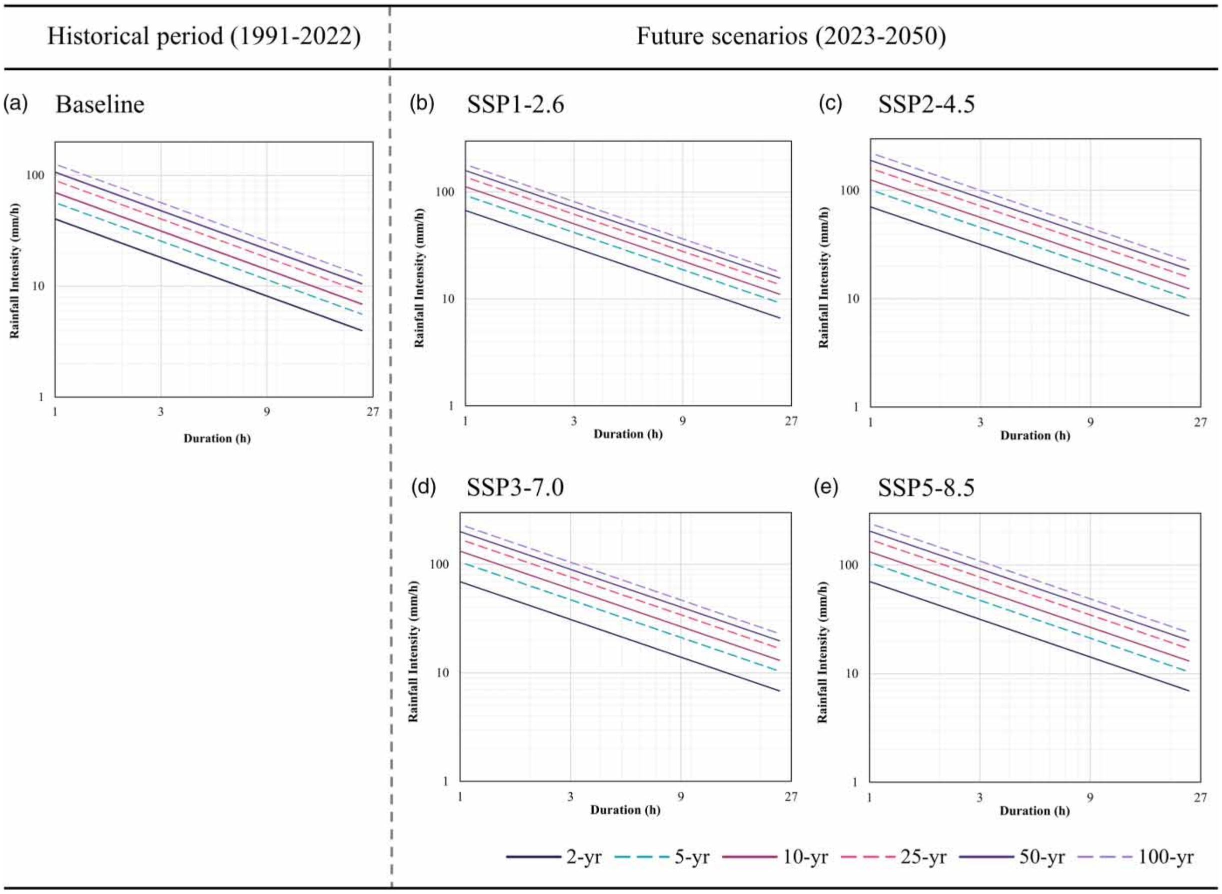


Figure 7 | IDF curves constructed using the simple scaling method for (a) baseline (1991–2022), (b) SSP1-2.6, (c) SSP2-4.5, (d) SSP3-7.0 and (e) SSP5-8.5 scenarios (2023–2050) for Khon Kaen City.

rainfall data. However, this study is limited by the unavailability of highly detailed temporal rainfall series (i.e., 0.25, 0.50, 0.75, 1 and 2 h). As a result, the developed IDF curves are applicable for durations ranging from 3 to 24 h. Our study revealed new insights regarding the application of the simple scaling method. The results from this method are sensitive to the sample size, the range of rainfall durations and the chosen probability distribution.

Furthermore, our work went beyond the boundaries of historical data. We applied the simple scaling method to bias-corrected rainfall data obtained from CMIP6 GCMs, thereby projecting future IDF curves under four distinct scenarios: SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. The results of these projections revealed crucial insights into the potential impacts of different climate pathways on rainfall patterns. In conclusion, our study significantly contributes to the field of water resources engineering and climate adaptation. We propose a new methodological framework for generating IDF relationships under climate change conditions. This framework encompasses the selection of GCMs and probability distribution along with the application of the simple scaling method. The IDF curves developed can be essential for sustainable water resource management and infrastructure planning in the changing climate of Khon Kaen City. Our future research in this direction will focus on enhancing confidence in the development of IDF curves. This includes investigating the applicability of GCMs for simulating extreme daily rainfall events. Future work is also needed to improve temporal scaling methods for estimating sub-daily extreme rainfalls.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Anaraki, M. V., Kadkhodazadeh, M., Morshed-Bozorgdel, A. & Farzin, S. 2023 Predicting rainfall response to climate change and uncertainty analysis: Introducing a novel downscaling CMIP6 models technique based on the stacking ensemble machine learning. *Journal of Water and Climate Change* **14** (10), 3671–3691. doi: 10.2166/wcc.2023.477.

Adib, A. & Rad, S. G. 2019 Development of a new integrated method for generation of IDF curves based on three scenarios of climatic changes. *Scientia Iranica* **26** (2), 742–751. doi:10.24200/SCI.2017.4593.

Alzahrani, F., Seidou, O. & Alodah, A. 2023 Assessing the performance of daily to subdaily temporal disaggregation methods for the IDF curve generation under climate change. *Journal of Water and Climate Change* **14** (4), 1339–1357. doi:10.2166/wcc.2023.507.

Bara, M., Kohnová, S., Szolgay, J., Gaál, L. & Hlavčová, K. 2010 Assessing of IDF curves for hydrological design by simple scaling of 1-day precipitation totals. *Slovak Journal of Civil Engineering* **18** (3), 1–6. doi:10.2478/v10189-010-0010-8.

Crévolin, V., Hassanzadeh, E. & Bourdeau-Goulet, S.-C. 2023 Updating the intensity-duration-frequency curves in major Canadian cities under changing climate using CMIP5 and CMIP6 model projections. *Sustainable Cities and Society* **92**, 104473. doi:10.1016/j.scs.2023.104473.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J. & Taylor, K. E. 2016 Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development* **9** (5), 1937–1958. doi:10.5194/gmd-9-1937-2016.

Fang, G. H., Yang, J., Chen, Y. N. & Zammit, C. 2015 Comparing bias correction methods in downscaling meteorological variables for a hydrologic impact study in an arid area in China. *Hydrology and Earth System Sciences* **19** (6), 2547–2559. doi:10.5194/hess-19-2547-2015.

Gupta, V. K. & Waymire, E. C. 1990 Multiscaling properties of spatial rainfall and river flow distributions. *Journal of Geophysical Research* **95** (3), 1999–2009.

IPCC 2023 *Summary for Policymakers*. Climate Change 2023: Synthesis Report, Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland.

Justel, A., Pefia, D. & Zamar, R. 1997 A multivariate Kolmogorov-Smirnov test of goodness of fit. *Statistics and Probability Letters* **35** (3), 251–259.

Khadka, D., Babel, M. S., Abatan, A. A. & Collins, M. 2022 An evaluation of CMIP5 and CMIP6 climate models in simulating summer rainfall in the Southeast Asian monsoon domain. *International Journal of Climatology* **42** (2), 1181–1202. doi:10.1002/joc.7296.

Kourtis, I. M., Nalbantis, I., Tsakiris, G., Psiloglou, B. E. & Tsihrintzis, V. A. 2023 Updating IDF curves under climate change: impact on rainfall-induced runoff in urban basins. *Water Resources Management* **37** (6), 2403–2428. doi:10.1007/s11269-022-03252-8.

Liang-Liang, L., Jian, L. & Ru-Cong, Y. 2022 Evaluation of CMIP6 HighResMIP models in simulating precipitation over Central Asia. *Advances in Climate Change Research* **13** (1), 1–13. doi:10.1016/j.accre.2021.09.009.

Maity, S. S. & Maity, R. 2022 Changing pattern of intensity-duration-frequency relationship of precipitation due to climate change. *Water Resources Management* **36** (14), 5371–5399. doi:10.1007/s11269-022-03313-y.

Martel, J. L., Brissette, F. P., Lucas-Picher, P., Troin, M. & Arsenault, R. 2021 Climate change and rainfall intensity-duration-frequency curves: overview of science and guidelines for adaptation. *Journal of Hydrologic Engineering* **26** (10), 03121001. doi:10.1061/(ASCE)HE.1943-5584.0002122.

Menabde, M., Seed, A. & Pegram, G. 1999 A simple scaling model for extreme rainfall. *Water Resources Research* **35** (1), 335–339.

Nhat, L. M., Tachikawa, Y., Sayama, T. & Takara, K. 2008 Development of the regional rainfall intensity-duration-frequency curves based on scaling properties. *Annual Journal of Hydraulic Engineering* **52**, 85–90.

Nooni, I. K., Ogou, F. K., Chaibou, A. A. S., Nakoty, F. M., Gnitou, G. T. & Lu, J. 2023 Evaluating CMIP6 historical mean precipitation over Africa and the Arabian Peninsula against satellite-based observation. *Atmosphere* **14** (3). doi:10.3390/atmos14030607.

Pimonsree, S., Kamworapan, S., Gheewala, S. H., Thongbhakdi, A. & Prueksakorn, K. 2023 Evaluation of CMIP6 GCMs performance to simulate precipitation over Southeast Asia. *Atmospheric Research* **282**, 106522. doi:10.1016/j.atmosres.2022.106522.

Semenov, M. A. & Brooks, R. J. 1999 Spatial interpolation of the LARS-WG stochastic weather generator in Great Britain. *Climate Research* **11** (2), 137–148.

Soltani, S., Helfi, R., Almasi, P. & Modarres, R. 2017 Regionalization of rainfall intensity-duration-frequency using a simple scaling model. *Water Resources Management* **31** (13), 4253–4273.

Switanek, M. B., Troch, P. A., Castro, C. L., Leuprecht, A., Chang, H. I., Mukherjee, R. & Demaria, E. M. C. 2017 Scaled distribution mapping: a bias correction method that preserves raw climate model projected changes. *Hydrology and Earth System Sciences* **21** (6), 2649–2666. doi:10.5194/hess-21-2649-2017.

Wilby, R. L., Dawson, C. W., Yu, D., Herring, Z., Baruch, A., Ascott, M. J., Finney, D. L., Macdonald, D. M. J., Marsham, J. H., Matthews, T. & Murphy, C. 2023 Spatial and temporal scaling of sub-daily extreme rainfall for data sparse places. *Climate Dynamics* **60** (11), 3577–3596. doi:10.1007/s00382-022-06528-2.

Yamoat, N., Hanchoowong, R., Yamoad, O., Chaimoon, N. & Kangrang, A. 2023 Estimation of regional intensity-duration-frequency relationships of extreme rainfall by simple scaling in Thailand. *Journal of Water and Climate Change* **14** (3), 796–810. doi:10.2166/wcc.2023.430.

Yu, P.-S., Yang, T.-C. & Lin, C.-S. 2004 Regional rainfall intensity formulas based on scaling property of rainfall. *Journal of Hydrology* **295** (1), 108–123. doi:10.1016/j.jhydrol.2004.03.003.

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