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RESEARCH ARTICLE

Constructing short-duration IDF curves using coupled dynamical–statistical approach to assess climate change impacts

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This study demonstrates a methodology to construct short-duration rainfall intensity–duration–frequency (IDF) curves and to quantify the variability in the rainfall intensities for different return periods with respect to the changing climate. A dynamical downscaling approach using the regional climate model (RCM) Weather Research and Forecasting (WRF) has been used to assess present and future climates using the downscaling of an ensemble of three global climate models (GCMs) (CSIRO-ACCESS1.3, MPI-ESM-MR ECHAM6 and NIES-MIROC5) under the Coupled Model Intercomparison Project phase 5 (CMIP5). Furthermore, a statistical approach using the well-known simple scaling method has been applied to extend the 6-hourly WRF precipitation output to the finer temporal scale of 10 min. The short-duration IDF curves were then constructed for the present and future climates under two representative concentration pathway (RCP) scenarios RCP4.5 and RCP8.5. A preliminary examination for this case study over Bac Ninh, an industrial area in the northern Vietnam, shows that there is a substantial increase in short-duration rainfall intensity in the future with respect to the baseline climate. The highest increase is towards the end of the century (2071–2100) ranging from 56 to 61% for a 10- and 100-year return period for 24-hr duration, respectively, while the increase is about 40–45% for the 10-min duration. These results strongly suggest that severe flooding in the future climate over the study region may be likely. The study results might be useful for policymakers and infrastructure planning and for insurance companies around the study area.

KEYWORDS

climate change, downscaling, dynamical, IDF, simple scaling, statistical

1 | INTRODUCTION

Studying extreme rainfall return periods for urban areas, especially in a changing climate, is crucial. One of the traditional methods to study such extreme events using the intensity–duration–frequency (IDF) curves that are being applied in most drainage infrastructure designs. The annual maximum rainfall intensity values at different durations (from minutes to daily) are often used to construct these IDF curves. In addition, for cities located in the tropical and coastal regions, even a short and heavy downpour can cause severe flooding. However, it is difficult to obtain such records of short-duration rainfall for a sufficiently long period of time, especially for developing countries, where financial budget and technology are the main limitations. Therefore, problems arise when there is a need to know the return period of an extreme rainfall event when it comes to planning and adaptation.

As a result of global warming, the occurrence of maximum rainfall is expected to enhance in both intensity and frequency (Kharin *et al.*, 2007). Especially for urban areas, where concentrated a high population density, any change in extreme climate events would cause significant damages to infrastructures, traffics, properties and lives. Hence, the need for information on future extreme rainfall is strongly felt for planning purposes. The IDF curves have been long known to be effective tools for designing drainage infrastructure. The IDF curves provide information on the maximum rainfall intensity for a certain duration of pre-defined return periods of an event. Usually, sufficiently long records of annual maximum rainfall intensities (AMRI) (~20 years) at different durations are required to construct these IDF curves.

Although global climate models (GCMs) provide global climate information on key climate variables including precipitation, the mismatch in the spatial resolutions between GCMs and the downstream end-user needs (regional/local) necessitates "downscaling". The applications of regional climate models (RCMs), through dynamical downscaling, to assess climate projections have matured, yet, there is still a limitation in the use of RCM outputs to construct IDF curves at short (sub-hourly) durations because most of the available outputs of RCMs are usually 6-hourly. To date, there are not many studies on the applications of RCMs to study IDF curves at short durations (sub-hourly). Kuo *et al.* (2015) applied the precipitation outputs from the RCM MM5 at a temporal resolution of 15 min to construct short-duration storm IDF curves of up to 15-min duration. Although this approach was able to construct 15-min duration IDF curves directly from RCMs, it is computationally expensive to run for longer periods, especially in larger domains. In addition, it is impossible to utilize the existing RCM outputs from projects such as PRUDENCE (Christensen and Christensen, 2007) and ENSEMBLES (van der Linden and Mitchell, 2009) to construct local-scale IDF curves at sub-hourly durations. Therefore, in this study, we introduce a statistical method to construct short-duration (sub-hourly) IDF curves based on the 6-hourly temporal outputs from an RCM. This statistical "simple scaling" approach, developed by Menabde *et al.* (1999), has been applied globally in a few studies as that of Bara *et al.* (2009), Nhat *et al.* (2007), Rodriguez *et al.* (2014), Vu *et al.* (2017) and Yu *et al.* (2004). The "simple scaling" approach is suitable to derive sub-hourly IDF curves based on higher-duration (d) (d > 1 hr) AMRI via scaling exponents for the moment of the data set. Vu *et al.* (2017) applied simple scaling to construct hourly duration IDF curves based on 6-hourly RCM output. Rodriguez *et al.* (2014) applied simple scaling approach to outputs from statistical downscaling of GCMs and constructed hourly duration IDF curves for Barcelona. Nguyen *et al.* (2007) also applied simple scaling approach to output from statistical downscaling of GCMs to construct sub-hourly IDF curves, based on daily AMRI.

In this context, this study investigates the climate change impacts on short-duration (sub-hourly) maximum rainfall over one of the urbanized area, Bac Ninh in northern Vietnam, one of the busiest industrial parks. We applied the 6-hourly rainfall output from the Weather Research and Forecasting (WRF) model. Three GCMs, CSIRO-ACCESS1.3, MPI-ESM-MR ECHAM6 and NIES-MIROC5, from the Coupled Model Intercomparison Project phase 5 (CMIP5), were downscaled under the current climate (baseline) period 1986–2005 and under both RCP4.5 and RCP8.5 scenarios of the future climate spanning the 2011–2100 period. This ensemble of six downscaled GCMs/scenarios provides a wide range of uncertainties of climate change impacts. The main objective of this study is to derive the sub-hourly IDF curves (for durations up to 10 min) from the 6-hourly rainfall outputs from the RCM, by using the simple scaling approach. The overall work flow is displayed in Figure 1. The article is divided into different sections: Section 2 introduces the study area with in situ data, model, and methodology with details on the simple scaling approach. Section 3 presents the results and discussions while some conclusions are drawn in section 4.

2 | MODEL, DATA AND METHODOLOGY

2.1 | Station data

The study region, Bac Ninh, lies in the in the north of Vietnam, about 30 km from the capital city, Hanoi. This area is one of the key economic zones of the country as it is located with many industrial zones such as Vietnam

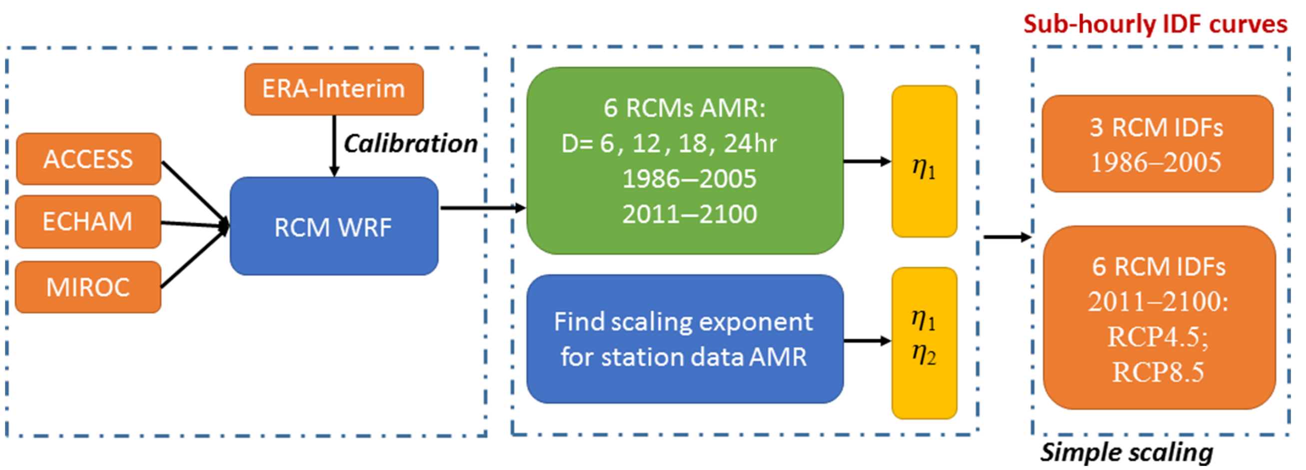

FIGURE 1 Schematization of methodology [Colour figure can be viewed at wileyonlinelibrary.com]

Singapore Industrial Park (VSIP), Samsung, Que Vo Industrial Park 1, 2, 3 and Tien Son Industrial Park. Therefore, it is a crucial area that needs high protection during the flooding season (August–October).

The total annual rainfall is about 1,700 mm with the rainy season coinciding with the southwest monsoon season from May through to October. There are not many rainfall stations in the province that have long enough records for extreme precipitation case study. The selected Bac Ninh station is the only rain gauge that has the longest records and hence suitable to examine the IDF curves for the 1986–2005 period. The location of the rainfall station, Bac Ninh area, and the RCM grid points are displayed in Figure 2a.

The annual maximum rainfall intensity data for Bac Ninh have been collected for 10 durations: 10 min, 15 min, 30 min, 60 min (1 hr), 90 min, 2 hr, 4 hr, 8 hr, 12 hr and 24 hr, spanning the period 1986–2005. The quality-controlled data were provided by the Vietnam Institute of Meteorology, Hydrology and Climate Change (IMHCC). The empirical cumulative distribution functions (CDFs) for AMRI of Bac Ninh station for different durations are displayed in Figure 2b.

2.2 | WRF model

Developed at the National Center for Atmospheric Research (NCAR), Boulder, CO, the WRF model is suitable for a broad spectrum of applications across scales ranging from metres to thousands of kilometres. The model incorporates advanced numeric and data-assimilation techniques, multiple nesting capabilities and numerous state-of-the-art physics options and is a widely used RCM by the climate research community around the globe. Additional information can be obtained from http://www.wrf-model.org and Raghavan *et al.* (2016).

The WRF model was initially driven by the global reanalyses ERA-Interim to benchmark its performance over the 20-year baseline climate period of 1986–2005. Climate outputs were generated at 6-hourly temporal resolutions at a spatial resolution of 20 km with 60 grid points in the east–west directions and 70 grid points on the north–south covering the country. As the WRF model comes with a suite of physics options or parameterizations, the best set of physics options that well simulate the tropical climate of this region was chosen. These are: the Grell cumulus scheme (Grell, 1993); the Thomson microphysics scheme ((Thompson *et al.*, 2004); the Yongsei University planetary boundary layer scheme (Hong and Pan, 1996); the rapid radiative transfer model (RRTM) and the four-layer soil moisture and temperature Noah land surface model (Chen and Dudhia, 2001).

Subsequently, the WRF model was driven by the three GCMs ACCESS1.3, ECHAM6 and MIROC5 for both the baseline (1986–2005) and future climates (2011–2100) forced under the emission scenarios, RCP4.5 and RCP8.5. The future periods were divided into three-time slices for further analyses: 2011–2040, 2041–2070 and 2071–2100. For simplicity in reading, the simulations of the WRF model driven by the GCMs ACCESS1.3, ECHAM6 and MIROC5 are referred to, in this article, as WRF/ACCESS, WRF/ECHAM and WRF/MIROC, respectively. The 6-hourly rainfall output from the WRF model was bi-linearly interpolated to the Bac Ninh rainfall station point then used to calculate the AMRI for 6, 12, 18 and 24 hr, for the baseline (current) and future climates.

2.3 | Simple scaling for deriving IDF curves

The simple scaling methodology initiated by Gupta and Waymire (1990) was further developed by Menabde *et al.* (1999) which assumes that the intensity of a variable duration I_d has the same distribution with the intensity of the duration I_D if:

$$I_d \overset{\text{dist}}{=} (d/D)^{-\eta} I_D, \tag{1}$$

in which η is the scaling exponent. D is constant duration to be scaled. Normally, the duration D represents daily

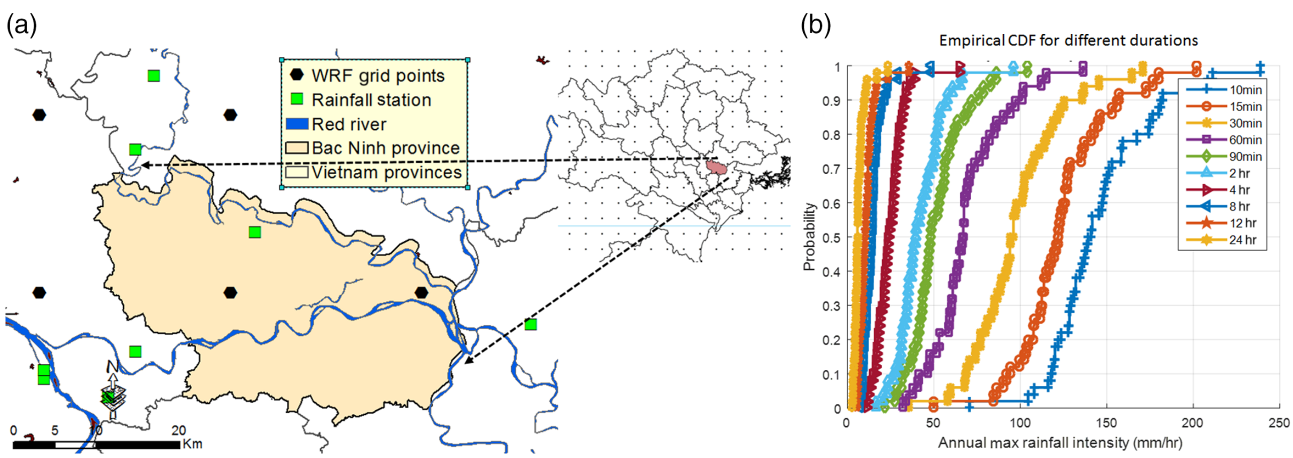

FIGURE 2 (a) WRF grid points covering Bac Ninh region and rainfall station. (b) Empirical CDF from AMRI for different durations for Bac Ninh station [Colour figure can be viewed at wileyonlinelibrary.com]

duration or 24-hr duration and duration d represents hourly or sub-hourly. We raised both side of Equation 1 to power q and computed the ensemble average to retrieve the relationship between the qth moment E[]:

$$E\left[I_d^q\right]=(d/D)^{-\eta q}E[I_D^q], \tag{2}$$

$$E\left[I_d^q\right]=E[I_D^q]D^{\eta q}d^{-\eta q}. \tag{3}$$

Equation 3 describes the scaling properties of the moments of station data with duration from 10 min to 24 hr. We plotted the moment $E\left[I_d^q\right]$ on the log–log chart order of moments q with all durations d for the studied station in Figure 3. The coefficient of determination R^2 displayed in Figure 3 is computed between $E\left[I_d^q\right]$ for different duration/moment q and the linear fitting. We can see that all R^2 are closer to 1 which infers a linear relationship and that the coefficient $E[I_D^q]D^{q\eta}$ is constant with d. As seen in Figure 3, there is a breakpoint at duration 1 hr denoting the existing of two different regimes of duration: (a) sub-hourly and (b) hourly. The breakpoint at the location of 1-hr duration could imply a transition in the rainfall dynamics from a steep slope for short duration rainfall (that indicates a high variability of rainfall intensities in convective cells) to a milder slope for long-duration rainfalls that could be due to the smaller variability of frontal rainfall systems (Nhat *et al.,* 2007). The breakpoint at 1-hr rainfall duration has also been described by Bougadis and Adamowski (2006) for four stations over Ontario (Canada); by Nguyen *et al.* (2007) for 15 rain gauges in Quebec (Canada); by Nhat *et al.* (2007) for Nagoya (Japan), Daegu (Korea), Geraldton (Australia), S3117070 (Malaysia); for six stations in Barcelona (Spain) by Rodriguez *et al.* (2014) and by a few others. However, the breakpoint of 45 min was found for Singapore by Chang and Hiong (2013). We additionally compared breakpoints at 45 min and 1 hr (not shown) and found that the breakpoint at 1 hr provided a higher R^2 value than at 45 min. Therefore in this study, we only use breakpoint at 1-hr duration to differentiate sub-hourly and hourly regimes.

From Equation 2, it can be rewritten as

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

in which $K(q) = -\eta q$ is the scale function and λ is the ratio between sub-daily duration with 24 hr. According to Menabde *et al.* (1999), if $K(q)$ is linear, the process is simple scaling. If not, $K(q)$ would be some nonlinear function and the process would then be multi-scaling (Gupta and Waymire, 1990).

We plotted $K(q)$ vs. moment q in Figure 4 for two regimes of duration: minute to hourly (sub-hourly) and hourly to daily. For both regimes, linear fittings are found with $\eta_1 = -0.36$ for sub-hourly and $\eta_2 = -0.64$ for the above 1-hr regime. Therefore, the simple scaling process is certainly applicable for this study station.

In some of the previous studies over Vietnam, the extreme value type I: "Gumbel" distribution was used to fit the AMRI (Nhat *et al.,* 2007; Vu *et al.,* 2017). Therefore in this study, we apply the "Gumbel" distribution to fit the AMRI of Bac Ninh rainfall. The CDF of "Gumbel" distribution is represented by the equation:

$$F_d(i)=\exp\left[-\exp\left(-\frac{i-\mu_d}{\sigma_d}\right)\right], \tag{5}$$

where μ_d and σ_d are taken as the Gumbel location and scale parameters (estimated using maximum likelihood approach) of AMRI at sub-daily duration d and can be scaled to daily scale (24 hr) using equations:

$$\begin{aligned}\mu_d&=(d/D)^{-\eta}\mu_D,\\ \sigma_d&=(d/D)^{-\eta}\sigma_D,\end{aligned} \tag{6}$$

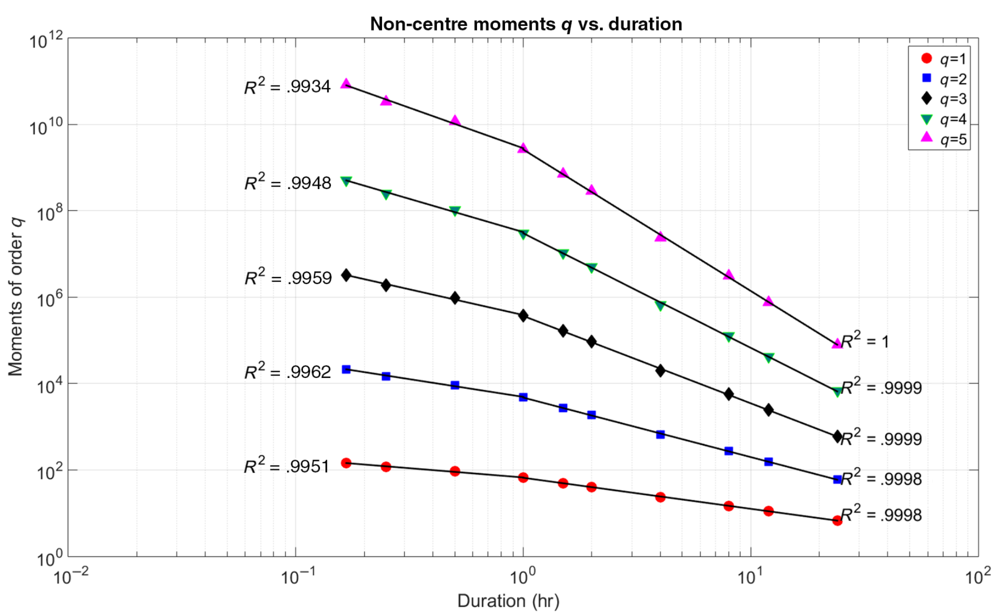

FIGURE 3 Relationship between order of NCM q vs. durations d [Colour figure can be viewed at wileyonlinelibrary.com]

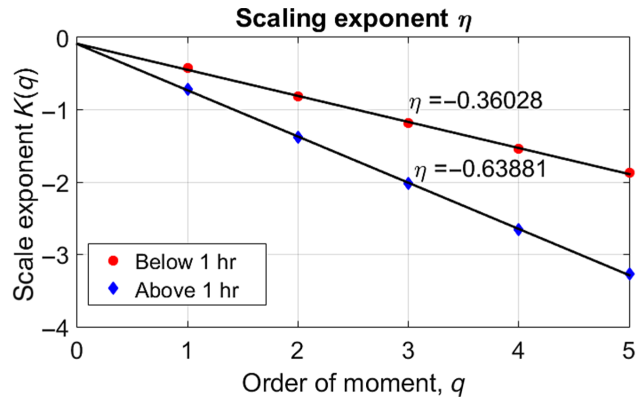

FIGURE 4 Relationship between scale exponent $K(q)$ and order of moment q [Colour figure can be viewed at wileyonlinelibrary.com]

where η is the scaling exponent obtained from the linear slope of the non-centre moment (NCM) of order q as seen in Figure 4. The final formula to calculate the intensity as a function of duration and return period, derived from the Gumbel distribution, is shown in Equation 7 (Menabde *et al.,* 1999):

$$i(d,T)=\frac{\mu-\sigma\ln\{-\ln(1-1/T)\}}{d^{\eta}}, \tag{7}$$

where i is the rainfall intensity (mm/hr) which is a function of duration d and return period T (year). The three parameters μ, σ, η, where $\mu = \mu_{24}{}^{*}24^{\eta}$ and $\sigma = \sigma_{24}{}^{*}24^{\eta}$, are constants, with 24 representing data at duration 24 hour.

From Equation 7, the short-duration extreme rainfall intensity for a certain return period can be calculated from daily rainfall with known μ, σ and the scaling exponent η. Thus, for any duration of sub-daily/sub-hourly scale d, it is possible to calculate the intensity according to a certain return period T as formulated by an Equation 7.

3 | RESULTS AND DISCUSSIONS

3.1 | Simple scaling approach for Bac Ninh station

As the AMRI of Bac Ninh data were collected for 10 different durations (10 min, 15 min, 30 min, 1 hr, 1.5 hr, 2 hr,

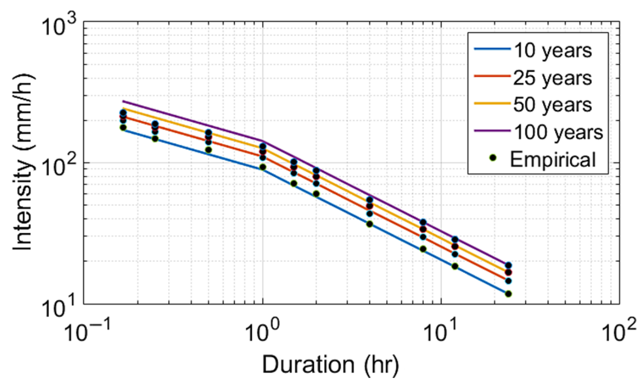

FIGURE 5 Simple scaling log–log-scale IDF curve for Bac Ninh station [Colour figure can be viewed at wileyonlinelibrary.com]

4 hr, 8 hr, 12 hr and 24 hr; Figure 2b) for the baseline period 1986–2005, the scaling behaviour of the annual extreme rainfall series was investigated by calculating the NCM of the extreme rainfall for each duration. Subsequently, examining the log–log plots for these moments against their durations (Figure 3) shows that the relationship between the NCMs and the durations are linear with two different slopes for two different regimes: (a) 10 min–1 hr and (b) 1–24 hr. In addition, the slopes of the straight lines in the log–log plot (Figure 4) are used to find the scaling exponents η in the scaling relationship.

Based on the Equation 7, the IDF curves for Bac Ninh were derived using the Gumbel distribution functions for four return periods (10, 25, 50 and 100 years), with durations ranging from 24 hr to 10 min. These are displayed in Figure 5 in a log–log scale. The empirical values from the station data are plotted as points in Figure 5 to compare against the simple scaling approach (curves). The goodness-of-fit tests used to compare the simple scaling and empirical data are the coefficient of determination (R^2) and the relative anomaly, as in Equation 8

$$\mathrm{Anom}=\frac{\mathrm{Sim}-\mathrm{Obs}}{\mathrm{Obs}}*100\%, \tag{8}$$

where ‘Sim’ refers to RCM simulations and ‘Obs’ refers to observations.

It can be seen from Figure 5 and Table 1 that the simple scaling (curves) are in good agreement against the empirical data sets (points) with high values of the coefficient of determination R^2. The anomalies for return periods of 10 and 25 years are low at around ±5%. Over longer return periods (50 and 100 years), the simple scaling approach overestimates the empirical value for sub-hourly durations by about 9 and 13%, respectively. Overall, the simple scaling using the Gumbel distribution proves itself as a good approach to construct the IDF curves for Bac Ninh from sub-hourly durations to 24 hr at lower return periods though overestimating for higher return periods.

3.2 | Use of RCMs to construct IDF curve for baseline 1986–2005

As described in section 2.3, once the location and scale (μ, σ) parameters of 24-hr duration with the scaling exponents η are known, the IDF curve can be constructed for any return period T. Therefore, the η values were first calculated

TABLE 1 Goodness-of-fit tests: IDF from simple scaling and empirical (1986–2005)

T (years)	R^2	Anomaly (%)
10	.9987	−3.50
25	.9972	4.50
50	.9955	9.29
100	.9936	13.30

based on the NCM approach with order q using 6, 12, 18 and 24-hr AMRI data sets using the model WRF/EC-HAM, WRF/ACCESS and WRF/MIROC AMRI outputs.

Figure 6a1–a3 represents the statistical moments q of these three model realizations and it shows a good scaling for the four sub-daily durations. The corresponding scaling exponents η were then calculated based on the linear slope of the moments order q (Figure 6b1–b3). Among the three scaling exponents, the $\eta = -0.66$ by WRF/ECHAM agrees well with the station data ($\eta = -0.64$) while the other two ($\eta_{ACCESS} = -0.73$, $\eta_{MIROC} = -0.53$) show overestimation and underestimation, respectively. The linear lines that connect the order of moments q in Figure 6a2,b2,c2, conform to the simple scaling methodology by Gupta and Waymire (1990).

Figure 7 shows the baseline IDF curves (1986–2005) for four different return periods $T = 10$, 25, 50 and 100 years, with durations ranging from 1–24 hr and the three scaling exponents for above 1-hr scheme η from Figure 6b. The shaded regions are the maximum–minimum boundaries for the IDF curves constructed using the simple scaling methodology using the three WRF model simulations with their own sets of (μ, σ, η). The dashed black and solid red lines in Figure 7 are the empirical IDF (observed) and the average of the three WRF model simulations using ERA-Interim, respectively. As seen in Figure 7, the IDF curves constructed using the station data and the averaged (ensemble) WRF data are in good agreement with each other, for all four return periods. This is because the location and scale (μ, σ) parameters at 24-hr station data and WRF are also in close agreement. The scaling component η found using station data and the RCM data for both the baseline and future climates are tabulated in Table 2.

As seen in Table 2, the η for above 1-hr regime of both station data and WRF ensemble average for baseline climate is −0.64 which suggests that they all have the same slope. As seen in Figure 4, the of station data of regime 1 and regime 2 are −0.64 and −0.36, respectively. However, because the WRF model's output is 6-hourly, it is

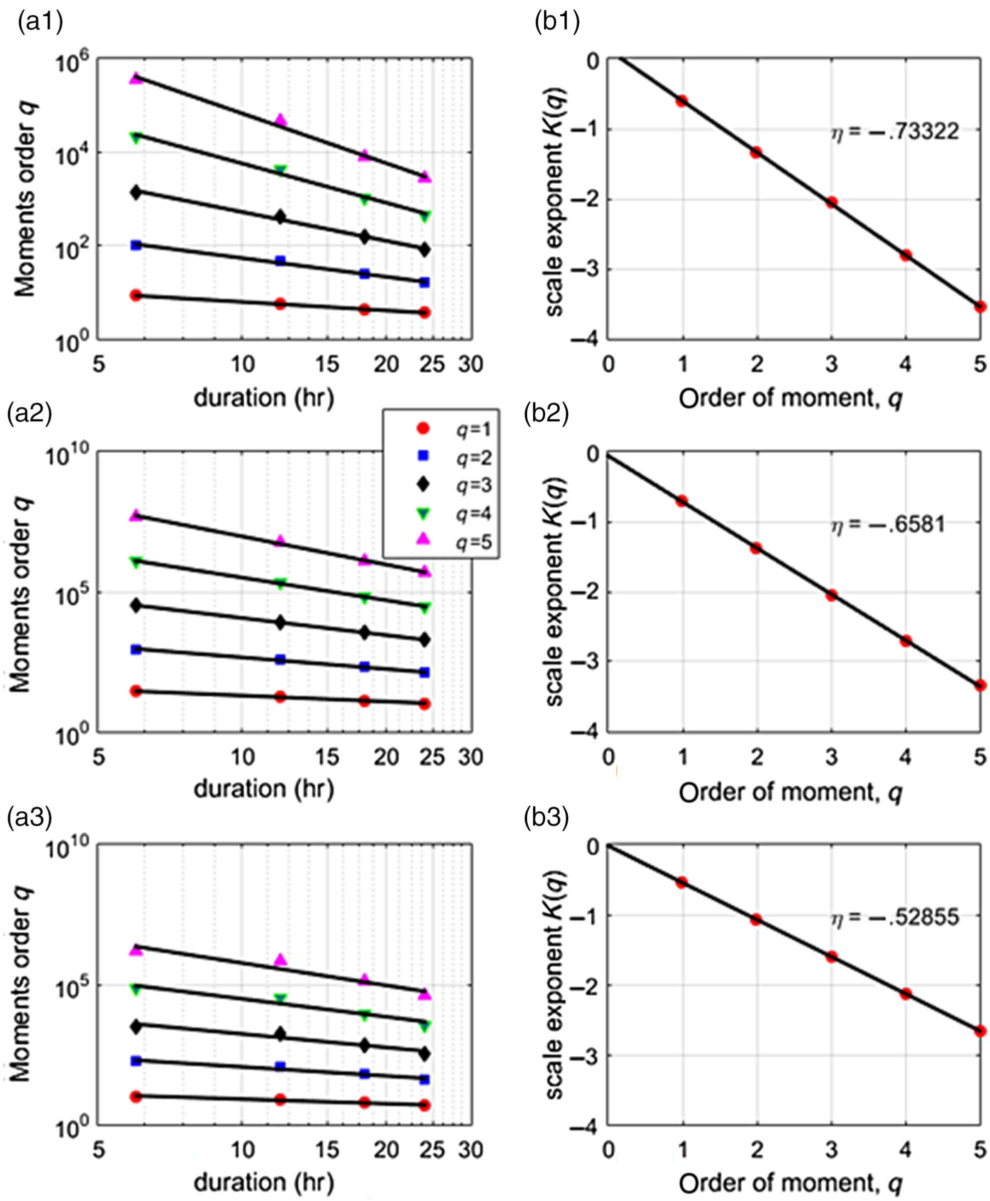

FIGURE 6 WRF simple scaling of (a) moment of q vs. duration d. (b) Scale exponent $K(q)$ vs. moment q (1) WRF/ACCESS, (2) WRF/ECHAM, (3) WRF/MIROC [Colour figure can be viewed at wileyonlinelibrary.com]

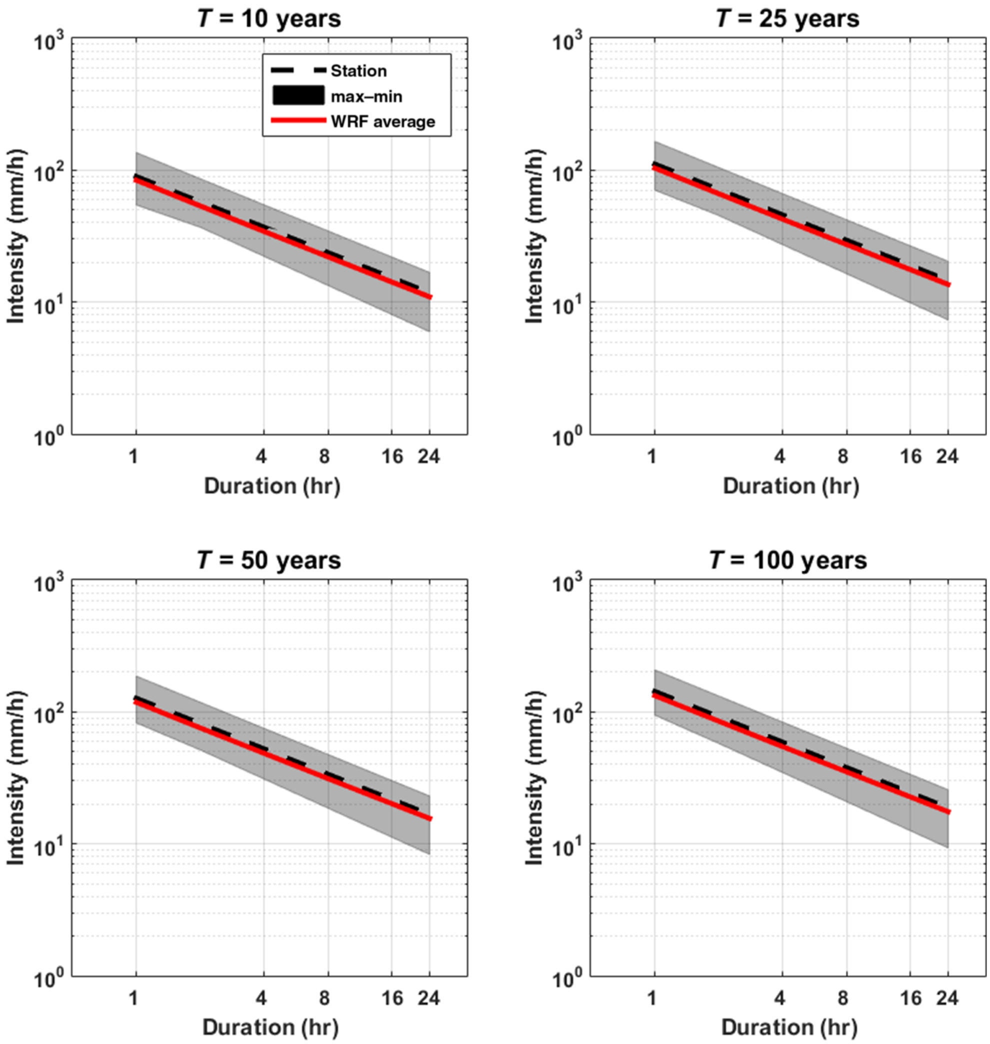

FIGURE 7 Simple scaling log–log-scale IDF curve for Bac Ninh (duration 1–24 hr) using ensemble WRF 1986–2005; return periods (a) 10 years, (b) 25 years, (c) 50 years, (d) 100 years [Colour figure can be viewed at wileyonlinelibrary.com]

impossible to find the for regime 1 as in this case. Given the above constraints with same values for section 2 between the station and WRF average model, we assume that the of regime 1 for the WRF downscaling is the same as that of the station data. Hence, we apply the $\eta = -0.36$ for WRF to construct the IDF curve of regime less than 1 hr. IDF curves constructed for four return periods with durations ranging from 10 min to 24 hr are displayed in Figure 8. The goodness-of-fit tests using the coefficient of determination R^2 and relative anomaly (%) between the averaged WRF data and the empirical point values are shown in Table 3, for baseline climate 1986–2005.

As seen in Figure 8 and Table 3, the empirical points are close to both station and WRF data with a good coefficient of determination ($R^2 \sim 1$) and low biases (relative anomaly $< \pm 5\%$, except for $T = 10$ years return period). This implies that the assumption of the above conditions is correct. The RCM WRF model results have hence been useful to construct the short-duration IDF curves for Bac Ninh for the baseline period. In the next section, we construct the IDF curves for Bac Ninh over the future climate.

3.3 | Construction of the short-duration IDF curves for Bac Ninh in future climate

The location and scale parameters (μ, σ) for 24-hr duration have been calculated for all WRF simulations over the three

TABLE 2 Absolute η values (above 1 hr regime) of section 2 for baseline and future time slices, scenario RCP8.5 and RCP4.5

		2011–2040		2041–2070		2071–2100	
Data\period	**1986–2005**	**RCP8.5**	**RCP4.5**	**RCP8.5**	**RCP4.5**	**RCP8.5**	**RCP4.5**
Station	.64						
ECHAM	.66	.56	.64	.60	.49	.51	.52
ACCESS	.73	.73	.76	.62	.74	.75	.70
MIROC	.53	.64	.71	.82	.68	.65	.70
Average	.64	.64	.70	.68	.64	.64	.64

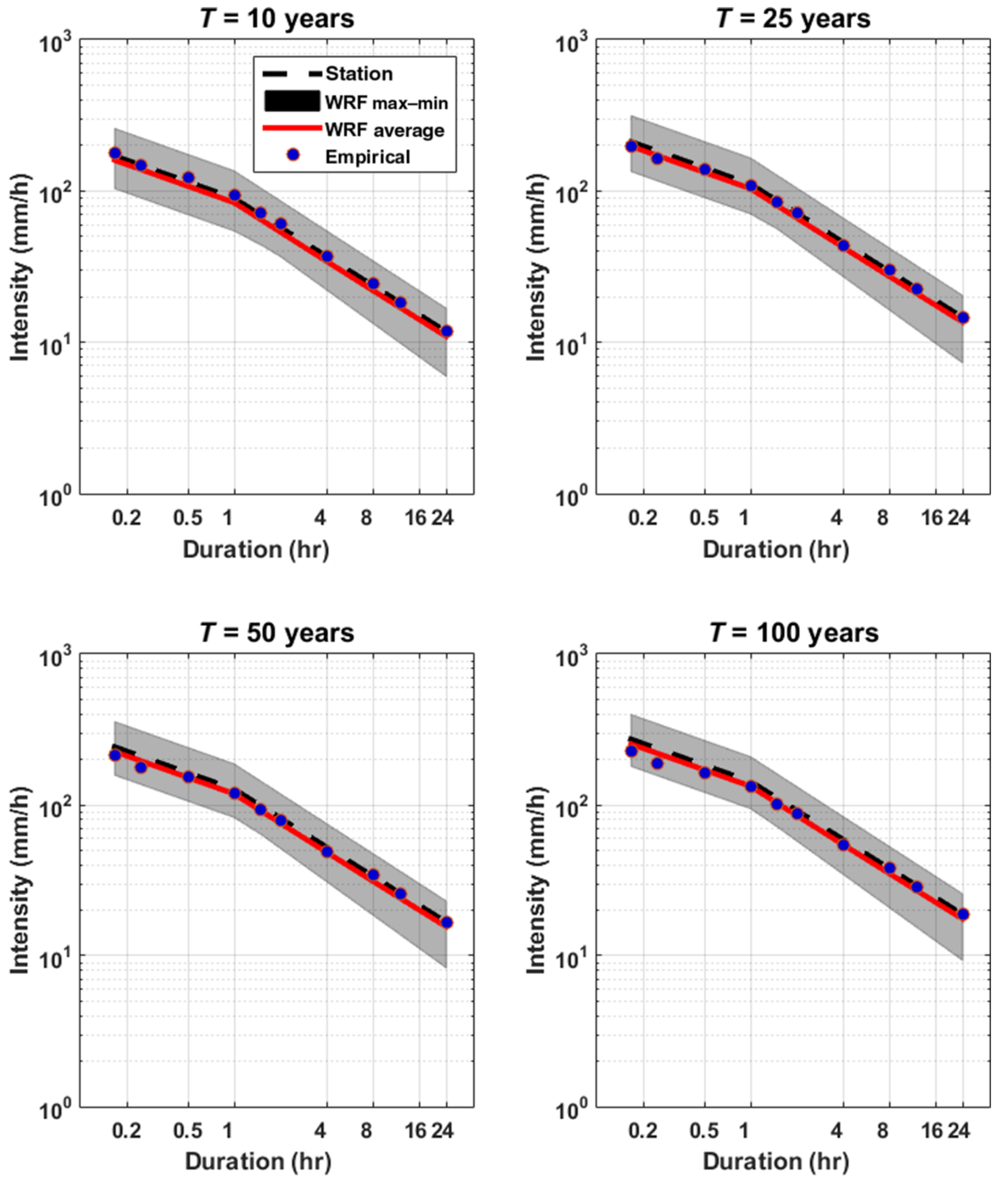

FIGURE 8 Simple scaling log–log-scale IDF curve for Bac Ninh (duration 10 min–24 hr) using ensemble WRF 1986–2005 with assumption of scaling exponent η for section 1; return periods (a) 10 years, (b) 25 years, (c) 50 years, (d) 100 years [Colour figure can be viewed at wileyonlinelibrary.com]

future time slices 2011–2040, 2041–2070 and 2071–2100. Table 2 shows the scaling exponent parameters of all data sets for the baseline and the three time slices in the future. It can be seen that four out of the six average scaling exponent parameter η of the future time slices (of 2011–2040 RCP8.5, 2041–2070 RCP4.5, 2071–2100 RCP4.5 and RCP8.5) are −0.64, similar to the baseline average and station data. The other two (2011–2040 RCP4.5, 2041–2070 RCP8.5) are marginally smaller than −0.64 (−0.70 and −0.68, respectively). It is therefore expected that the scaling exponent parameter η does not vary much over time. What varies are the location and scale parameters (μ, σ) of 24-hr duration, which would raise the magnitude of the IDF curves.

With the above finding, we assume that the scaling exponent parameter η of all future time slices for regime 1 is equal to the station data at −0.36. Hence, we are able to construct the IDF curves for all future time slices for all durations. Figure 9 displays the future IDF curves and maximum–minimum boundary for the three model simulations with two projection scenarios, WRF/ACCESS, WRF/ECHAM and WRF/MIROC, respectively. The average of these three WRF simulations for the baseline 1986–2005 is represented in a black line while the future climate scenarios RCP4.5 and RCP8.5 are marked as red and blue lines, respectively.

The change in the future IDF curves averaged from an ensemble of six scenarios of the WRF model (three GCMs and two scenarios) with respect to baseline period for selected two regimes: (a) 10 min–1 hr and (b) 1–24 hr are tabulated in Table 4. The anomaly is calculated as in Equation 9:

TABLE 3 Goodness-of-fit tests: IDF from simple scaling using WRF and empirical (1986–2005)

T (years)	R^2	Anomaly (%)
10	.9987	−9.77
25	.9972	−2.57
50	.9955	1.70
100	.9935	5.26

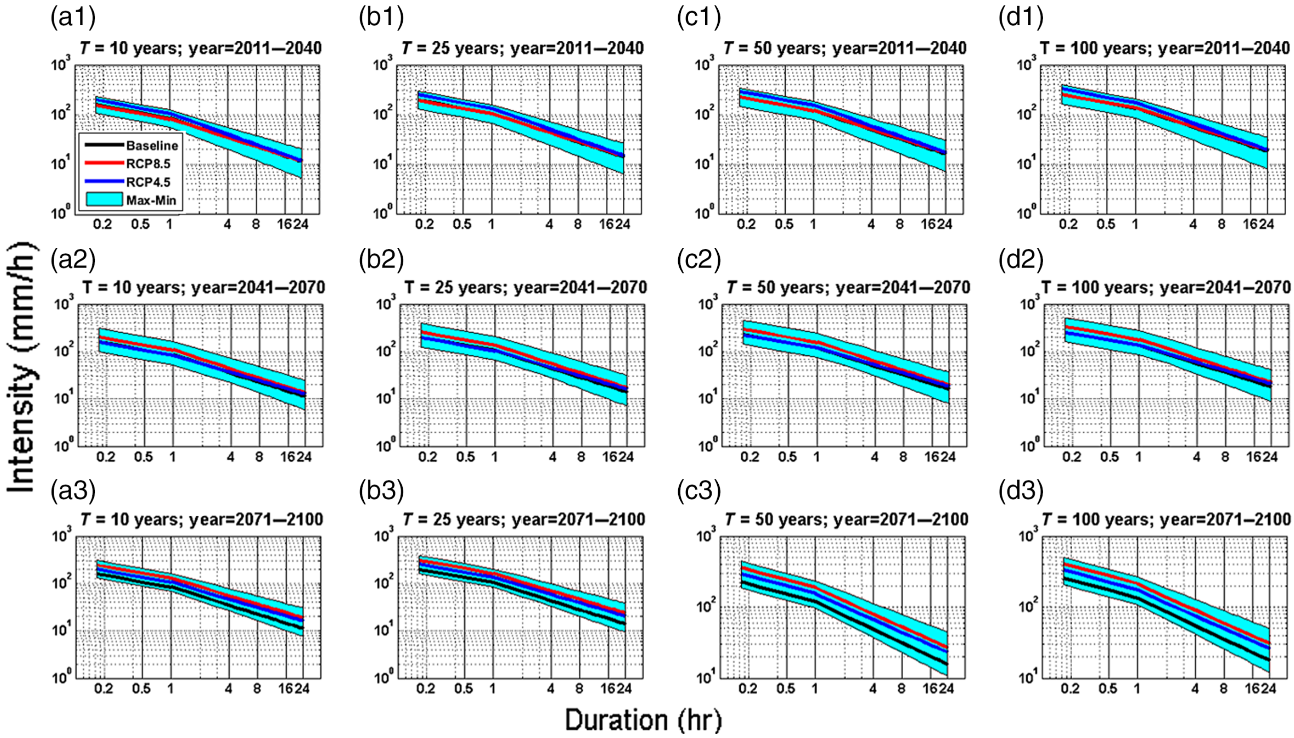

FIGURE 9 Projection of simple scaling log–log-scale IDF curve for Bac Ninh using ensemble WRF: return periods (a) 10 years, (b) 25 years, (c) 50 years, (d) 100 years; (1) 2011–2040, (2) 2041–2070, (3) 2071–2100 [Colour figure can be viewed at wileyonlinelibrary.com]

$$\Delta = \frac{\mathrm{WRF}_{\mathrm{future}} - \mathrm{WRF}_{\mathrm{baseline}}}{\mathrm{WRF}_{\mathrm{baseline}}} * 100\%. \quad (9)$$

As seen in Table 4, the positive anomalies are obtained from the ensembles values for all three periods. At a closer look, it can be seen that there is a steady increase in the averaged IDF curves from the first time slice 2011–2040 to the last, over the chosen four return periods. For example, by 2011–2040, there is an increase of 10–16% of the averaged IDF curve for regime 1 with the return period of 10–100 years. These values are 13–16% for 2041–2070 and by the end of 21st century, the change is 40–45%, respectively. The regime 2 starts with lower anomalies from 3 to 8% for the first period and lasts with a higher increase by the end of the 21st century at 56–61% with a return period of 10–100 years.

For the ensemble IDF projections as displayed in Figure 9, over 2011–2040, the RCP8.5 scenario ensemble does not change largely with respect to the baseline period,

TABLE 4 Relative anomaly (%) of future IDF with respect to baseline period (average among all six ensembles)

		T (years)			
Period	**Duration**	**10**	**25**	**50**	**100**
2011–2040	10 min–1 hr	9.86	12.87	14.45	15.68
	1–24 hr	3.46	5.79	7.00	7.94
2041–2070	10 min–1 hr	12.35	14.32	15.36	16.17
	1–24 hr	16.99	18.71	19.61	20.30
2071–2100	10 min–1 hr	39.62	42.47	43.97	45.13
	1–24 hr	56.52	58.79	59.97	60.89

whilst the RCP4.5 scenario shows a higher increase for regime 1 (Figure 9a1,b1,c1,d1). The second time slice 2041–2070 indicates a reversed trend with a higher increase in the RCP8.5 scenario and a decrease under the RCP4.5 scenario (Figure 9a2,b2,c2,d2). This is in agreement with the premise of the RCP8.5 scenario that technology and GHG gases emission are poised to grow larger during this second period. The last time slice 2071–2100 shows an obvious increase in both scenarios when compared to the baseline 1986–2005, with RCP8.5 increasing higher than RCP4.5, for all return periods (Figure 9a3,b3,c3,d3).

4 | SUMMARY AND CONCLUSIONS

1. In this article, we coupled the dynamical downscaling approach to a statistical simple scaling methodology to construct short-duration IDF curves to assess future climate projections over an industrial area in northern Vietnam. Given location and scale parameters at 24 hr (daily) values, with known (or assumed) scaling exponents, one is able to derive the sub-hourly/sub-daily IDF curves. This approach is useful in applying any available RCM output data to construct short duration IDF curves. Future research might include the use of daily output from statistical downscaling approach (as in Vu, Aribarg, Supratid, Raghavan, and Liong (2016)) to derive the sub-daily and sub-hourly IDF curves. It is also able to apply this methodology to statistical

downscaling of GCMs as in Vu *et al.* (2016) to construct shorter duration IDF curves.

2. We built a statistical simple scaling relationship between sub-hourly/sub-daily AMRI with 24-hr AMRI based on in situ station data. Two regimes were assessed (a) less than 1 hr (regime 1) and (b) above 1 hr (regime 2) with linear scaling. A feasible assumption has been made to use the scaling approach for the regime 1 with scaling factor $\eta = -0.36$.
3. The IDF curves constructed for the baseline period 1986–2005 shows a good match against station data. The projections of IDF curves for the chosen four return periods show that there is a steady increase in the future IDF of rainfall from 2011–2040 until 2071–2100. The RCP8.5 scenario has a higher increasing rate than RCP4.5 both in the mid-century and by the end of the century. The ensemble average increase is 56–61% for the regime 2 and 40–45% for regime 1 by the end of 21st century, for different return periods. These results provide some initial trends of larger rainfall changes to come and possible threats of flooding in the future that requires prudent planning.

It is recommended to use a larger number of model realizations from the latest climate scenarios and using more GCMs to improve the confidence in these findings. As such, these initial findings could still be of use to policy-makers in their preliminary consideration of strategies for adaptation while more work remains to be performed.

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Conflict of interests

The authors declare no potential conflict of interests.

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