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Assessing extreme flood inundation and demographic exposure in climate change using large ensemble climate simulation data in the Lower Chao Phraya River Basin of Thailand

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A R T I C L E I N F O

Keywords:
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A B S T R A C T

Study region: Lower Chao Phraya River Basin (LCPRB), Thailand.
Study focus: This study aims to make a robust assessment based on a large ensemble d4PDF dataset and a flood-inundation model Inundation Model Coupling Rainfall-runoff (IMCR) for the LCPRB. Inundation area and depth for 100-year flooding are evaluated for the flood volume of capacity greater than 2000 m^3/s for both past (1951–2010) and future (2051–2100) climates. This study also evaluates the affected population exposure in the region for both past and future climate scenarios.
New hydrological insights for the region: The IMCR inundation simulation findings indicate that compared to the historical climate, the inundation area increases by an average of 1.0–1.4 times, and the critical area (depth >3 m) increases by an average of 1.1–1.3 times. On the other hand, the exposed population in the future, with respect to the SSP5 scenario "Taking the Highway," is expected to decrease on average by 0.7–0.9 times in comparison to the past climate for depth > 0 m. However, keeping the population constant as in the past, the exposed population is likely to increase on average by 1.3–1.4 times in comparison to the past climate for depth > 0 m.

1. Introduction

Over the past few decades, flooding and climate change have had a considerable impact on Thailand. Several flooding events occurred in 1959, 1964, 1972, 1980, 1983, 1995, 1996, 2002, 2006, 2011, and 2021 (GWP, 2017; Loc et al., 2023), affecting a vast population in the Lower Chao Phraya River Basin (LCPRB) of Thailand. The LCPRB is an important region; a considerable number of people reside here as it is home to a number of significant industries and large agricultural areas, including the capital city, Bangkok. The Chao Phraya River Basin (CPRB) spawns 66 % of the nation's Gross Domestic Product (GDP), out of which the LCPRB generates 78.2 % of the CPRB's GDP (GWP, 2017).

The profound effect of impacts on hydro-meteorological parameters due to anthropogenically induced climate change plays a crucial role in increasing flood risk in Asian regions (Hu et al., 2019; Try et al., 2020). Furthermore, in populated areas, such as Bangkok, urbanization also significantly contributes to increased flood risk since cities with dense populations are typically located in low-lying terrains and thus are particularly susceptible to flooding (Amnuaylojaroen and Chanvichit, 2019; Abhishek et al., 2021). Numerous flood models have, therefore, been developed to identify exposed, vulnerable flood areas and possible water depths (Luo

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et al., 2018; Pinos and Timbe, 2019; Eccles et al., 2021; Padulano et al., 2021; Nandi and Reddy, 2022). Emerging evidence shows that climate change is likely raising the likelihood of high rainfall events and catastrophic flood occurrences around the globe, particularly in Southeast Asia (Ajjur and Al-Ghamdi, 2022; Huang and Swain, 2022; Padiyedath Gopalan et al., 2022). The catastrophic flood

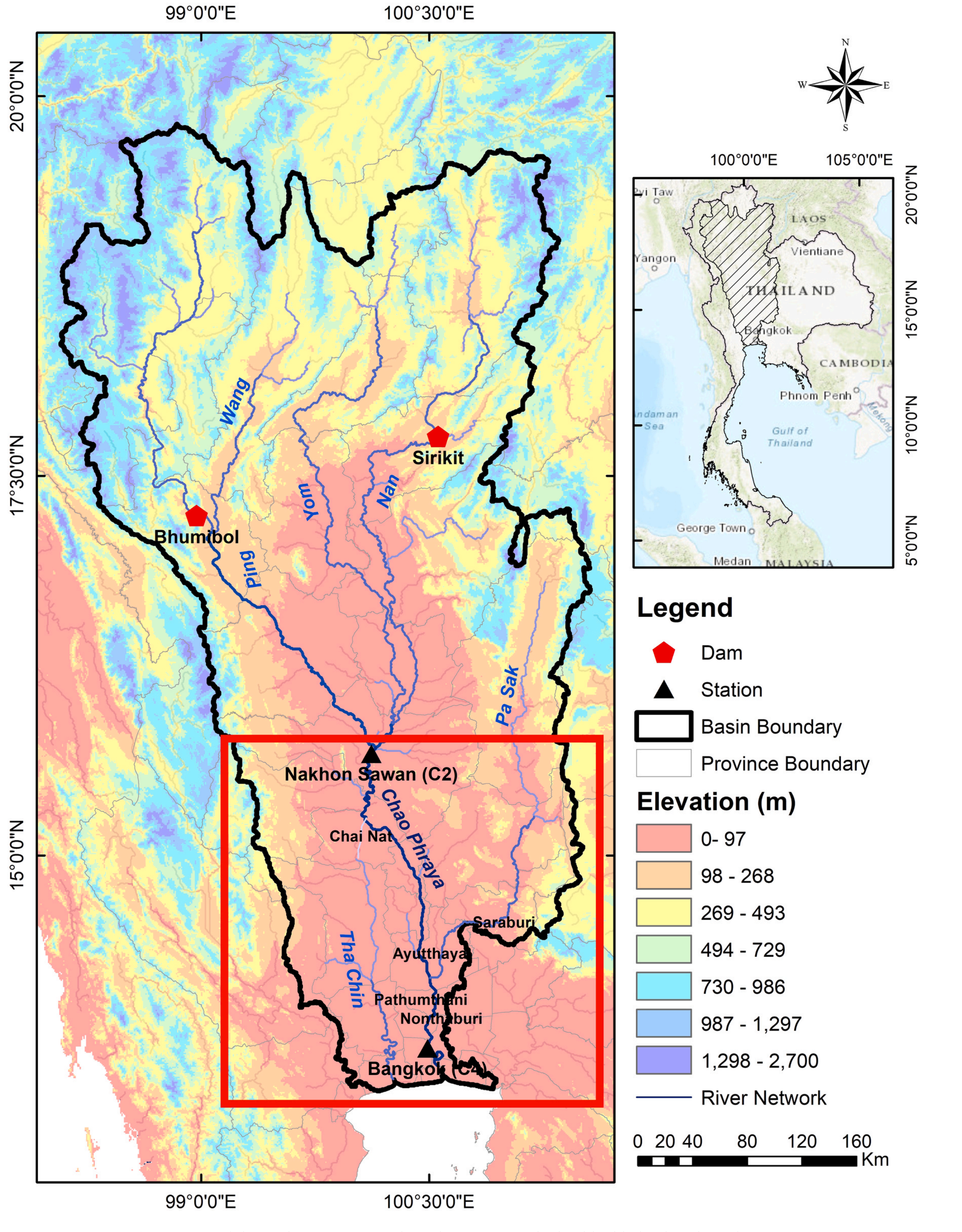

Fig. 1. Map of the study area (Lower Chao Phraya Basin, Thailand highlighted in the red square).

events coupled with climate change are projected to pose severe damage in Southeast Asia compared to the global average (Padiyedath Gopalan et al., 2022). Therefore, it is highly essential to provide a robust future projection of the resulting inundation propagation as well as exposure as a result of climate change to assist regional flood risk management.

A number of studies have studied the CPRB from a hydrological and hydrodynamic perspective (Padiyedath Gopalan et al., 2022; Sriariyawat et al., 2022; Yang et al., 2023). However, its translation into future projections under the combined impact of climate and urban changes is less studied (Miller and Hutchins, 2017; Sebastian et al., 2019). Instead, there is a need for flood risk assessment to expand the target to population or gross domestic product (GDP) at a global scale (Arnell and Gosling, 2016; Dottori et al., 2018) as well as at a regional scale (Tanoue et al., 2020). As the next step, future projections of extreme floods and their translation into flood extent and demographic exposure are essential to supporting regional decision-making.

Regional climate change studies for extreme floods are now supported by a large ensemble approach (Mitchell et al., 2017; Tanaka et al., 2020; Yang et al., 2018). A high-resolution multi-ensemble database called the "Database for Policy Decision-making for Future Climate Change" (d4PDF) (Mizuta et al., 2017) is one of the major products available at a global scale (see its comprehensive review in Ishii and Mori, 2020). The application of large ensemble climate simulation results from d4PDF datasets to generate past and future ensemble flood risk has been widely used in various regions (Tanaka et al., 2018; Try et al., 2020). To reinforce the impact of climate change on flood magnitude in Thailand, Budhathoki et al. (2022) applied d4PDF to the entire CPRB with a robust bias correction by multi-site correction and found that all flood characteristics (peak, volume, starting month, and duration) will be more severe in the 4-degree rise climate scenario at the Nakong Sawan station (C2), a pivotal reference station in the basin.

On these backgrounds, to assess a probabilistic flood inundation with respect to the impact of climate and demographic changes, this study simulates the flood inundation and populations exposed to extreme flood events in the past and in the future. It utilizes the large ensemble of d4PDF dataset from past and future population data for the LCPRB. This is to identify if climate change has a significant impact on the likelihood of "less frequent but high-consequence" flood disasters and if the impact assessment is affected by future population change. By integrating the d4PDF dataset into the impact assessment models, it is feasible to estimate water-related hazards with return periods of thousands of years in any geographical location (Ishii and Mori, 2020). Specifically, the future projection of inundation extent and population exposure under flood depths higher than 0.45 m and 3 m are also undertaken in this study as typical and critical levels, respectively, accounting for the future population change. Compiling knowledge of the combined impact of climatic and social changes on affected populations will help understand the expected future flood risk in rapidly developed urban cities in general.

2. Materials and methods

2.1. Study area

The Chao Phraya River, also named the "River of Kings", is the prime and largest river in Thailand, formed by the convergence of four major rivers (Yom, Wang, Nam, and Ping) in the uplands of northern Thailand. After the confluence of these four tributaries forming the Chao Phraya River at Nakhon Sawan lies the LCPRB (Bidorn et al., 2021) as shown in Fig. 1. The LCPRB covers an area of approximately 50,000 km^2 with crisscross river branches forming a flat river delta. The quantity of water in the river varies dramatically with the seasons, with a tenfold variation between the dry (January to May) and wet (June to December) seasons. Its low-lying elevation is one of the major reasons for numerous flooding events in the basin (Abhishek et al., 2021).

River flooding is useful for rice cultivation; however, some downstream cultivation areas are affected when the discharge at the C2 station exceeds 2000 m^3/s. A large increase in the discharge of more than 3500 m^3/s will dramatically increase the flood risk, resulting in extensive inundation areas and massive financial damage in the LCPRB reaches. The peak river discharge at the C2 station outreached 3500 m^3/s in some years, such as 2006 (5960 m^3/s), and 2011 (4686 m^3/s) which caused extensive damage in the basin (Jamrussri and Toda, 2017). The discharge at the C2 station is crucial for decision-making on the flood control and watershed management of the LCPRB.

The Great 2011 Thailand flood is known to be the world's third-most expensive catastrophe to date. The aberrant rainfall pattern in 2011 was the highest in the country's 60-year precipitation record, and the overall sediment transport during the flood was approximately six times more than the typical sediment discharge (Bidorn et al., 2015; Gale and Saunders, 2013). When the two major dams (Bhumibol and Sirikit) reached their full capacity, the surplus water was released towards the south of the Chao Phraya River. This resulted in an escalated spread of floodwater over the Chao Phraya delta plain, rupturing 10 major flood control gates. The C2 acts as a constricting yet key station, collecting water from upstream channels Ping and Nan and diverging into other tributaries, losing water to the delta (Loc et al., 2020). The Ayuthaya region withstood the floodwaters for several weeks until October 11, 2011, eventually flooding the region with flood depths of more than 2 m, which lasted for several months later (Meesuk et al., 2017). Furthermore, the King's Dyke, which is meant to defend northern Bangkok, was constructed largely to manage low-level floods instead of uncommon but high-level floods. In 2011, the King's Dyke was broken in two places, causing large damage to the nearby vicinities (Marks and Elinoff, 2020).

Similarly, several other factors contribute to this level of a disastrous and costly flood event. Higher river flow due to continuous heavy rainfall for a prolonged duration is one of the prime reasons. The other factor is topology, which comprises a gentle slope downstream and a high volume of water passing through the bottlenecked river system. It led to a large volume of water upstream, which broke the control structures, making the downstream unable to handle it (Komori et al., 2012). To make problems worse, non-structural solutions such as the quantity and size of retention ponds were insufficient to hold the waters, along with inadequate landuse restrictions in the Bangkok Metropolitan Region (BMR).

2.2. Flood-inundation model IMCR

For inundation simulations in the study, the Inundation Model Coupling Rainfall-runoff model (IMCR) is used (Fig. 2). It is a two-dimensional flood model to analyze the inundation depth and area. This model is constructed based on the river flow and flood flow models for the LCPRB. The one-dimensional channel flow is used to compute the grid of the river section, and the two-dimensional floodplain flow is used to compute the grid of the flood section. Both river and floodplain flows are governed by the local inertial equations, whose momentum and continuity equations for the two-dimensional case are shown below:

X-direction momentum equation

$$\frac{\partial q_x}{\partial t} + gh \quad \frac{\partial (h+z)}{\partial x} + \frac{gn^2|q_x|q_x}{h^{7/3}} = 0 \tag{1}$$

Y-direction momentum equation

$$\frac{\partial q_y}{\partial t} + gh \quad \frac{\partial (h+z)}{\partial y} + \frac{gn^2|q_y|q_y}{h^{7/3}} = 0 \tag{2}$$

Continuity equation

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = q_0 \tag{3}$$

Where q_x , $q_y$are the unit discharges in the x-direction and y-direction respectively, h is the water depth, z is the riverbed elevation, g is the gravity acceleration, x is the flow path distance, and t is the time.

2.3. Data

2.3.1. d4PDF dataset

The National Institute of Environmental Study, the Atmosphere and Ocean Research Institute of the University of Tokyo, the Disaster Prevention Research Institute of Kyoto University, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), and the University of Tsukuba collaborated together to create the d4PDF dataset (https://search.diasjp.net/en/dataset/d4PDF_RCM_3D_Plev). It is provided under several fixed climate change levels with an atmospheric General Circulation Model (GCM) MRI-AGCM 3.2 s. The past climate comprises 100 ensembles of 60-year simulations from 1951 to 2010 (6000-year data); the + 4 K experiment has 90 ensemble members of 60-year simulations from 2051 to 2100 with a fixed climate change level of the global mean temperature by 4 degrees warmer (5,400-year data) consisting of 15 sets of oceanic perturbations with 6 representative spatial patterns of sea surface temperature (SST) projections. Since MRI-AGCM 3.2 s is an atmospheric GCM, future SST is provided by six atmospheric-ocean coupled GCMs noted as CC, GF, HA, MI, MP, and MR from their names (country): CCSM4 (USA), GFDL CM3 (USA), HadGEM2-AO (Korea), MIROC5 (Japan), MPI-ESM-MR (Germany), and MRI-CGCM3 (Japan), respectively (Mizuta et al., 2017). The climate data was not generated stochastically but simulated using physically based climate models (GCM). This dataset has been widely used in Thailand and nearby regions (Budhathoki et al., 2022; Try et al., 2020).

2.3.2. Topography data

Topography data for the 1-D river flow simulation is provided based on local surveying data from Sayama et al. (2015) for the IMCR inundation model. Two-dimensional elevation data in the study region is obtained from the Multi-Error-Removed Improved-Terrain Digital Elevation Model (MERIT DEM) by Yamazaki et al. (2017) and up-scaled from the original 30 arc-seconds (~ 90 m) to 60 arc-seconds (~ 2 km). Manning's Roughness coefficient in the rivers and floodplains is set to 0.05 $m^{-1/3}s$. These data are used for 2011 model validation as well as for d4PDF past and future climate.

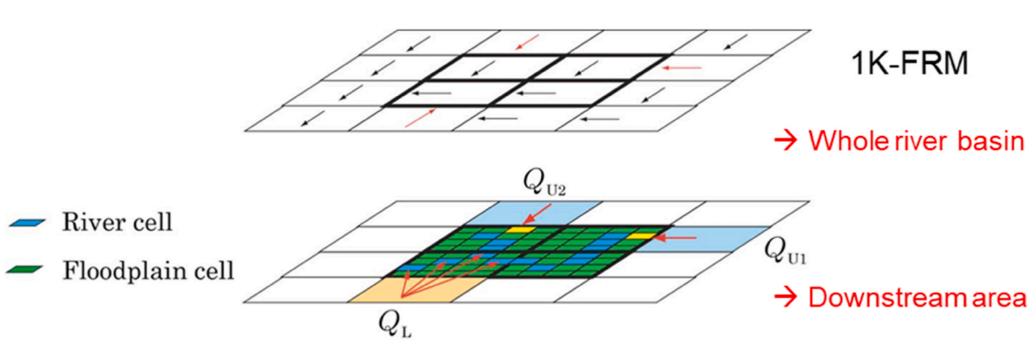

Fig. 2. Inundation Model Coupling Rainfall-runoff model (IMCR).

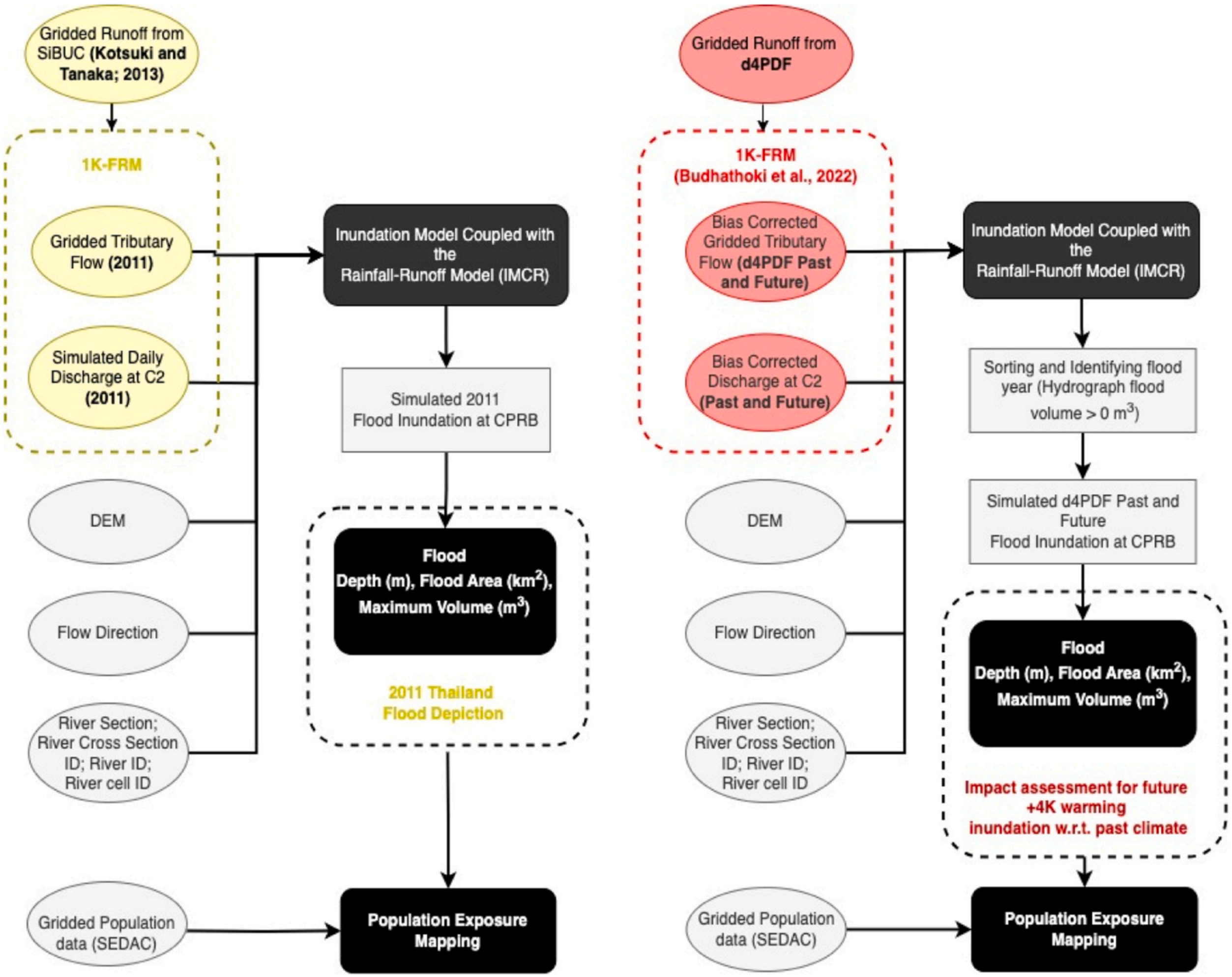

Fig. 3. The overall methodological framework opted in the LCPRB (a) 2011 Thailand Flood for model validation and (b) d4PDF past and future climate.

2.3.3. Population exposure data

This study also requires population data to analyze past and future population exposure in the LCPRB. However, the governmental population data is not publicly available (Tierolf et al., 2021), including the future projections of these data in many Southeast Asian countries. Therefore, as a widely available dataset, the Gridded Population of the World (GPW) from the Socioeconomic Data and Applications Center (SEDAC) at 30 arc-seconds (~ 1-km) resolution (https://sedac.ciesin.columbia.edu/data/collection/gpw-v4) is employed in this study. For the 2011 and past climate cases, the data for the year 2010 is utilized as the population estimates are available for 5 target years: 2000, 2005, 2010, 2015, and 2020 in GPW version 4.

The dataset further includes future gridded projections of the population based on the Shared Socioeconomic Pathways (SSP) scenarios. These projections are calculated based on the parameterized gravity-based downscaling model to generate spatial population change projections that are quantitatively consistent with SSP national population and urbanization projections and qualitatively consistent with SSP narrative assumptions about spatial development patterns (Jones and O'Neill, 2016, Gao, 2017). For future predictions, thedata for SSP 5 for the year 2100 is used because the + 4 K increase scenario corresponds to RCP 8.5 towards the end of the century.

2.4. Experimental design

This study constructs a flood inundation model and examines the flood simulation for the past and future climates in the LCPRB. The experimental design is shown in Fig. 3. First, the model is simulated for the 2011 flood as shown in Fig. 3(a), as validation with the actual case. After the model validation, a climate change impact assessment is carried out for the d4PDF past and future climates, as shown in Fig. 3(b).

2.4.1. Model validation

The 2011 flood is selected for model validation in the study because it is regarded as the highest to date in terms of flood damage, and following it, the basin still lacks significant hydrological and hydrodynamical infrastructures that are in practice. For the validation of the 2011 flood, first, the gridded runoff data simulated using a land surface model SiBUC forced by the observed precipitation in the CPRB was obtained from Kotsuki and Tanaka (2013). This is then used as an input to the 1 K-FRM, a 1-km resolution flow routing model (https://hywr.kuciv.kyoto-u.ac.jp/products/1K-DHM/1K-DHM.html) to obtain gridded tributary discharge and daily river discharge at C2 station, which are used as the input to the IMCR model. The 1 K-FRM model setup is the same as Budhathoki et al. (2022).

As can be seen from Fig. 2, the gridded resolution in the IMCR model is smaller than in the 1 K-FRM model – 2 km and 10 km, respectively, in this case. Therefore, the inundation model must process the 10 km 1 K-FRM data results into 2 km data as an input. Such a coupling of the river routing model to the inundation model is facilitated based on Tanaka et al. (2019). After the simulation of the IMCR model, different indices such as flood depth, flood area, and maximum volume are calculated for 2011. The flood/inundation area is the maximum area submerged (flood depth > 0 m) during a flood event, whereas the maximum volume is the total volume of the maximum depth multiplied by the area of each grid cell. The simulated flood area is validated with the data from the Thailand Flood Monitoring System (TFMS) (https://flood.gistda.or.th/) provided by Geo-Informatics and Space Technology Development (GISTDA).

2.4.2. d4PDF past and future climate simulation

For past and future climate simulations, the d4PDF runoff data is used as the input to the 1 K-FRM model. The d4PDF runoff is simulated using the SiB land surface model (Hirai et al., 2007). Like the model validation simulations, the 1k-FRM outputs simulated daily discharge at the C2 station and gridded tributary river discharge, which are then used as inputs to IMCR.

The simulated daily river discharge is bias corrected to use as a boundary condition for the IMCR model. The bias correction method is the quantile-quantile mapping technique and also considers the spatial structure of river discharge bias (Budhathoki et al., 2022). Another boundary condition to the IMCR model is the lateral tributary flows along the target river lines. Since the simulated tributary discharge from 1 K-FRM is based on d4PDF gridded runoff data, it is assumed to overestimate actual lateral inflow similar to the C2 station. Hence, the same bias correction to the simulated lateral tributary flow is applied (i.e., the same bias correction factor to daily river discharge as that at the C2 station). The lower boundary condition is given as a steady flow condition.

To reduce the computational burden of 2-dimensional inundation simulations by IMCR, this study identified flood years when the annual maximum river discharge at the C2 station is over 2000 m^3/s above which some downstream is flooded (Komori et al., 2012) using these river discharge products (Budhathoki et al., 2022). As a result, 2700 flood years out of 6000 years of past climate and 405 flood years out of 900 years in the SST ensemble GCM for the future + 4 K rise experiment are simulated. Similar to the 2011 flood, flood depth, flood area, and maximum volume for past and future d4PDF are analyzed.

2.4.3. Population exposure mapping

Thailand's 2011 flood presents comprehensive examples of how water resources may materialize in a complicated matter of geography, culture, and political management through flood catastrophes. With the continuous flooding occurring in Thailand, it saw its worst floods in more than half a century. The inundation information, thus overlaying the population information in the basin, is crucial for the evaluation of flood risks. Such assessments are highly needed to avoid any impulsive decisions, considering the demographic situation (Smith et al., 2019). Therefore, to understand the effects on the population, this study investigates the exposed population to the 2011 Great Thailand flood. The translation of inundation depths to population exposure is based on the gridded

SEDAC population data. Similarly, both the past and future climate simulations are translated into population exposure for different inundation depths for flood risk assessment, considering the SSP 5 (Fossil-fueled development) scenario for the years 2010 and 2100, respectively.

3. Results and discussion

3.1. Model validation with the 2011 inundation simulation

The spatial distribution of the maximum inundation depth simulated using IMCR and the validation of the 2011 flood area with the flood map from TFMS is shown in Fig. 4. The maximum inundation area for the 2011 simulation is 11,256 km^2. The inundation area is well represented, including the King's dyke in the basin, where large populations are settled. Fig. 4 also shows that the inundation extent is fairly simulated in comparison to the remote sensing data and the results shown in the hydrological sensitivity analysis of CPRB based on the RRI model evaluated by (Sayama et al., 2017).

The 2011 flood event in Thailand is considered to be as once in a 70–100-year flood event according to several studies (Budhathoki et al., 2022; The World Bank, 2012). Therefore, a comparison of the d4PDF past and future climate simulations for 100-year events is evaluated in this study. The capital of Thailand, the Bangkok metropolitan region, is protected by King's Dyke (shown in yellow box) to protect from river flooding, and in this study, no flooding in the region (a whole area in the lower floodplain in Fig. 4) is observed. This indicates that the IMCR implemented with the MERIT-DEM is a good representation of this reality. Similar results is also shown in other studies (Komori et al., 2012; Loc et al., 2023) for the 2011 case. The simulation accurately depicts the overall scope of the flooding, particularly towards the southern part of Nakhon Sawan. The flooding in the Saraburi and Ayutthaya regions (southern and central part, respectively) are significantly valuable regions, especially in terms of agriculture and industries, which is also well depicted in this study.

3.2. Past and future d4PDF inundation simulation

3.2.1. Comparison of inundation area and maximum volume based on return period

As explained earlier, from simulated discharge at the C2 station, the flood years (2700 for the past and 405 for each future GCM) are

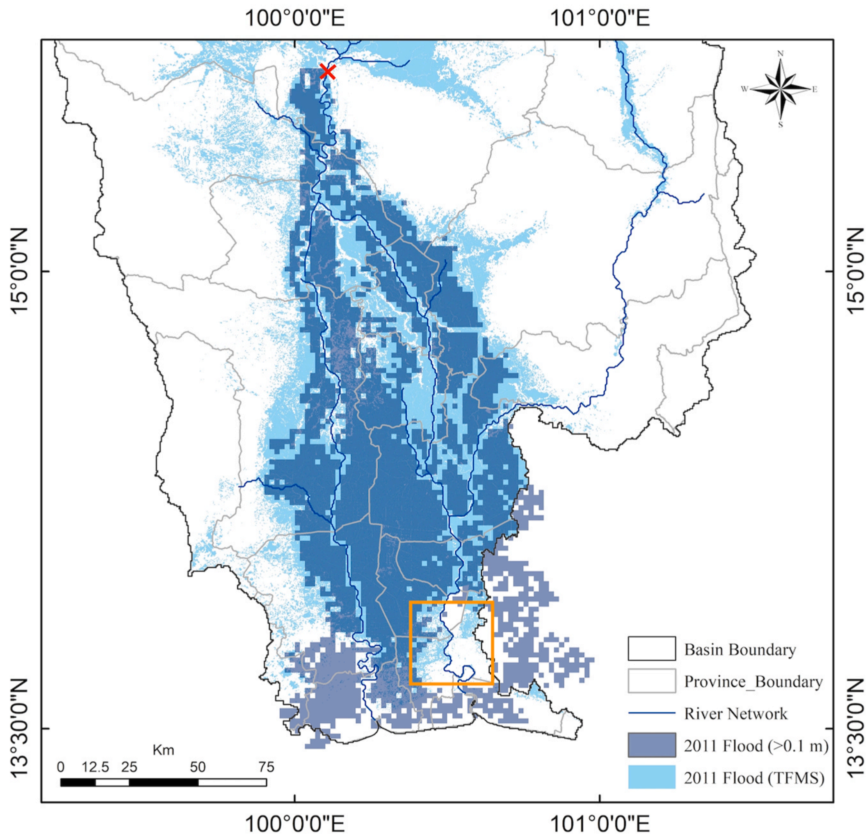

Fig. 4. Simulated maximum inundation depth for the 2011 flood overlaid with the Thailand Flood Monitoring System flood area for 2011 for the LCPRB. The red cross represents the C2 station and yellow box represents the King's Dyke in the LCPRB.

selected as sufficient coverage for representation. Fig. 5(a) and (b) show the past and future d4PDF comparison for inundation area and maximum volume for the past and future flood years based on different return periods.

All the future SST ensembles show that for a 100-year return period, there is an increase in inundation area and maximum volume compared to the past climate experiment (Fig. 5(a) and (b)) with a certain spread by different scenarios of the future SST. Although the member MI shows the smallest increase and a similar trend to the past climate, most ensembles show a significant increase in the probability distribution. The results of inundation simulation (IMCR) are also corresponding with the river-routing simulation (1 K-FRM) discharge as in the study undertaken by Budhathoki et al. (2022).

The most affected area across the basin depicted an inundation depth of 2.1–4 m for a return period of 50 years, while the most affected area across the basin for the return period of 100 and 200-years depicted an inundation depth between 4.1 and 6 m. According to P.C. et al. (2022), most of the LCPRB area, including the industrial park, shows maximum depths of greater than 3 m to be highly critical for disaster preparedness and management. The inundation depth of 0.45 m is assessed in this study based on the discussion among the authors, as greater than this elevation is commonly considered as property loss due to flooding in Japan (Kobayashi et al., 2016).

Therefore, in addition to the inundation area, this study also analyses the 100-year inundation area over 3 m (hereinafter, critical flood area). Table 1 shows the change ratio in inundation parameters for a 100-year event. The results show that the inundation area increases about 1.0–1.4 times and the critical flood area increases about 1.1–1.4 times than the past d4PDF climate. Similarly, the maximum volume increases by 1.1–1.4 times and peak discharge increases by 1.2–1.6 times in the past climate. Even critical flood area shows a similar increasing ratio as the whole flood area, indicating that with the increase of flood magnitude, not only flood area will expand but also flood depth will become deeper, particularly in critical zones.

To analyze the attribution of hydrograph characteristics at C2 station (upstream boundary) to the simulated inundation and its future change, the inundation area and volume from IMCR (inundation simulation) are compared with the peak discharge and hydrograph flood volume (total discharge volume over 2000 m^3/s) at C2 station from 1 K-FRM (river routing simulation) in Fig. 6. The future climate scenario (red) shows a higher magnitude in both peak discharge and flood area or volume compared with the past climate scenario (blue), indicating that future extremes are going to be higher. The gradient for both (a) and (b) of Fig. 6 becomes milder for high peak discharge resulting in a large extent of inundation area and volume for both the past and future. Note that there is not much difference in the relationship between peak discharge and the flood index of the past and future in each figure, indicating that the physical relationship between the climates is kept similar. Similarly, for Fig. 6(c) and (d), the comparisons between inundation area and maximum volume with the hydrograph flood volume (volume greater than 2000 m^3/s discharge capacity) are shown for GF. Both the comparisons correspond to past and future trends keeping the physical properties the same. For all four cases, both flood area and maximum volume of the future climate scenario tend to be at the higher edge in the range of the past climate scenario. It may be due to the same peak discharge (Fig. 6(a) and (b)), but the inundation is likely to be more severe due to other factors such as hydrograph flood volume (and vice versa in Fig. 6(c) and (d)). This indicates that both hydrograph flood volume and peak discharge at the C2 station as a reference station equally contribute to the future increase of downstream flood area and volume. The results are also in line with the other 5 SST ensemble GCMs (CC, HA, MI, MP, and MR) as well and only one representative GCM (GF) is shown in this study.

3.2.2. Inundation maps of 100-year flood of d4PDF past and future simulation

Fig. 7 shows the flood depth map of LCPRB for a 100-year flood based on flood area. The inundation area for the past climate at the 100-year return period is 8,425 km^2. As shown in Fig. 5, for the 6 SST GCMs, the maximum inundation area for a 100-year flood are 11,540 km^2 (CC), 12,080 km^2 (GF), 10,612 km^2 (HA), 8585 km^2 (MI), 11,356 km^2 (MP), and 11,752 km^2 (MR). It is evident from the figures that all the cases for future SST GCMs are higher than the past climate for a 100-year flood. The maximum volume for a 100-

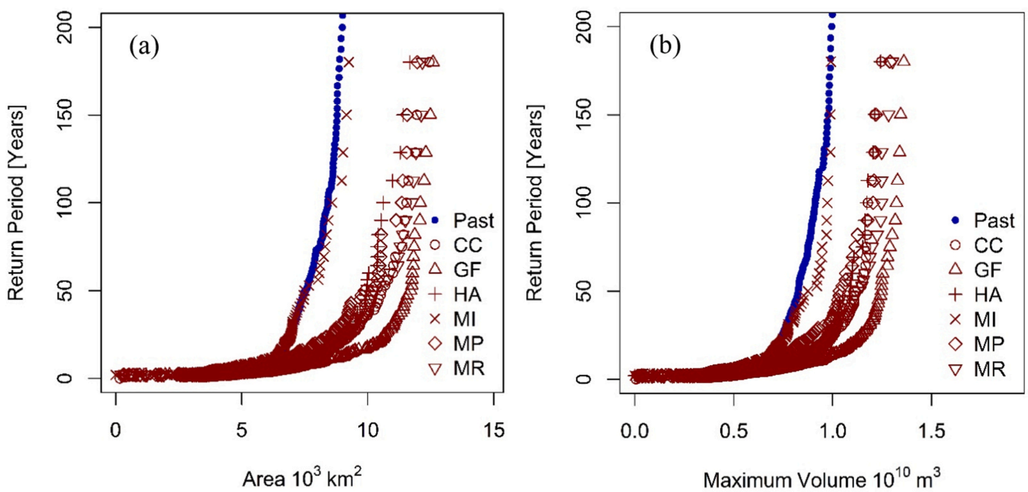

Fig. 5. Comparison between past and future (6 SST GCMs) d4PDF (a) inundation area and (b) inundation maximum volume.

Table 1
The d4PDF past climate inundation area, maximum volume, peak discharge and area (depth >3 m) and its change in ratio respectively for future d4PDF climate 100-year return period floods.

	Past [Unit]	CC	GF	HA	MI	MP	MR
		Change in GCMs with respect to past climate					
Maximum Area	8561 [km^2]	1.3	1.4	1.2	1	1.3	1.4
Maximum Volume	9.2 [Billion m^3]	1.3	1.4	1.3	1.1	1.3	1.3
Peak Discharge	4668 [m^3/s]	1.3	1.6	1.3	1.2	1.3	1.4
Area (Depth >3 m)	576 [km^2]	1.2	1.4	1.3	1.1	1.3	1.3

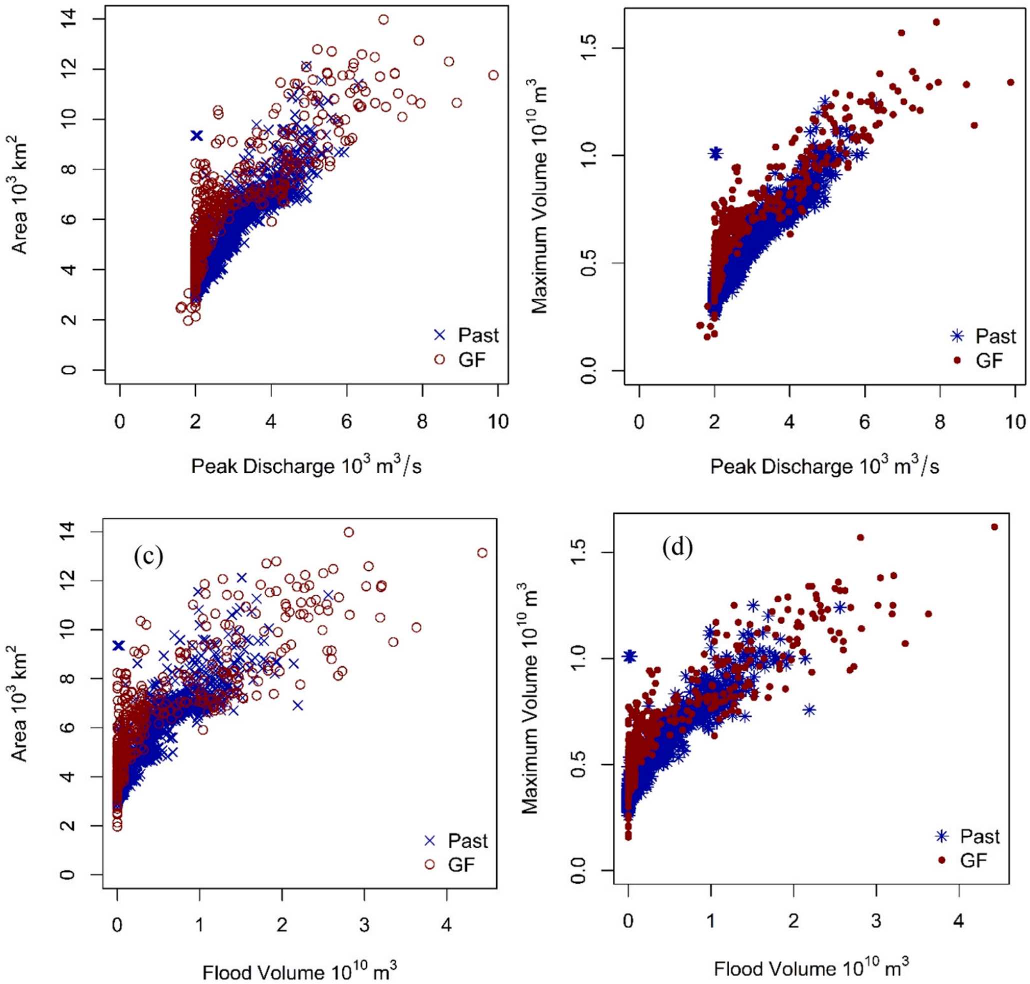

Fig. 6. Comparison plots of peak discharge with inundation (a) area (b) maximum volume and hydrograph flood volume with inundation (c) area and (d) maximum volume for the past and future (GF) climate.

year future flood event are 11.7 billion m^3 (CC), 13.2 billion m^3 (GF), 11.7 billion m^3 (HA), 9.7 billion m^3 (MI), 12.1 billion m^3 (MP), and 12.5 billion m^3 (MR) (Fig. 5). Compared to the area the maximum volumes are likely to increase in the future compared to the past climate for all 6 SST GCMs. Since the 2011 flood was similar to the 70–100-year flood in the LCPRB, there is an urgent need for adaptation and mitigation measures to be implemented in the basin to prepare for severe situations in the future. Additionally, the King's Dyke area, as shown in the Fig. 4 is also protected for the past and future + 4 K warming scenario in all six SST GCMs, as shown in Fig. 7.

The findings of this study are consistent with other regional as well as global research. The analysis of Yang et al. (2023) shows that under the SSP126 scenario (the most sustainable route), the 100-year historical flood with respect to the return period in the Chao Phraya region will rise by 1.6 times, while it will rise by 4.5 times under the SSP370 scenario (the most pessimistic rocky-road pathway). This also validates that extreme d4PDF flooding is likely to be more intensive. It shows that the intensified inundation extent and depth are likely to be affected more if further adaptation and mitigation approaches are not undertaken. Studies in the

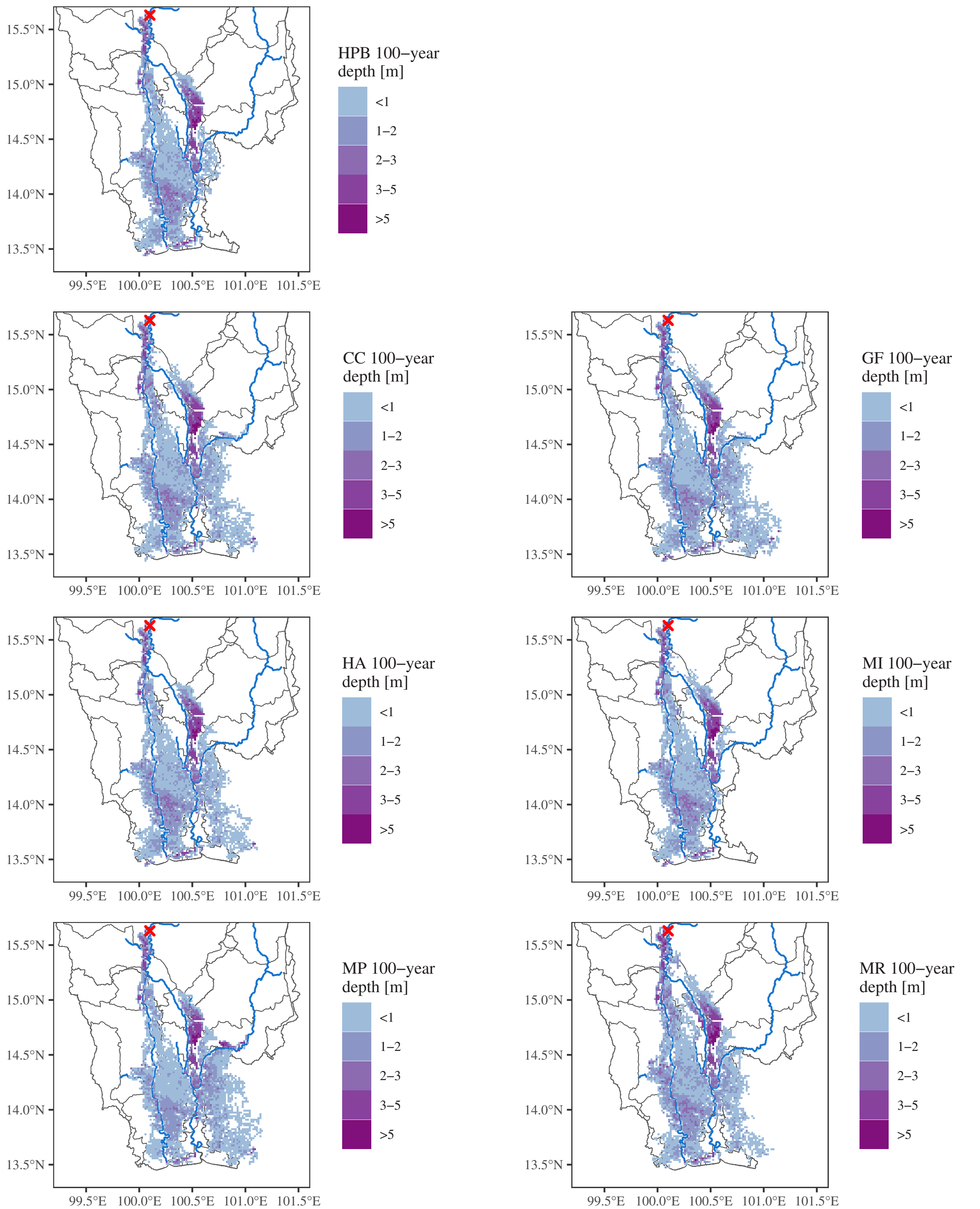

Fig. 7. Flood inundation area and depth simulated from d4PDF data corresponding to the return period of 100-year for flood area for the past (HPB) and 6 future climate SST GCMs (CC, GF, HA, MI, MP, and MR) in the LCPRB. The color bar represents the inundation depth in meters.

future climate change impact assessment of the Chao Phraya flooding under various climate change scenarios for 100-year flooding show the spatial characteristics over the basin that make this region prone to flood risk (Kotsuki et al., 2014; Liew et al., 2016; Yang et al., 2023). Additionally, using three GCMs, MRI-CGCM3, MIROC5, and HadGEM2-ES, for the flood inundation in the Ciliwung River Basin of Indonesia, the inundation area for depth <1.5 m, is likely to increase by 1.2 times, and for depth > than 1.5 m is likely to increase by 1.5 times for 100-year floods in the future (Mishra et al., 2018). Another research in the Hadahe River Basin of China emphasizes that the increase in inundation area is likely to increase with the inundation depth. The results show that the future inundation area for depth between 1.0 and 2.0 m, 2.0–3.0 m and >3 m is projected to increase by 5.4 %, 12.3 % and 22 % for RCP 8.5 in the basin (Zhang et al., 2019). These studies suggest that measures for reduction of emissions are suggested as the effects on the inundation area are more for the RCP 8.5 scenario which is also similar to the +4 K warming scenario, as in this study.

3.3. Population exposure mapping

Fig. 8 shows the population exposure map throughout the LCPRB calculated by overlaying the flood inundation area with the population data for the 2011 flood. The figure indicates that most of the population that surrounds Bangkok towards to lower part of the basin is highly affected. The total population exposed below C2 station is found to be 8,832,743.

Followed by the 2011 population exposure, this study examines the population exposure for the d4PDF past and future 100-year climate flood inundations. Fig. 9 shows the past and 6 future SST ensemble's 100-year population exposure maps. The total population exposed to flood inundation is approximately 5,585,602 for the past climate. The d4PDF past climate shows that Bangkok and its nearby provinces are more highly populated than the upstream region. However, due to the presence of King's Dyke surrounding the Bangkok region, the people in this region are less likely to be affected by river flooding. However, moving toward the Ayutthaya region, where a large industrial, agricultural, as well as residential area lies, the exposed population due to flooding is likely to increase.

Towards the end of the century, based on the projected population, the population exposed is likely to be around 0.6–1.0 times compared to the past climate for different SST ensembles, as shown in Table 2. The exposure maps show intensified flood extent, but the population exposed is slightly less or similar. This may be due to the decrease in population towards the end of the century. The exposed population for future climate remains similar to the past climate in the lower part of the study area (i.e., capital city), where the population is kept higher than upstream of the basin. This study also analyzes the population exposed to flood depths greater than 0.45 m and 3 m. The exposed population is likely to change about 0.6–1.0 times and 0.7–0.8 times for inundation depths greater than 0.45 m and 3 m, respectively, as illustrated in Table 2.

Additionally, this study also looked into the impact on exposed populations in the future keeping the change in population constant. For a 100-year year flood, the change in exposed population in the future is likely to rise by 1.1–1.4 times the past climate exposed population for the case of depth greater than 0 m. In this case, the increasing ratio is constant between area and exposure, and hence, the added inundation area, especially towards the southern part of LCPRB, should be similarly populated. This also states that for the projected population case, the climate change impact may cancel the impact of population exposure due to the decline in population towards 2100. The population growth of the SSP5 scenario for Thailand based on fertility, mortality, migration, and education scenarios (Jones and O'Neill, 2016; Kc and Lutz, 2017) is used as an input in the study. Since Thailand is grouped under "Low fertility

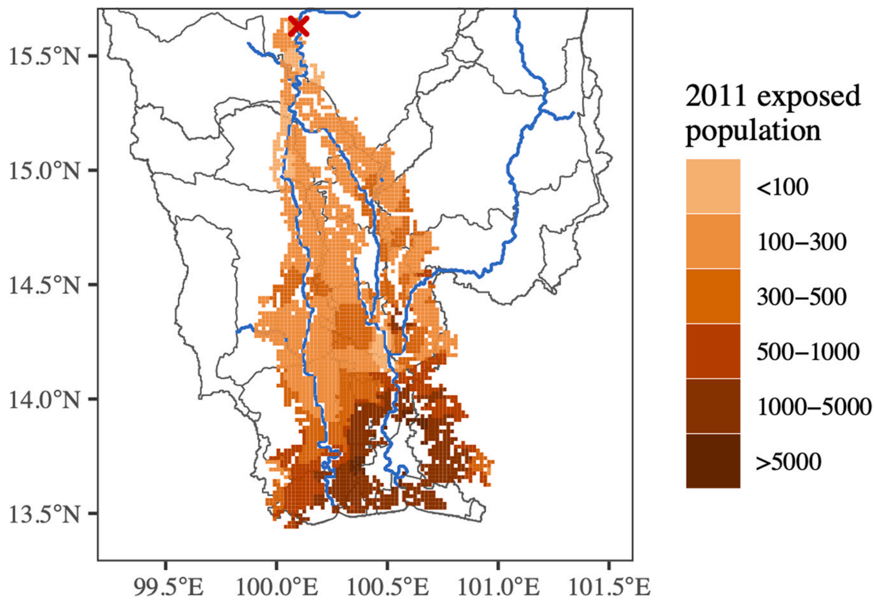

Fig. 8. Population exposure map of 2011 flood in the LCPRB. The color bar represents the number of exposed population.

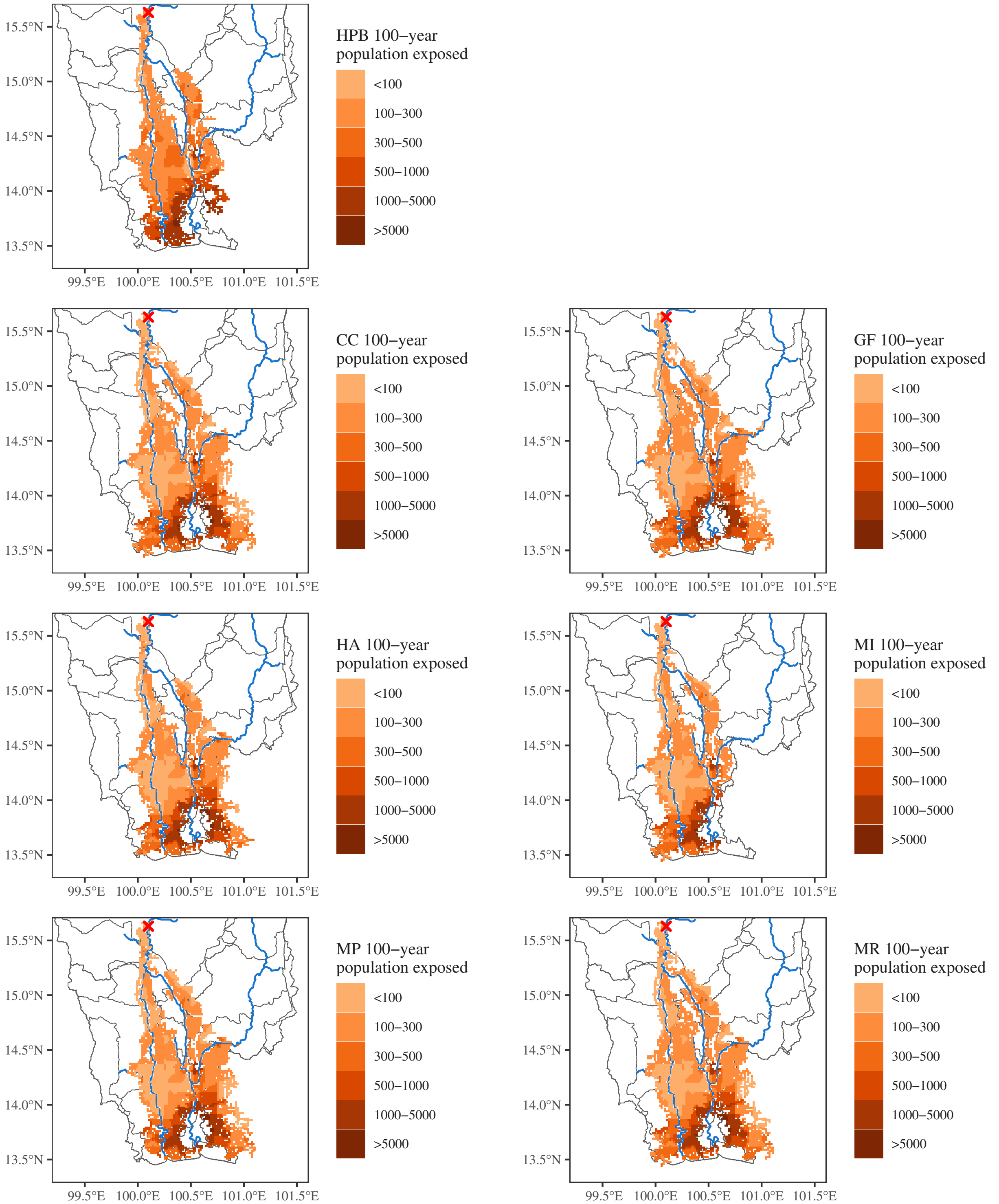

Fig. 9. Population exposure for d4PDF past (HPB) and 6 future climate SST GCMs (CC, GF, HA, MI, MP, and MR) for 100-year flood in the LCPRB. The color bar represents the number of exposed population.

countries" where the population growth rate is expected to be low towards the end of the century, this study also shows a similar rate for the exposed population.

A research carried out for 100-year flood-exposed population under climate change for 14 main catchments around the globe using

Table 2
Exposed population and its change in projected exposed population for depth greater than 0 m, 0.45 m, 3 m; and for constant population with depth greater than 0 m for 6SST GCMs in the future for 100-year flood.

Model	Past	CC	GF	HA	MI	MP	MR
	Nos.	Change in future with respect to past climate					
Population Exposed (Depth > 0 m)	5,585,602	0.9	1.0	0.9	0.6	0.9	1.0
Population Exposed (Depth > 0.45 m)	3,692,536	1.0	1.0	0.9	0.6	0.9	0.9
Population Exposed (Depth > 3 m)	210,326	0.7	0.8	0.8	0.7	0.7	0.8
Population Exposed (Const. Pop. Depth > 0 m)	5,585,602	1.2	1.4	1.3	1.1	1.3	1.3

the SEDAC gridded population data as in our study shows that there is a decrease in the population exposed to flooding in the catchments that contain dams (Boulange et al., 2021). Tierolf et al. (2021) states that in Thailand, after 2040, the population is expected to decrease 11 % resulting in the exposed population to flooding. In contrast, Gu et al. (2020) state that there is increase in extreme flood exposure to population and a decrease in population exposure to moderate floods. There is an increase of 11.6 % and 9.7 % increase in the exposed population with respect to flood magnitude in the SSP5 scenario. The future analyses of risks associated with global floods would also profit from the development of plausible future population projections that consider population behavior in terms of migration, adaptation, movement during warning measures, etc.

4. Conclusion

The Lower Chao Phraya Basin (LCPRB) is the predominant region in Southeast Asian and inhabits a large population. Due to this large opportunity, a lot of people reside in the capital city and its surrounding provinces. This study analyses the 100-year flooding in the basin in terms of flood area and depth with the help of a large ensemble climate simulation dataset d4PDF and flood-inundation simulations, further assessing its impact on the population by combining climate projections with population projections.

The future 100-year flooding for +4 K rise is likely to be more severe in terms of both maximum volume and inundation area compared to the past climate. Approximately, the inundation area and volume in the +4 K scenario are likely to increase at maximum by 1.4 times that in the past climate. The inundation area and depth simulation, thus overlaying them with the demographic data, show the affected number of people in the basin. The exposed population in the future is likely to be 0.6–1.0 times as the past climate. A similar ratio is expected for depths greater than 0.45 m and 3 m. Moreover, the analysis of keeping the population change constant in the future for 100-year flood exposure is likely to increase by 1.3 times on average for depths greater than 0 m, which states that the climate change impact is significant in the basin as is the demographic change. Due to the decrease in projected population towards 2100 years, the climate change impact nullifies with population exposure. The overall analysis of this study suggests that even though overall population exposure will not highly increase due to combined effect of climate change and population decline, more number of people is likely to be exposed if population decrease becomes milder in the future. Therefore, actions are required in terms of structural and non-structural measures for better adaptation and mitigation approaches to support the inhabitants by the respective agencies and ministries.

There is uncertainty in hazard models, which is brought on mainly by an incomplete representation of complicated local drainage networks, which limits evaluations of flood exposure. Population data may also have uncertainty due to the use of a global dataset. The future study can be addressed with more detailed risk assessment, such as economic damage in different sectors such as agriculture and urban buildings, employing local statistical data.

CRediT authorship contribution statement

Tachikawa Yasuto: Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Resources, Software, Supervision, Visualization, Writing – review & editing. **Tanaka Tomohiro:** Conceptualization, Formal analysis, Methodology, Resources, Supervision, Validation, Visualization, Writing – review & editing, Data curation, Investigation, Software. **Budhathoki Aakanchya:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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