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Progress in Earth and Planetary Science (2023) 10:36
https://doi.org/10.1186/s40645-023-00569-9

Progress in Earth and Planetary Science

RESEARCH ARTICLE Open Access

A macroscopic analysis of the demographic impacts of flood inundation in Thailand (2005–2019)

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Abstract

In Thailand, floods are occurring more frequently due to climate change, and recent economic development and population growth may have altered the way in which people interact with floods, including migration to other regions. In this study, we analyzed the relationship between flooding and population distribution across Thailand from 2005 to 2019 to improve measures for minimizing flood damage. We used population distribution point data from 2009 to 2019 produced by Oak Ridge National Laboratory to analyze trends in population movement and distribution, by examining whether population sizes were greater than, less than, or equal to estimated values in regions throughout Thailand. The results suggest that floods in 2011 and 2017 caused temporary migration to areas that were not inundated or to the metropolitan Bangkok area. Flood responses changed after the 2011 floods, which have been described as the worst flood in Thai history. Next, we examined the relationship between the number of regions with lower than estimated population and flood data for the previous year including precipitation, inundated area, and deaths caused by flooding. Inundation area had a significant impact on population decline, with correlation coefficients of 0.426 and 0.501 for the north and northeast, respectively. The number of deaths caused by flooding in a given year also led to a population decline in the following year. However, precipitation did not exhibit the same trend. Therefore, population demographics after floods have shown regional characteristics in recent years, with Thai people shifting from a flood-tolerance lifestyle to a flood-avoidance lifestyle, mainly in local urban areas and the metropolitan Bangkok area.

Keywords Demographics, Flood, Inundation, Thailand

1 Introduction

Floods, and especially large-scale floods, are frequent in Thailand, resulting in considerable property damage, injury, and loss of life. However, as rivers are an important source of water, including for agriculture, local populations have chosen to remain in areas at risk of flooding by developing measures to cope with floods (Phanthuwongpakdee 2016). Traditional flood mitigation measures include the selection of micro elevations, channel excavation, and construction of stilt houses and earthen mounds (Iwaki 2013), all of which recognize the characteristics of floods in Thailand, where many rivers have gentle gradients, water levels rise slowly during flooding, and inundation is not rampant. These characteristics stand in contrast to those of flooding in Japan, for example, where many rivers flow swiftly and heavy rains are frequent, such that the intervals between inundations are short.

Rapid population growth in Thailand since the beginning of the twentieth century has led to the expansion and greater density of urban areas and increased

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socioeconomic development. Extensive road construction, the widening of existing roads, and an increasingly Westernized lifestyle in Thailand have been accompanied by declines in the number of stilt houses and earthen mounds in rural areas (Iwaki 2013). Instead, the government has constructed levees and causeways, reflecting a shift from an emphasis on relatively small-scale control measures that allow local populations to live with floods to larger-scale measures. However, the latter is far from sufficient, as construction has not kept pace with faster-than-anticipated growth and effective planning has been hindered by the country's political turmoil. The Thai government is aware of the disadvantages of these urbanization trends and has recently introduced green infrastructure including water supply in regions requiring flood control (Climate Bonds Initiative 2022). Nong Bon Lake and the Nong Bon Water Sports Center in southeastern Bangkok are an artificial lake and park constructed to prevent autumn floods; similar green infrastructure is already in place in urban areas. In the Chao Phraya Basin, Loc et al. (2020) found that 73.7% of the total flood volume during the 2011 flood was caused by precipitation and 25.3% by river runoff. Park et al. (2021) reported that the Bhumibol Dam and Sirikit Dam, located in the upper part of the basin, are the main resources for sediment absorption. Therefore, the changes in demographics and the government's approach to flood control may lead to significant changes in the way in which Thai people deal with floods and their choice of where to live. Through the analysis of global examples of disasters such as nuclear accidents, forest fires, and heat waves, Karácsonyi and Taylor (2021) concluded that seven factors explain the complex and diverse links between populations and disasters: population impacts, vulnerability, mass relocation, spatial and regional approaches, climate change, urbanization, and response methods.

Bangladesh provides an example of a country-specific relationship between population dynamics and disaster. In Bangladesh, floods cause short-term, but few long-term, population movements, in contrast to agricultural crop failures (Gray and Mueller 2012). An econometrics analysis detected no significant long-term impact of three types of natural disaster (earthquakes, tornadoes, and hurricanes) on population density increases in the US counties (Wang 2019). Mizutani (1989) studied the factors driving population declines in disaster areas in Japan, including quantitative relationships, and the population recovery process. Inoue (2021) compared the population structure and future population estimates in an area of expected inundation in Mabi-Cho, Kurashiki City, Okayama Prefecture, Japan, with nationwide data, finding a significant decrease in population density in the expected inundation area relative to non-inundation areas nationwide.

The tracking of macro-population dynamics after disasters has been facilitated by the use of cell phone SIMs and location-based services (Bengtsson et al. 2011; Yabe et al. 2020). Observations of the movement trajectories of cell phone users before and after five large-scale disasters in the USA, Puerto Rico, and Japan showed that population recovery patterns can be approximated by a common negative exponential function (Yabe et al. 2020). However, in a review of 83 research papers, Thompson et al. (2017) found that far fewer studies have examined the relationship between floods and evacuation than have addressed the relationship between hurricanes and cyclones and evacuation. The one paper in their sample that focused on Thailand examined the relationship between tsunamis and evacuation.

The 2011 floods in Thailand were the worst in the country's history, with damage occurring in 61 provinces. A recent study of floods and demographics in Thailand involved comparison of the results of a nationwide analysis of household evacuation responses in 2011 with those of a partial analysis focusing on Ayutthaya Province (Bhula-or et al. 2020). Household evacuation decisions were shown to depend on a complex and diverse set of factors; specifically, vulnerable groups, such as women and elderly individuals, but also individuals with more assets and more stable employment, were less likely to evacuate, whereas households with reduced opportunity were more likely to evacuate to avoid loss and death. In a study of the relationship between floods and demographics on a regional scale (Tahira and Kawasaki 2015), rural poor families living in flood-prone areas were shown to have remained for generations, not because of any advantage conferred by staying, but rather because of the difficulty of moving due to economic factors and the high ratio of elderly individuals in this population.

Analyses of the relationship between flooding and population dynamics must take into account the demographic characteristics of areas at risk of future large floods to enable the development of disaster prevention and evacuation plans. However, few such studies have been conducted using time series data throughout Thailand.

Kiguchi et al. (2021) analyzed the effects of climate change and adaptation measures in Thailand and found that most climate models showed an increasing trend in the national average precipitation in the future (2080–2099) compared with the baseline period (1980–1999). Given the increases in urbanization and densification in the country, heavy rainfall events and subsequent large-scale floods will likely cause more damage and affect a larger proportion of the population. Komori et al. (2013)

reported that the heavy rainfall that caused the 2011 flood corresponded roughly to a 1/100-year probability of occurrence, and we found no evidence that climate change is implicated in the large-scale floods described in this study. Based on these projections, further studies are needed to determine whether the Thai approach of "living with flooding" will continue to be possible or desirable, and of whether the lifestyle and mobility patterns of Thai people are changing to avoid floods.

Thus, the objective of this study is to examine the recent (2005–2019) relationship between flood and population dynamics in Thailand, including regional characteristics and the impacts of recent lifestyle and socioeconomic changes. Therefore, this study is the first to clarify the relationship between inundation and population dynamics using recent time series data throughout Thailand, and its findings will contribute to the development of flood protection measures and urban policy under a changing climate.

2 Data and methods

A flowchart of the overall study design is presented in Fig. 1.

2.1 Data

The data are summarized in Table 1. For the inundation area, polygon data for the period 2005–2019 were obtained from the Thailand Flood Monitoring System, provided by the Geo-Informatics and Space Technology Development Agency (GISTDA 2005–2019). These data are based on ALOS/PALSAR and THEOS-2 satellite images, with areas inundated at least once during the year considered to be inundated. However, according to Kawasaki et al. (2012), this definition likely overestimates inundation areas, as it leads to the inclusion of paddy fields and wetlands.

The LandScan Global population data from Oak Ridge National Laboratory were used (e.g., Bright et al. 2006). The data are annual, and for this study covered the period 2005–2019. This global population distribution dataset has a resolution of 30 arc seconds, thus covering the potential activity space of people throughout the day and night rather than merely at residential locations. Population data for the Thailand region were extracted. According to data from the Office of Registration Administration, Department of Provincial Administration, the population of Thailand increased steadily from 2005 to 2019, with no decrease during any year (Official statistics registration system 2005–2019). However, when the data were used to calculate the change in Thailand's overall population from 2005 to 2019, the population was shown to decline from 2010 to 2011. Thus, instead of using the population data as obtained, we used the rate of change for each data point, converted from raster data, for the analysis.

Model grid precipitation data from the JRA-55 Reanalysis conducted by the Japan Meteorological Agency, covering the period of 1958–2021 (Kobayashi et al. 2015), were used. These data output 0–3 h (00–03, 06–09, 12–15, and 18–21 UTC; mm/day) and 3–6 h (03–06, 09–12, 15–18, and 21–24 UTC; mm/day) forecast averages with a spatial resolution of 0.5625°. Daily and monthly precipitation amounts, calculated by integrating these data, were used for the analysis.

2.2 Methods

The population distribution data were used to analyze trends in population movement and distribution, by examining whether the population size at each point throughout Thailand was greater than, less than, or the same as the estimated value. If the actual population of an inundated area in a given year was lower than the estimated population in the following year, then we inferred that people in that area moved to another area because of inundation. If the actual population in an urban area was larger than the estimated population, then we inferred that the urban population became more concentrated than predicted. Specifically, for each population data point from 2009 to 2019, the value estimated based on a natural population increase or decrease was determined, and the difference from the actual population value (D_t) was calculated as shown in Eqs. (1) and (2).

$$D_t = Pop_t - \widehat{Pop}_t, \tag{1}$$

$$\widehat{Pop}_t = \frac{1}{3} \times \left(\frac{Pop_{t-3} - Pop_{t-4}}{Pop_{t-4}} + \frac{Pop_{t-2} - Pop_{t-3}}{Pop_{t-3}} + \frac{Pop_{t-1} - Pop_{t-2}}{Pop_{t-2}} \right) \times Pop_{t-1} + Pop_{t-1}, \tag{2}$$

where Pop_t is the actual population value, $\widehat{Pop}_t$ is the estimated value due to a natural population increase or decrease, and t is the year for which the difference is calculated. This calculation requires population data from the previous 4 years for estimation of the population in a certain year. As the distribution data required to estimate the population for the years 2005–2008 were not available, t ranged from 2009 to 2019. In Eq. (2), $\widehat{Pop}_t$ is the population calculated from the change in the natural population averaged from year 4 to year 3, year 3 to year 2, and year 2 to year 1. Averaging the change in the population over the previous 3 years, rather than over

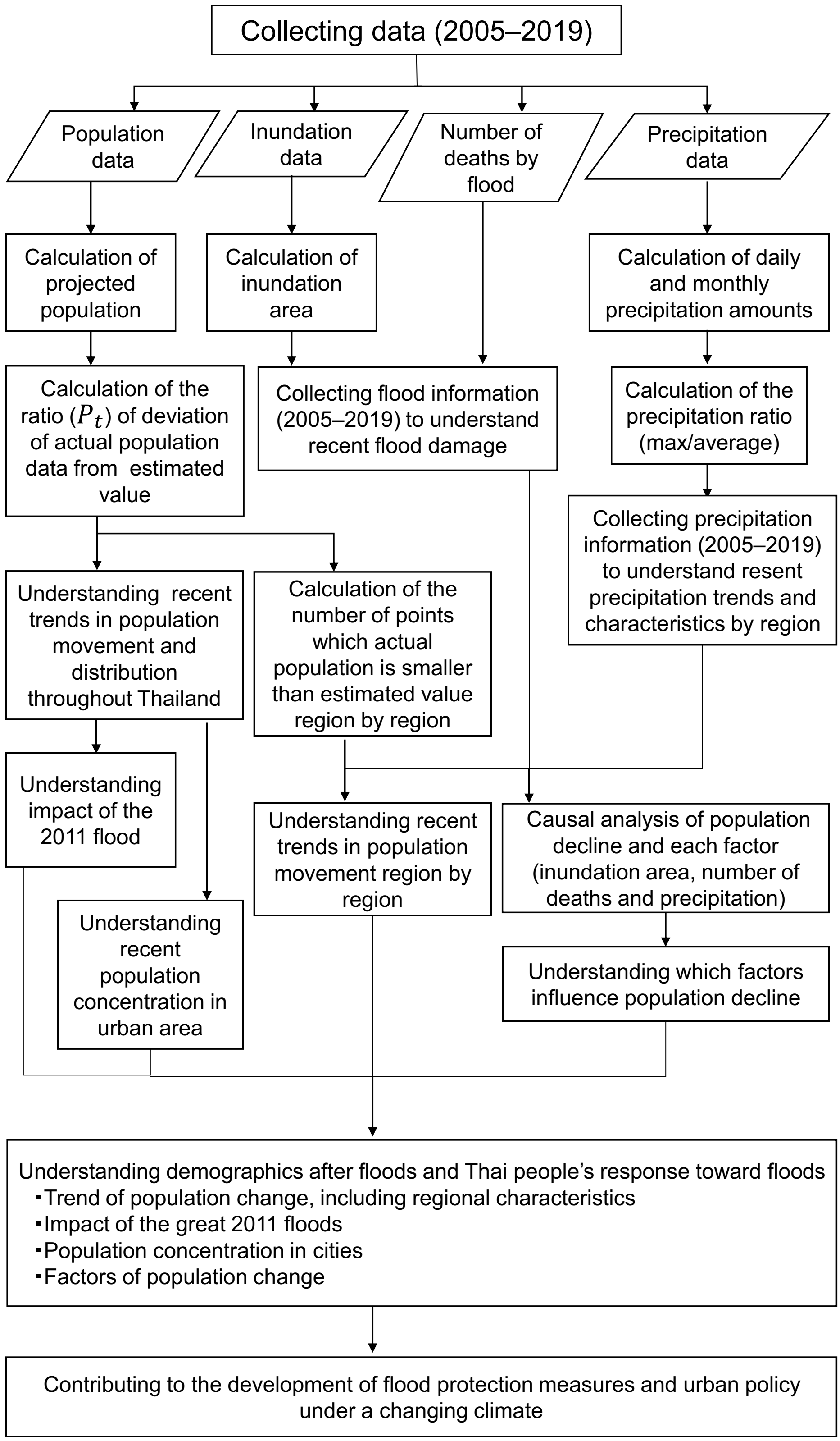

Fig. 1 Flowchart of this study. The overall framework of this study, including input data and process, and objectives of each process

Table 1 Data information

Data	Data name	Organization	Period	Format (resolution)
Inundation area data	Thailand Flood Monitoring System	GISTDA	2005–2019	Polygon data
Population data	LandScan Global	Oak Ridge National Laboratory	2005–2019	Raster data (30 arc seconds)
Precipitation data	The JRA-55 Reanalysis	Japan Meteorological Agency	1958–2021	Raster data (0.5625°)
Deaths by flood	Thailand Country Report	ADRC	2005–2019	PDF file

We used inundated area data, population data, precipitation data, and number of deaths by flood for analysis. Data information which includes the source for each type of the data, period, their formats, and resolution

only 1 year, minimized the effects of irregular population changes, such as temporary rapid population increases or decreases. Equation (3) presents P_t, defined as the ratio of the deviation of the actual population data from the estimated value.

$$P_t = \frac{D_t}{Pop_t} \times 100(\%). \tag{3}$$

Table 2 shows yearly flood information for 2005–2019: the inundated area, the most severely affected areas, the number of deaths caused by flooding, and precipitation information. The total inundated area for the years 2005–2019 was calculated using ArcGIS Pro and the inundated area data. Data on the main areas affected by floods each year and the total annual number of deaths due to flooding were based on qualitative information from the Asian Disaster Reduction Center (ADRC 2005–2019).

The average daily and monthly precipitation for the years 1958–2021 and the annual maximum daily and monthly precipitation for each year between 2005 and 2019 were calculated for each data point converted from raster data (Fig. 2a, b). The location of the annual maximum daily and monthly precipitation and the ratio of the annual maximum daily and monthly precipitation to the average daily and monthly precipitation are shown in Fig. 2c, d, and the ratio of the annual maximum daily and monthly precipitation to the average daily and monthly precipitation is also shown in Table 2. Monthly precipitation was calculated for quantitative evaluation of the magnitude of rainfall related to flooding on monthly bases and for the identification of rainfall characteristics for each region and year. The trends in the distributions of average daily and monthly precipitation in Thailand from 1958 to 2021 were similar, but those for the distributions of the ratio of the annual maximum to the average daily (monthly) precipitation from 2005 to 2019 differed. The distribution of the daily precipitation ratio was

Table 2 Flood information for each year from 2005 to 2019

Year	Flood area (km^2)	Main affected area	Total deaths by flood (ADRC)	Precipitation ratio (max/average)	
				Daily	Monthly
2005	9881.8	South, North	75	22.07	2.92
2006	28,804.3	North, Northeast, Central	446	12.24	2.38
2007	11,507.6	South, North and Central	36	24.25	2.92
2008	14,407.2	South, North and Northeast	113	16.21	2.58
2009	7952.9	South	53	12.36	3.58
2010	34,260.6	Northeast, North	266	32.15	7.26
2011	49,762.0	Central and Northeast, South	1026	29.40	2.85
2012	8479.9	South	About 10	21.67	4.14
2013	18,571.3	North and Northeast, South	About 140	15.38	2.44
2014	4493.9	South	About 20	13.21	2.87
2015	925.9	North	0	27.02	3.45
2016	7458.0	South	99	22.75	2.76
2017	27,777.4	South, North and Central	44	17.40	2.66
2018	3975.3	North and Central, South	8	14.73	4.28
2019	8171.2	Northeast, South	5	20.52	2.74

Flood information includes the inundated area, the most severely affected areas, the number of deaths caused by flooding, and precipitation information which are the precipitation ratio of the annual maximum daily and monthly precipitation to the average daily and monthly precipitation for the years 1958–2021

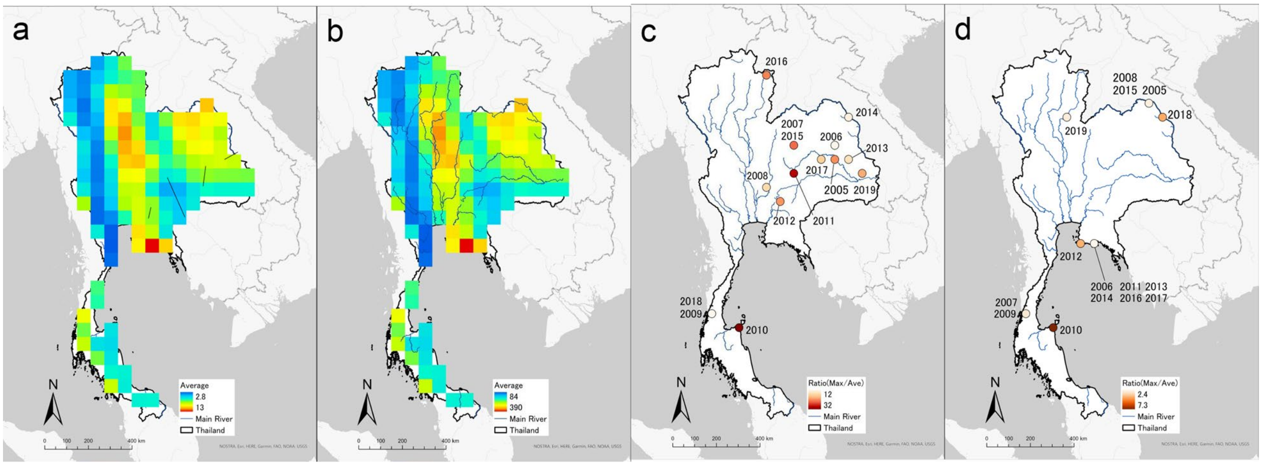

Fig. 2 Maps of precipitation in Thailand shown in Table 2. **a** The average daily precipitation for the years 1958–2019 [mm], **b** The average monthly precipitation for the years 1958–2019 [mm], **c** The location of the annual maximum daily precipitation, and the ratio of the annual maximum daily precipitation to the average daily precipitation for each year between 2005 and 2019, **d** The location of the annual maximum monthly precipitation, and the ratio of the annual maximum monthly precipitation to the average monthly precipitation for each year between 2005 and 2019

concentrated mainly in the northeastern inland and southern coastal areas, whereas the distribution of the monthly precipitation ratio showed that rainfall in 2010 was highest in the southern region and was concentrated in the northeast, north, and east. Overall, daily and monthly precipitation tended to be higher in the northeast, east, and south.

Using this flood information, we analyzed the relationship between the inundation area, number of deaths, precipitation, and population distribution. We predicted that larger values of inundation area, deaths, and precipitation would have a greater impact on population decline in the following year. However, it is also possible to compare the size of these factors by comparing their causal relationships.

We also analyzed the relationship between inundation and population on a regional basis, i.e., northern, northeastern, central, eastern, and southern Thailand and the metropolitan Bangkok area (Fig. 3). Our analysis of the relationship between flood information and population distribution for each region allowed us to clarify regional characteristics of population movement. In the metropolitan Bangkok area, which has a rapidly growing population, floods may not have a significant impact on population movement, and population growth and in-migration may exceed any population decline caused by flooding. Figure 4 shows the topographical features of Thailand from the MERIT DEM (Yamazaki et al. 2017) and the flood frequency during the 16-year period from 2005 to 2020, as calculated by the Thailand Flood Monitoring System. These results were compared with the calculated distribution of P_t to determine the impact of inundation on the population distribution and the trend of population migration in recent years.

3 Results

According to the ratio of inundated area to the regional area, the largest flooded areas were recorded in the 2011 flood throughout Thailand and in the northern and southern regions inundated in 2017, followed by the 2006 flood in the metropolitan Bangkok and eastern regions, and the 2010 flood in the northeastern and metropolitan Bangkok regions (Fig. 3).

Figure 5 shows the distribution of P_t values for 2009–2019. The blue points show that the actual population was smaller than estimated based on natural population changes, and the red points show that the actual population was larger than estimated, with darker colors indicating larger changes. The range of $-5 < P_t \leq 5$ (%) was the cutoff for a small difference between the actual and estimated populations (Fig. 5). Points within this range are white. For 2009 and 2010, areas with mixes of blue and red points are present; the largest number of white points is present for 2011. In 2012, the actual population differed from the estimated value in many areas across the country, indicating that the 2011 floods, the worst in Thailand's history, had a significant impact on the population distribution. In particular, many points with $P_t \geq 90$(%) fall in the vicinity of Bangkok, and for the Mun and Chi river basins many points indicate that the actual population was smaller than the estimated value. For 2013, the opposite distribution was often observed. For example, a concentration of points representing $P_t \leq -5$ (the actual population is smaller than the estimated value) is present near Bangkok for 2013, although

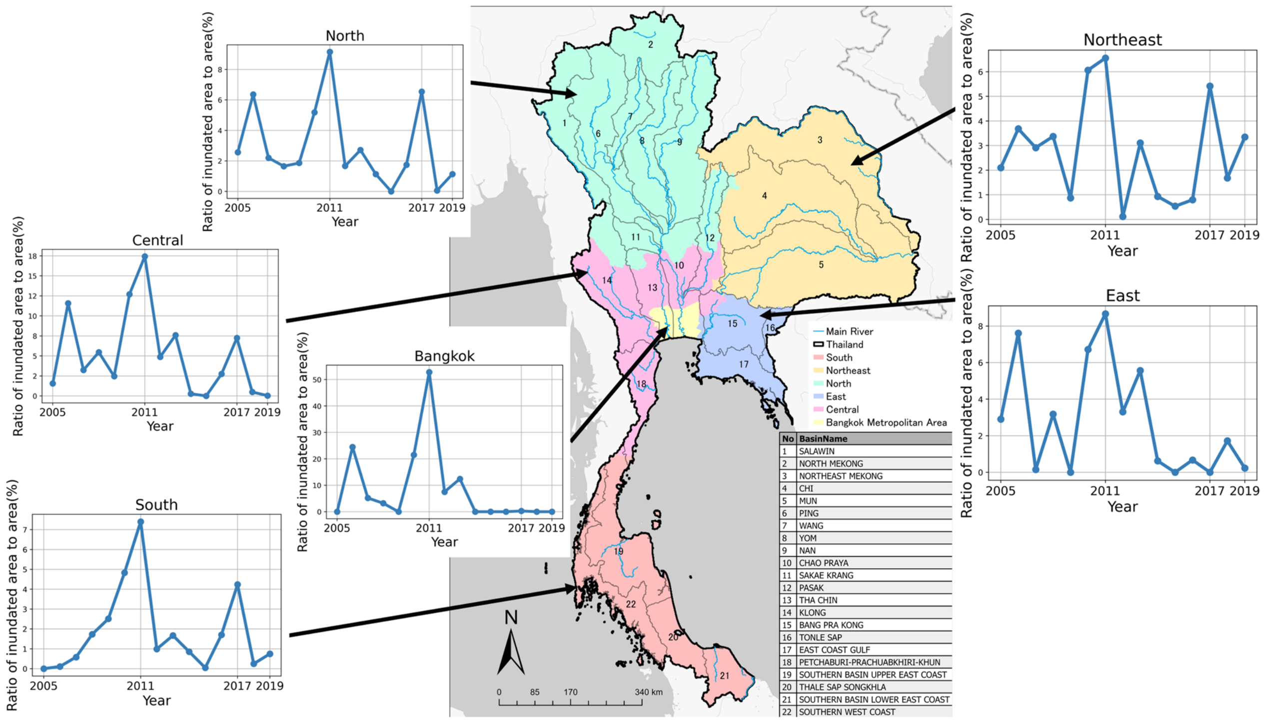

Fig. 3 Map of regions and watersheds in Thailand. The map of six regions and 22 watersheds in Thailand, and the change over time of the inundated area in each region as a percentage of the total area of the region from 2005 to 2019

a concentration of points representing $P_t > 5$ (the actual population is larger than the estimated value) is present for 2012. Conversely, in the Mun and Chi river basins, a concentration of points representing $P_t \leq -5$ is present for 2012 and a concentration of points representing $P_t > 5$ is present for 2013. The trend for 2014 and 2015 was the same as that for 2013, whereas areas of $P_t \leq -5$ points and $P_t > 5$ points were mixed for 2016 and 2017. For 2018, $P_t > 5$ points were concentrated in some parts of the eastern region, in the metropolitan Bangkok area, and in the southern region, with $P_t \leq -5$ areas concentrated elsewhere. For 2019, points that were $P_t \leq -5$ in 2018, such as those in the north, northeast, and south, tended to be $P_t > 5$ points.

Figure 6 shows the changes over time in points with $P_t \leq -5$ and $P_t > 5$ as a percentage of the total number of points in each region (north, northeast, central, metropolitan Bangkok area, east, south, and all of Thailand). The two graphs in Fig. 6 show opposite trends except in 2011, when large numbers of points were in the range of $-5 < P_t \leq 5$ (%) (white points in Fig. 5).

Comparison of the P_t results with the previous year's flood data revealed the previous-year factors that affected the population distribution in the following year and whether they differed by region. Figure 7 shows the relationship between the area inundated in the previous year and the population decline in the following year in each region, analyzed by the relationship between the ratio of the number of points with $P_t \leq -5$ (%) in each region to the total number of points in that region and the ratio of the inundated area in the previous year to the regional area. For example, In the metropolitan Bangkok area and Eastern area, significant inundation damage was occurred in the 2011 floods, but the impact on population decline was small, a trend different from other regions. The correlation coefficients and the p value for the northern and northeastern regions were $r=0.426$, $p=0.191$ and $r=0.501$, $p=0.055$, respectively, so these values indicated a statistically significant trend in the northeastern region.

Figure 8 shows the relationship between the number of points with $P_t \leq -5$ as a percentage of the total number of points for all of Thailand and the number of deaths by flooding in the previous year. The latter was determined using data from the ADRC. The correlation for the effect of the number of deaths by flooding in the previous year on population decline in the following year was positive ($r=0.503$, $p=0.114$), although it was largely attributable to the results obtained for 2012.

Figure 9 shows the relationship between the ratio of the annual maximum daily and monthly precipitation in the previous year to the average daily precipitation from

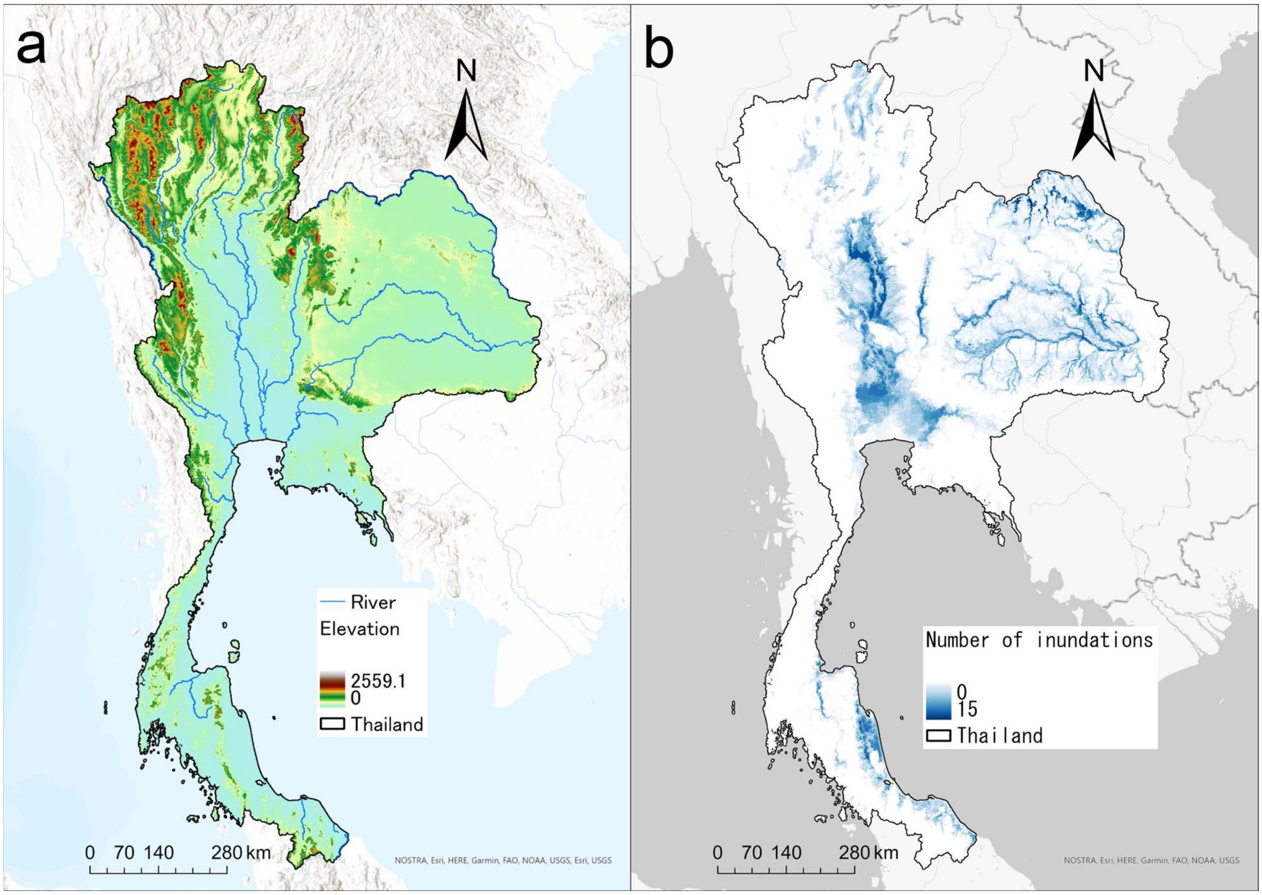

Fig. 4 Maps of elevation and flood frequency in Thailand. **a** Physiographic (elevation) map of Thailand from MERIT DEM, **b** Flood frequency map to visualize the concentration of inundation from 2005 to 2020, calculated by the Thailand Flood Monitoring System

1958 to 2021 and the ratio of the number of points with $P_t \leq -5$ to the number of points in each region, including the location with annual maximum daily or monthly precipitation. A slightly positive correlation was obtained for the daily precipitation, whereas a negative correlation ($r = -0.395$, $p = 0.229$) was obtained for monthly precipitation.

4 Discussion

4.1 Trend of population change

The difference in the distribution of P_t (Fig. 5) and the increase in the percentage of points with $P_t \leq -5$ in 2012 relative to 2013 only in the metropolitan Bangkok and eastern regions (Fig. 6) suggest that the 2011 floods caused people to move to the metropolitan Bangkok area in 2012, but to return to the areas they had left in 2013.

In previous studies, we examined whether the population decline in the inundated area from 2011 to 2012 was due not only to repeated inundations, but specifically to the 2011 floods (Tsuda et al. 2022a,b). The ratio of the number of points inundated only in 2011 with $D_{2012} < 0$ to the number of points inundated only in 2011 was 87.9% for the whole of Thailand, indicating that the 2011 inundations alone had a significant effect on people's mobility. This study showed that this migration was temporary, as affected people returned to their previous residences in 2013.

Migration into the metropolitan Bangkok area after the 2011 floods may have been driven by the government's flood control policy. Water overflowing the Chao Phraya River would normally have flowed to the western and southern parts of Bangkok, which are at lower elevations than the eastern part. However, the floodgates were closed, and large sandbags were piled up to prevent the water from entering the center of the city, such that flooding was confined to northern Bangkok (Tamada 2013). This government response may have caused people to move into the King's Dike area, based on the assumption that it would be protected during flooding. These findings indicate that the 2011 floods affected the population distribution, but that most migration was short term. Similar changes in the population distribution were

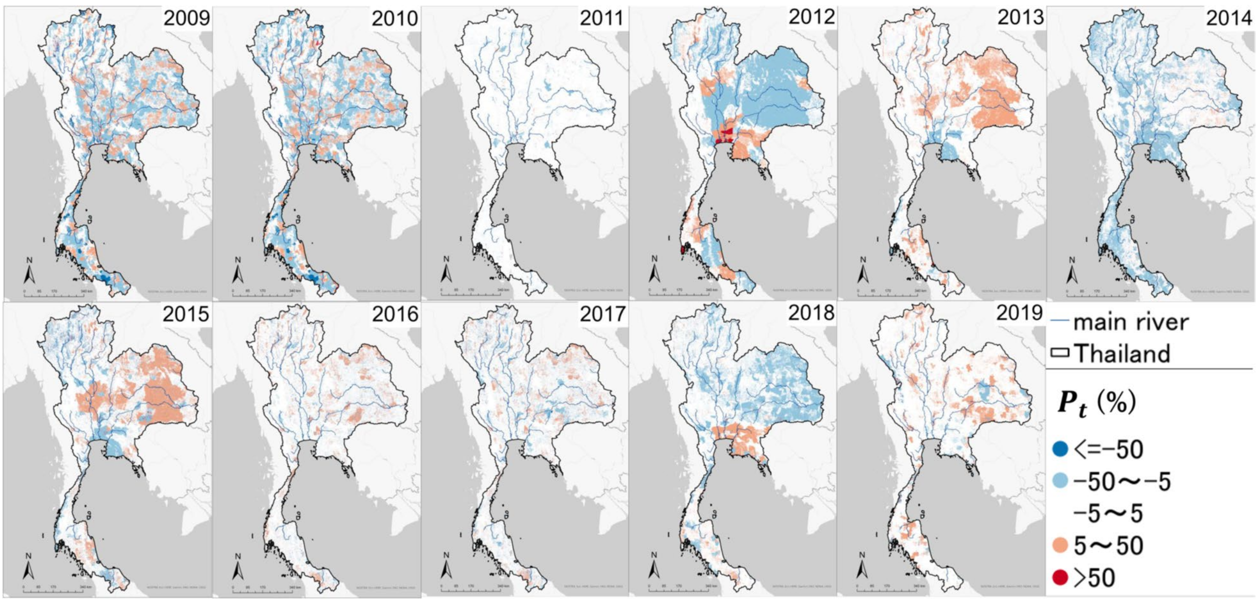

Fig. 5 Maps of the distribution of P_t values for 2009–2019. Points indicating that the actual population was smaller (larger) than estimated based on natural population changes are blue (red), with darker colors indicating larger increases (declines). The range of $-5 < P_t \leq 5$ (%) was the cutoff for a small difference between the actual and estimated populations

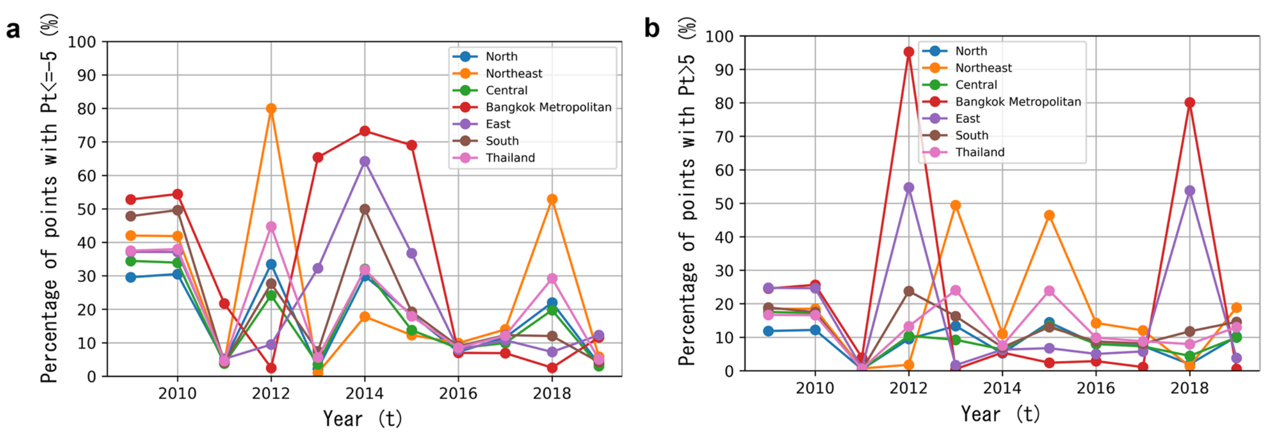

Fig. 6 Percentage of points with $P_t \leq -5$ (%) and $P_t > 5$ (%) shown in Fig. 5. The change over time in points with $P_t \leq -5$ as a percentage of the total number of points in each region: north, northeast, central, Bangkok metropolitan area, east, south, and all of Thailand (**a**). The change over time in points with $P_t > 5$ as a percentage of the total number of points in each region (**b**)

observed in 2018 and 2019 and reflect the consequences of the flood damage that occurred in 2017, especially in southern and northern Thailand. However, the changes were less remarkable than those occurring in 2012 and 2013.

Our findings suggest that in 2014 and 2015, as in 2013, the population decline in the metropolitan Bangkok area and migration to other regions such as northeastern Thailand were mainly influenced by political factors such as anti-government demonstrations and the military coup that occurred in 2013–2014. In particular, the coup led to the implementation of martial law and triggered the current military regime in Thailand, which affected migration.

4.2 Impact of the great 2011 floods

The percentage of points with $P_t \leq -5$ (%) (Fig. 6) decreased from 2014–2015 to 2015–2016 in all regions. This reduction can be attributed to the occurrence of less inundation damage in 2014 and 2015, such that the increases in the population distribution in 2015 and 2016 corresponded to areas where the actual population

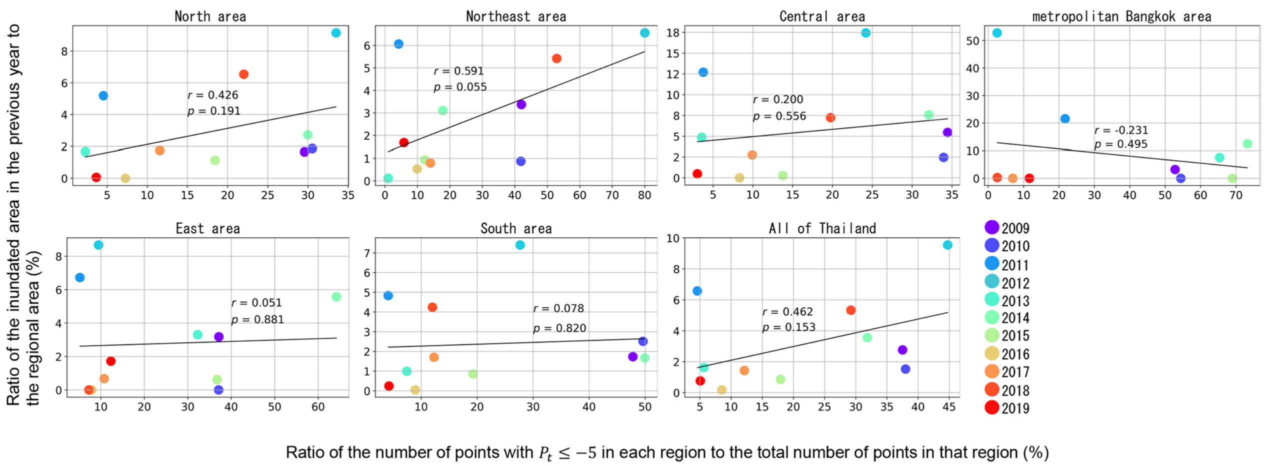

Fig. 7 Relationship between the area inundated in the previous year and the population decline. This is indicated by the relationship between the ratio of the number of points with $P_t \leq -5$ (%) in each region to the total number of points in that region and the ratio of the inundated area in the previous year to the regional area

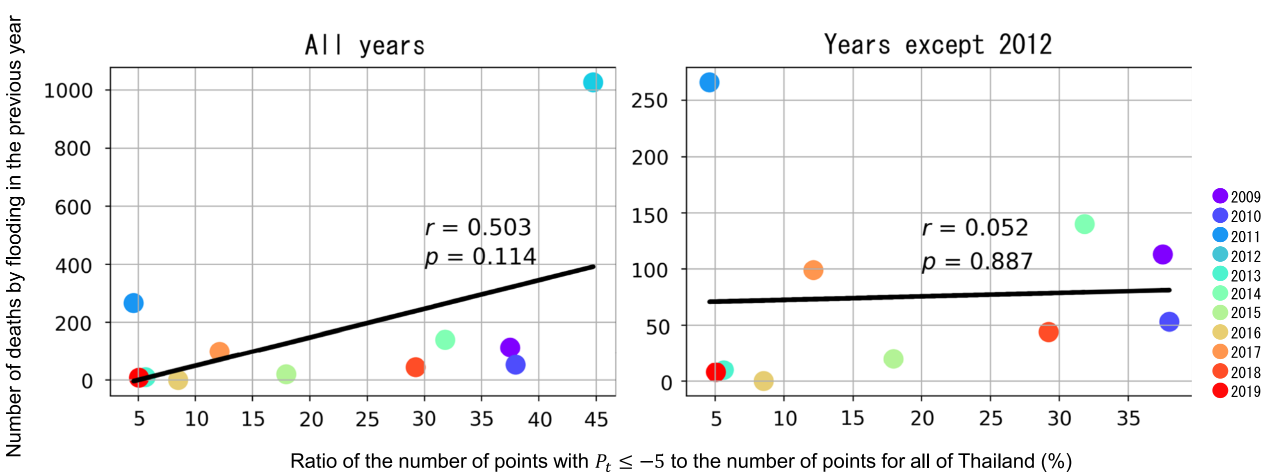

Fig. 8 Relationship between the number of deaths by flooding and population decline. This is indicated by the relationship between the number of points with $P_t \leq -5$ as a percentage of the total number of points for all of Thailand and the number of deaths by flooding in the previous year, and the right panel is scatterplot for excluding the case t = 2012

was slightly larger than or almost equal to the estimated population. However, in a year following a year with relatively extensive inundation damage, such as 2011 or 2017, the percentage of points with $P_t \leq -5$ tended to increase. The exception was in 2010, when the total inundation area was 34,260.6 km^2, the second largest after 2011, and approximately 250 flood-related deaths occurred. The absence of a significant impact on the population distribution can be explained by the fact that the large 2010 flood was one of many floods that occurred in Thailand that year and thus did not cause people to move. However, the 2011 floods may have changed people's attitudes toward evacuation and residential mobility, such that the relatively large floods in 2013 and 2017 may have affected the population distribution. People who had previously felt that the benefits of staying in place and living with floods outweighed the risk may have decided to move to urban and metropolitan areas protected from flooding, or to areas where inundation is rare.

4.3 Population concentration in cities

A closer examination of Fig. 5 shows that regions with red points are clustered in the center of the region with blue points throughout the country, which indicate people tend to concentrate in cities from suburbs. This suggests increased population concentration in urban areas

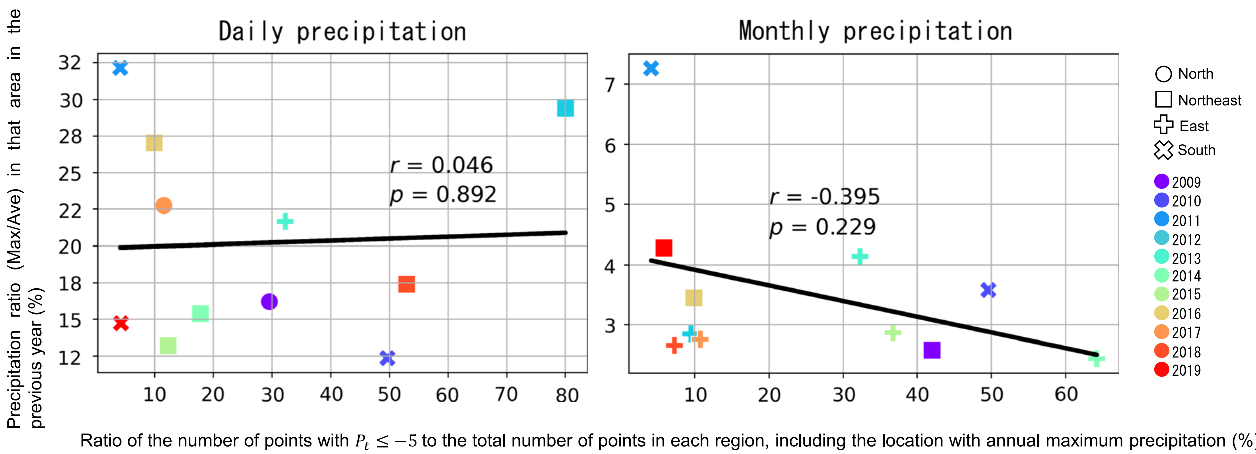

Fig. 9 Relationship between daily and monthly precipitation in the previous year and population decline. This is indicated by the relationship between the ratio of the annual maximum daily and monthly precipitation in the previous year to the average daily precipitation from 1958 to 2021 and the ratio of the number of points with $P_t \leq -5$ to the number of points in each region, including the location with annual maximum daily or monthly precipitation

and depopulation of the surrounding areas. When cities are affected by floods, the dense urban population is at high risk for injury or death and property loss, which increases public demand for faster implementation of flood countermeasures.

The objective of this study was to determine whether the traditional lifestyle of living with floods remains suitable for the current Thai population, or whether their lifestyle and post-flood migration patterns have already changed with recent socioeconomic development, indicating a shift to a flood-avoidance lifestyle. As indicated in Sect. 4.2, it was clear that post-flood movement has become more active since the 2011 flood, and the population has become more concentrated in urban areas. We inferred that Thai people are shifting from a flood-tolerance lifestyle to a flood-avoidance lifestyle, with higher concentrations of people in urban areas where stronger flood mitigation measures are in place.

4.4 Factors of population change

Figures 7, 8 and 9 show the factors that have induced population distribution changes in each region and in Thailand as a whole. In Fig. 7, the correlation between the percentage of points with $P_t \leq -5$ and the percentage of the area inundated in the previous year versus the total area of the region was negative only for the metropolitan Bangkok area. Thus, in the metropolitan Bangkok area, where economic development and population growth are rapid, the inundation is not a key factor in population movement, and the speed of population growth is greater than that of population loss due to inundation.

The number of deaths by flooding in the previous year was associated with a population decline in the following year for all of Thailand (Fig. 8). However, the impact of the 2011 floods on population movements was significantly large, while the number of deaths from the previous year's floods had a relatively small impact on population decline in the following year. These findings suggest that the total amount of damage that is outside the scope of this study and the aforementioned area inundated may have a greater impact than the number of deaths on the population decline after floods in Thailand.

The effects of daily and monthly precipitation in the previous year on population decline in the following year were also analyzed (Fig. 9). The daily precipitation did not significantly affect the population distribution in the following year, and no regional characteristic could be identified. The number of points representing a smaller-than-predicted population increased with the ratio of the annual maximum monthly precipitation to the average monthly precipitation, possibly due to the concentration of maximum monthly precipitation points in the northeastern, eastern, and southern regions, where people are accustomed to long-lasting rainfall and thus unlikely to migrate because of it.

5 Conclusions

This study was conducted to examine the relationship between flooding and population distribution across Thailand. Our aim was to contribute to the planning of adaptation measures to minimize the flood damage caused by climate change. The results suggest that the 2011 and 2017 floods, which inundated 9.5% and 5.3% of the total area of Thailand, respectively, caused the temporary migration of people to areas that were not inundated or to the metropolitan Bangkok area. They also suggest that people's response to floods changed after the 2011 floods.

The correlation between the number of points indicating a smaller-than-estimated population and the area inundated in the previous year in each region was positive especially for the northeastern area ($r = 0.501$, $p = 0.055$). The slightly different trend in the metropolitan Bangkok area compared to the other regions can be attributed to the vertical structure of Bangkok's urban fabric. According to this relationship, a larger area inundated in the previous year has a greater impact on population decline. Similarly, the positive correlation between the number of points indicating a smaller-than-predicted population and the number of deaths by flooding in the previous year in all of Thailand ($r = 0.503$) indicates that the number of deaths by flooding in the previous year led to a population decline in the following year. However, an analysis of the effects of precipitation in the previous year on the population decline in the following year showed a slightly positive correlation for daily precipitation and a negative correlation ($r = -0.395$) for monthly precipitation. Thus, precipitation in the previous year did not account for the population decline in the following year.

In recent years, population concentration in urban areas has increased vulnerability to flooding in Thailand. These factors suggest that the Thai people are shifting from a lifestyle that included living in harmony with floods to an avoidance of inundation, mostly in urban areas, where flood control measures are more stringent.

Finally, changes in population distribution cannot be attributed solely to flooding, but also reflect the effects of droughts and government policies. Additional research is needed to separate flood-related factors from such other factors. Therefore, it is necessary to collect data on drought and government policies to separate population movements caused by floods from those caused by other factors. However, it is difficult to obtain detailed data on these factors throughout Thailand. To confirm our results, we are conducting a survey of flood awareness among Thai people, including questions about flood experiences and movement after floods. As more detailed population data, including location data and detailed demographic data, become available, it will be easier to characterize migration patterns in Thailand.

Abbreviations

ADRC	Asian Disaster Reduction Center
ALOS	Advanced Land Observing Satellite
GIS	Geographic Information System
GISTDA	Geo-Informatics and Space Technology Development Agency
JRA-55	Japanese 55-year Reanalysis
PALSAR	Phased Array Type L-band Synthetic Aperture Radar
SIM	Subscriber Identity Mmodule
THEOS	Thailand Earth Observation Satellite

Acknowledgements
This research was partially supported by the JST/JICA SATREPS program and the SICORP e-ASIA JST.

Author contributions
HT processed the data and analyzed the simulation results with TT; both authors read and approved the final manuscript.

Funding
This study was supported by the Japan Science and Technology Agency (JST)/Japan International Cooperation Agency (JICA) Science and Technology Research Partnership for Sustainable Development (SATREPS) program (PI: Prof. Taikan OKI) and the Strategic International Collaborative Research Program East Asia Joint Research Program (SICORP e-ASIA JRP; PI: Prof. Taikan OKI) (Grant nos. 21338544, 15543675).

Availability of data and materials
Data on inundation area were obtained from the Thailand Monitoring System provided by the GISTDA (https://flood.gistda.or.th/). LandScan Global population distribution data were obtained from Oak Ridge National Laboratory (https://landscan.ornl.gov/). Statistic population data were obtained from the statistics registration system of the Registration Technology Development and Management Division Office, Department of Provincial Administration (https://stat.bora.dopa.go.th/stat/statnew/statMenu/newStat/home.php). JRA-55 reanalysis precipitation data were downloaded from the National Center for Atmospheric Research (NCAR, https://rda.ucar.edu/datasets/ds628.0/). JRA-55 reanalysis data are available for download to those with a user ID and password obtained through registration with NCAR (https://rda.ucar.edu/index.html?hash=data_user&action=register). Elevation data were downloaded from the MERIT DEM provided by the Yamazaki Laboratory, University of Tokyo (http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_DEM/).

Declarations

Competing interests
The authors declare that they have no competing interests to report.

Received: 5 August 2022 Accepted: 5 July 2023
Published online: 13 July 2023

References

ADRC (2005–2019) Member country disaster prevention information-Thailand. https://www.adrc.asia/disaster_j/. Accessed 9 Sept 2021

Bengtsson L, Lu X, Thorson A, Garfield R, von Schreeb J (2011) Improved response to disasters and outbreaks by tracking population movements with mobile phone network data: a post-earthquake Geospatial Study in Haiti. PLoS Med 8(8):e1001083. https://doi.org/10.1371/journal.pmed.1001083

Bhula-or R, Nakasu T, Mokkhamakkul T, Anantsuksomsri S, Amornkitvikai Y, Prathumchai K, Duangkaew S (2020) Households' evacuation decisions in response to the 2011 flood in Thailand. J Disaster Res 15(5):599–608

Bright E, Coleman P, King A (2006) LandScan Global 2005, Oak Ridge National Laboratory. https://doi.org/10.48690/1524201. Accessed 11 Jan 2022

Climate Bonds Initiative (2022) Green infrastructure investment opportunities: Thailand 2021 Report

GISTDA (2005–2019) Thailand flood monitoring system. https://flood.gistda.or.th/. Accessed Jan 2022

Gray CL, Mueller V (2012) Natural disasters and population mobility in Bangladesh. Proc Natl Acad Sci USA 109(16):6000–6005

Inoue T (2021) Demographic characteristics of potential flood inundation areas. In: Inoue T, Wada K (eds) Natural disasters and population. Demographic library, vol 20. Hara Shobo, Tokyo, pp 187–206 **(in Japanese)**

Iwaki Y (2013) Earthen mounds and stilt houses: traditional flood control measures in bangkok and their limitations. In: Yamamoto H, Nishi Y (eds)

Thai society as reflected by floods: the shape of society through disaster response. CIAS Discussion Paper, vol 31. Center for Integrated Area Studies, Kyoto University, London, pp 23–28 **(in Japanese)**
Karácsonyi D, Taylor A (2021) The ontological praxis between disaster studies and demography extension of the scope. In: Karácsonyi D, Taylor A, Bird D (eds) The demography of disasters. Springer, Berlin
Kawasaki A, Komori D, Nakamura S, Kiguchi M, Nishijima A, Oki K, Oki T, Meguro K (2012) Emergency response during the 2011 Chao Phraya River flood in Thailand focusing on information sharing and coordination among governmental agencies. J Soc Saf Sci 17:109–117 **(in Japanese with an English abstract)**
Kiguchi M, Takata K, Hanasaki N, Archevarahuprok B, Champathong A, Ikoma E, Jaikaeo C, Kaewrueng S, Kanae S, Kazama S, Kuraji K, Matsumoto K, Nakamura S, Nguyen-Le D, Noda K, Piamsa-Nga N, Raksapatcharawong M, Rangsiwanichpong P, Ritphring S, Shirakawa H, Somphong C, Srisutham M, Suanburi D, Suanpaga W, Tebakari T, Trisurat Y, Udo K, Wongsa S, Yamada T, Yoshida K et al (2021) A review of climate-change impact and adaptation studies for the water sector in Thailand. Environ Res Lett. https://doi.org/10.1088/1748-9326/abce80
Kobayashi S, Ota Y, Harada Y, Ebita A, Moriya M, Onoda H, Onogi K, Kamahori H, Kobayashi C, Endo H, Miyaoka K, Takahashi K (2015) The JRA-55 reanalysis: general specifications and basic characteristics. J Meteorol Soc Japan 93(1):5–48
Komori D, Kiguchi M, Nakamura S, Nunomura A (2013) The reality of Thailand's 2011 floods. In: Tamada Y, Hoshikawa K, Funatsu T (ed) Thailand 2011 floods: a record and lessons learned. Situation analysis report, vol 22. Institute of Developing Economies, Japan External Trade Organization, pp 13–42 (**in Japanese**)
Loc HH, Park E, Chitwatkulsiri D, Lim J, Yun S, Maneechot L, Phuong DM (2020) Local rainfall or river overflow? Re-evaluating the cause of the Great 2011 Thailand flood. J Hydrol. https://doi.org/10.1016/j.jhydrol.2020.125368
Mizutani T (1989) Processes of decrease, migration and recovery in urban population after disasters. Geogr Rev Japan 62A–3:208–224 **(in Japanese with an English abstract)**
Official statistics registration system (2005–2019) Population. https://stat.bora.dopa.go.th/stat/statnew/statMenu/newStat/home.php. Accessed 3 March 2022
Park E, Lim J, Ho HL, Herrin J, Chitwatkulsiri D (2021) Source-to-sink sediment fluxes and budget in the Chao Phraya River, Thailand: a multi-scale analysis based on the national dataset. J Hydrol. https://doi.org/10.1016/j.jhydrol.2020.125643
Phanthuwongpakdee N (2016) Living with floods: moving towards resilient local-level adaptation in Central Thailand. Dissertation, King's College London and the National University of Singapore
Tahira Y, Kawasaki A (2015) The impact of the Thai flood of 2011 on the rural poor population living in the flood plain. J Soc Saf Sci 27:167–177 **(in Japanese)**
Tamada Y (2013) Conflicts and politics over floods. In: Tamada Y, Hoshikawa K, Funatsu T (ed) Thailand 2011 floods: a record and lessons learned, situation analysis report, vol 22. Institute of Developing Economies, Japan External Trade Organization, pp 123–160 (**in Japanese**)
Thompson RR, Garfin DR, Silver RC (2017) Evacuation from natural disasters: a systematic review of literature. Risk Anal 37(4):812–839
Tsuda H, Tebakari T, Matsuura T, Koyama N (2022a) Demographic Impact of Flooding in Thailand: The Case of the 2011 Floods. Abstract presented at the 49th JSCE Kanto Branch Technical Conference, virtual, 03–08 March 2022 (**in Japanese**)
Tsuda H, Tebakari T, Matsuura T, Koyama N (2022b) Demographics impact of the 2011 floods in Thailand. Abstract presented at the Asia Oceania Geosciences Society 19th Annual Meeting 2022b, virtual, 01–05 August 2022
Wang C (2019) Did natural disasters affect population density growth in US counties? Ann Reg Sci 62:21–46
Yabe T, Tsubouchi K, Fujiwara N, Sekimoto Y, Ukkusuri SV (2020) Understanding post-disaster population recovery patterns. J R Soc Interface 17:20190532
Yamazaki D, Ikeshima D, Tawatari R, Yamaguchi T, O'Loughlin F, Neal JC, Sampson CC, Kanae S, Bates PD (2017) A high-accuracy map of global terrain elevations. Geophys Res Lett 44(11):5844–5853

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