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Flood impact on Mainland Southeast Asia between 1985 and 2018—The role of tropical cyclones

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Abstract
Floods are disastrous natural hazards accused of human live losses. As a flood-prone area, Mainland Southeast Asia (MSEA) has often been hit by floods, resulting in the highest fatality in the world. Despite the destructive flood impacts, how has flood occurrence changed over the past decades, and to what extent did floods affect the MSEA are not yet clear. Using the Dartmouth Flood Observatory large flood data archive, we aim to assess the trend of flood occurrence in the MSEA in 1985–2018, and quantify the associated impacts on humans. Particularly, the contribution of tropical cyclone (TC) landfall induced floods (TCFloods) is quantified, because of the frequent TC landfalls. Results show that (a) occurrence and maximum magnitude of floods by all causes (ALLFloods) significantly increased ($p < .01$), but not for TCFloods; (b) On average, TCFloods accounted for 24.6% occurrence of ALLFloods; (c) TCFloods caused higher mortality and displacement rate than ALLFloods did. As low flood protection standards in Cambodia and Myanmar is considered a reason for high flood-induced mortalities, building higher flood protection standards should be taken as a priority for mitigating potential flood impacts. With quantifying flood occurrence and impacts, this study offers scientific understandings for better flood risk management.

KEYWORDS
floods, Mainland Southeast Asia, mortality, tropical cyclone

1 | INTRODUCTION

Floods are one of the most devastating natural hazards, claiming about 6,000 deaths and 700 billion United States Dollars (USD) worth damages per year globally in 1980–2018 (CRED, 2019). Flood occurrence and impacts on economic losses and fatalities are spatially heterogeneous (Hu, Zhang, Shi, Chen, & Fang, 2018; Kundzewicz, Kanae, et al., 2012a). More values of exposed assets exist in developed regions, whereas more people are exposed to floods in Asian countries (Jongman, Ward, & Aerts, 2012; Jonkman, 2005). Located in the Mainland Southeast Asia (MSEA, see Figure 1), Mekong River Basin's five riparian countries, namely, Cambodia, Lao PDR, Myanmar, Thailand, and Vietnam are high flood-prone countries with large flood-induced mortalities (Hu et al., 2018; MRC, 2015; Osti, Hishinuma, Miyake, & Inomata, 2011). In particular, being a frequent tropical cyclone (TC) landfall region, the MSEA has often been hit by TCs, resulting in extreme floods and causing fatalities and property damage, due to the associated heavy rainfall (Chhin, Trilaksono, & Hadi, 2016; MRC, 2015). Local residents in the MSEA often lack necessary measures to cope with destructive floods and storms, neither have sufficient supplies for restoration from hazards (ADB, 2009; ASEAN, 2017; Bangalore, Smith, & Veldkamp, 2019; MRC, 2010). Thus, floods especially TC-induced ones are threatening the livelihood of millions of people living in the MSEA.

Previous studies have assessed historical trend of floods and associated impacts on human lives and properties at various scales, such as, global (Hu et al., 2018; Jongman et al., 2015; Winsemius et al., 2016), continental (Kundzewicz, Pińskwar, & Brakenridge, 2012b; Paprotny, Sebastian, Morales-Nápoles, & Jonkman, 2018), and national scale (i.e., the United States (Berghuijs, Woods, Hutton, & Sivapalan, 2016; Pielke & Downton, 2000), Bangladesh (Call, Gray, Yunus, & Emch, 2017), Thailand (Gale & Saunders, 2013; Haraguchi & Lall, 2015), and Vietnam (Chau, Holland, Cassells, & Tuohy, 2013; Hung et al., 2012; Ngoc Thuy & Ha Anh, 2015)). Despite increasing trends of flood occurrence globally (Hu et al., 2018; Paprotny et al., 2018), there have been falling mortality rates of each flood event between 1975 and 2016 (Hu et al., 2018).

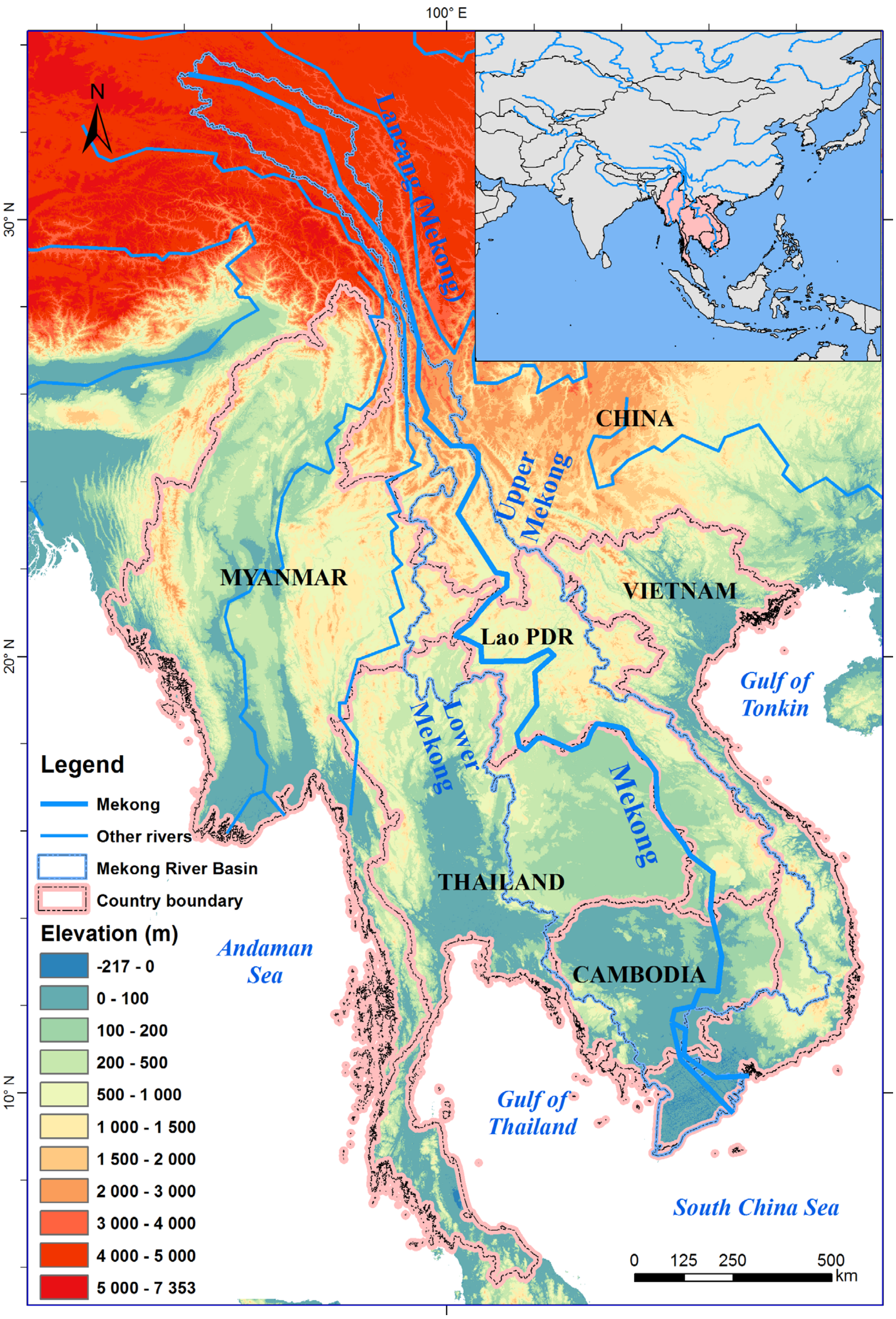

FIGURE 1 Terrain map showing Mainland Southeast Asia

In respect of the MSEA, studies of flood impacts mostly paid attention to Vietnam (Balica, Dinh, Popescu, Vo, & Pham, 2014; Chau et al., 2013; Hung et al., 2012; Ngoc Thuy & Ha Anh, 2015), and Thailand (Gale & Saunders, 2013; Haraguchi & Lall, 2015). For Vietnam, existing studies have focused on flood risk mapping and assessing the impacts on rice production (Chau et al., 2013; Ngoc Thuy & Ha Anh, 2015; Sakamoto et al., 2007). In Thailand, several studies focused on causes and impacts of the extreme flood in 2011 which induced 41 billion USD damage (Gale & Saunders, 2013; Haraguchi & Lall, 2015; MRC, 2015). In addition, concentrating on 10 countries from southern and eastern Asia including, Cambodia, Lao PDR, Thailand, and Vietnam, Osti et al. (2011) identified major responsible environmental and socioeconomic factors for flood damage, and Osti & Nakasu, (2016) analysed causes and effects of 21 serious flood events.

So far, the past studies have seldom assessed the spatiotemporal change of the regional floods in the MSEA. As TC intensity is a critical factor for its impact because the majority of losses arises from intense TCs (Park, Ho, & Kim, 2014; Pielke et al., 2008), increasing TC intensity is predicted in the main source ocean region of TCs landfall in the MSEA over the 21st century by downscaling global climate models, which will affect the MSEA (Emanuel, 2013). Moreover, climate change and socioeconomic growth are expected to push a severe rise of flood risk in Southeast Asia by the end of 21st century (Hirabayashi et al., 2013; Winsemius et al., 2016). Henceforth quantitatively assessment of the historical flood occurrence and impact change are needed for better flood risk management in the MSEA.

Using the Dartmouth Flood Observatory Global Active Archive of Large Flood Events (DFO; http://floodobservatory.colorado.edu/Archives/index.html, last accessed on 15th May 2019), this study aims to investigate the spatiotemporal characteristics of floods occurred in the MSEA for 1985–2018, assess the flood impacts, and quantify the attribution of TC-induced floods. DFO database is a global large flood events database that contains information of each flood event (Brakenridge, 2019). It has been widely used in flood impact assessments, for example, Cunado and Ferreira (2015), Ferreira and Ghimire (2012), and Kundzewicz, Pińskwar, et al., (2012b). Results from this study offer scientific evidences for better understanding of the flood occurrence and impacts on the flood-prone MSEA, and hence offer solid scientific evidence to help the government and relevant decision makers for future flood prevention and mitigation measures. The structure of the following sections is organised as: Data and method are described in Section 2; in Section 3 Results are presented; Discussion and Conclusions are in Section 4 and 5, respectively.

2 | DATA AND METHOD

2.1 | Data

2.1.1 | Floods data

DFO documented any floods from 1985 that is "large" with for example significant damage to structures or agricultures: including country, location, time, affected population and area, flood severity, flood magnitude, and main causes (Brakenridge, 2019). Severity is divided into three discrete classes: 1, 1.5, and 2, to represent the flood recurrence interval and damages (see Table S1). Flood magnitude however also includes flood duration and area extent revealing the critical aspects of floods (Kundzewicz, Pińskwar, et al., 2012b):

$$\text{Magnitude} = \log(\text{Duration} \times \text{Severity} \times \text{Affected area}) \quad (1)$$

As DFO records spatial extent of each flood event, it offers an opportunity for investigating spatial pattern of floods, and has promoted various flood analysis, that is, flood trend and impacts on economy and population (Cunado & Ferreira, 2015; Hu et al., 2018; Kundzewicz, Pińskwar, et al., 2012b). We will evaluate the flood impact on mortality and displacement rate, because economic loss is not recorded in this archive.

Various causes of floods are recorded in the DFO, such as, heavy rain, TCs, extra-TC, dam/levy break or release, tidal surge. To mention that the number of deaths and displacement for TCs in the DFO are totals from all causes, but TCs without significant river flooding are not included (Brakenridge, 2019); 90.0% of mortality by TCs were caused by drowning because of storm surges and floods (Hu et al., 2018; Jonkman, Maaskant, Boyd, & Levitan, 2009; Rappaport, 2000; Rappaport, 2014). Hence, the number of death and displacement for TCs from DFO were treated as impact from TC-induced floods. We investigated two groups of floods: floods by all causes, and TC-induced floods, referred as ALLFloods and TCFloods hereafter, respectively. By definition TCFloods are part of the ALLFloods.

2.1.2 | Gridded population data

The gridded population data used was from the National Aeronautics and Space Administration (NASA) Socioeconomic Data and Applications Center (SEDAC): Global Population Count Grid Time Series Estimates, v1 (GPCv1) (CIESIN, 2011, 2017), and Gridded Population of the World, Version 4 (GPWv4): Population Count, Revision 11 (CIESIN, 2018). GPCv1 provides a back-cast time series of population grids data for every 10 years from 1970 to 2000 (CIESIN, 2011, 2017), and GPWv4 provides estimates of population count data for every 5 years from 2000 to 2020. To match the analysed time period of flood events for 1985–2018, we employed data of 1980–2000 from GPCv1 (1980, 1990, and 2000), and 2005–2020 from GPWv4 (2005, 2010, 2015, and 2020). Data of 2000 was obtained from GPCv1, because of the higher similarity to the national data derived from the World Bank (http://www.worldbank.org/, last accessed on 5th June 2019).

2.1.3 | Flood protection standard

An evolving global database of flood protection standards – FLOodPROtection Standards (FLOPROS) (Scussolini et al., 2016) was used in assistant of analysing flood impact on each country. Based on a wide range of sources and modelling approach, FLOPROS is the first global database of flood protection standards, consisting of information of different spatial scales' flood return period associated with protection measures. Flood return period is defined as the inverse of the annual exceedance probability of flood events. For example, a 100-year return period flood indicates an occurrence likelihood of once a 100 year.

2.2 | Method

To assess flood impact, normalisation for flood loss changes over time and space is necessary (Neumayer & Barthel, 2011). Actually, rising mortality can be attributed by increasing population density instead of increasing flood intensity (Jonkman, 2005; Neumayer & Barthel, 2011; Peduzzi et al., 2012). Interested readers can find more discussion of normalising natural hazards loss in Neumayer and Barthel (2011). As we assessed the flood impact on human live loss and displacement, normalisation of flood impact on humans were based on the gridded population data that was processed as follows. First, estimates for intermediate years' interpolation were derived by calculating the annual exponential growth rate from the available years (Balk et al., 2006; Doxsey-Whitfield et al., 2015). A gridded annual population series from 1985 to 2018 for the MSEA was thus obtained. This newly derived gridded population data was used to calculate the potential influenced population of floods at the corresponding year, defined as the total population number within the flood spatial extent. For instance, potential influenced population of a flood event happened in 1988 was measured by the sum of population numbers within its flood spatial extent by using gridded population data in 1988. We then defined the normalised mortality and displacement rate of each flood event, calculated as (Cunado & Ferreira, 2015; Jonkman, 2005; Neumayer & Barthel, 2011):

$$\text{Mortality} = \log\left(1 + \frac{\text{Number of dead}}{\text{Potential influenced population per million persons}}\right) \tag{2}$$

$$\text{Displacement rate} = \log\left(1 + \frac{\text{Number of displaced}}{\text{Potential influenced population per million persons}}\right). \tag{3}$$

To detect the trend of flood occurrence and impacts, the nonparametric Mann-Kendall trend test for monotonic trends (Kendall, 1938) was applied with a confidence level of 95% ($p < .05$). Besides, Sen's slope (Sen, 1968) was used for measuring trend magnitude. The positive Sen's slope means increasing trend, and vice versa. Both methods have been widely used in meteorological and hydrological time series data trend analysis (Feng & Zhou, 2012; Wu, Wang, Cai, & Li, 2016).

3 | RESULTS

Annual flood number of ALLFloods and TCFloods in the MSEA varied over 1985–2018 (Figure 2). In detail, ALLFloods rose up until 2007 and then fell down, with large variability between 1 and 18, showing significant increasing trend for 1985–2018 ($p < .01$, Figure 2a). TCFloods fluctuated between 0 and 5 over the years with no significant trend. As for the ratio of TCFloods to ALLFloods, it also varied along the years, ranging between 0 and 100%. On average, TCFloods accounted for 24.6% of ALLFloods. The annual distributions of flood numbers present apparent seasonal patterns, with most floods occurring in the wet season during June and November (Figure 2b). ALLFloods reached peak in August–October, whereas TCFloods summitted in October–November. The big error bar indicated by the high standard deviation also reveals large interannual variabilities of floods in the MSEA.

Similar to annual flood numbers, impact areas of ALLFloods and TCFloods fluctuated during the time period with no significant trend (Figure S1). On average, TCFloods' impact area constituted 27.2% of area affected by ALLFloods. The spatial extent of floods for 1985–2018 clearly demonstrates spatial heterogeneous distribution of ALLFloods and TCFloods (Figure 3). ALLFloods scattered across the five riparian countries in the MSEA (Figure 3a), but TCFloods primarily happened in the eastern area by the coast with disproportionately high occurrence in Vietnam (Figure 3b).

In comparison with flood numbers, the annual mean flood indexes had divergent trends during 1985 and 2018 (Figure 4). For ALLFloods, significant increasing trends of annual mean flood severity ($p < .01$, Figure 4a), duration ($p < .05$, Figure 4b), and maximum magnitude ($p < .05$, Figure 4c) were observed, which was accompanied by decreasing trend of flood-induced mortality and displacement rate (the trends were significant for 1988–2018, $p < .05$, Figure 4d,e). For TCFloods, its annual mean severity significantly rose ($p < .05$, Figure 4a), and flood-induced displacement rate decreased (for 1988–2018, $p < .05$). These results suggest reducing trends of normalised flood-induced mortality and displacement rate over the time period; but aberrant peaks in some years occurred with extreme events of high mortalities.

Relationship between flood magnitude and numbers, mortality and displacement rate by every 11 years for 1985–2017 (i.e., 1985–1995, 1996–2006, and 2007–2017) in the MSEA is shown in Figure 5. In general, both ALLFloods and TCFloods were of normal distribution, with the largest flood numbers occurring at magnitude of 5 (Figure 5a); however, their relationships between flood magnitude and numbers were inconsistent. Specifically, for ALLFloods, 1996–2006 was a flood-rich period with the largest flood numbers (42.7% of all floods events for 1985–2017), and more intense flood events at higher magnitudes happened in 2007–2017. 1996–2006 was a calm period with fewer floods for TCFloods; however, more intense floods also occurred in 2007–2017. No clear trends for the flood mortality and displacement rate under the two groups (ALLFloods and TCFloods) at the time periods were found (Figure 5b,c). Nevertheless, higher impacts of TCFloods in the MSEA is found when considering the relative flood impacts. In particular, TCFloods were associated with relatively high mortality and displacement rate than ALLFloods at most of the magnitudes in the same time periods (e.g., 2007–2017).

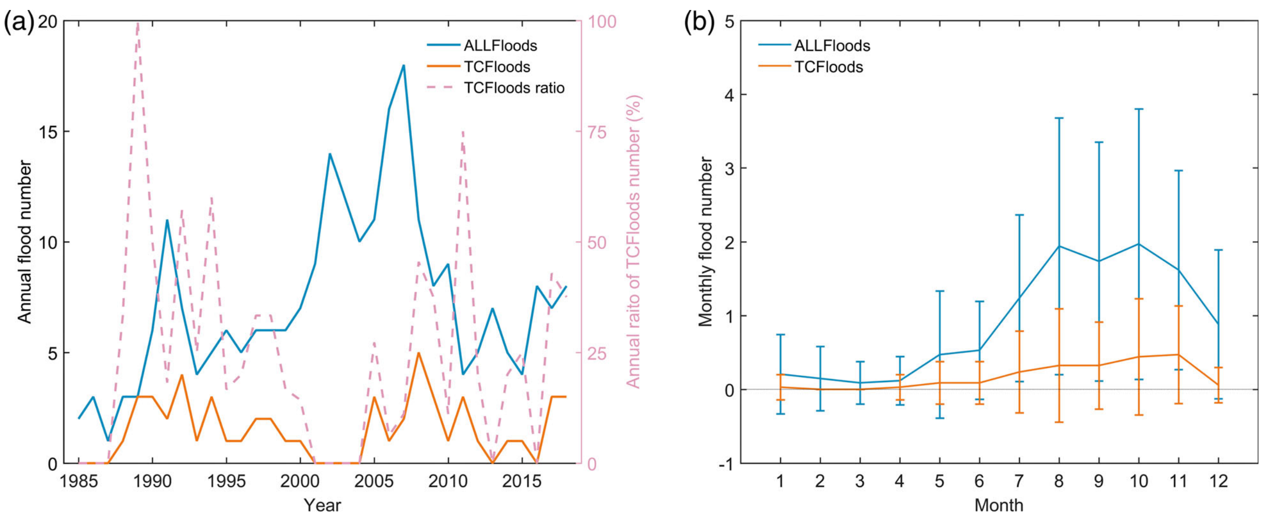

FIGURE 2 Time series of floods in the Mainland Southeast Asia for 1985–2018. (a) annual flood number and ratio of tropical cyclone-induced floods (TCFloods) to floods by all causes (ALLFloods), and (b) annual distribution of floods occurred in the Mainland Southeast Asia. The error bar indicates $a \pm 1$ standard deviation. Data source: the Dartmouth Flood Observatory Global Active Archive of Large Flood Events (http://floodobservatory.colorado.edu/Archives/index.html)

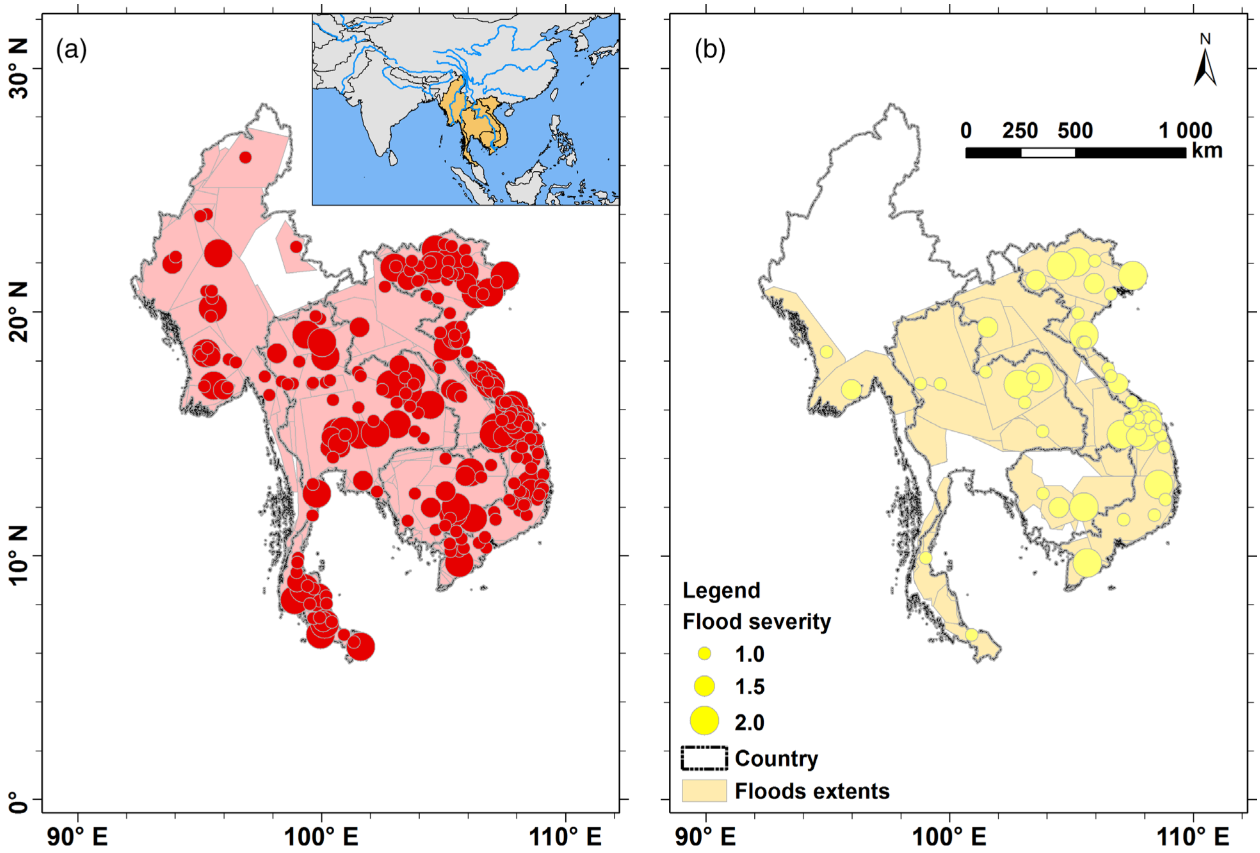

FIGURE 3 Spatial extent of floods and severity in the Mainland Southeast Asia in 1985–2018. (a) Floods by all causes and (b) tropical cyclone-induced floods. The colour filled area indicates the spatial extent of floods. The location of circles denotes the flood centers, and the size of circles indicate the severity of floods. Flood centers and extents happen in such as, Malaysia, and China, are part of the main flooding which are taking place in the Mainland Southeast Asia. Data source: the Dartmouth Flood Observatory Global Active Archive of Large Flood Events (http://floodobservatory.colorado.edu/Archives/index.html)

Time series of annual floods and mortality at country level reveal unevenly distributed flood events among the riparian countries in 1985–2018 (Figure 6). Regarding flood numbers of both ALLFloods and TCFloods, large discrepancies of flood occurrence existed among the countries. Vietnam had the highest flood occurrence (ALLFloods: 3.7 yr^{-1}, and TCFloods: 1.1 yr^{-1} respectively), followed by Thailand, Myanmar, Cambodia, and Lao PDR (Figure 6, and Table S2). TCFloods constituted 29.8% of ALLFloods in Vietnam (21.4% in Cambodia, 16.7% in Lao PDR, 11.7% in Thailand, and 7.7% in Myanmar, respectively). Although the sequence of flood mortality in the five countries was similar to flood occurrence, flood mortalities in Myanmar and Cambodia were not in parallel with their flood occurrences. For example, both ALLFloods and TCFloods occurred less often in Myanmar, which were 21.0% and 5.4% of Vietnam's floods occurrence, respectively; however, mortality of ALLFloods and TCFloods in Myanmar were 34.4% and 24.3% of Vietnam's, respectively. This means that the flood-induced mortality rate in Myanmar was higher than Vietnam, in terms of per flood occurrence. Furthermore, TCFloods in the five countries were associated with high mortality rate as the ratio of TCFloods mortality to ALLFloods mortality was much higher than the ratio of TCFloods occurrence to ALLFloods occurrence generally. Specifically, 30.0% of TCFloods occurrence in Vietnam led to 64.0% of the flood mortality, and in Myanmar 8.0% of TCFloods occurrence was linked with 45.0% of the flood mortality.

The spatial patterns of annual flood frequency for 1985–2018 also display different spatial flood occurrence (Figure 7). ALLFloods took place in all five riparian countries (Figure 7a), but TCFloods mainly occurred in Vietnam and Thailand (Figure 7b). This is similar to the spatial flood extents (see Figure 3). Both ALLFloods and TCFloods had highest annual frequency in central Vietnam, with a value of 1.3 yr^{-1} and 0.6 yr^{-1}, respectively. However, the ratio of TCFloods to ALLFloods showed divergent spatial pattern that high ratio from TCFloods was located in the Northern Lao PDR and North Vietnam (Figure 7c). Except Myanmar, TCFloods widely contributed to ALLFloods spreading over

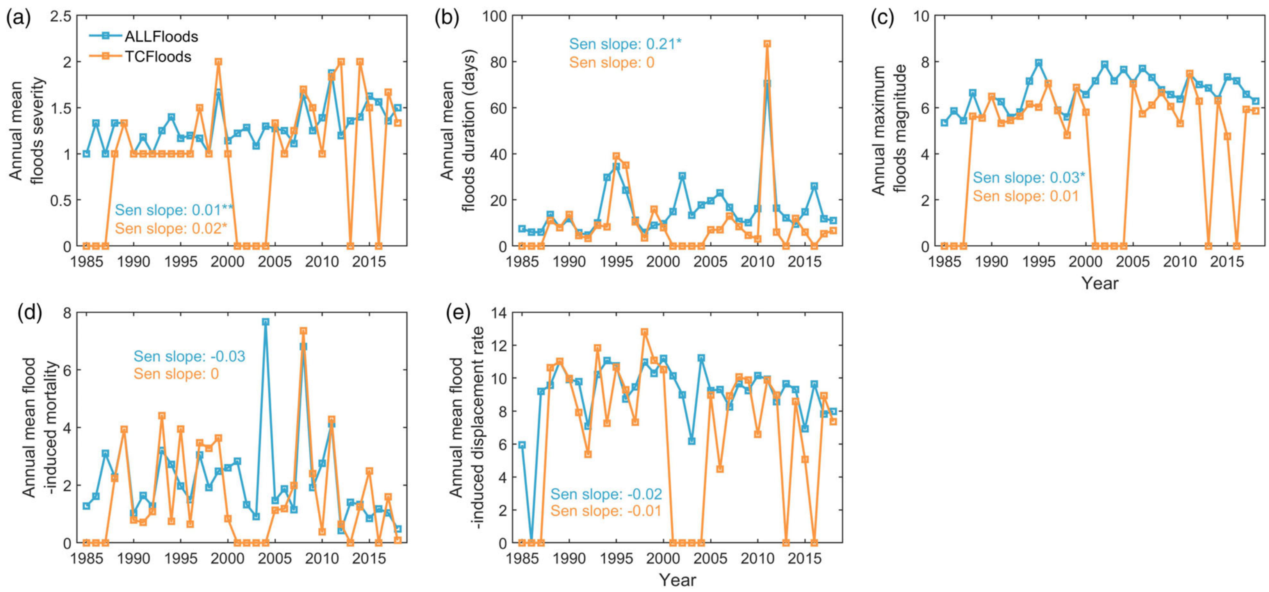

FIGURE 4 Time series of annual mean floods indexes in the Mainland Southeast Asia for 1985–2018. (a) Severity, (b) duration, (c) maximum magnitude, (d) mortality, and (e) displacement rate. ALLFloods represent floods by all causes, and TCFloods represent tropical cyclone-induced floods. *, **: Statistically significant Sen slope were defined as those $p < .05$, and $p < .01$, respectively

the MSEA. Similar spatial patterns were also observed in terms of annual mean flood frequency of all floods with high flood magnitude (flood magnitude equals to and greater than 5) (Figure S2). Respecting the proportion of high magnitude flood to all floods, on average, 89.1% area in the MSEA experienced more than 80.0% of high magnitude floods, indicating a wide impact of high magnitude floods in this region.

4 | DISCUSSION

Precipitation is the most notable factors affecting floods (Kundzewicz, Kanae, et al., 2012a). Located at the intersection area of the Indian Summer Monsoon, East Asian Monsoon, and Western North Pacific Monsoon (Darby, Leyland, Kummu, Räsänen, & Lauri, 2013; Delgado, Merz, & Apel, 2010; Räsänen & Kummu, 2013), precipitation over the MSEA is strongly influenced by large scale atmospheric circulations, including the El Niño-Southern Oscillation (Räsänen & Kummu, 2013; Räsänen, Lindgren, Guillaume, Buckley, & Kummu, 2016) and the Pacific Decadal Oscillation (Delgado, Merz, & Apel, 2012). TC landfall in the MSEA is also correlated with such large scale atmospheric circulations (Goh & Chan, 2010; Wang, Huang, & Wu, 2013). Induced by for example, heavy monsoonal rainfall and TC rainfall, flood occurrence over the MSEA are strongly influenced by large scale atmospheric circulations (Jongman et al., 2014; Ward, Eisner, Flo Rke, Dettinger, & Kummu, 2014).

Driven by different climate factors, floods from TCs and other causes present divergent spatial distributions in the MSEA. As monsoon rainfall is a main cause for floods in the MSEA (Delgado et al., 2010), ALLFloods scatter over the MSEA spatially (see Figures 3 and 6). TCFloods mostly occur in the eastern MSEA, because TCs landfall in the MSEA are primarily from the Western North Pacific and South China Sea via Vietnam coastline (MRC, 2015). TCs from the North Indian Ocean/ Bay of Bangel contribute relatively less to the total amount of precipitation in MSEA (Chen, Ho, Chen, & Azorin-Molina, 2019). The timing of monsoon and TC landfall also lead to different peaks of ALLFloods and TCFloods (Chen et al., 2019; Nguyen-Thi, Matsumoto, Ngo-Duc, & Endo, 2012; Wang & Chan, 2002). Respecting the insignificant trend of annual TCFloods in 1985–2018, it can be partly explained by insignificant trend of landfall TC intensity for 1979–2010 (Park et al., 2014), regardless the significant decreasing TC landfall number and duration in the Mekong River Basin (Chen et al., 2019).

In general, TCFloods pose higher impact on the MSEA than ALLFloods do. Occurring in the late monsoon season and carrying heavy rainfall, TCs often result in floods in the MSEA due to the highly spatiotemporal concentrated TCs (Chen et al., 2019; MRC, 2015), even though annual TC-induced rainfall does not contribute much to total precipitation in this area (Chen et al., 2019). Aberrant peaks of flood-induced mortality and displacement rate caused by TCs also indicate extreme impact from uncommon TCFloods events

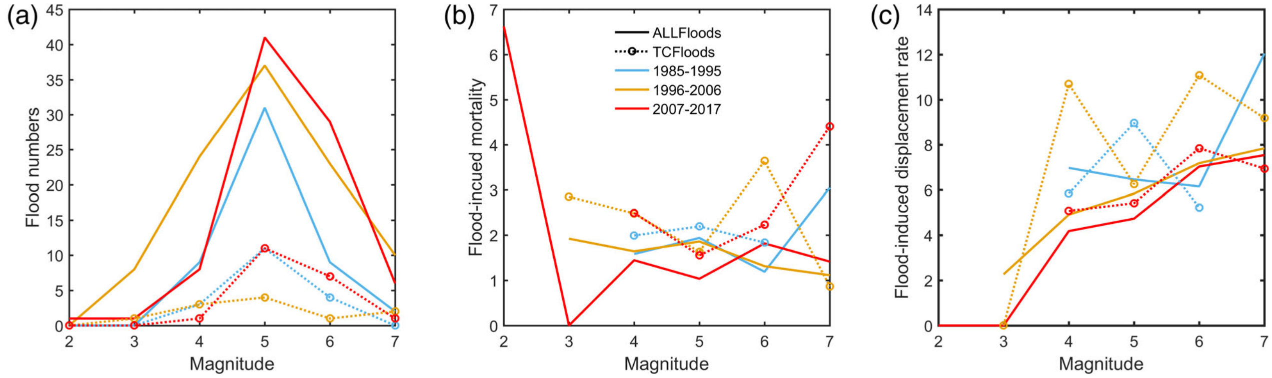

FIGURE 5 Relationship between flood magnitude and other flood indexes by every 11 years: 1985–1995, 1996–2006, and 2007–2017 in the Mainland Southeast Asia. (a) Flood numbers, (b) mortality, and (c) displacement rate. The blue, orange, and red colour denote the time period of 1985–1995, 1996–2006, and 2007–2017, respectively. The solid line represents floods by all causes (ALLFloods), and the dashed line with circle marker represents tropical cyclone-induced floods (TCFloods)

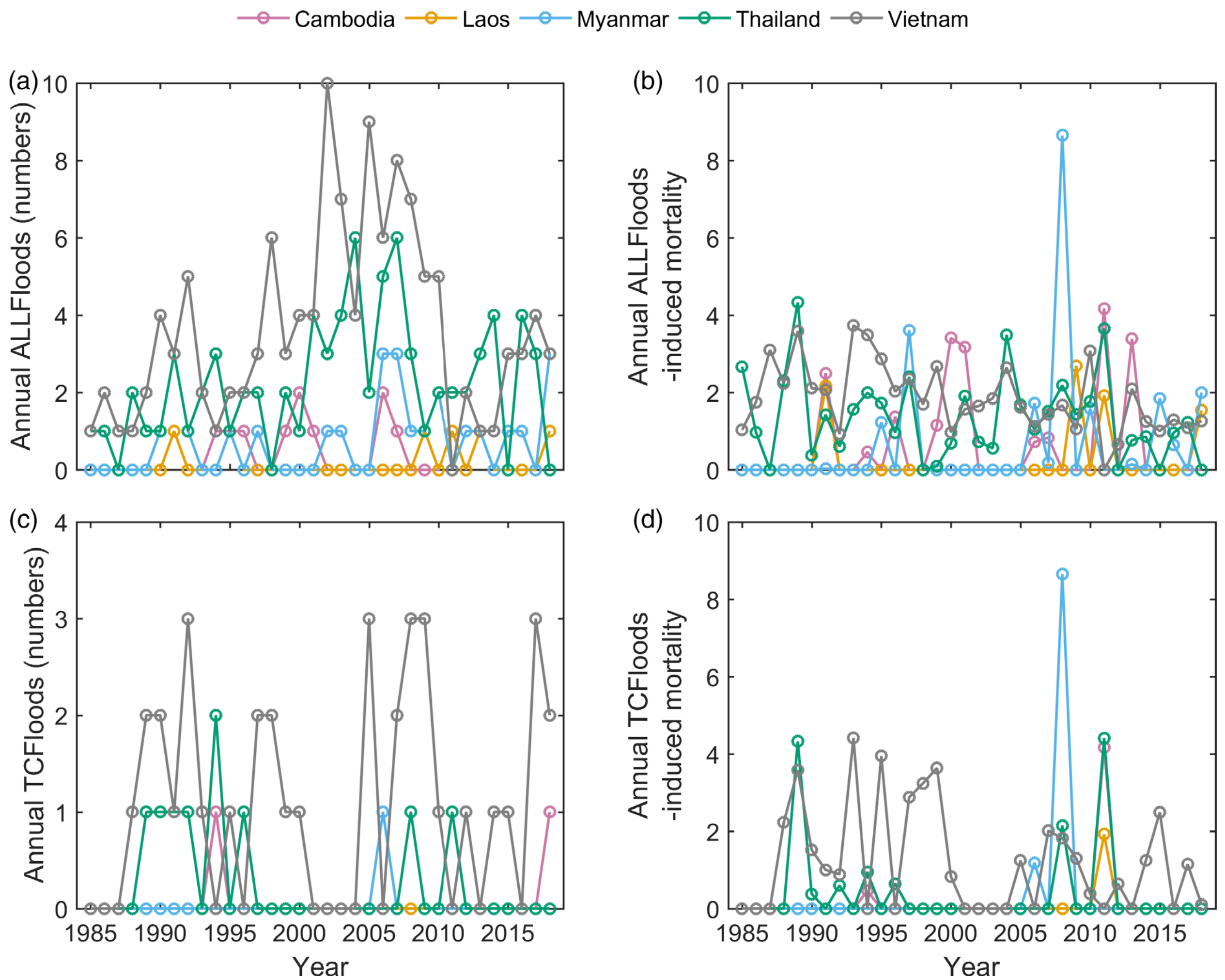

FIGURE 6 Time series of annual floods and mortality on riparian countries of the Mainland Southeast Asia for 1985–2018: Cambodia, Lao PDR, Myanmar, Thailand, and Vietnam. (a) floods by all causes (ALLFloods), (b) ALLFloods-induced mortality, (c) tropical cyclone-induced floods (TCFloods), and (d) TCFloods-induced mortality

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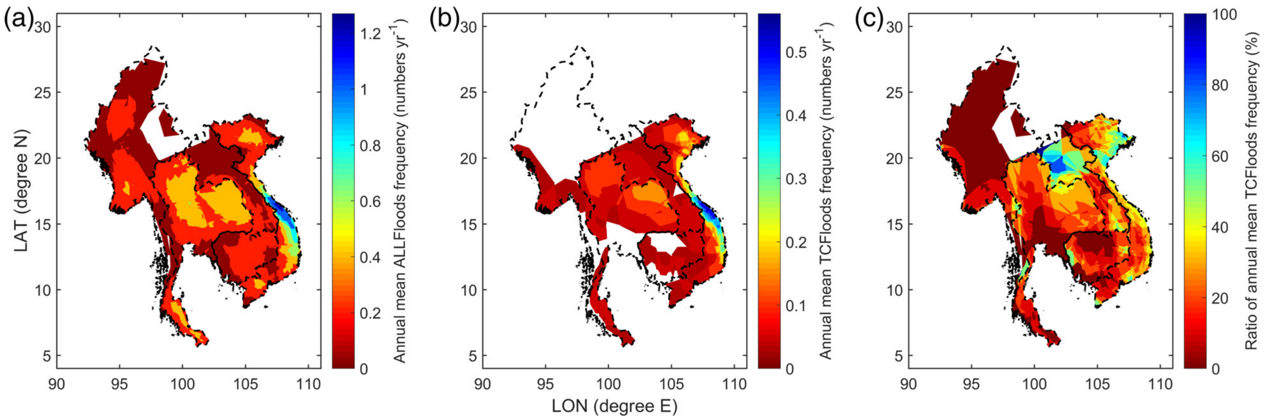

FIGURE 7 Spatial pattern of annual mean flood frequency in the Mainland Southeast Asia for 1985–2018. (a) floods by all causes (ALLFloods), (b) tropical cyclone-induced floods (TCFloods), and (c) ratio of TCFloods frequency to ALLFloods frequency

(Doocy, Dick, Daniels, & Kirsch, 2013). For example, extremely severe Cyclone Nargis in 2008 induced storm surge that caused exceptional flood event over densely populated area in Myanmar and claimed more than 138,000 fatalities; however, slow disaster relief operations exacerbate the tragedy (Swiss Reinsurance Company Ltd, 2009).

Our results show that flood occurrence and the impact distribution on countries do not match. In particular, fewer floods take place in Myanmar, but its flood-induced mortality rate is higher than other countries. In fact, flood protection standards in the MSEA show divergent distributions among and within the five countries including Cambodia, Thailand, and Vietnam (Figure 8a). Generally, the low flood protection standards in Myanmar (2.2 years flood return period on average) and less experience with tackling floods can be major reasons for such high flood impacts. The high flood protection standards in Thailand (17.9 years return period) among the five countries is an essential means of diminishing the magnitude of overall flood losses (Jongman et al., 2014; Palmer, 2013; Scussolini et al., 2016). Though Vietnam has a national flood protection standard of 10.4 years, some of the provinces in Vietnam with high flood occurrence are facilitated with higher protection standards ranging from 10 to 120 years floods. In particular, Thừa Thiên Huế province in the central Vietnam where the highest flood frequency occurs has a flood protection standard of 52.0 years return period, and Vietnam's capital and second largest city (Hanoi) has the highest flood protection standards of 120.0 years return period that experiences more TCFloods. Except the Phnom Penh area, both Cambodia (3.4 years return period) and Myanmar basically have no sufficient flood protection standards.

Overall, the existing flood protection standards in the five countries of MSEA are not yet capable for preventing high magnitude flood events as they suffer from high mortality induced by floods. In combination with population distribution in 2015 in the MSEA (Figure 8b), the higher flood protection standards are taken in high population density large cities (i.e., Phnom Penh in Cambodia, Hanoi in Vietnam, Bangkok and other a few cities in Thailand). However, many areas with high population density and flood occurrence such as Yangon Division in Myanmar, Vientiane in Lao PDR, and Mekong Delta in Vietnam are lacking sufficient flood protections. The Mekong Delta in particular is facing challenge from the sea rise and land subsidence (Erban, Gorelick, & Zebker, 2014).

Overall, floods are joint results of climate and socioeconomics. For instance, the combined influence of unusual high rainfall from monsoon and tropical storms, high exposure of population and economic values, and poor water governance, caused the extreme flood hit Thailand in 2011, which is ranked as the country's most damaging flood to date (Gale & Saunders, 2013; Haraguchi & Lall, 2015). Considering the intensifying future TC landfall (Emanuel, 2013) and increasing future floods in the MSEA (Hirabayashi et al., 2013; Hoang et al., 2016; Shrestha & Lohpaisankrit, 2017), the emerging economics and fast urbanisation will add more exposures to future floods (Winsemius et al., 2016). Hence, the livelihood of millions of people living in the MSEA are under the pressure of future floods. On the one hand, future studies should include both socioeconomic development and climate change into flood projections; on the other hand, necessary measures and adaptations are urgent for mitigating the potential impacts from floods, including building higher standard of flood protection especially in vulnerable areas with high population density and flood occurrence, such as Yangon Division in Myanmar, Vientiane in Lao PDR, and Mekong Delta in

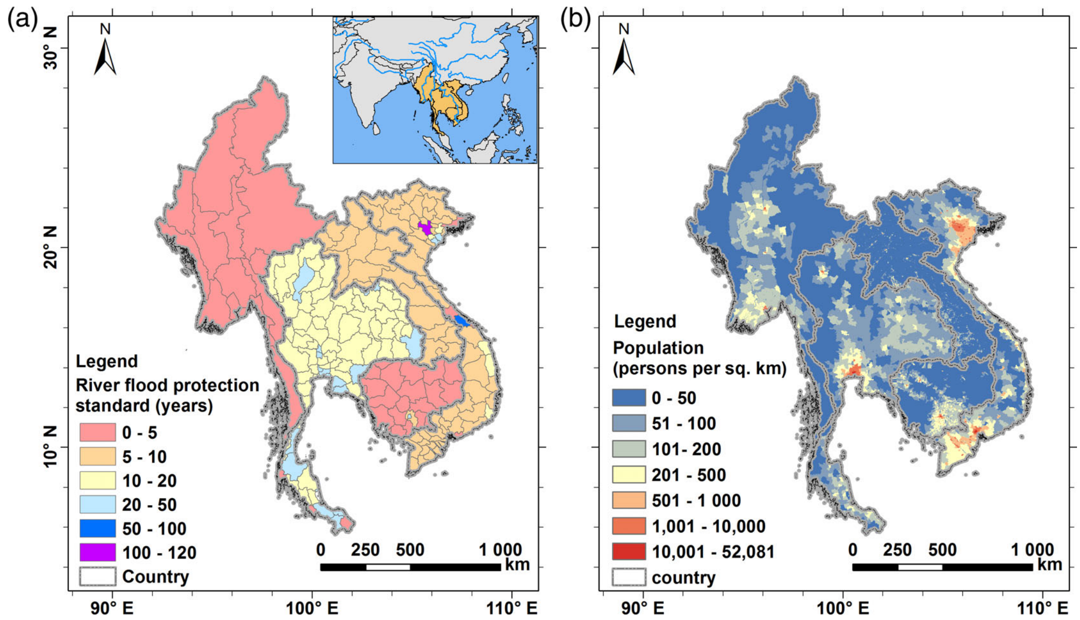

FIGURE 8 Spatial pattern of flood protection standards and population count in the Mainland Southeast Asia. (a) flood protection standards (years) and (b) gridded population in 2015 (persons per km^2). The flood protection standards data is FLOodPROtection Standards (FLOPROS) from Scussolini et al. (2016). Population data is Gridded Population of the World, Version 4 (GPWv4): Population Count, Revision 11 (CIESIN, 2018)

Vietnam; and improving governance qualities of early warning system and post-disaster reconstruction (Osti et al., 2011).

Many existing flood impact assessments focus on either individual flood event by using climatic or hydrological indicators to investigate the impact area of floods, that is, extreme precipitation/discharge (Pielke & Downton, 2000; Räsänen & Kummu, 2013; van der Wiel et al., 2018). Research related to TCFloods are also mainly about individual event (Takahashi, Fujinami, Yasunari, Matsumoto, & Baimoung, 2015). Meanwhile, many studies use gridded population to assess the impacts of the floods (Osti et al., 2011). These studies however, fail to portray the actual impacts of floods. In other words, the extreme discharge can be an indicator for exploring potential floods, but it does not contain information of the local inundation information (Kundzewicz, Kanae, et al., 2012). The complicated relationship between rainfall and flood response in a catchment, depending on for instance the catchment topography, land use and land cover change, and antecedent conditions (Gale & Saunders, 2013; Kundzewicz, Kanae, et al., 2012a), large amount of rainfall does not always result in floods. Moreover, flood impact is not only related to hydro/meteorological factor, because flood-associated damage is a function of flood intensity, exposure, governance, and flood protection standards (Kundzewicz, Kanae, et al., 2012a; Osti et al., 2011; Osti & Nakasu, 2016; Schumacher & Strobl, 2011). Therefore, only considering the extreme climatic/hydrological indicators with the help of gridded population information cannot explicitly detect the actual impacts on humans.

The DFO archive which actively records information of any "large" floods occurring in the world, deriving from news, governmental, instrumental, and remote sensing sources (Brakenridge, 2019), is a dataset that contains floods joint attributed by natural and socioeconomic factors. By employing the DFO, we are able to investigate the spatiotemporal characteristics of floods occurred in the MSEA, and assess the associated impact on human mortality and displacement.

5 | CONCLUSIONS

Using the DFO large flood data archive, this study quantitatively assessed flood occurrence in the MSEA for 1985–2018, and the associated impacts on human mortality and displacement. The contribution of TC landfall-induced floods was also quantified. The conclusions are shown as follows:

- Floods occurrence and maximum magnitude of ALLFloods significantly increased for 1985–2018 ($p < .01$), but not for TCFloods;
- Impacts on mortality from ALLFloods (TCFloods) significantly decreased for 1985–2018 (1988–2018); however, they were associated with uncommon high-impact flood events;

- TCFloods accounted for 24.6% of ALLFloods occurrence on average, which was spatially heterogeneous with high contribution in Northern Lao PDR, and North Vietnam;
- TCFloods had higher mortality and displacement rate than ALLFloods;
- Myanmar and Cambodia suffered higher flood-induced mortality, despite of fewer flood occurrence. This was at least partly caused by the low flood protection standards in these two countries.

With the investigating of flood occurrence and impacts, this study offers scientific evidences for a better flood risk management. We recommend that the riparian countries in the MSEA should take action in building high standard of flood protection in vulnerable areas such as Mekong Delta, and investing in early flood warning system, to mitigate impacts from future floods.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

These data were derived from the following resources available in the public domain: The flood data that supports the findings of this study is available in the Dartmouth Flood Observatory Global Active Archive of Large Flood Events at http://floodobservatory.colorado.edu/Archives/index.html. The gridded population data that supports the findings of this study is from the National Aeronautics and Space Administration (NASA) Socioeconomic Data and Applications Center (SEDAC): Global Population Count Grid Time Series Estimates, v1, and Gridded Population of the World, Version 4 (GPWv4): Population Count, Revision 11 at https://sedac.ciesin.columbia.edu/. The global database of flood protection standards data that supports the findings of this study is available in the FLOodPROtection Standards (FLOPROS) (Scussolini et al., 2016).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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