Risk assessment of rainstorm disasters in the Guangdong–Hong Kong–Macao greater Bay area of China during 1990–2018

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ABSTRACT
With climate change and urbanization, the rainstorm disaster has become one of the major climate risks in constructing the Guangdong–Hong Kong–Macao Greater Bay Area (GBA). Based on daily precipitation, socio-economic data and a comprehensive evaluation method, the characteristics and risks of rainstorm disaster in the GBA at county level are investigated in this paper. Considering the hazard, vulnerability and exposure, the risks of rainstorm disasters are high (Level 3) and very high (Level 4) in Zhuhai, Zhongshan, Dongguan, Jiangmen and Shenzhen. From 1990 to 2018, the frequency and intensity of rainstorms in the GBA have increased by 10 times and 2 mm per decade, respectively. Moreover, the population, gross domestic product, and built-up areas have increased significantly in the GBA, while the vegetation coverage has decreased. The combination of these changes results in an increase in the frequency of rainstorm disasters by two times from 2005 to 2018 compared with that from 1990 to 2004. The findings of this study can provide a positive reference for local governments to improve the pertinence of the strategies for rainstorm disaster prevention and mitigation.

1. Introduction

In recent years, climate change has resulted in frequent extreme rainstorm events in coastal cities (IPCC 2014; Canter et al. 2014; Silva et al. 2017), which has seriously restricted the comprehensive, coordinated and sustainable development of the economy and society (Zhou et al. 2017; Demirdjian et al. 2018; Kang et al. 2018; Lyu et al. 2018). At the same time, land cover change, sea level rise, inadequate drainage...
facilities and emergency management furtherly exacerbate the vulnerability of rainstorm disasters in coastal cities (Reguero et al. 2015; Vousdoukas et al. 2018; Islam and Raja 2021). For example, from 2001 to 2018, rainstorm disasters affected more than 40 million people and caused more than $10 billion in economic losses each year in urban areas of eastern China (Sun et al. 2020).

Rainstorm disasters cover flood and waterlogging caused by excessive precipitation. The rainstorm disaster risk refers to the expected losses of human property and socioeconomic development caused by the flood and waterlogging (Li et al. 2020) and it is determined by the hazard, as well as the exposure and vulnerability (Cardona et al. 2012; Ahmad and Simonovic 2013; Kim and Marcouiller 2017; UNDRR 2019; Islam and Raja 2021). Recently, Scholars have made significant achievements in rainstorm disaster risk assessment in China (Zhou et al. 2019). For example, Sun et al. (2020) revealed the spatial pattern of waterlogging risk in 89 cities of eastern China by comprehensive analyses on extreme rainfall, exposure and urban adaptability. Ma et al. (2021) established an assessment index system based on urban vulnerability, adaptability and resilience to achieve multi-regional quantitative assessment of urban rainstorm and flood disasters in China. Moreover, some studies investigated the vulnerability and risks of flood disasters in a single city. For instance, Quan et al. (2014) indicated that the water depth, vulnerability, and economic losses in Shanghai tend to increase as the rainstorm intensity increases based on hydrological modeling and a geographic information system. Hu (2016) used a genetic programming algorithm to accomplish the risk zoning of rainstorm flood disasters in Beijing, and revealed that the risk values are higher in urban areas.

Guangdong–Hong Kong–Macao Greater Bay Area (GBA), as one of three megacity clusters in China, is located in the lower reaches of the Pearl River Basin and the central coastal region of Guangdong Province. In the context of global warming and urbanization, extreme precipitation and heavy precipitation days in the Pearl River Basin showed increasing trends since 1960 (Zhao et al. 2014; Liu et al. 2016). Since 1990, the frequency of regional heavy rainstorm processes in Guangdong has significantly increased by 0.21 times per decade (Wu et al. 2019). During 1961–2019, the number of heavy (daily precipitation ≥ 25 mm) and very heavy (daily precipitation ≥ 50 mm) precipitation days, the extreme precipitation amount, maximum 1-day precipitation amount and maximum 5-day precipitation amount have increased by 0.6 days·10a⁻¹, 0.2 days·10a⁻¹, 12.5 mm·10a⁻¹, 0.7 mm·10a⁻¹ and 3.5 mm·10a⁻¹, respectively in GBA (Wang et al. 2021a). During 2010–2018, extreme precipitation in Guangdong caused a total direct economic loss of 49 billion yuan (Zhang et al. 2021). For example, the areal precipitation of 479.2 mm from June 12 to 24, 2005 caused a 100-year-return-period flood disaster in the West River and North River of the Pearl River Basin, which affected 4.4 million people, causing the deaths of 65 people and direct economic losses of 5 billion yuan in Guangdong (Guangdong Meteorological Service 2006).

Moreover, rapid population growth, unplanned urbanization, and climate extremes are the major triggering factors making rainstorm waterlogging disasters more frequent in recent years in the GBA (Xiao et al. 2013; Chen et al. 2015). Since China’s reform and opening-up in 1978, the GBA has experienced remarkable urbanization, resulting in a dramatic change in land use from vegetative cover to construction land
The urban impervious area in the GBA has increased from 12,129 km$^2$ in 2006 to 20,189 km$^2$ in 2016, with an annual growth rate of 6.65% (Feng and Fan 2018). Currently, urban rainstorm waterlogging has become an ‘urban agglomeration disease’ that must be mitigated by local government and urban agglomeration planning agencies in the planning and construction stages of the GBA (Liu et al. 2016). For example, the 3-h precipitation with 586 mm broke historical record in Zengcheng District of Guangzhou on May 7, 2017, resulting in 6 deaths as well as 118 spots of central city zone and 1,409 vehicles flooded. In this disaster, the direct economic loss was about 540 million yuan (Zhang et al. 2019).

Recently, several scholars investigated the vulnerability and risks of flood disasters in the Pearl River Delta (Yang et al. 2015; Wang et al. 2017; Zhang et al. 2019) or in a single city of the GBA such as Guangzhou (Li et al. 2014; Chen et al. 2015) and Shenzhen (Zhou et al. 2017). Li et al. (2019) coupled hydrological and hydrodynamic models to simulate and assess risk and sensitivity of flash floods in a mountainous river basin of South China. Lin et al. (2020) improved analytic hierarchy process method and integrated maximum likelihood clustering algorithm to assess the flash flood risk in Guangdong province. Liu et al. (2016) applied the kernel density estimation and the spatial autocorrelation analysis to reveal the driving factors for rainstorm waterlogging in the GBA during 2013–2017. It is found that all of the driving factors enhance the impacts on rainstorm waterlogging through their interactions. Although there have been a lot of studies on rainstorm disasters risk assessment, there are still some research problems to be addressed. For instance, how to construct a comprehensive or systematic risk index to make the index reasonable? Are there any spatial differences in various driving factors of rainstorm disasters in the GBA? At county level, where are the areas with high risks of rainstorm disasters in the GBA?
Based on the above reasons, it is of great practical significance to analyze rainstorm disaster risks to reduce the disaster losses in the GBA. In this paper, we select 48 counties of the GBA as evaluation objects and proposed a comprehensive index for rainstorm disasters. This study aims to obtain a risk map at county level in the GBA. The risk assessment and zoning of rainstorm disasters can provide a scientific reference for mitigation measures and risk management strategies in the GBA, and also serves as a method reference for those well-developed regions in the world.

2. Study area

Located near the Pearl River Estuary, the GBA is surrounded by the South China Sea to the south and by mountains on other three sides, with a long coastline and complex natural geographical conditions. The terrains of the GBA are high in the north and low in the south. The central-southern GBA is mainly featured by alluvial plains, where the major cities of the GBA are located. The GBA is composed of two Special Administrative Regions (Hong Kong and Macao) and 9 cities (Guangzhou, Foshan, Zhaoqing, Shenzhen, Dongguan, Huizhou, Zhuhai, Zhongshan and Jiangmen) including 48 districts and counties, as shown in Figure 1. It covers an area of 56,000 km² and has a population of more than 70 million. The drainage network in the GBA includes the three main tributaries of the Pearl River, namely, West River, North River and East River.

The GBA is located at a subtropical monsoon climate region, with the annual temperature averaged during 1981–2010 being 22.2°C, the monthly temperature being highest in July (28.7°C) and lowest being in January (13.9°C), as shown in Figure 2. In addition, the average annual precipitation in the GBA is 1874 mm, but the precipitation is unevenly distributed among different seasons, with less precipitation in winter and more precipitation in summer. Due to favorable configuration of water vapor, heat and dynamic conditions, this region has a long rainy season when rainstorms with strong intensity frequently occur, which causes severe disasters that affect widespread areas (Zhou et al. 2019).

3. Data and method

3.1. Data

The daily precipitation data during 1990–2018 is from 29 meteorological stations in the GBA of the Chinese mainland. It is derived from the National Meteorological
Information Centre of China Meteorological Administration (CMA), which is subjected to strict data quality control (Ren et al. 2012). In the classification of meteorological disasters by the CMA, disasters caused by typhoon-induced rainstorms are categorized as typhoon disasters. Therefore, the rainstorm disasters investigated in this study are those caused by non-typhoon related rainstorms (hereinafter referred to as the rainstorm disaster).

The digital elevation model (DEM) data and river data with a spatial resolution of 1 km used in this study paper are derived from the terrain database at a scale of 1:250,000 from the National Geomatics Center of China (Wang et al. 2001). The 1-km land use data is from the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (Xu et al. 2018), and the vegetation coverage data is calculated based on the Normalized Difference Vegetation Index (NDVI) product (1-km resolution) from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Didan 2015). The population and gross domestic product (GDP) data with a spatial resolution of 1 km in the GBA are from the Resources and Environmental Science and Data Center, Chinese Academy of Sciences (http://www.resdc.cn/Default.aspx).

3.2. Methods

The rainstorm disaster risk index consists of three indexes, namely, the hazard index \( H \), the exposure index \( E \) and the vulnerability index \( V \), as shown in Eq. (1) (Cardona et al. 2012):

\[
\text{Risk} \ (R) = \text{Hazard} \ (H) \times \text{Exposure} \ (E) \times \text{Vulnerability} \ (V) \tag{1}
\]

By utilizing the hazard, exposure, and vulnerability assessments, a rainstorm disaster risk map is developed for the GBA at the county level for the first time. The
schematic diagram of components for assessing rainstorm disaster risk is presented in Figure 3. The detailed methods for hazard, exposure, vulnerability and risk index are described in the following sections.

In order to make the scales of different indexes comparable, the normalization method of all elements in this study is as follows (Eq. 2) (NCC 2009).

$$D_i = 0.5 + 0.5 \times \frac{A_i - min_i}{max_i - min_i}$$  

where $D_i$ denotes the normalized value of the $i$ th element, $A_i$ the $i$ th element value, $min_i$ the minimum of the $i$ th element, and $max_i$ the maximum of the $i$ th element.

### 3.2.1. Hazard index

The hazard of rainstorm disasters is mainly determined by the intensity and frequency of rainstorms. Generally, the greater the intensity and the higher the frequency, the more the losses caused by rainstorm disasters. According to the Grade of precipitation issued by the CMA (GB/T 28592-2012), the day with the daily precipitation amount greater than or equal to 50 mm at a meteorological observation station is regarded as a rainstorm day. In addition, if the number of consecutive rainstorm days recorded at a single station is greater than or equal to one day, or there is no more than one day with the precipitation amount reaching the moderate rain level ($\geq 10 \text{ mm}$ and $< 50 \text{ mm}$) between two rainstorm days, it is recorded as a rainstorm process. The hazard index ($H$) of rainstorm disasters reflects the danger level of a rainstorm process. There are some other hazard indexes for rainstorm processes (Ren et al. 2012; Ye et al. 2019), but they are quite similar. In this study, the hazard index is calculated by Eq. (3) (Ye et al. 2019).

$$H = I \cdot \sqrt{D}$$  

where $I$ denotes the intensity of a rainstorm process, which is expressed by the average daily precipitation during the rainstorm process; $D$ represents the duration of a rainstorm process, which is expressed by the number of days that the rainstorm process lasts.

Based on comprehensive consideration of the study period (~30 years) and the uncertainty in return period calculation, the hazard index value of 20-year return period is selected to represent the danger level of rainstorm disasters (Kharin et al. 2013; Sillmann et al. 2013), which is estimated through the generalized extreme value distribution.

### 3.2.2. Exposure index

Many existing researches adopt the population density or per unit of GDP as the exposure indicator, especially for grid-based risk assessments (Wu et al. 2011; Li et al. 2021). In this research, both the two indicators of per unit of population and GDP at 1-km grid spacing in the GBA are used to establish the socio-economic exposure index ($E$), which is calculated with equal weight after normalization, as shown in Eq. (4) (Sun et al. 2020).
$E = 0.5 \times \text{POP} + 0.5 \times \text{GDP}$, \hspace{1cm} (4)

where $\text{POP}$ denotes the population data per square kilometer.

### 3.2.3. Vulnerability index

There are significant differences in the understanding and definition of vulnerability among scholars, and most of them believe that the vulnerability is a combination of natural and human factors (Cardona et al. 2012). In this study, the vulnerability refers to the sensitivity of geographical environment to rainstorm disaster (NCC 2009). For rainstorm with the same intensity, the higher the sensitivity of disaster–pregnant environment, the more the losses caused by rainstorm disasters. Numerous researches have indicated that terrain, land cover/land use, river network density, infrastructure, and drainage pipeline density are natural factors driving the frequent occurrence of rainstorm disaster (Sun et al. 2020; Islam and Raja 2021; Li et al. 2021; Wang et al. 2021b). Here, we adopt the terrain ($T$), river network ($R$) and vegetation coverage ($C$) to characterize the integrated vulnerability of rainstorm disaster–pregnant environment. The terrain and drainage network are positive contributors to increase rainstorm disaster vulnerability, while the vegetation coverage is a negative contributor. Considering different contributions of the three indicators to the sensitivity of rainstorm disaster–pregnant environment, the weighting coefficients for $T$, $R$ and $C$ are respectively set as 40, 30, and 30% based on the expert scoring method. The expert scoring method is mainly based on the results of questionnaires to determine the weight of each evaluation index through the hundred-mark system (He et al. 2008). Note that in this study, 10 questionnaires are collected from experts with abundant knowledge and practical experiences.

The vulnerability index ($V$) can be calculated by Eq. (5) (NCC 2009).

$$V = 0.4 \times T + 0.3 \times R - 0.3 \times C.$$ \hspace{1cm} (5)

#### 3.2.3.1. Terrain.

Elevation and slope are considered to be two influencing factors for rainstorm disasters (Meraj et al. 2015; Bui et al. 2016). In general, rainstorm disasters tend to occur in regions with relatively lower elevations and flatter slopes. Therefore, in this study, the two topography factors of the absolute elevation and slope are selected to represent the terrain characteristics. Slope is expressed by the standard deviation of elevation with a grid spacing of 1 km. The terrain index ($T$) is assigned according to different combinations of the absolute elevation and the standard
deviation of elevation graded by experts. The lower the elevation and the smaller standard deviation of elevation, the greater the $T$ and the more sensitive the rainstorm disasters. The specific assignment scheme is shown in Table 1, which refers to the technical specification for risk zoning of rainstorm and flood disaster (NCC 2009).

**3.2.3.2. River network.** River density and distances from waterbodies are common factors charactering the drainage network (Liu et al. 2019; Sun et al. 2020). The places with greater drainage density and closer to rivers, lakes, and large reservoirs are at a higher risk of rainstorm disasters. A local standard in Zhejiang, i.e., the Assessment technical specification for the risk level of rainstorm processes (DB33/T 2025-2017), specifies that the total length of the rivers within 1 km $\times$ 1 km is adopted as the drainage density of the central grid point, and the distances to water bodies can be obtained by calculating the buffering function zones through the Geographic Information System. Buffer zones categorized into three levels of 4, 8 and 12 km are assigned with 0.9, 0.8 and 0.7, respectively. In addition, the value for non-buffer zones is assigned with 0.5. After normalizing the drainage density and the impacts of buffer zones, the river network index ($R$) is obtained by the weighted average method, with a weight of 0.5 for each factor (NCC 2009).

**3.2.3.3. Vegetation coverage.** Green space is the typical land use/land cover type that can characterize surface permeability, and has a negative impact on rainstorm disasters (Liu et al. 2021). Since the vegetation has a strong function of water and soil conservation, the higher the vegetation coverage, the lower the risks of rainstorm disasters. Vegetation coverage refers to the percentage of the area with vegetation to the total land area. Based on the meteorological industry standard QX/T494-2019 (CMA 2019), the vegetation coverage index ($C$) can be obtained by the 1 km resolution NDVI product of the MODIS, as shown in Eq. (6).

$$C = (\text{NDVI} - 0.05)/0.9.$$  \hspace{1cm} (6)

**3.2.4. Risk index**

The risk of rainstorm disasters is the comprehensive result of hazard, exposure and vulnerability. In this study, the rainstorm disaster risk index at grid spacing of 1 km can be calculated by Eq. (1). The risks of rainstorm disasters are classified into four levels by the classification method of natural breaks in the ArcGIS, including low risk (Level 1), medium risk (Level 2), high risk (Level 3) and very high risk (Level 4). The ranges of risk values at each level are shown in Table 2.
4. Results

Due to the lack of both the daily precipitation and the number of records of rainstorm disasters in Hong Kong and Macao, the results of this research only include 9 cities of the GBA in Chinese mainland.

4.1. Hazard

From 1990 to 2018, a total of 4,286 non-typhoon related rainstorm processes are recorded at 29 meteorological stations in the GBA. Among them, the rainstorm processes lasting for 1 and 2 days account for 83% and 12%, respectively.

The changes in the frequency of non-typhoon related rainstorm processes in the GBA during 1990–2018 (Figure 4a) suggest that the maximum frequency appeared in 1998 (214), followed by 2016 (205). Since 1990, the total number of rainstorm processes in the GBA has increased at a tendency rate of 10 times per decade. However, the tendency rate failed the significance test ($p < 0.05$). In addition, the average intensity of rainstorm processes has increased at a tendency rate of $2$ mm10a$^{-1}$, but with significant interdecadal changes ($p < 0.05$). The intensities of rainstorm processes during the period of 2000–2009 were relatively stronger, with the strongest being 88.4 mm·day$^{-1}$ in 2006, while those during the period of 1990–1999 were weaker.
During the period of 2010–2018, although the rainstorm intensity presented a decreasing trend, it was still stronger than those in 1990–1999 (Figure 4b).

From the spatial distribution of the frequencies of the annual rainstorm processes (Figure 5a), it is found that the southwestern coastal area of the GBA has the most rainstorm processes, among which Enping and Doumen have an average annual rainstorm processes of 6.9 times. The reason for this situation is that this area is located at the southeastern foot of the Yunwu Mountain, which is thus affected by terrain conditions and water vapor transport over the ocean, and it is one of the rainstorm centers in Guangdong Province (Zheng et al. 2019). The frequency of rainstorm processes in the northwest of the GBA is relatively lower, being only 3.2 and 3.5 times in Deqing and Fengkai, respectively. The spatial distribution of the changes in rainstorm process frequency (Figure 5b) suggests that increases in the frequencies of rainstorm processes are found at 79.3% of the observation stations since 1990. Among them, the frequencies in Guangzhou, Dongguan, Foshan and Southeastern Zhaoqing have increased the most significantly ($p < 0.05$), with a tendency rate of 0.6–1.3 times $10^{-1}$.

The large value areas of the average intensity of rainstorm processes from 1990 to 2018 are located in coastal areas of the GBA, where the largest is in Zhuhai (90.8 mm), followed by Shangchuan Island (90.7 mm). The average intensity of rainstorm processes from 1990 to 2018 is relatively small in the northwestern cities of Zhaoqing, with the smallest in Fengkai (68.1 mm) and Huaiji (68.9 mm), as shown in Figure 5c. The changes in rainstorm process intensity in the past 30 years indicate that 72.4% of the observation stations have recorded an increase in intensity.
(Figure 5d). Among them, the intensities in Guangzhou, Zhongshan, northern Jiangmen, western Huizhou, and Southern Zhaoqing have increased significantly ($p < 0.05$) at a tendency rate of more than $2.0 \text{mm} \cdot 10^{-1} \text{a}^{-1}$.

Figure 6 shows that the hazard index in coastal areas is mostly greater than 0.7. At county level, the hazard index is the highest (greater than 0.8) in Xiangzhou, Doumen and Jinwan Districts of Zhuhai, Taishan and Enping Districts of Jiangmen, as well as Futian, Nanshan and Luohu Districts of Shenzhen. While it is the lowest (less than 0.6) in Chancheng and Sanshui Districts of Foshan as well as most counties of Zhaoqing. At city level, the average hazard index is the highest in Zhuhai (0.91), followed by Jiangmen (0.80), Zhongshan (0.78) and Shenzhen (0.78), while the lowest in Zhaoqing (0.55) (Table 3).

4.2. Exposure

In the GBA, the high GDP densities with more than 1 billion yuan per square kilometer are located in the most of Shenzhen, central Dongguan, and Yuexiu, Huangpu and Tianhe Districts of Guangzhou, while Zhaoqing, Jiangmen and most of Huizhou have less than 100 million yuan per square kilometer (Figure 7a). The high population density with more than 10,000 people per square kilometer are located in southern Shenzhen and Tianhe, Zhuhai and Yuexiu Districts of Guangzhou, while Zhaoqing, Jiangmen and the most of Huizhou have less than 1,000 people per square kilometer (Figure 7b). Figure 7c suggests that Guangzhou, Shenzhen, Dongguan Zhongshan and Foshan have relatively higher socio-economic exposure, while the exposure is relatively lower in Huizhou, Zhuhai, Jiangmen, and Zhaoqing. At county level, the exposure is the highest in Yuexiu and Haizhu Districts of Guangzhou and Futian District of Shenzhen, which exceeds 0.8. In 2018, the more densely populated and developed cities in the GBA were Shenzhen, Dongguan, Foshan, Zhongshan and Guangzhou, where the population densities per square kilometer in these cities were...
Table 3. Averages of hazard, exposure, vulnerability and risk indexes of cities in the GBA.

| City     | Hazard | Exposure | Vulnerability | Risk | Risk level |
|----------|--------|----------|---------------|------|------------|
| Dongguan | 0.72   | 0.53     | 0.75          | 0.70 | 3          |
| Zhuhai   | 0.91   | 0.51     | 0.70          | 0.75 | 4          |
| Shenzhen | 0.78   | 0.55     | 0.67          | 0.68 | 3          |
| Zhongshan| 0.78   | 0.52     | 0.78          | 0.73 | 4          |
| Huizhou  | 0.75   | 0.50     | 0.63          | 0.64 | 2          |
| Jiangmen | 0.80   | 0.51     | 0.69          | 0.67 | 3          |
| Foshan   | 0.61   | 0.53     | 0.79          | 0.64 | 2          |
| Guangzhou| 0.67   | 0.58     | 0.69          | 0.63 | 2          |
| Zhaoqing | 0.55   | 0.50     | 0.63          | 0.55 | 1          |

Figure 7. The spatial distribution of GDP (a), POP (b) and exposure index (c) in the GBA. Inverse distance weighted (IDW) interpolation technique in ArcGIS was used to create the figure.

6705, 3426, 2083, 1898 and 1286, respectively, and the GDP densities were 1247 million yuan, 340 million yuan, 262 million yuan, 175 million yuan and 317 million yuan, respectively (Table 4).

4.3. Vulnerability

For the distribution of terrain vulnerability, the northern and western GBA are mountainous area with high altitude, which are thus less sensitive to rainstorm disasters. The central GBA has low-lying and flat terrains, making it more sensitive to
rainstorm disasters (Figure 8a). In terms of river network, the central GBA has a relatively denser distribution of rivers, making it more sensitive to rainstorms and floods than other areas (Figure 8b). The multi-year average vegetation coverage in the GBA during 1990–2018 suggests that Zhaoqing and Huizhou have high vegetation coverage and low sensitivity to rainstorm disasters, while the central and southern GBA have low vegetation coverage and are thus more sensitive to rainstorm disasters (Figure 8c). Based on topography, river network and vegetation, the vulnerability index is calculated following Eq. (5). As shown in Figure 8d, the result suggests that Foshan, Western Guangzhou, Northern Zhongshan, Eastern Zhuhai, Northern Dongguan, Central Huizhou and Zhaoqing along the West River are highly vulnerable to rainstorm disasters, with the vulnerability index exceeding 0.7. However, most of Zhaoqing and northern Huizhou are less vulnerable to rainstorm disasters.

At county level, the vulnerability index is the highest (more than 0.83) in Liwan District of Guangzhhou, Shunde, Nanhai and Chancheng Districts of Foshan, as well as Jianghai District of Jiangmen. While it is the lowest (less than 0.61) in Conghua District of Guangzhou, Yantian District of Shenzhen and most counties of Zhaoqing. At city level, the vulnerability index is the highest in Foshan (0.89), followed by Zhongshan (0.78) and Dongguan (0.75), and the lowest in Zhaoqing (0.63), as shown in Table 3.

### 4.4. Risk

#### 4.4.1. Risk map

The distribution of rainstorm disaster risk levels (Figure 9) suggests that the Pearl River Estuary area in the GBA has a higher risk level of rainstorm disasters. The average risk index reaches Level 4 in Zhuhai and Zhongshan, Level 3 in Dongguan, Jiangmen and Shenzhen, Level 2 in Huizhou, Foshan and Guangzhou and Level 1 in Zhaoqing. The areas of the risk of Level 4 in Zhuhai, Zhongshan, and Dongguan account for 87.7%, 82.3% and 58.9% of their total areas respectively (Table 5). The main reason is that these places have higher disaster dangerousness, low-lying and flat terrains, higher sensitivity to rainstorm disasters, as well as developed economy and dense population. At county level, there are 12 counties (districts) with the risk of Level 4, 14 counties (districts) with Level 3, 14 counties (districts) with Levels 2 and 5 counties (districts) with Level 1. Among them, the risk index is the highest.

| City          | Built-up area (km²) 1990 | Built-up area (km²) 2015 | Vegetation area (km²) 1990 | Vegetation area (km²) 2015 | Population density (people/km²) 1990 | Population density (people/km²) 2018 | GDP density (1 million RMB/km²) 1990 | GDP density (1 million RMB/km²) 2018 |
|---------------|--------------------------|--------------------------|-----------------------------|-----------------------------|---------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| Guangzhou     | 623                      | 1435                     | 6129                        | 5267                        | 824                                  | 1286                                 | 0.4                                  | 317                                  |
| Shenzhen      | 339                      | 834                      | 1417                        | 999                         | 864                                  | 6705                                 | 8.8                                  | 1247                                 |
| Zhuhai        | 83                       | 349                      | 1195                        | 922                         | 406                                  | 1197                                 | 2.6                                  | 204                                  |
| Foshan        | 353                      | 1112                     | 2514                        | 1774                        | 736                                  | 2083                                 | 3.3                                  | 262                                  |
| Jiangmen      | 467                      | 723                      | 8214                        | 7801                        | 373                                  | 491                                  | 1.1                                  | 31                                   |
| Zhaoqing      | 250                      | 415                      | 14155                       | 13894                       | 215                                  | 279                                  | 0.4                                  | 15                                   |
| Huizhou       | 401                      | 740                      | 10553                       | 10202                       | 204                                  | 427                                  | 0.4                                  | 36                                   |
| Dongguan      | 362                      | 1268                     | 1800                        | 938                         | 717                                  | 3426                                 | 3.3                                  | 340                                  |
| Zhongshan     | 120                      | 493                      | 1205                        | 888                         | 716                                  | 1898                                 | 2.9                                  | 175                                  |

| Table 4. Changes in urban land use and socio-economic indicators in cities of the GBA (Didan 2015; http://www.resdc.cn/Default.aspx). | Built-up area (km²) | Vegetation area (km²) | Population density (people/km²) | GDP density (1 million RMB/km²) |
|---------------------------------------------------------------|---------------------|-----------------------|-------------------------------|----------------------|
| Guangzhou                                                    | 623                 | 1435                  | 824                           | 0.4                  |
| Shenzhen                                                     | 339                 | 834                   | 864                           | 8.8                  |
| Zhuhai                                                       | 83                  | 349                   | 406                           | 2.6                  |
| Foshan                                                       | 353                 | 1112                  | 736                           | 3.3                  |
| Jiangmen                                                     | 467                 | 723                   | 373                           | 1.1                  |
| Zhaoqing                                                     | 250                 | 415                   | 215                           | 0.4                  |
| Huizhou                                                      | 401                 | 740                   | 204                           | 0.4                  |
| Dongguan                                                     | 362                 | 1268                  | 717                           | 3.3                  |
| Zhongshan                                                    | 120                 | 493                   | 716                           | 2.9                  |
Figure 8. The distribution of terrain (a), river network (b), vegetation coverage (c) and vulnerability (d) indexes in the GBA. Inverse distance weighted (IDW) interpolation technique in ArcGIS was used to create the figure.

Figure 9. Risk levels of rainstorm disasters in the GBA from 1990 to 2018.

(greater than 0.75) in Yuexiu and Haizhu Districts of Guangzhou, Doumen and Xiangzhou Districts of Zhuhai, as well as Futian District of Shenzhen. However, Guangning, Huaiji, Fengkai and Deqing Counties of Zhaoqing and Longmen County of Huizhou have the lowest risk of rainstorm disasters.
4.4.2. Risk verification

In this research, the historical rainstorm disaster data is used to verify the rationality of the rainstorm disaster risk map. In addition, a disaster-inducing rainstorm is defined as a rainstorm that causes casualties or economic losses.

From 1990 to 2018, 956 disaster-inducing rainstorms are recorded at 29 meteorological observation stations, accounting for 22.3% of the total rainstorms (4286) in the GBA. Figure 10a indicates that the number of disaster-inducing rainstorms is more than 30 in Baoan and Longgang Districts of Shenzhen, Huicheng District and Longmen County of Huizhou, Guangning County, Huaiji County, and Gaoyao District of Zhaoqing, as well as Shunde District of Foshan. At county level, the spatial correlation coefficient between the risk index and the number of disaster-inducing rainstorms has passed the significance test at 99.5% confidence level. A total of 584 disaster-inducing rainstorms are recorded in areas with the risk of Levels 3 and 4, accounting for 60.02% of the total disaster-inducing rainstorms. Therefore, the risk index constructed in this study can well reflect the characteristics of rainstorm disasters. However, rainstorm disasters also frequently occur in mountainous areas, such as Zhaoqing, northeastern Guangzhou, and northern Huizhou, but the risks in these areas are not high. This is because we do not consider the potential spots of geological disasters as a vulnerability factor.

Rainstorms may cause floods (including basin-wide flood and mountain torrent), urban waterlogging, and geological disasters (collapse, landslide and debris flow). In past 30 years, 299 urban waterlogging disasters, 145 floods, and 159 geological disasters are recorded in the GBA, accounting for 31.2, 15.1 and 16.6% of the rainstorm-induced disasters, respectively. Specially, urban waterlogging disasters account for more than 60% of the rainstorm-induced disasters in 17 districts including Huangpu, Baiyun, Zengcheng, Liwan, Nansha, Tianhe, and Yuexiu Districts of Guangzhou, Nanshan, Futian, Longgang, Baoan, and Luohu Districts of Shenzhen, Doumen, Jinwan, and Xiangzhou Districts of Zhuhai, Dongguan and Zhongshan (Figure 10b). The risks in most of these regions are Level 3 and above. Therefore, it can be regarded that the high-risk areas of rainstorm disasters in the GBA mainly suffer urban waterlogging. In addition, the risk is Level 3 in Chancheng and Shunde Districts of Foshan, as well as Enping City of Jiangmen. The floods account for 50.0, 36.7 and 46.3% of the rainstorm-induced disasters, respectively (Figure 10c). Because Zhaoqing is located in the hilly and mountainous region, the frequency of geological disasters in Zhaoqing reaches as high as 33 (Figure 10d). However, the risk level is relatively lower in this area, which is mainly because the

| City   | Level 1 | Level 2 | Level 3 | Level 4 |
|--------|---------|---------|---------|---------|
| Dongguan | 0.0 | 12.0 | 29.1 | 58.9 |
| Zhuhai | 0.0 | 0.0 | 12.3 | 87.7 |
| Shenzhen | 0.0 | 16.7 | 47.6 | 35.6 |
| Zhongshan | 0.0 | 1.4 | 16.3 | 82.3 |
| Huizhou | 1.2 | 52.1 | 42.1 | 4.6 |
| Jiangmen | 0.4 | 18.9 | 55.2 | 25.5 |
| Foshan | 1.7 | 38.1 | 53.8 | 6.4 |
| Guangzhou | 4.4 | 54.4 | 29.2 | 11.9 |
| Zhaoqing | 77.5 | 19.7 | 2.7 | 0.1 |
potential spots of geological disasters are not considered as a vulnerability factor in this study.

4.4.3. Disaster-induced rainstorm

Mainly due to increases in extreme rainstorms and vulnerability, statistics on the frequency of the GBAs rainstorm disasters in the calendar year 1990–2018 (Figure 11) show that the tendency rate of rainstorm disasters has increased significantly with 8.9 times/10a ($p < 0.01$). Of these, 11 occurred each year on average from 1990 to 2004, while 32 occurred each year on average from 2005 to 2018, three times the frequency of the previous 15 years. Besides the increase of frequency and intensity of rainstorm process analyzed in Section 4.1, the causes of the increase in rainstorm disasters are also related to the development of the GBA’s urbanization.

Over the past 30 years, the population density in the GBA increased from 525 per square kilometer people to 1,180 people per square kilometer. The population density in Shenzhen (6,705 people per square kilometer), Dongguan (3,426 people per square kilometer), and Foshan (2,083 per square kilometer) exceeded 2,000 people per square kilometer in 2018, which have respectively increased by 6.8 times, 3.8 times and 1.8 times, compared with those in 1990. The GDP per square kilometer have increased from 1.3 million yuan to 149 million yuan by more than 100 times. The GDP growth rate is the fastest in Shenzhen. Overall, the exposure to rainstorm disasters in the GBA has increased significantly in the past 30 years, which undoubtedly increases the risk of rainstorm disasters.
Comparing the land use in 1990 and with that in 2015 in the GBA, it is found that the urban built-up area has expanded significantly (Table 4). The built-up area in 1990 was only 3,177 km², accounting for 5.8% of the area of Guangdong, Hong Kong and Macao. By 2015, it increased to 7,591 km², accounting for 13.7% of the area of Guangdong, Hong Kong and Macao, which is 2.39 times that of 1990. Specially, the built-up areas of Guangzhou, Dongguan and Foshan are relatively larger, reaching 1,435, 1,268 and 1,112 km², respectively, in 2015. Over the past 30 years, Zhuhai, Zhongshan and Dongguan have experienced the fastest urban expansion, and the urban built-up areas in 2015 have respectively increased by 3.2, 3.1 and 2.5 times compared with those in 1990. In contrast, the vegetation coverage (including forest, grassland and farmland) area in 2015 has decreased by 9.4% for the GBA compared with that in 1990, and by more than 20% for Dongguan, Shenzhen, Foshan, Zhongshan and Zhuhai (Table 4).

5. Discussion and conclusions

In this study, the hazard, exposure and vulnerability are used to assess the rainstorm disaster risk at county level in GBA. The main conclusions are as follows.

1. The frequency and intensity of rainstorm processes during 1990–2018 in the GBA have increased by 10 times and 2 mm per decade, respectively. The increases are found at 79.3% of observation stations for the frequency of rainstorm process and at 72.4% of stations for the intensity of rainstorm process. Rainstorms in southwestern coastal area of the GBA are the most frequent.
2. The socio-economic exposure is relatively higher in Guangzhou, Shenzhen, Dongguan Zhongshan and Foshan. The vulnerability is higher in Foshan, Zhongshan and Dongguan. In city level, the rainstorm disaster risks of Level 4 locate in Zhuhai and Zhongshan, Level 3 in Dongguan, Jiangmen and Shenzhen, Level 2 in Huizhou, Foshan and Guangzhou, and Level 1 in Zhaoqing. At county level, there are 12 districts reaching the risk of Level 4, including Doumen, Doumen and Xiangzhou Districts of Zhuhai, Zhongshan, Futian, Nanshan and
Luohu Districts of Shenzhen, Jianghai Districts of Jiangmen, as well as Yuexiu, Haizhu, Tianhe and Liwan Districts of Guangzhou.

3. Over the past 30 years, the population, GDP and built-up areas in the GBA have respectively increased by 1.25 times, 100 times and 1.39 times compared with those in 1990, while the vegetation coverage has decreased by 9.4%. Such changes combined with hazard changes made the frequency of rainstorm disasters during 2005–2018 increase by 2 times compared with 1990–2004. Moreover, urban waterlogging, floods, and geological disasters account for 31.2%, 15.1% and 16.6% of the rainstorm disasters, respectively. The Levels 3 and 4 risk areas mainly suffer urban waterlogging, which accounts for more than 60% of the rainstorm disasters.

In this study, for the hazard index, the historical observation data has limitation in spatial resolution. The precipitation at only one station cannot accurately describe the precipitation situation across the whole county. In the vulnerability assessment, indicators such as terrain, river network and vegetation coverage adopted all belong to natural conditions, while the differences in urban adaptability and emergency management capacity are not considered. The weights mainly indicate the relative importance of the three indicators. The risk of rainstorm disasters is the result of the interaction among multiple influencing factors, while some factors cannot be accurately described by mathematical models (Fang et al. 2015). For example, over the past 30 years, rainstorms in Zhaoqing have caused frequent geological disasters such as landslides and debris flows. However, since potential spots of geological disasters are not considered as a vulnerability factor, the risk of this city is quite different from the observed rainstorm disasters. At present, it is difficult to find all specific quantifiable factors to evaluate the risks of rainstorm disasters, which should be considered in future research work.

In the future construction of the GBA, it is necessary to take corresponding measures to prevent rainstorm disasters according to the different levels of rainstorm disaster risks. For the areas with high and very high risk of rainstorm disasters, improving the defenses against floods through engineering measures, increasing green space and reasonably designing the spatial patterns of impervious surfaces would provide useful ways to mitigate the risks of rainstorm disasters. For the areas with low and moderate risks of rainstorm disasters, the spatial structure of impervious surfaces should be further rationally planned, and the underground drainage pipe network system should be optimized to mitigate the risks of rainstorm disasters.

**Credit author statement**

All authors have participated in the research and article preparation. Dr. Yujie Wang designed the methods, analyzed the results and wrote the paper. Dr. Jianqing Zhai calculated and analyzed the results. Dr. Ge Gao provided the data and analyzed the results. Dr. Qiufeng Liu analyzed the results. Prof. Lianchun Song analyzed the results.
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Data availability statement (DAS)
The data that support the findings of this study are openly available on websites (www.resdc.cn and www.data.cma.cn).

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