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REVIEW ARTICLE

Investigation into the tempo-spatial distribution of recent fire hazards in China

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Abstract Fire hazards are considered to be one of the most dangerous hazards in the world, which could lead to significant casualties and economic losses. This paper summarizes the fire hazards in China during the period from 2000 to 2016 in daily life, transportation, storages, industrial production, etc. In this research, the tempo-spatial distribution of fire hazards that result in fatalities, injuries and direct economic losses was studied. The place distribution of fire hazards was analyzed, and the primary causes of fire hazards were also discussed. In addition, an extensive fire hazard induced by an explosion incident at Tianjin harbor was studied and discussed. Linear regression relationships between the four indicators of fire hazard and the average gross domestic product were

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developed and analyzed. Based on the analyzed results, recommended mitigation measures against fire hazards were recommended.

Keywords Fire hazard · Tempo-spatial distribution · Regression analysis · Mitigation measures

1 Introduction

With the rapid urbanization in China, the movement of large population migrating to mega cities has resulted in large-scale urban construction (Yan et al. 2012; Shen et al. 2014, 2016; Xu et al. 2017), which includes mass transportation system construction (Ren et al. 2018), sponge city construction, large-scale shopping mall (Qiao et al. 2017), large housing and large logistics storage complexes (Peng and Peng 2018). These large-scale urban constructions may pose the potential risk of hazards during construction and operation. During construction in soft deposit, long-term stability is a problem due to the rheological behavior of soil (Leblon et al. 2002; Khoury 2002; Yao et al. 2008, 2009; Yao and Zhou 2013; Yin et al. 2011, 2013, 2015, 2016, 2017a, b) and groundwater pumping is required to maintain stability (Shen et al. 2013a, b, 2017a, b; Tan and Lu 2017, 2018; Wu et al. 2015a, 2016, 2017a, b). However, groundwater pumping may cause subsidence of the surrounding areas (Shen and Xu 2011; Wu et al. 2015b; Xu et al. 2012, 2014, 2016, 2017; Tan et al. 2017, 2018).

The number of the natural hazards has increased with the rapid development of the economy in China in recent years, which will lead to economic losses and casualties. Many of the natural hazards, such as heavy storm-induced flood hazards (Lyu et al. 2016, 2018a), groundwater contamination (Du et al. 2012, 2014a, b), earthquake hazards, fire hazards (Cao and Guo 2011) and engineering collapse hazards (Chai et al. 2014, 2018), have been reported on previously (Shen et al. 2014, 2016; Cheeda et al. 2015; Cheng et al. 2017a, b, 2018; Weckman 2017; Stroh et al. 2017).

Fire hazards are one of the significant hazards to threaten human lives and properties (Bendelius 2002; Bettelini 2002; Hwang and Edwards 2005; Chen et al. 2007; Babrauskas 2016). Fire hazards not only cause significant damage to properties (San-Miguel-Ayanz and Ravail 2005; Cao and Guo 2011; Sun et al. 2015; Adab 2017; Fateh et al. 2017) but also lead to a serious negative impact on social stability. The annual number of deaths due to the fire hazards exceeds 10,000 worldwide, according to the United Nations World Fire Statistics Center (Budnick 2012; Xie 2014). Since the reforming and opening-up policy of China was released in 1979, fire hazards have occurred more than 5 million times, leading to 82,794 fatalities, with more than 10 thousand people injured and 52 billion RMB economic loss (Xie 2014). Thus, the fire hazards have led to catastrophic impacts in China and the world (Garlock et al. 2012; Spinardi 2016; Veeraswamy et al. 2018). The improvement of fire awareness and the promotion of fire safety knowledge may need to be a priority, government investment. Once a fire hazard initiates, it develops rapidly and the time to conduct evacuation is extremely short, thereby resulting in considerable property damages and casualties.

Fire hazards are categorized by the Ministry of Public Security in China, according to the production safety accident report. Investigation and handling regulations are an important indicator for fire hazard categorization, which are announced by the State Council. Three aspects regarding the number of deaths or number of injuries or direct economic losses can be categorized into four primary categories in terms of the fire hazard damage level: special great fire, great fire, large fire and general fire (Lu 2012).

Table 1 shows a summary for the four fire hazard categories. As evident, the special great fire category is based on the number of deaths being equal to or more than 30 people or the number of injury being equal to more than 100 people or the direct economic loss being equal to more than 100 million RMB. The great fire is categorized based on the number of deaths being in the range of 10–30 people or the number of injury being in the range of 30–100 people, or the direct economic losses being in the range of 50–100 million RMB. The large fire category is based on the number of deaths, being in the range of 3–10 people or the number of injury being in the range of 10–50 people or direct economic loss being in the range of 10–50 million RMB. The general fire corresponds to the number of death being less than 3 people or the number of injury being less than 10 people or the direct economic loss being less than 10 million RMB (Lu 2012).

It is known that fire hazards can be fatal and can cause serious casualties and property losses. The objectives of this paper are: (1) to analyze the tempo-spatial distribution of the fire hazard in China in the period from 2000 to 2016 and (2) to recommend the mitigation measures against the fire hazard.

2 Methodology

2.1 Data sources

The data of fire hazard classifications and China's major fire hazards in recent years were obtained from reports and publications (Cao and Guo 2011; Lu 2012). The data, including the number of fire hazards, the number of casualties and the economic loss and the average GDP, were obtained from the Yearbook of China Fire (Li 2016), the Web site of National Bureau of Statistics of the People's Republic of China (http://data.stats.gov.cn) and other relevant publications (Chen et al. 2007; Lu 2012; Sun et al. 2015). Moreover, the data of time distribution, places distribution and causes are extracted from publications (Cao and Guo 2011; Fu 2014; Qi 2017). Finally, the data of the large-scale fire hazard at Tianjin Port sources were obtained from China's official report (https://baike.so.com).

2.2 Data analysis

a. Chart statistical analysis

Firstly, the data collected were classified into categories such as time factor, place factor and cause factor. Then, a chart is drawn for each category (Lu 2012), correspondingly

Table 1 Four groups of fire hazards. Data from (Lu 2012)

Fire hazards	Number of deaths	Number of serious injuries	Direct economic loss (million RMB)
Special great fire	≥ 30	≥ 100	≥ 100
Great fire	10–30	50–100	50–100
Large fire	3–10	10–50	10–50
General fire	< 3	< 10	< 10

reflecting the time distribution of fire hazards, the places distribution and the causes. This enables prediction of the trend of the fire hazards and provides the basis for scientific fire prevention. At the same time, a timetable was prepared based on the process of fire hazard at Tianjin harbor, which clearly reflected the process of this fire hazard and identifies the key deterioration of the fire hazard, in order to provide an approach for similar fire hazards.

b. Linear regression

The relationship between the number of fire hazards, fire casualties, the economic loss and the average GDP has been studied, by using linear regression.

Firstly, the dependent variable *X* and the independent variable *Y* are defined (Jin et al. 2016a, b, c, 2017a, b, 2018). Second, scatter plots about *X* and *Y* are drawn. If the dependent variable *X* and the independent variable *Y* show a clear linear relationship, the next step can be proceeded with. Thirdly, the parameters, including the dependent variable *X* and the independent variable *Y*, were normalized by introducing Eq. (1), on account of the difference in the data size and dimension. The mean value of the normalized data was equal to zero, and the associated standard deviation was identical to one. The linear regression relationship between *Y* and *X* can be analyzed and *Z*(*Y*) can be derived, by substituting the independent variable *X* into the regression formula derived.

$$z = \frac{v - \mu}{\sigma} \tag{1}$$

$$\mu = \frac{1}{n}\sum_{i=1}^{n} v_i \tag{2}$$

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (v_i - \mu)^2} \tag{3}$$

where z = normalized data, v = original variable, μ = mean value, σ = standard deviation.

Fourthly, a regression model was set up (Yin et al. 2018). The regression equation is presented in Eq. (4). Then, the regression constant β_0 and the regression coefficient β_1 should be estimated by the ordinary least square method (OLSE) (He and Liu 2001) as Eqs. (5) and (6).

$$y = \beta_0 + \beta_1 x \tag{4}$$

$$\beta_1 = \frac{\sum_{i=1}^{n} (x_i - \bar{x}) y_i}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{5}$$

$$\beta_0 = \bar{y} - \beta_1 \bar{x} \tag{6}$$

where β_0 = the regression constant, β_1 = the regression coefficient,$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$, $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$, x_i an observation selected of the dependent variable *X*, y_i an observation selected of the independent variable *Y*, n = the total number of the dependent variable *X* or the independent variable *Y*.

Finally, to do significance test of the correlation coefficient *R*,

$$R = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{7}$$

The correlation coefficient R can be calculated by Eq. (7) (He and Liu 2001). According to Table 2, when the absolute value of R is less than the value corresponding to $\alpha = 5\%$, there is no obvious linear correlation between x and y; otherwise, x and y have an obvious linear correlation. Moreover, r means the critical value of simple correlation coefficient when $\alpha = 5\%$.

3 Recent fire hazards in China

Figure 1 shows the distribution of the special great fire hazard in China for the period from 2000 to 2016 (Zhang et al. 2017), while Fig. 2 shows the relationship between the number of fire hazards and the number of deaths as well as the economic losses in the same period, according to the data of China Fire Statistical Yearbook (Li 2016). It is worth noting that the size of the dot in Fig. 1 represents the scale of the special great fire. It can be seen from Fig. 1 that the special great fire hazards were mostly concentrated at China's mega cities located on the east coastline. The number of fire hazards was initially increased with the rapid economic development and then decreased due to the financial crisis in the period from 2007 to 2009. However, this descending tendency continued until 2012, where this number began to increase again with economic development. The number of deaths or injuries presented a tendency similar to that from the number of fire hazards.

4 Tempo-spatial distribution analysis

4.1 Fire hazard

Figure 3a shows that fire hazards frequently occurred from 10:00 to 22:00 in the period from 2010 to 2013 where human activities consumed significant electricity and gas resources, leading to a high potential of fire hazards. Figure 3b indicates that the casualties induced by fire hazards were generally distributed from 00:00 to 08:00 in the same period, in which human activities were decreased leading to an inadequate awareness of the fire hazard. Additionally, Fig. 3c, d reveals that both the number of injury and the direct economic loss varied in an arbitrary manner from 00:00 to 24:00 in the period from 2010 to

Table 2 Critical value of simple correlation coefficient. (After He and Liu 2001)

$n-2$	1	2	3	4	5	6	7	8	9
$\alpha = 5\%$	0.997	0.950	0.878	0.811	0.754	0.707	0.666	0.632	0.602
$n-2$	10	11	12	13	14	15	16	17	18
$\alpha = 5\%$	0.576	0.553	0.532	0.514	0.497	0.482	0.468	0.456	0.444
$n-2$	19	20	21	22	23	24	25	26	27
$\alpha = 5\%$	0.433	0.423	0.413	0.404	0.396	0.388	0.381	0.374	0.367
$n-2$	28	29	30	35	40	45	50	60	70
$\alpha = 5\%$	0.361	0.355	0.349	0.325	0.304	0.288	0.273	0.25	0.217

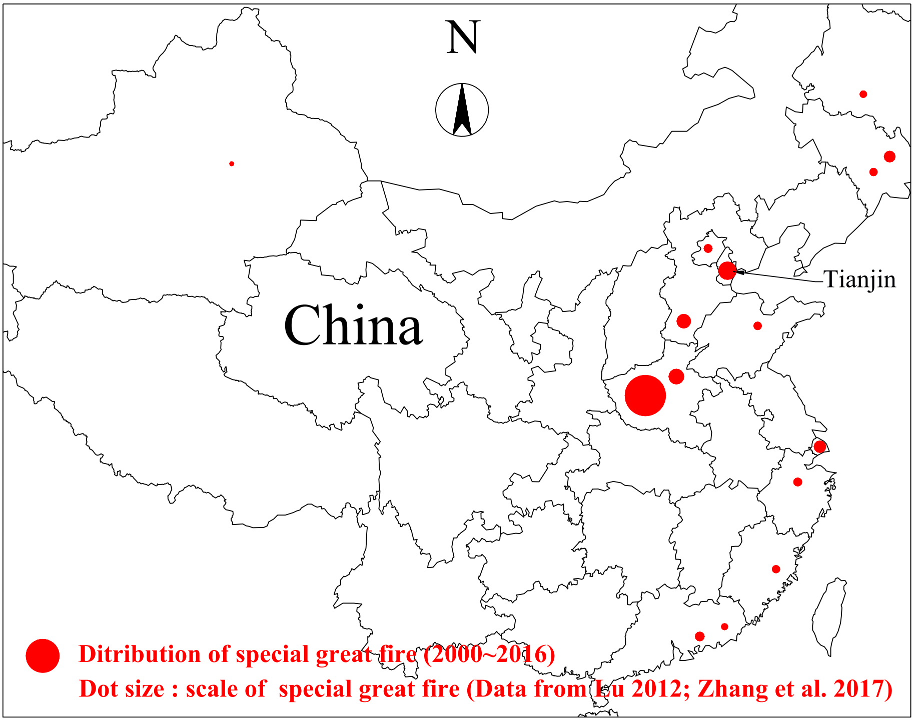


Fig. 1 Place distribution of special great fire hazards in China in the period from 2000 to 2016

Fig. 2 Relationship between the number of fire hazard and the number of death as well as the direct economic loss in China in the period from 2000 to 2016

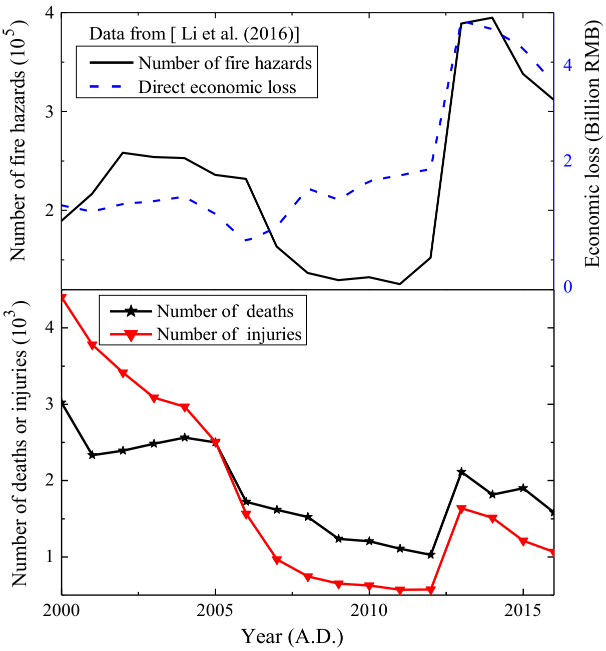


Fig. 3 Temporal distribution of fire hazards from 2010 to 2013: **a** number of fire hazards, **b** number of deaths, **c** number of injuries, **d** direct economic loss

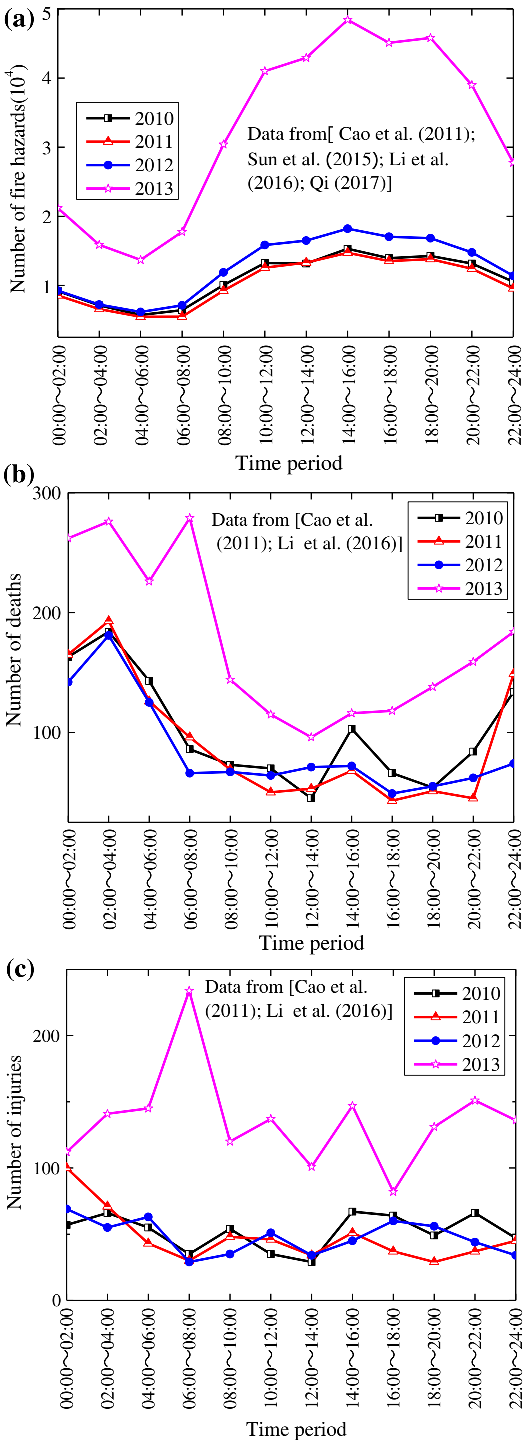
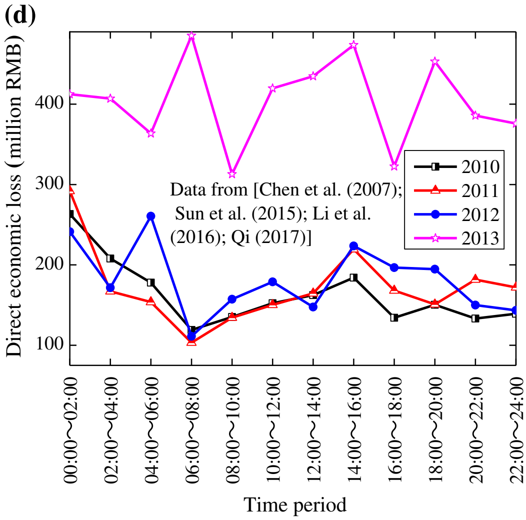


Fig. 3 continued



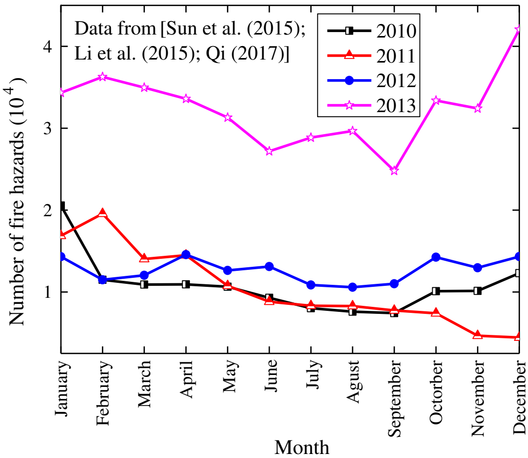
2013. It is also noted from Fig. 3d that the relatively significant economic losses occurred in two main time windows, that is, 00:00 to 02:00 and 14:00 to 16:00.

Figure 4 shows the monthly distribution of the fire hazard in the period from 2010 to 2013. As evident, fire hazards occurred more frequently in the months of January, February, April, October and December and their temperatures were generally very low. This is most likely due to the fact that the consumption of electricity and gas was greater in such cold climates, thereby leading to a significant potential of the fire hazard.

4.2 Places of fire hazard

Figures 5 and 6 present the place distribution of the fire hazard in 2012 and 2013, respectively. It can be seen from Figs. 5a and 6a that the residential building, assembly occupancies, vehicle and factory building were fire-prone zones, with the total percentage

Fig. 4 Monthly distribution of fire hazards in the period from 2010 to 2013



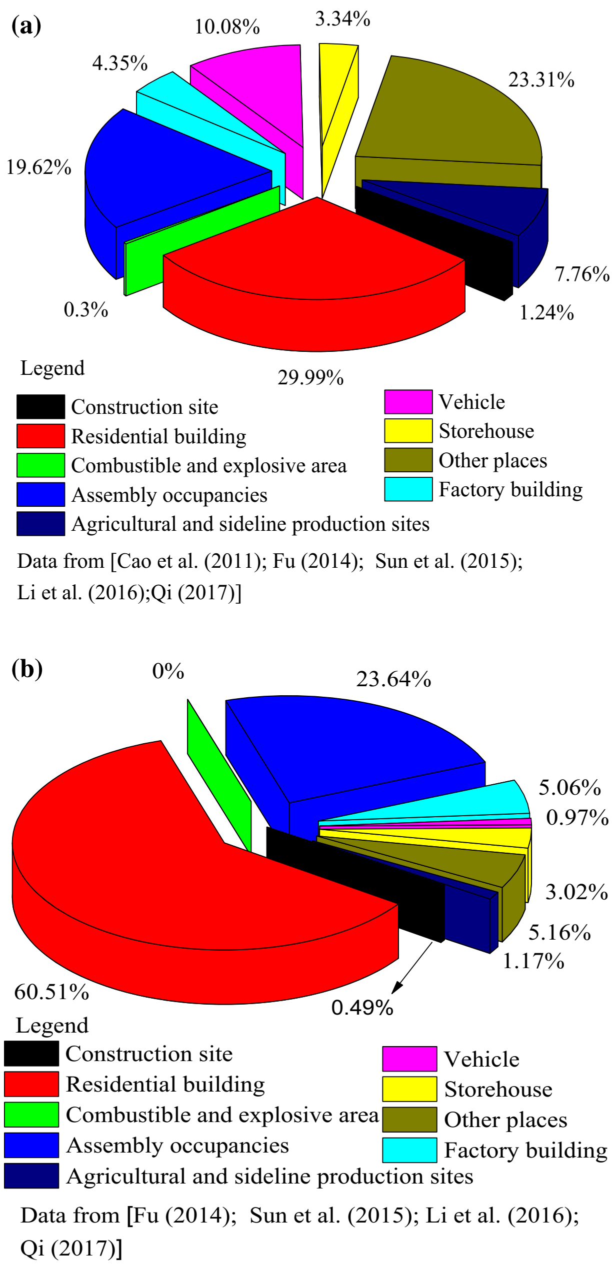
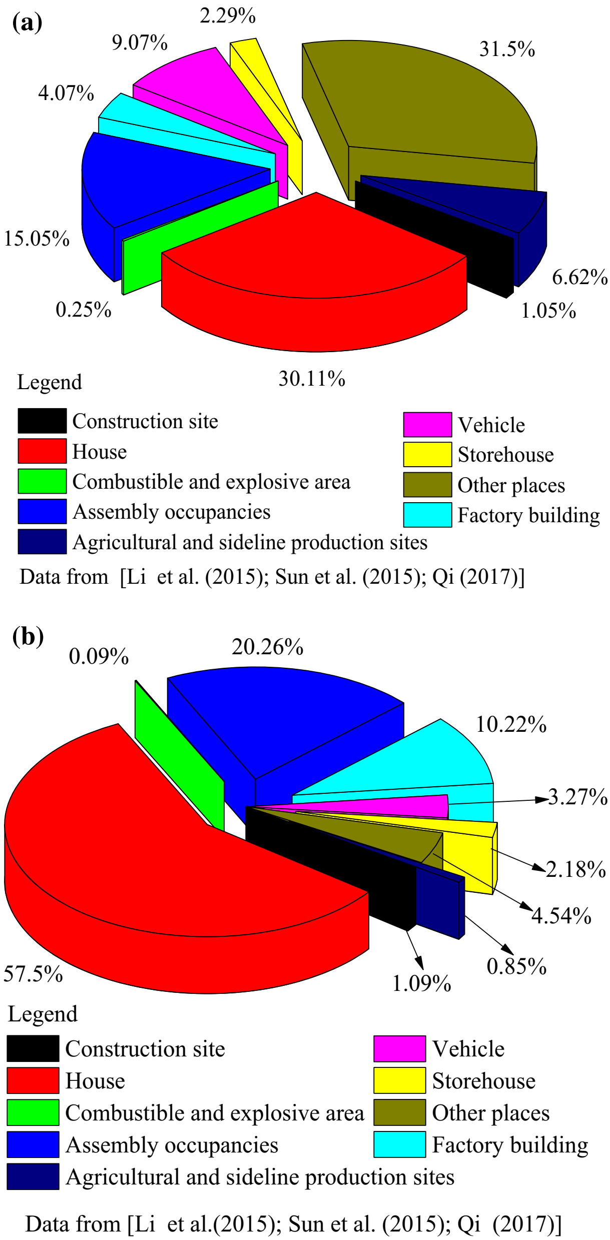


Fig. 5 **a** Place distribution of fire hazards in 2012 (with proportion to number of fire hazards). **b** Place distribution of fire hazards in 2012 (with proportion to number of deaths)

of fire hazard numbers being more than 55%. It can also be seen from Figs. 5b and 6b that the residential building, assembly occupancies and factory building were the places triggering the most significant casualties induced by fire hazards, with a total percentage of up to 88%.

Fig. 6 **a** Place distribution of fire hazards in 2013. **b** Place distribution of fire hazards in 2013



4.3 Causes of fire hazard

Figure 7 shows the number distribution of fire hazards induced by various causes including electrical equipment error, living power, smoking, setting fire and spontaneous combustion in the period from 2010 to 2013. The distribution of causes of fire hazard each year from 2010 to 2013 is similar; therefore, the situation in 2012 has been analyzed as per Fig. 8.

Fig. 7 Statistics of fire causes from 2010 to 2013

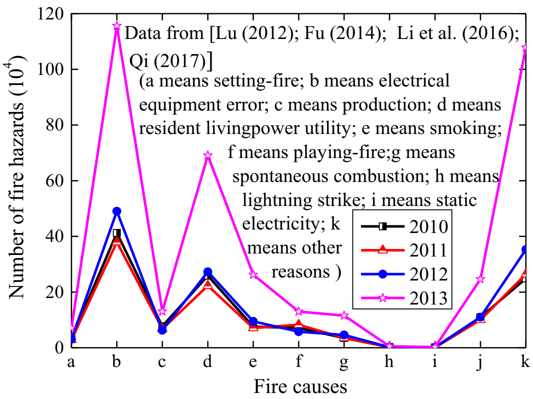


Fig. 8 Statistics of fire causes in 2012

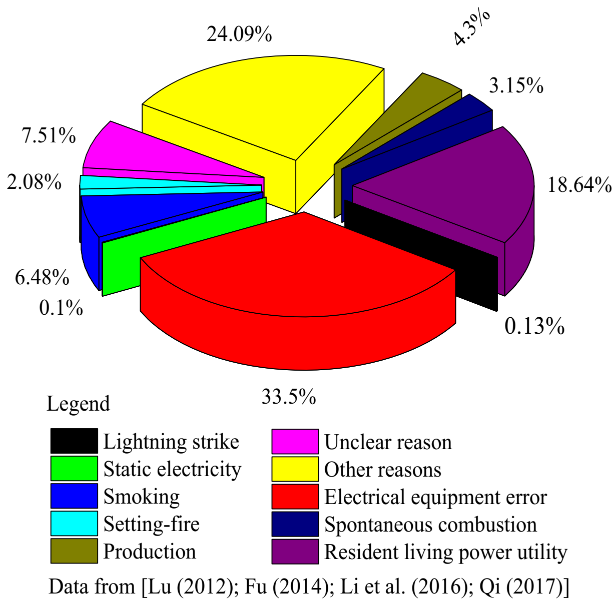


Figure 8 shows faulty electrical equipment and resident living power utility occupied more than half of proportion in terms of the fire hazards.

5 Analysis of a large-scale fire hazard case

At 23:30 of August 23, 2015, a large-scale fire hazard was triggered by an explosion incident at a Swiss company dangerous goods warehouse located at Tianjin harbor, Binhai New Area. The location of Tianjin, a big northern city in China, is depicted in Fig. 1. Figure 9 shows the photographs taken from the fire hazard induced by the explosion incident at Tianjin harbor. This fire hazard eventually resulted in a total of 165 deaths, with 8 people missing, 798 people injured, 304 buildings collapsed, 12,428 vehicles damaged,

Fig. 9 Fire hazard caused by explosion incident at Tianjin harbor. (Photograph courtesy of http://image.so.com/)

7533 burned down. The direct economic losses reached 6.9 billion RMB. Among the deaths, 22 people were rescuers, 75 people were firefighters, 11 people were police officers, and 55 people were employees of the surrounding enterprises (Zhao 2016).

Table 3 lists the critical timetable for the large-scale fire hazard at Tianjin harbor. It can be seen from Table 2 that the fire hazard developed very quickly and eventually led to this explosion incident in a period of an hour. Additionally, the flammable and explosive materials were not securely transported and stored. The firefighters and police officers were also not aware of where the flammable and explosive materials were stored. Thus, this resulted in a prolonged period of 12 h for firefighting operations, during which time field investigations were undertaken to clarify where the flammable and explosive materials were stored. Additionally, the proportion of the number of deaths involved in the rescue

Table 3 Critical timetable for the fire hazard at Tianjin harbor. (Data from https://baike.so.com)

Time	Incident
2015/8/12 22:25	Dangerous chemical stacking was fired
2015/8/12 23:34	First explosion
2015/8/12 23:35	Second explosion
2015/8/12 23:40	Receiving alarm
2015/8/12 23:50	Began to put out the fire
2015/8/13 11:00	Stop rescuing at the scene, and to start scene investigation
2015/8/14 7:05	Rescue the first survivor
2015/8/14 9:00	Rescue 32 survivors
2015/8/14 15:00	56 people were killed, including 21 firefighters;
	721 hospitalized patients
2015/8/14 18:00	Fire was put out
2015/8/15 10:00	85 people were killed, including 21 firefighters
	721 patients in hospital
2015/8/16 10:00	104 people were killed
2015/8/18 11:00	114 people were killed
2015/9/11 15:00	165 people were killed, including 110 people participating in rescue work

operation was as high as 66.7%, thereby indicating that teamwork and response period of the firefighters and the police officers may require improvement.

6 Discussion

The data from 1979 to 2016 were utilized to undertake a linear regression analysis with regard to four indicators of fire hazard and average GDP. The average GDP has been considered to be the independent variable X. The number of fire hazards Y_1, direct economic losses Y_2, number of deaths Y_3 and number of injuries Y_4 were regarded to be the dependent variables and were utilized to investigate the occurrence mechanism of fire hazard. Due to the difference in the data size and dimension, the data collected were first normalized by introducing Eq. (1). The linear regression relationship between Y_1 and X, Y_2 and X, Y_3 and X, and Y_4 and X can be analyzed and Z(Y_1), Z(Y_2), Z(Y_3) and Z(Y_4) can be derived, respectively, by substituting the independent variable X into the regression formula derived.

The fitting curve 1 in Fig. 10 shows two sections. R_{11} and R_{12} indicate the correlation coefficient of the first section and the second, respectively. In detail, $n_{11} - 2 = 24–2 = 22$, so $r_{11} = 0.404$(when $\alpha_{11} = 5\%$) and $R_{11}^2 = 0.69 = (0.831)^2 > r_{11}^2 = (0.404)^2$. At the same time, $n_{12} - 2 = 10–2 = 8$, so $r_{12} = 0.632$(when $\alpha_{12} = 5\%$) and $R_{12}^2 = 0.82 = (0.906)^2 > r_{12}^2 = (0.0.632)^2$. As a result, $Z(Y_1)$ and $Z(X)$ show a clear linear relationship. The same can be obtained; $Z(Y_2)$ and $Z(X)$, $Z(Y_3)$ and $Z(X)$, and $Z(Y_4)$ and $Z(X)$ show a clear linear relationship, respectively. However, $R_{32}^2 = 0.14 < r_{32}^2 = (0.456)^2$(when $\alpha_{32} = 5\%$, $n_{32} - 2 = 19–2$) and $R_{42}^2 = 0.07 < r_{42}^2 = (0.553)^2$(when $\alpha_{42} = 5\%$, $n_{42} - 2 = 13–2$) do not satisfied with the significance test of the correlation coefficient. These data corresponding

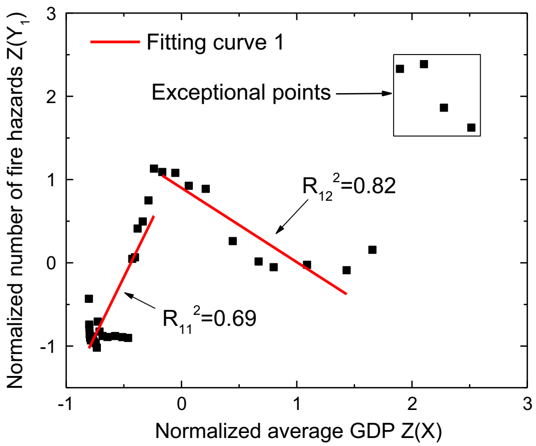


Fig. 10 Relationship between normalized number of fire hazards *Z*(*Y*1) and normalized average GDP *Z*(*X*)

with R_{32}^2 *and* R_{42}^2 in Figs. 12 and 13 are on fluctuating development with the average GDP growth.

It should be pointed out that in this study only simple linear regression analysis was conducted, so that the correlation coefficient is very low. In fact, there are many factors affecting the results and these may be nonlinear correlations among factors. In future, after sufficient information has been collected, more sophisticated analysis such as optimizing methods (Jin et al. 2016a, b, 2017, 2018; Yin et al. 2018) should be applied and more accuracy results can be obtained. Moreover, risk analysis should be adopted to provide judgment tool for decision-making for government (Lyu et al. 2016, 2017, 2018a, b).

Figure 10 shows the relationship between the normalized average GDP and the normalized number of fire hazards. As shown in Fig. 10, with the average GDP growth, people's consumption level increases and yet the fire protection investment is insufficient, resulting in the probable increase of fire hazards numbers. However, when the average GDP exceeds a certain value, as the average GDP increases, both people's awareness of fire safety and fire protection investment have been increased, leading to the decrease in the fire hazards number.

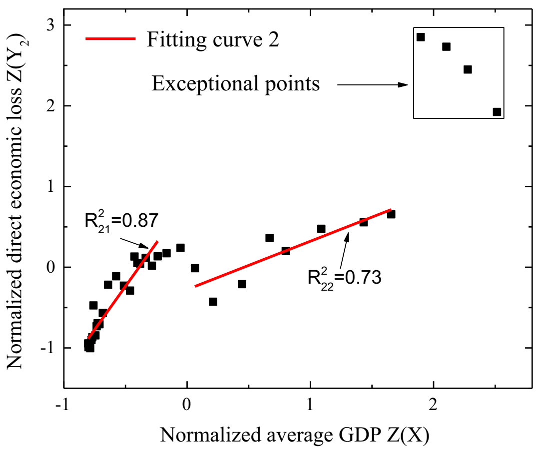


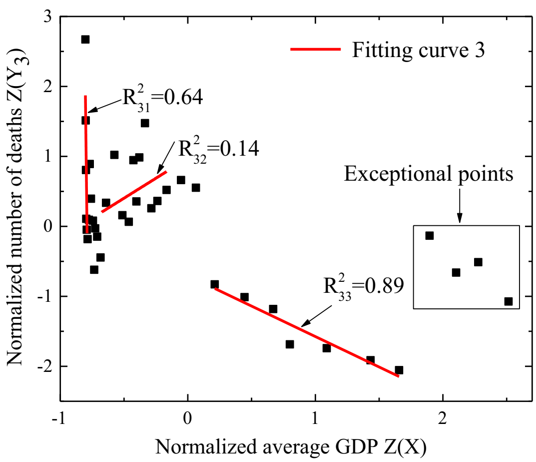
Fig. 11 Relationship between normalized direct economic losses $Z(Y_2)$ and normalized average GDP *Z*(*X*)

Figure 11 indicates that direct economic losses increased in a dramatic manner as the average GDP increased, which indicated a direct proportion of the direct economic loss to the average GDP. In detail, Fig. 11 shows two parts. The growth rate of the second part corresponding is smaller than the first part. Thence, when the average GDP exceeds a certain value, the growth rate of the direct economic loss is smaller than before with the average GDP growth.

Figures 12 and 13 indicate that the number of casualties decreased significantly as the average GDP increased, revealing that the number of casualties was inversely proportional to the average GDP. Moreover, Fig. 12 is involved in 3 parts and Fig. 13 is involved in 4 parts. In Fig. 12, the reduction rate of the first part is very rapid and the second part fluctuates around a certain value, and the reduction rate of the third one is smaller than the first part. In Fig. 12, the reduction rate of the first part is very rapid, the second part fluctuates around a certain value, and the reduction rate of the third one is smaller than the first part. Similarly, in Fig. 13, the reduction rate of the first part is very rapid, the second part fluctuates around a certain value, the reduction rate of the third one is smaller than the first part, and the reduction rate of the fourth part is smaller than the third part. Wherefore, when the average GDP exceeds a certain value, the reduction rate of the number of casualties decreased is lower than before with the average GDP growth. As evident, enhancement regarding the attention and prevention of fire hazard may still be the priority government investment securing the safety of life and property of our nationals.

Additionally, it can be noted from Figs. 10, 11, 12 and 13 that there were four exceptional points, which represented the data from 2013 to 2016, respectively. With large population migrations into Beijing, Shanghai, Guangzhou and Shenzhen in recent decades since 2012, the urban villages, in which most of those people live, are dominated by low crowded illegal buildings, densely populated areas and lack of enough firefighting device, resulting in frequent fire hazards and serious casualties from 2013 to 2016. At present, many local governments have been stepping up efforts to manage urban villages, to improve their living environment.

Fig. 12 Relationship between normalized number of deaths *Z*(*Y*3) and normalized average GDP *Z*(*X*)



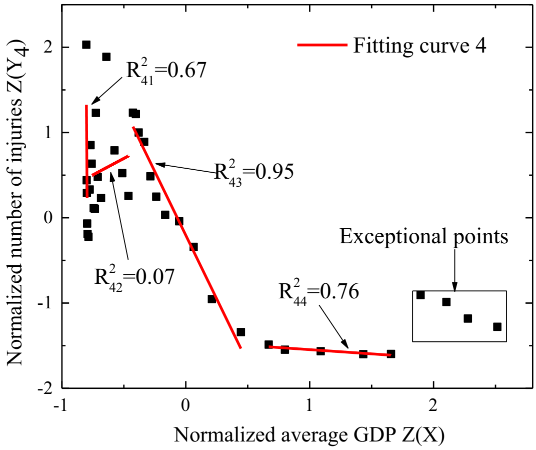


Fig. 13 Relationship between normalized number of injuries *Z* (*Y*4) and normalized average GDP *Z*(*X*)

7 Conclusions

Based on the results of the statistical analysis for the fire hazards which occurred in the period from 2000 to 2016, the following conclusions can be drawn:

1. The number of fire hazards, direct economic losses and number of casualties were generally increased with the increasing economic growth, with the exception of the financial crisis in the period from 2007 to 2009. In other words, the number of fire hazards was generally proportional to the average GDP. The number of deaths or injuries showed the tendency similar to that from the number of fire hazards.
2. The months of January, April, October and December and the time window of 10:00 to 22:00 possessed a high fire hazard potential. Additionally, the casualties induced by the fire hazard were concentrated in the time window of 00:00 to 08:00. More attention from the community security guards may be given for the mitigation of casualties.
3. Based upon the statistical analysis undertaken in this study, the residential building, assembly occupancies and factory building were the fire-prone places. The fire-prone places triggered the most significant casualties. Additionally, the electrical equipment error and living power utility triggered more than half proportion of fire hazards.
4. The large-scale fire hazard at Tianjin harbor led to a painful lesson for China. According to the fire hazard and results of the linear regression analysis, the fire-prone places and flammable and explosive materials should be securely managed by the authorities to not only prevent future similar incident from reoccurring, but also reduce the potential of fire hazard.

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