Landslides (2023) 20:1243–1264
DOI 10.1007/s10346-023-02034-6
Received: 3 January 2022
Accepted: 1 February 2023
Published online: 7 March 2023
© Springer-Verlag GmbH Germany, part of Springer Nature 2023

Shuai Zhang · Can Li · Jingyu Peng · Yiling Zhou · Shuairong Wang · Yunmin Chen · Yao Tang

Fatal landslides in China from 1940 to 2020: occurrences and vulnerabilities

Abstract Landslides result in severe casualties every year in China. However, few historical fatal landslide databases are available for quantitatively assessing the temporal and spatial distribution and the impacts of landslides. Thus, this study constructed a database incorporating fatal landslides from 1940 to 2020 based on multiple data sources. A total of 1470 nonseismic-triggered landslides resulting in 14,394 fatalities in China were collected in the database. The incorporated landslides were classified into anthropogenic and natural landslides, which could also be categorized as the following types of displacements: fall, slide, flow, and other landslides. Spatial and temporal distributions demonstrated that the fatal landslides in China were mainly distributed in 13 provinces in Southwest China. Fifty-seven landslides and 1413 landslides before and after 2000 were incorporated into the database, respectively. Fatal landslides usually occurred during the Chinese rainy seasons, i.e., between April and September. Considering the impacts posed by various human activities, this study revealed for the first time the relationship between the gross domestic product growth rate/urbanization rate and anthropogenic landslides. Then, the affected populations in seven regions of China (Northwest China, North China, Northeast China, Central China, East China, South China, and Southwest China) from 2000 to 2020 were estimated using the geographical information system. The average number of fatalities caused by landslides per decade gradually decreased. Finally, the human vulnerability to landslides in China, which also showed a decreasing trend, was quantitatively assessed using the constructed database. These findings on human vulnerability are of critical importance in the elimination of landslide risks.

Keywords Database · Fatal landslide · Rainfall · Risk · Vulnerability

Introduction

China is among the many countries that suffer severe casualties due to landslides (Petley 2012; Lin et al. 2017a, b). There are three main reasons for the frequent occurrence of fatal landslides in China (Lin and Wang 2018; Zhang and Zhang 2014; Zhang et al. 2020). First, the overexploitation of natural resources and the destruction of vegetation have increased the failure probability of the surface soil (Nadim et al. 2006; Zhang et al. 2018). Second, the frequency of extreme rainfall events and the area affected by these events are gradually increasing. Third, the process of urbanization, especially in mountainous areas, has increased the population affected by landslides (Li et al. 2017). Thus, quantitatively assessing landslide hazards, vulnerabilities, and risks is both urgent and significant for tracking and preventing landslide hazards in China. Establishing a historical national fatal landslide database and then using it for the quantitative assessment of vulnerability play an important role in this quantitative assessment of landslide risks.

At present, worldwide and Chinese national landslide databases can be divided into two categories: event-based landslide databases and historical landslide databases (Damm and Klose 2015). Event-based landslide databases refer to those incorporating landslides caused by specific triggering events (e.g., earthquakes and typhoons) (e.g., Harp and Jibson 1996; Rodríguez et al. 1999; Owen et al. 2008; Qi et al. 2011; Fan et al. 2012; Li et al. 2013; Pascal et al. 2013; Xu et al. 2014a, b, 2015, 2018; Tiwari et al. 2017; Marc et al. 2019; Chang et al. 2020). They are usually used to analyze the causes and consequences of a single disaster event. In comparison, historical landslide databases usually collect landslides at a global, continental, national, or regional scale over time (e.g., Guzzetti 2000; Devoli et al. 2007; Kirschbaum et al. 2010; Foster et al. 2012; Damm and Klose 2015; Komac and Hribernik 2015; Rosser et al. 2017; Valenzuela et al. 2017; Lin and Wang 2018; Blahut et al. 2019; Aristizábal and Sánchez 2020).

Current studies have also attempted to apply landslide databases to assessing and managing the risks of landslides (e.g., Damm and Klose 2015; Froude and Petley 2018; Ghosh et al. 2020; Görüm and Fidan 2021; Zhang et al. 2021a, b a, b; Peng et al. 2021). Some works determined the spatiotemporal trends and typical characteristics of landslides using statistical methods. For instance, Damm and Klose (2015) presented a landslide database covering landslides over the past 15 years to eliminate gaps in landslide databases on the national scale in Germany. Froude and Petley (2018) constructed a global fatal nonseismic landslide database and presented a spatiotemporal analysis of the incorporated landslides from January 2004 to December 2016. Blahut et al. (2019) outlined a comprehensive global database of giant landslides on volcanic islands as part of the activities of the International Consortium on landslides.

Several other previous studies using constructed databases focused on the susceptibility assessment of landslide hazards or the factors influencing landslides. Rupp and Damm (2020) developed a rockfall database with approximately 700 recorded rockfall events in Germany. Monthly distributions and three elevation classes of rockfalls were studied to demonstrate the characteristic seasonal occurrence of rockfalls in Germany. Görüm and Fidan (2021) compiled a new database of 389 fatal landslide events resulting in 1343 fatalities from 1929 to 2019 in Turkey. Spatiotemporal distribution analysis was conducted to illustrate the relationship between the number of fatalities and fatal landslides and human activities. The potential impact of economic crises and political steadiness on fatal landslide trends are also remarked on this study. Landslide susceptibility mapping can also be conducted using landslide databases (Ghosh et al. 2020). The detailed geographic information on landslides in these databases is essential in such studies.

However, only a few previous studies attempted to develop landslide databases to study the socioeconomic impacts of landslides for two reasons: (1) detecting and observing the process of landslide events and recording their consequences in detail are difficult because the occurrence of landslides is usually sudden and random. (2) The data sources of existing landslide databases so far are so diverse that there are inevitably big differences in their data formats, making their analysis difficult. Current studies focused only on the impact of landslides. Díaz et al. (2020) presented an inventory of landslides in Mexico from 1935 to 2017 and the affected people using the average annual growth rate method. Martha et al. (2021) compiled and cataloged a database of 45,334 landslides from 1998 to 2018 in India on a WebGIS platform. Exposure analyses at a national scale were conducted using four key socioeconomic parameters in 145 hilly districts. The results showed that the Rudraprayag District was most affected by landslides in India. Researches on the vulnerability of humans affected by landslides using landslide databases remain scarce.

This study was conducted to (1) establish a database covering fatal landslide events that occurred in China from 1940 to 2020 and collect the spatiotemporal information and consequences of these landslides; (2) analyze the spatiotemporal distribution of fatal landslides in China; (3) determine the impact of human activities on fatal landslides and the influencing factors of anthropogenic landslides; and (4) quantify the vulnerability of affected people according to different regions in China. The research findings on human vulnerability obtained using the fatal landslide database are essential for the assessment, management, and elimination of landslide risks.

Materials and methods

Data collection

In this study, a database was established by sourcing information on fatal landslides in China from 1940 to 2020 from various channels. These included the geological hazard report from the Ministry of Natural Resources of the People's Republic of China (http://www.mnr.gov.cn/gk/dzzhzqxqbg/), the National Geological Hazard Bulletin from 2008 to 2020, the Global Landslide Catalog (https://catalog.data.gov/dataset/global-landslide-catalog-export), the landslide blog of Petley (https://blogs.agu.org/landslideblog/), reports from different Chinese media, and previous literature (Table 1). Official government reports or bulletins were selected as the main sources when there were multiple sources for the same landslide event, supplemented by information from other sources.

The compilation of the landslide database was completed in three steps: (1) recording information on fatal landslide events from different sources; (2) filtering information from multiple sources to eliminate repeated information; and (3) standardizing and presenting information on landslide events in a unified form. Through the process, the duplicated information of the same landslide event has been sifted by careful comparison.

The fatal landslide database established in this paper contains four types of information for each fatal landslide event: basic information (number, province, detailed location, latitude, longitude, and date and time of the day of occurrence), classification (type of movement and trigger), consequence (number of fatalities and number of injuries), and remarks (information source). Table 2 lists the sample documentation of landslide events in the fatal landslide database. The locations of the landslides were recorded in as much detail as possible by the county administrative unit in China. The latitudes and longitudes of the landslide locations were obtained using Google Earth (http://www.earth.google.com) and other online query websites for latitudes and longitudes (http://jingweidu.bmcx.com/). For the date on which the fatal landslide occurred, if the landslide was triggered by continuous rainfall, the end date of the rainfall event was recorded as the date of the landslide event. The time of the occurrence of a landslide event was recorded in hours. For example, if the landslide occurred at 11:35 am on a certain day, the time was recorded as 11 am.

The landslides in the database in this study were merely classified according to movement types and triggers because of the lack of detailed descriptions of the landslide events in reports, news, and earlier literature. In terms of landslide movement types, the term "landslide" in this paper refers to the generalized definition of landslides, including slides, falls, flows, and other movements (European Commission 1994; Cruden and Varnes 1996). Landslide triggers were divided into rainfall, human activity, freeze–thaw, and unknown. The unknown triggers were due to the lack of any

Table 1 Multiple data sources of fatal landslide

Sources	Link	Period
Geological hazard report from MNR	http://www.mnr.gov.cn/gk/dzzhzqxqbg/	July 2011–December 2020
National Geological Hazard Bulletin	-	2008–2020
Global Landslide Catalog	https://catalog.data.gov/dataset/global-landslide-catalog-export	2007–2013
Landslide Blog of Petley	https://blogs.agu.org/landslideblog/	2008–2020
Chinese medias	-	2000–2020
Previous literature	-	1940–2020

Table 2 Sample documentation of landslide events in the fatal landslide database

Basic information							Classification		Consequence		Remarks
No	Province	Location	Long	Lat	Date	Time of the day	Type of movement	Trigger	No. of death	No. of injury	Source
1	Qinghai	Gonghe County, Hainan Tibetan Autonomous Prefecture	100.6201	36.2887	1943/2/7	-	Landslide	Rainfall	114	0	http://192.168.143.20:8080/handle/131551/4153
1159	Guangdong	Hengtaiyu Industrial Park, Hong'ao Village, Fenghuang Community, Guangming New District, Shenzhen City	113.9415	22.7216	2015/12/20	11	Debris flow	Human activity	85	23	http://www.360doc.com/content/15/1222/10/160073_522228588.shtml
1377	Guangxi	Huangnigang Village, Lianhua Town, Gongcheng County, Guilin City	111.0582	24.7197	2019/6/13	3	Debris flow	Rainfall	3	0	http://www.mnr.gov.cn/gk/dzzhzqxqbg/201906/t20190624_2441739.html
1455	Sichuan	Beijiang Village, Feixi Town, Xuzhou District, Yibin City	104.2637	28.9233	2020/7/26	1	Fall	Rainfall	2	0	https://3g.163.com/news/article_so/FIHJSIE305444WPE.html

description of the triggers in any information source. All landslides in the database were classified based on a single direct trigger. For example, if a landslide was influenced by pre-existing human activities and finally triggered by a rainstorm, it would be classified as a landslide triggered by rainfall. A database of fatalities caused by earthquake-induced landslides should be established for each single earthquake event using information from different sources because it was too difficult to distinguish the fatalities of landslides from fatalities caused by the earthquake. People who lost contact or went missing during the landslide events were included when calculating the number of fatalities. The information sources were recorded so that the information accuracy could be verified. Multiple information sources were listed together to supplement the landslide information when a single information source might not adequately describe a landslide. The definitions of the terms used in this paper are summarized in Table 3 to distinguish different landslide types. Especially, it can be seen that natural and anthropogenic landslides were indeed differentiated not just by triggers. Man-made slopes involving natural triggers were also deemed as anthropogenic landslides in our study since they were formed due to human activity.

Spatiotemporal distribution analysis

Landslide events and fatalities from 1940 to 2020 excluding those triggered by earthquakes in mainland China were collected, The number of events and fatalities were then counted at a provincial scale and regional scale, respectively. Mainland China was classified into seven regions according to natural geographical conditions: East China (Jiangsu Province, Zhejiang Province, Anhui Province, Fujian Province, Jiangxi Province, Shandong Province, and Shanghai City), South China (Guangdong Province, Guangxi Province, and Hainan Province), North China (Hebei Province, Shanxi Province, Beijing City, Tianjin City, and Inner Mongolia Autonomous Region), Central China (Hubei Province, Hunan Province, and Henan Province), Southwest China (Sichuan Province, Yunnan Province, Guizhou Province, Chongqing City, and Tibet Autonomous Region), Northwest China (Ningxia Hui Autonomous Region, Xinjiang Uygur Autonomous Region, Qinghai, Shaanxi, and Gansu), and Northeast China (Liaoning Province, Jilin Province, and Heilongjiang Province) (Fig. 1). The temporal distributions of the landslide events and fatalities were analyzed by counting them per 5 days and 25 days. Landslides triggered by natural factors were separately analyzed to assess the impact of human activities on landslide hazards. The monthly distribution and seasonality of landslides were also analyzed for the whole nation and each region.

The study of anthropogenic landslides

The anthropogenic landslides in the constructed database were further analyzed. The triggers of these anthropogenic landslides were analyzed. The temporal distributions of anthropogenic landslides of various triggers were studied by calculating the number of anthropogenic landslides. The number of fatalities was also calculated over years. The hourly distributions of these landslides in a day were also analyzed to illustrate the characteristics of this type of landslide. Furthermore, gross domestic product (GDP) and urbanization growth rates were chosen as the factors in studying the impact of human activities on landslides and the consequences of these landslides.

Table 3 Definitions of terms used to distinguish different types of landslides (based on Hungr et al. 2014)

Term	Definition
Fatal landslides	The landslides that caused human death.
Natural landslides	The landslides occurred due to the failure of natural slopes triggered by natural factors, such as rainfall and snow-melting.
Anthropogenic landslides	The landslides that are triggered by human activities such as illegal mining, legal mining, hill cutting, construction, dam failure, waste dump failure, leaking pipe, irrigation, recreation, and other unspecific human activities.
Falls	Rock or debris of any size is detached from a steep slope or cliff, along a surface on which little or no shear displacement takes place, and descends mostly through the air by free fall, leaping, bounding, or rolling.
Flows	The steady, slow, spatially continuous movement or deformation of rock or soil in one direction.
Slides	Sliding of a mass of weak rock or soil on a cylindrical or another rotational rupture surface.
Complex landslides	Landslide slope movements involve a combination of one or more of the principal types of movement such as slide, flow, and fall.
Topples	This kind of movement consists of the forward rotation of a unit or units about some pivot point, below or low in the unit, under the action of gravity and forces exerted by adjacent units or by fluids in cracks. It is tilting without collapse.
Unknown landslides	Movement of these landslides is not known.
Other landslides	Landslides that include complex landslides, unknown landslides, and topples.

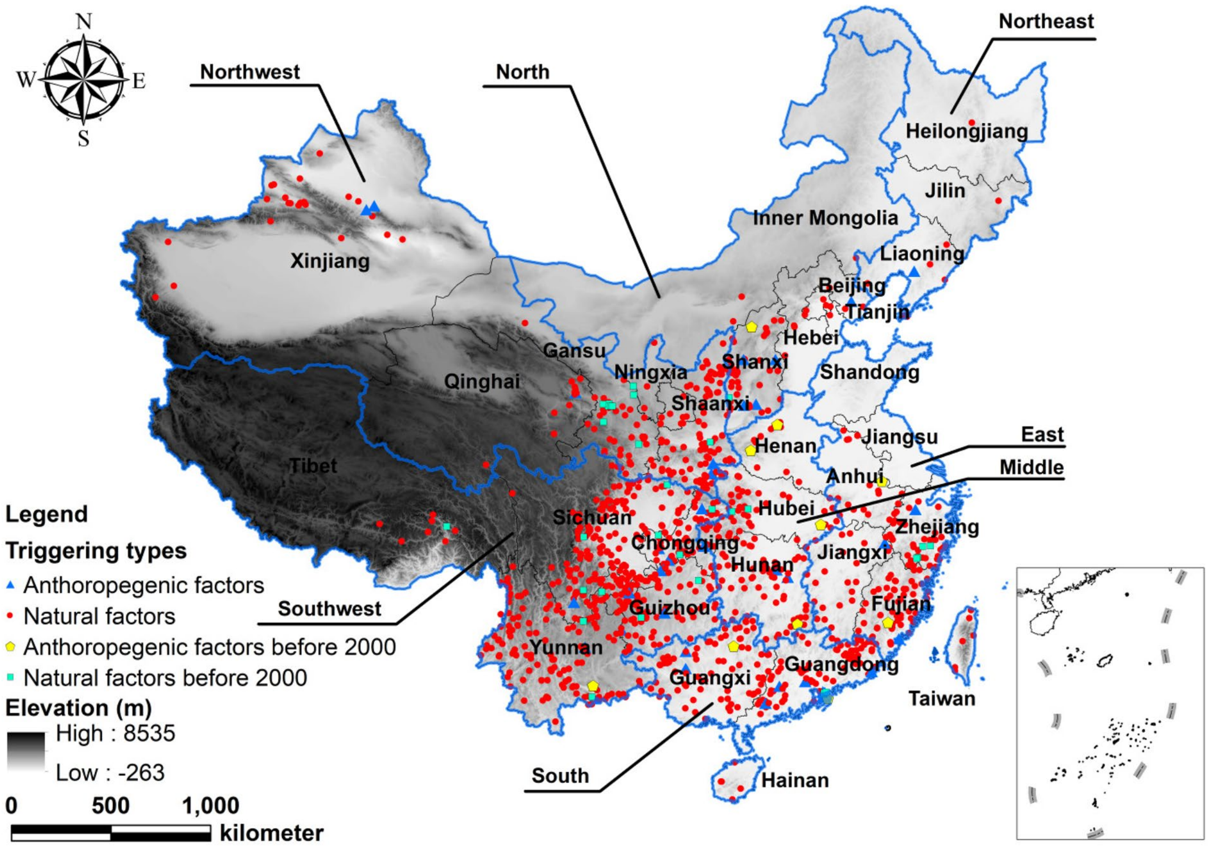


Fig. 1 Spatial distribution of fatal landslides in China

Estimation of the affected population

The period from 2000 to 2020 was selected as the research period when studying the affected population because there were very few landslides before 2000 in the established database (only accounting for 3.9% of the number of fatal landslides) and the affected population data before 2000 were difficult to obtain. The number of affected people was calculated in ArcGIS by creating layers with landslide information and population distribution. The latitude and longitude data in the database were used to build a landslide layer based on a national map in World Geodetic System 1984 (WGS84). Chinese population data from 2000 to 2020 from WorldPop (2018) were selected as the population data. The Geotiff format was utilized, with a resolution of 30arcs (about 1 km at the equator). The mapping approach of the population data was the random forest method based on isometric redistribution according to WorldPop (2018). The population data had the projected coordinate system of the WGS84 of which, the unit is the number of people per pixel. It was assumed that the affected area of a single landslide was 30 arcs. All the people in such an area represented by a pixel were affected.

The population affected by landslides was obtained by the following procedures shown in Fig. 2. The processes of creating a landslide point layer were as follows: (1) filtering out the landslide points of each year in the database and extracting the latitude and longitude coordinates; (2) using the latitude and longitude coordinates to enter the landslide point in the Chinese map with the coordinate system of WGS84; and (3) creating a landslide layer to store landslide data in point elements separately for each year. The spatial analysis tool “extracting values to points” in ArcGIS was used to extract raster pixel values based on points. The values were then recorded in the attribute table of the points as the new column named RASTERVALU. The population data in the pixel unit where each landslide point was located was regarded as the number of people affected by this landslide. The sum of the populations of all pixel units where the landslide points lay was the number of people affected. Landslides in different years of different provinces or different regions were considered.

Vulnerability assessment

Human vulnerability is defined in this context as the probability that an individual will be killed in a landslide (Corominas et al. 2014). The probability of death for an individual can be calculated as the ratio of the number of fatalities to the number of affected people (Michael-Leiba et al. 2005):

$$V = \frac{\text{Number of fatalities}}{\text{Number of affected people}} \tag{1}$$

In this study, the vulnerability was quantitatively evaluated at a regional scale because not all provinces were affected by landslides

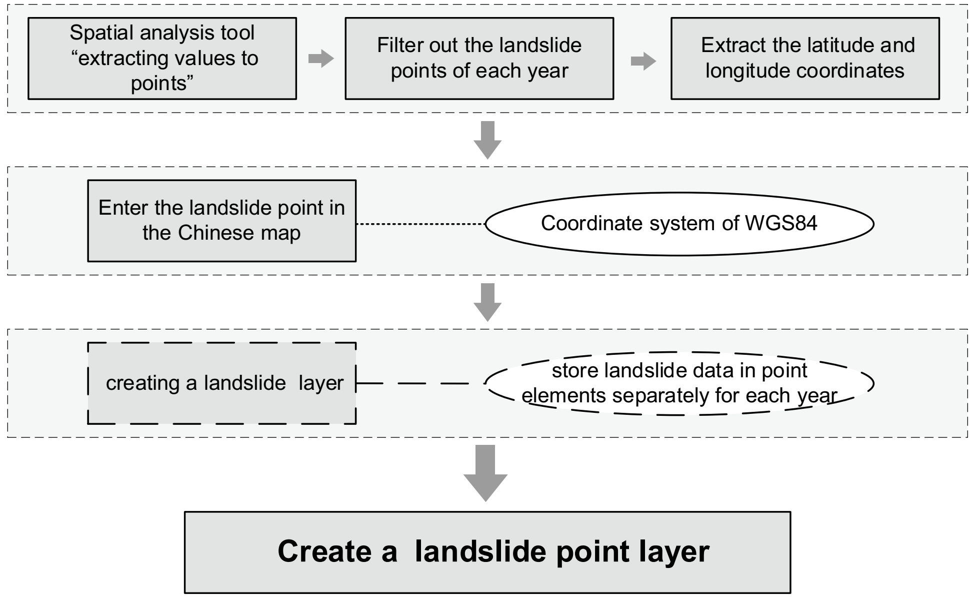


Fig. 2 Diagram of procedures for calculation of the affected population

each year. The number of fatalities was calculated by counting the fatalities from fatal landslides in the constructed database for each year.

Results

Classification of landslides

A total of 1470 landslide events in China with 14,394 fatalities from 1940 to 2020 were recorded in the fatal landslide database. Among these fatal landslides, there were 883 slides (60.1%), 343 flows (23.3%), 213 falls (14.5%), and 31 other landslides (18 complex landslides, 14 unknown landslides, and 2 topples) (Fig. 3a). These caused a total of 6172, 6253, 1533, and 436 fatalities, respectively, which accounted for 42.9%, 43.4%, 10.7%, and 3.0% of the total fatalities, respectively. The average fatalities per landslide of each type were 7, 18, 7, and 14.

The average fatalities per landslide by debris flows decreased to 13 after excluding an obvious outlier, the Zhouqu debris flow event, where a total of 1841 persons were killed. Once a debris flow event occurred, it usually had strong mobility and large kinetic energy. Therefore, it had a large impact area and caused a large number of fatalities. Among the fatal landslides in the database (Fig. 3b), 1014 landslides were triggered by rainfall (68.9%, among which 3.5% were triggered by rainstorms accompanied by typhoons), 270 landslides (11.2%) were triggered by human activities, 23 landslides (1.5%) were triggered by other factors, and the remaining 164 landslides (11.2%) were triggered by unknown factors because of the lack of detailed reports or documents. The landslides triggered by these different factors caused 76.6%, 18.1%, 3.3%, 1.7%, and 0.2% of the total fatalities, respectively.

Spatiotemporal trend analysis

Spatial trend analysis

The fatal landslides in China were mainly distributed in the Loess Plateau, Sichuan Basin, and Yunnan–Guizhou Plateau (Fig. 4). These areas were transition areas from plains to mountains, with complex geological structures, active geological activities, and loose-structured slopes. The interaction of the southeast and southwest monsoons frequently produces torrential rains, inducing extreme climate conditions.

As shown in Fig. 4, the fatal landslides were mainly distributed in 13 provinces: Yunnan, Sichuan, Shaanxi, Guangxi, Guangdong, Guizhou, Gansu, Hunan, Chongqing, Hubei, Fujian, Zhejiang, and Shanxi. Yunnan Province had the greatest number of fatal landslides at 201, followed by Sichuan Province with a total of 197 fatal landslides. More than 100 landslides occurred in Shaanxi, Guangxi, Guangdong, Guizhou, and Gansu from 2000 to 2020 at 194, 193, 116, 106, and 101, respectively. These 13 provinces have special topographies and climates that are prone to landslides. For instance, Yunnan, Guizhou, Sichuan, Chongqing, Hunan, and other provinces are located at the boundary of China's first and second ladders, which have lots of mountainous, irregular topographies and heavy rains. Shaanxi, Gansu, and other provinces lack vegetation which can effectively mitigate surface erosion and reduce the possibility of debris flows (Shen et al. 2017), whereas Guangdong, Guangxi, Fujian, Zhejiang, and other provinces are located in typhoon-prone coastal areas. The provinces with the most fatalities were Gansu, Yunnan, Sichuan, Shaanxi, Guizhou, Shanxi, Hubei, Guangdong, Zhejiang, Chongqing, Guangxi, Hunan, and Fujian. The fatal landslides in Gansu and Yunnan caused 2659 and 2655 fatalities, respectively. Gansu Province ranked first in the number of fatalities caused by fatal landslides among all provinces because of the catastrophic debris flow event in Zhouqu in 2010. If this special event were excluded, Gansu Province would rank fourth. The total fatalities in Gansu, Sichuan, Yunnan, Shaanxi, Guizhou, and Shanxi exceeded 500 from 2000 to 2020 at 2156, 1499, 1463, 837, 719, and 629, respectively, with the average number exceeding 25 per year. Although only 9 and 30 fatal landslides occurred in Tibet and Xinjiang, these caused 253 and 179 casualties, respectively, making the average number of fatalities relatively large.

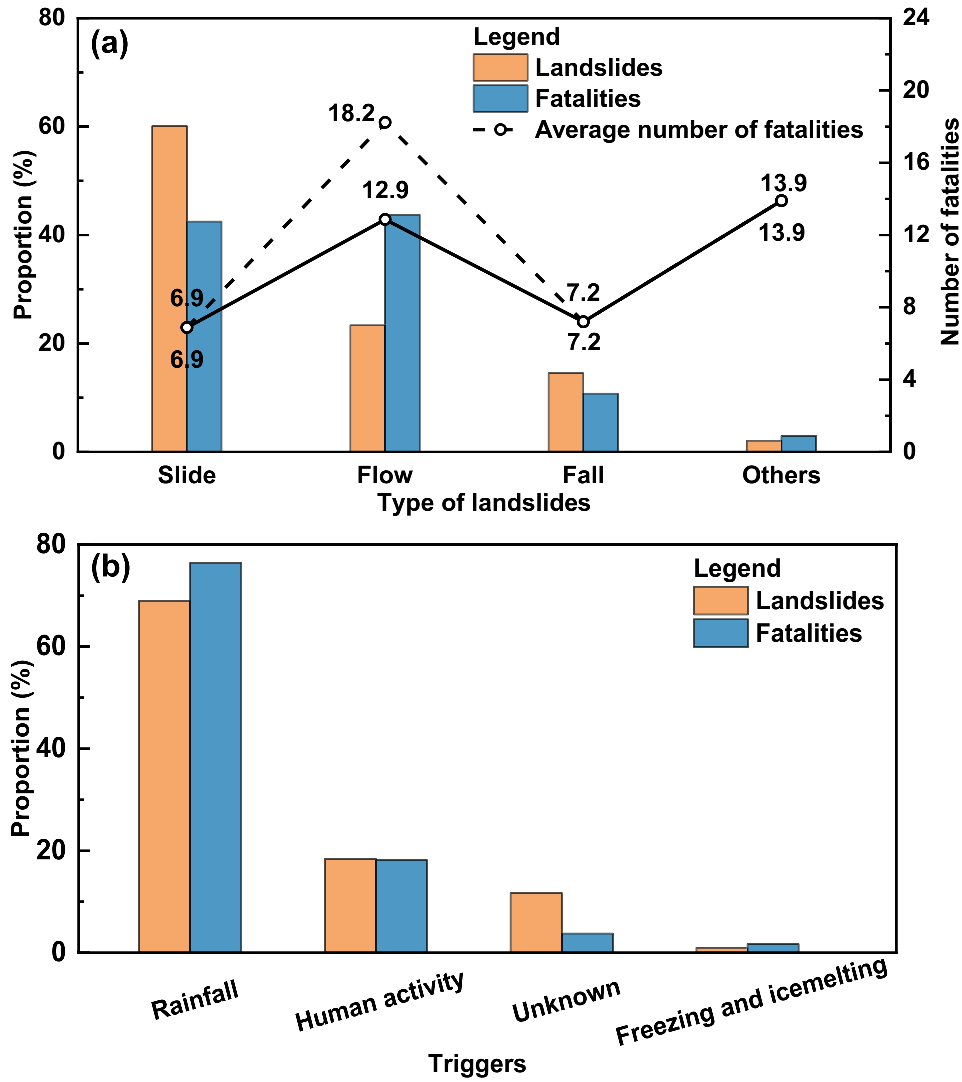


Fig. 3 Proportions for landslides classified by different types of movement and triggers: **a** type of movement and corresponding fatalities; **b** type of triggers

The landslide and fatality densities per 10,000 km^2 in each province are shown in Fig. 4b and c, which were presented in ArcGIS with six classes. There were more than 10 fatal landslides per 10,000 km^2 in eight provinces: Shaanxi, Chongqing, Guizhou, Yunnan, Guangxi, Guangdong, Fujian, and Zhejiang. Four provinces (Gansu, Chongqing, Yunnan, and Zhejiang) had more than 100 fatal landslides per 10,000 km^2. The fatality density had a direct proportion with the landslide density. However, the fatality density of Zhejiang Province ranked first among those of the coastal areas even though its landslide density was not the highest. This can be explained by the relatively infrequent occurrence of landslides therein and thus the weak landslide awareness of the people and government, which induced the high fatality density.

The number of fatal landslides and fatalities at the regional scale was also studied. As shown in Fig. 5, among the seven geological regions, Southwest China had the largest number of fatal landslides from 2000 to 2020, and the number of fatalities in Southwest China was also the largest in these years except for 2000, 2005, 2008, 2010, and 2015. This demonstrated that landslides posed the greatest threat to the southwest region of China. Besides, the unusually large landslides that occurred in other regions in the years 2000, 2005, 2008, 2010, and 2015 caused the number of fatalities in such regions to greatly exceed the average level, making them the regions with the largest number of fatalities in such years. For example, the debris flow event caused by a dam failure in Xiangfen County in 2008 resulted in 218 deaths, giving North China the largest number of fatalities that year.

The analysis results on Southwest China are similar to other study conclusions. Among the seven regions, Southwest China has the largest number of fatal landslide records. The Southwest China region is located in the Himalayan seismic belt, which has intense crustal movement, steep topography, and fragmented rock–soil bodies, along with heavy rains (Huang 2009). All regions except for Northeast China were threatened by landslides every year (see Sect. 3.5 for details). Thus, the risk management and mitigation of landslide hazards in China are crucial in protecting human life and property.

Temporal trend analysis

Temporal changes in the number of landslides and the number of fatalities over time since 2000 are shown in Figs. 6a, b and 7a, b. There were 57 and 1413 landslides in the database before and after

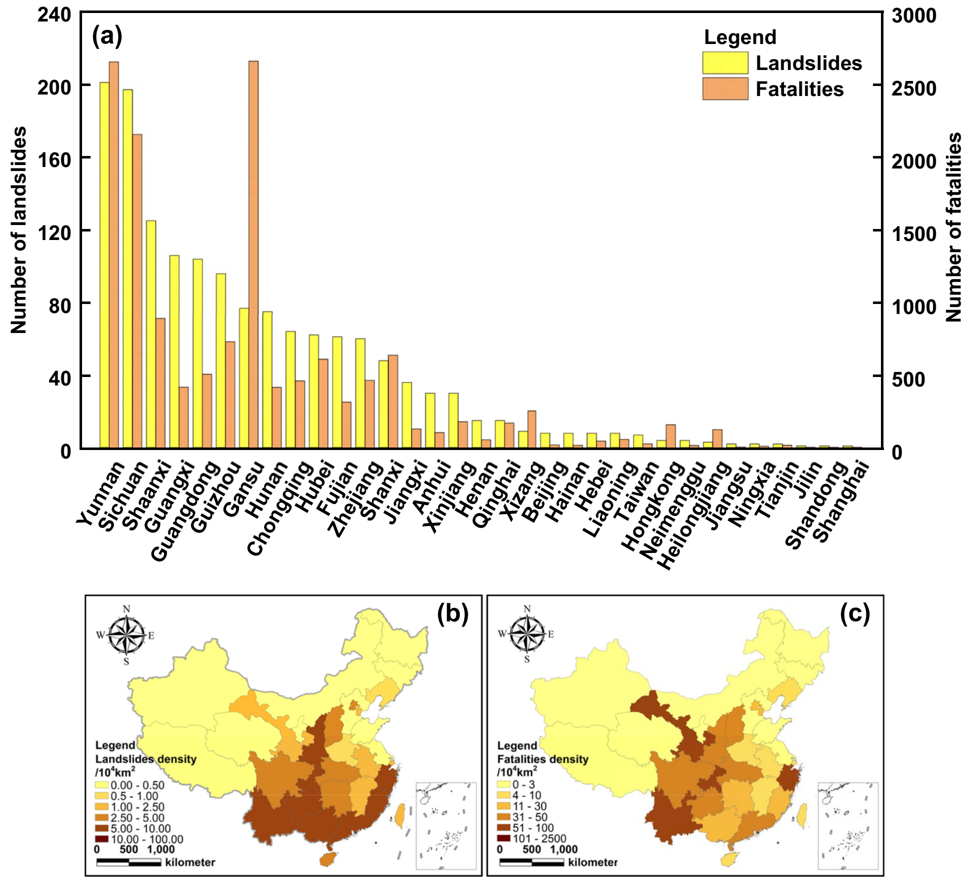


Fig. 4 The number and densities of fatal landslides and the resulting fatalities in each province: **a** number of landslides and fatalities; **b** density of landslides; **c** density of fatalities

2000, respectively. The vast difference in the average annual number of landslides partly resulted from the development of media and other recording methods. The data were arranged by pentads (5-day bins), starting on January 1 of each year. The 25-day moving averages for landslide events were shown in black. The number of fatal landslides and the number of fatalities in China fluctuated over the past 20 years, with 2010 having the largest number of both landslides and fatalities. In the past 10 years, 2018 had the lowest number of landslides and fatalities. Besides, Figs. 6c and 7c show the rainfall of southwestern China as a typical landslide-prone region over the past two decades. As can be seen, the trend of rainfall and the number of landslides that occurred in a year are similar which can somehow elaborate the impact of weather events on landslides but the influence of extreme rainfall events was too hard to be observed over this 20-year period. The temporal trends of the landslides and fatalities derived from our database were consistent with the national geohazard notification, reflecting the reliability of the constructed database to a certain extent.

The changes in the proportion of landslides of different fatality scales over the years from 1940 to 2020 are shown in Fig. 8. The scales of landslides were divided into four grades according to the regulations on the prevention and control of geological disasters in China: super-large landslides with fatalities of over 30, large landslides with fatalities of 10–30, medium landslides with fatalities of 3–10, and small landslides with fatalities less than 3. The proportions of super-large landslides with fatalities over 30 gradually decreased over time: 100%, 66.7%, 66.7%, 57.1%, 25.0%, 18.4%, 4.2%, and 2.4% during 1940–1950, 1951–1960, 1961–1970, 1971–1980, 1981–1990, 1991–2000, 2001–2010, and 2011–2020 when there were totally 1, 3, 6, 7, 20, 38, 644, and 751 landslides. Meanwhile, the average number of fatalities caused by landslides during these periods was 213, 69, 135, 91, 49, 25, 11, and 5, respectively, which also gradually decreased. It can be inferred that the increase in the number of small and medium-sized fatal landslides and the decrease in the average number of fatalities are to some extent due to the gradual completeness of landslide records, which is consistent with the study of Lin and Wang (2018).

For the seasonality, fatal landslides usually occurred in rainy seasons, particularly between April and September. As shown in Fig. 9, the number of landslides that occurred in rainy seasons was 1151, accounting for 78.3% of all landslides. These landslides resulted in a total of 11,852 deaths, which were 82.3% of the fatalities caused by all landslides. Summer was the season with the most landslides, with 770 landslides (52.4%) and 8789 deaths (61.6%). The number of fatal landslides and fatalities in winter was the smallest, with 104 fatal landslides (7.1%) causing 744 fatalities (5.2%).

Monthly variations of the number of fatal landslides in the seven geographical regions of China considering mean monthly rainfall are shown in Fig. 9. The monthly average rainfall data used came from the global climate background information of the China Meteorological Administration. The rainfall data of the central city of each region was selected to represent the regional

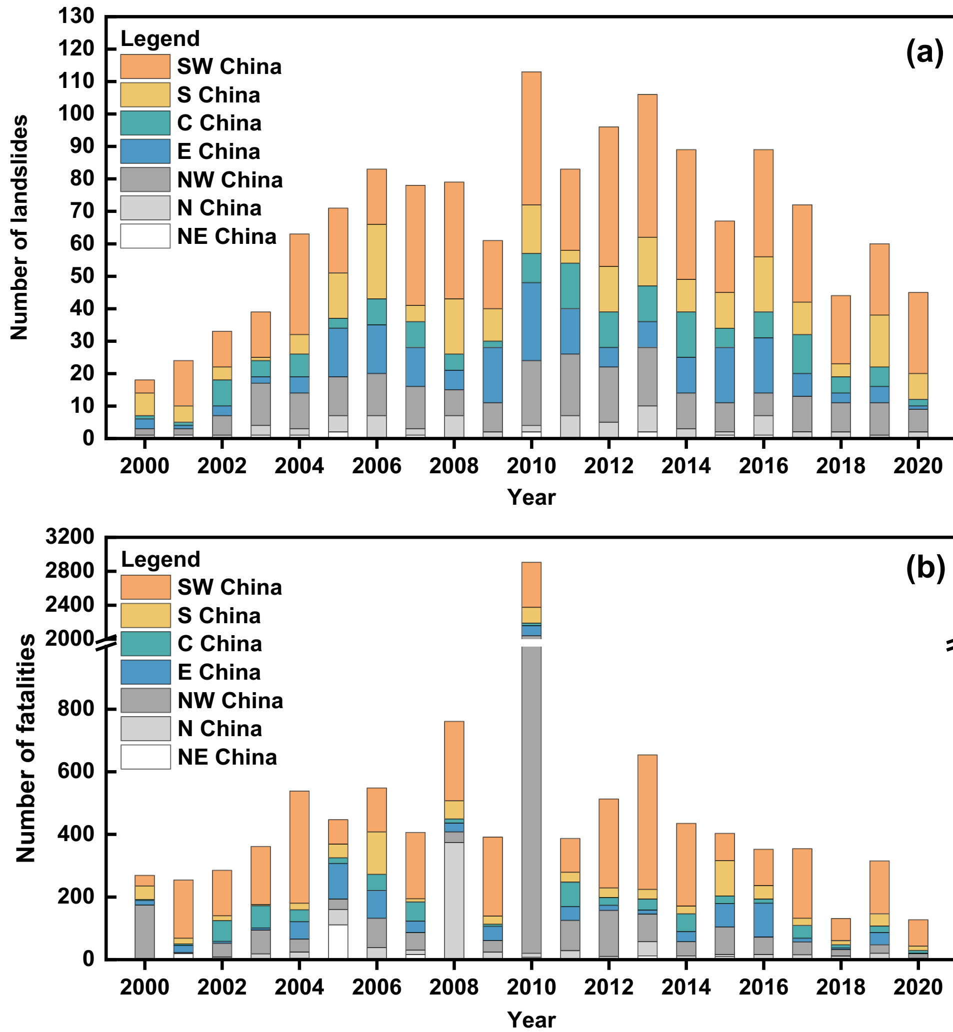


Fig. 5 Distribution of the number of landslides and fatalities in seven geographical regions of China: **a** number of landslides; **b** number of fatalities

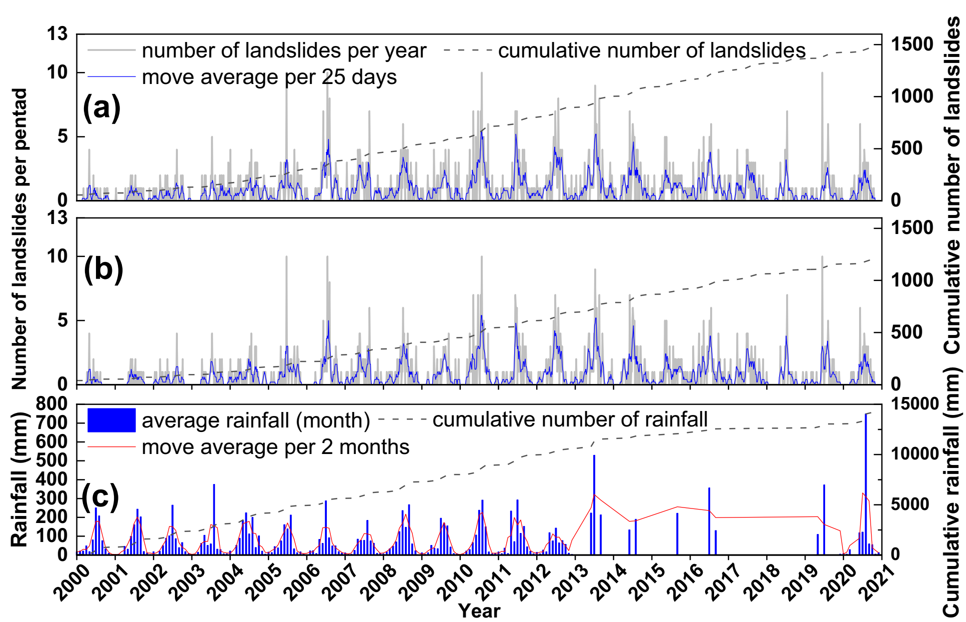


Fig. 6 Temporal distribution characteristics of landslides: **a** nonseismically triggered landslides; **b** nonseismically naturally triggered landslides; **c** monthly average rainfall

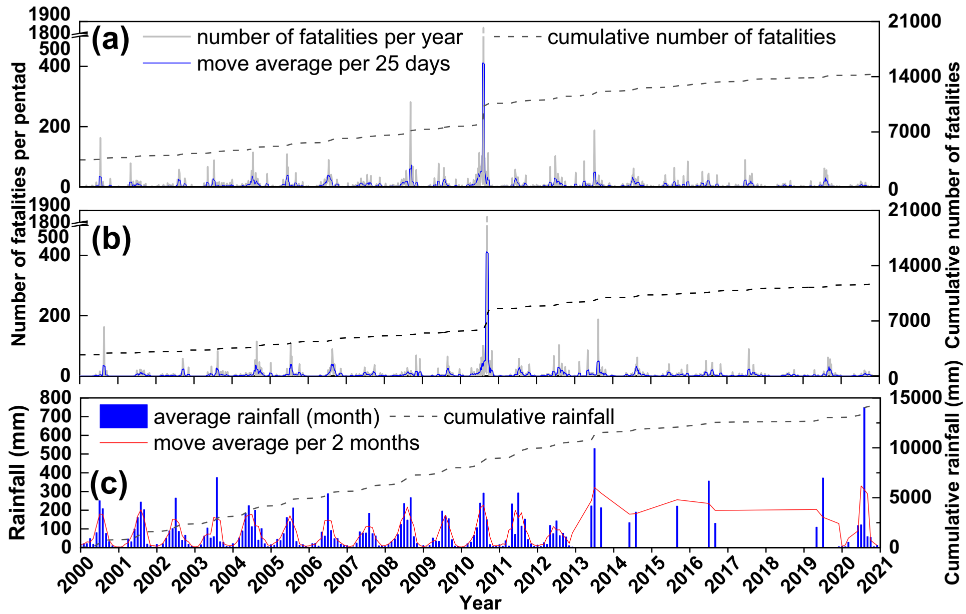


Fig. 7 The trends of the number of fatalities of landslides: **a** nonseismically triggered landslides; **b** nonseismically naturally triggered landslides; **c** monthly average rainfall

rainfall, and the national monthly average rainfall was calculated by summing up the average monthly rainfall of the seven regions. Spearman's rank correlation analysis was conducted between the mean daily rainfall and the mean daily landslides by month for the different regions, and the calculated correlation parameters are listed in Table 4. It can be deduced that there was a good correlation between the monthly average rainfall and the number of fatal landslides per month in each region ($P < 0.05$), with the southwest region having the strongest correlation ($P = 0$). On the national scale, the number of landslides was also consistent with the average monthly rainfall ($P = 0$), which indicated that the occurrence of fatal landslides in China was closely related to rainfall.

Analysis of anthropogenic landslides

Anthropogenic landslides are triggered by human activities such as illegal mining, legal mining, hill cutting, construction, tailings dam failure, waste dump failure, leaking pipes, irrigation, and recreation (as defined in Table 5). A total of 270 fatal anthropogenic landslides induced by human activities were then further subdivided according to the triggers mentioned in reports, news, the literature, and so on.

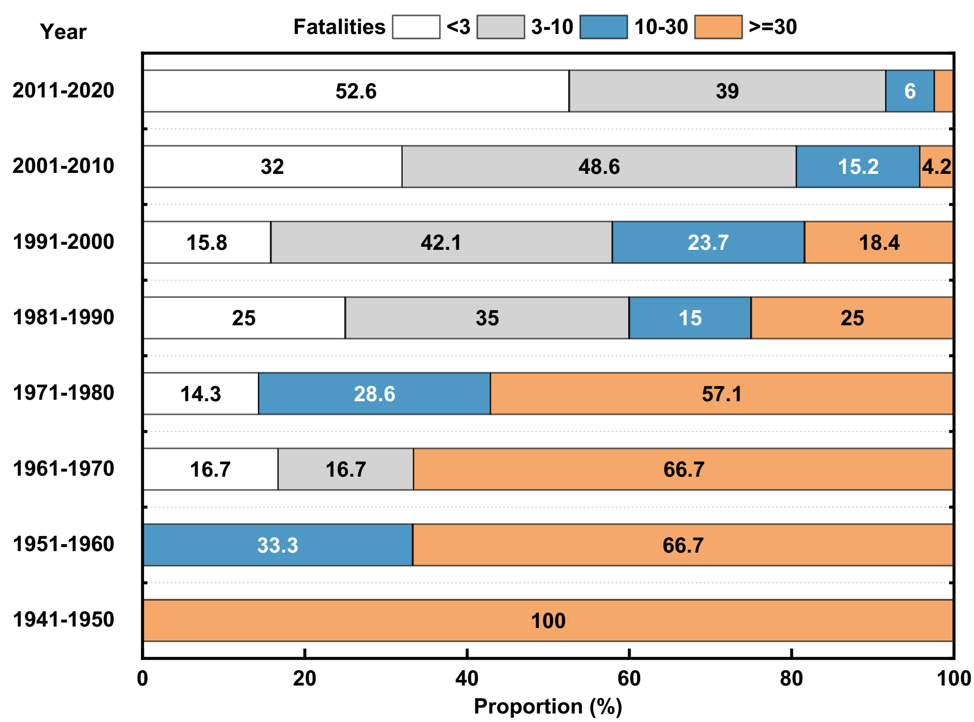


Fig. 8 The fatal landslide events in different levels of fatalities in different periods

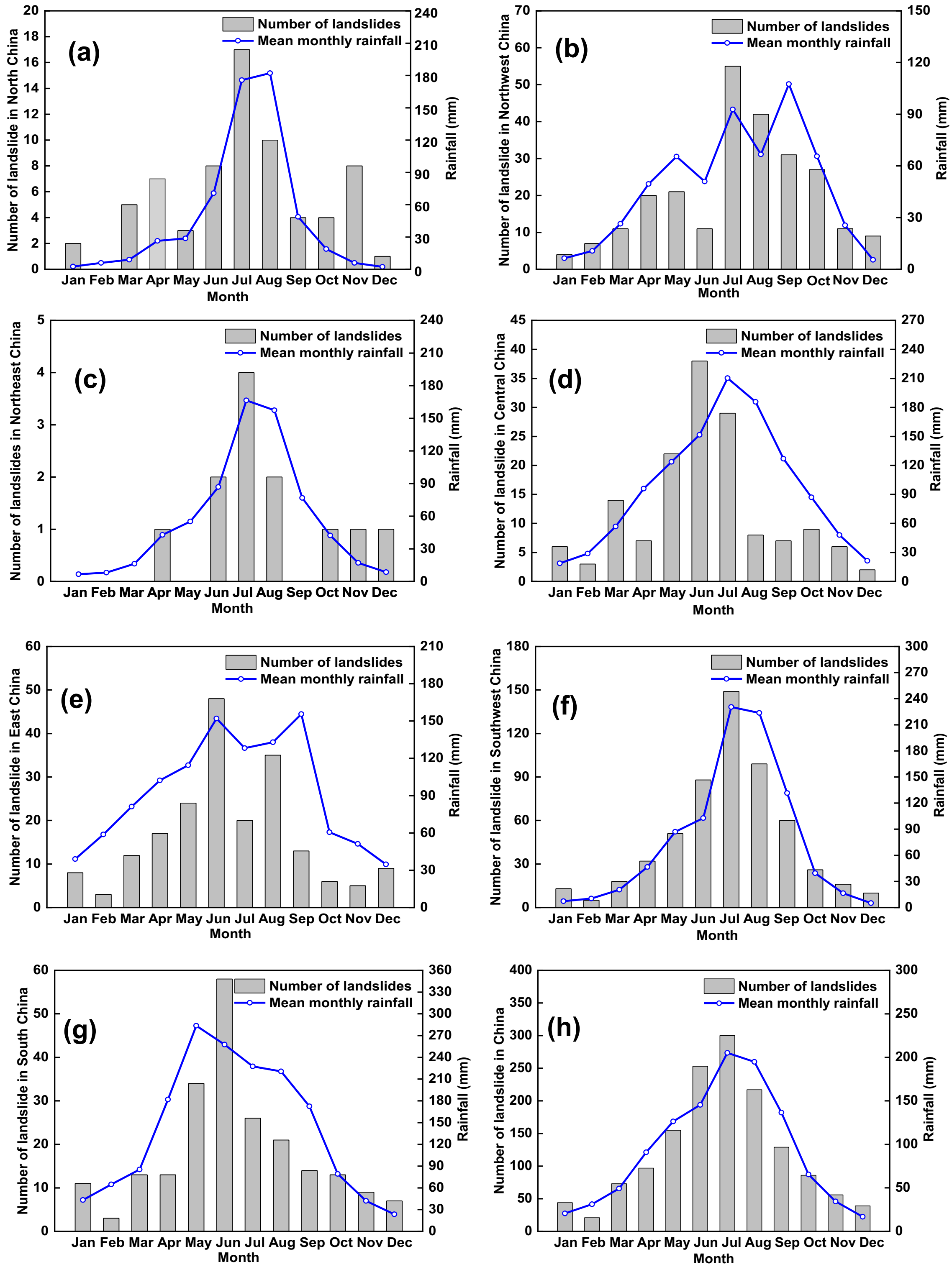


Fig. 9 Monthly variations of number of fatal landslides considering mean monthly rainfall in China: **a** North China; **b** Northwest China; **c** Northeast China; **d** Central China; **e** East China; **f** Southwest China; **g** South China; and **h** China

Trigger classification and temporal trends of anthropogenic landslides

The number of fatal landslides and fatalities induced by various human activities is shown in Fig. 10. Among various human activities, legal mining was responsible for the largest number of fatal landslides and fatalities. The construction and failure of tailing dams caused the second-largest number of fatal landslides and the second-largest number of fatalities. Particularly, the average

Table 4 Spearman's rank correlation between the mean daily rainfall and mean daily landslides by month for the different regions

Region	Correlation coefficient	*P* value
Northwest China	0.829	0.001
North China	0.814	0.001
Northeast China	0.784	0.003
Central China	0.650	0.022
East China	0.755	0.005
South China	0.784	0.003
Southwest China	0.949	0
China	0.940	0

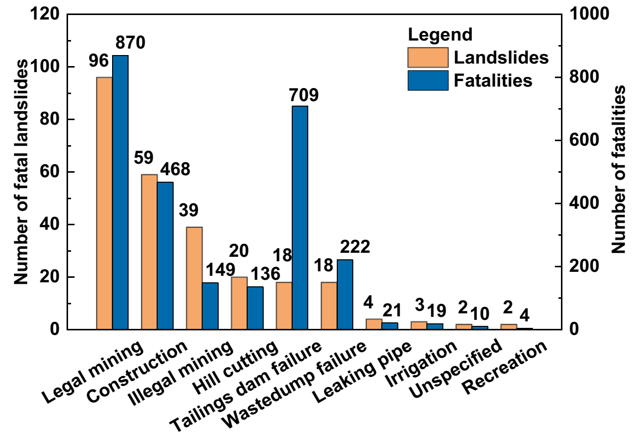


Fig. 10 The number of fatal landslides and the number of fatalities induced by various human activities

number of fatalities from landslides due to failure of tailing dams and waste dump ranked first and second, respectively. This was largely because tailing dams and waste dumps are usually located around the city or near factories. Thus, these two types of landslides pose a huge threat to human life once they occur. Therefore, conducting risk assessments and control of such anthropogenic sites is of great significance.

The temporal trends of the number and proportion of severely fatal landslides triggered by four types of human activities are shown in Fig. 11. The proportion of landslides triggered by construction apparently gradually increased nationally, demonstrating that the impact of construction activities on landslide events also gradually increased (Fig. 11a). The number and proportion of

Table 5 Trigger classification of anthropogenic landslides (based on Petley 2018)

Classification	Definition
Illegal mining	Unregulated or informal mining of slope materials in designated quarry or mine, where permission to extract material has not been granted.
Legal mining	Regulated and/or permitted mining of slope materials in designated quarry or mine, where permission to extract material has been granted and operations are managed.
Hill cutting	Hill cutting refers to the process of removing material from a hillslope for the purposes of altering its shape and/or obtaining slope material for use in construction, manufacture, or farming. It is differentiated from mining because it occurs on slopes that are not within a designated site of mining or quarrying; instead, hill cutting typically occurs on individual slopes on steep agricultural land or on man-made slopes such as those along transport routes. Hill cutting differs from construction because slope modification does not follow an engineering design to ensure slope stability. Hill cutting is assumed to be undertaken in an informal, unregulated manner (this is frequently noted in landslide reports).
Construction	Permitted modification of a slope for the purposes of a construction project undertaken by professional laborers, following planning approval.
Tailing dam failure	A tailings dam failure occurs when a tailings dam loses its structural integrity and releases tailings material from the impoundment.
Waste dump failure	Collapse of piles of municipal waste onto people, where stability of waste piles was disturbed by the passage of a person or persons.
Leaking pipe	Utility pipes carrying water have been damaged and leak water onto a slope surface or within the hillslope, compromising its stability.
Irrigation	Supplying dry land with water due to agricultural production, which carries water onto a slope surface or within the hillslope, compromising its stability.
Recreation	Triggered by passage of a person or persons walking or climbing over a hillslope for recreation.
Human action (unspecified)	Landslide report refers to a person or people present on a hillslope that collapses, without specifying the reason people occupied the slope or the landslide trigger.

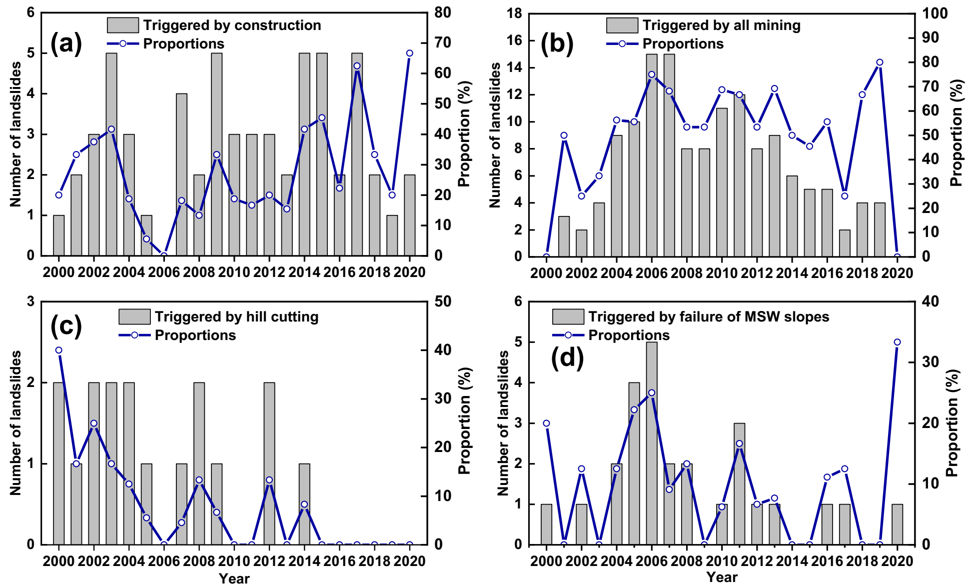


Fig. 11 The number and the proportion of landslides triggered per year by different types: **a** construction; **b** all mining; **c** hill cutting; **d** failure of MSW slopes

landslides triggered by legal mining and illegal mining are shown in Fig. 11b, with both showing initially increasing and then eventually decreasing trends. The turning point was around 2011. As China was in a stage of rapid GDP growth before 2011, the scale of construction and mining activities rapidly grew during this process, causing gradually increasing impacts on landslides. In 2011, the Chinese

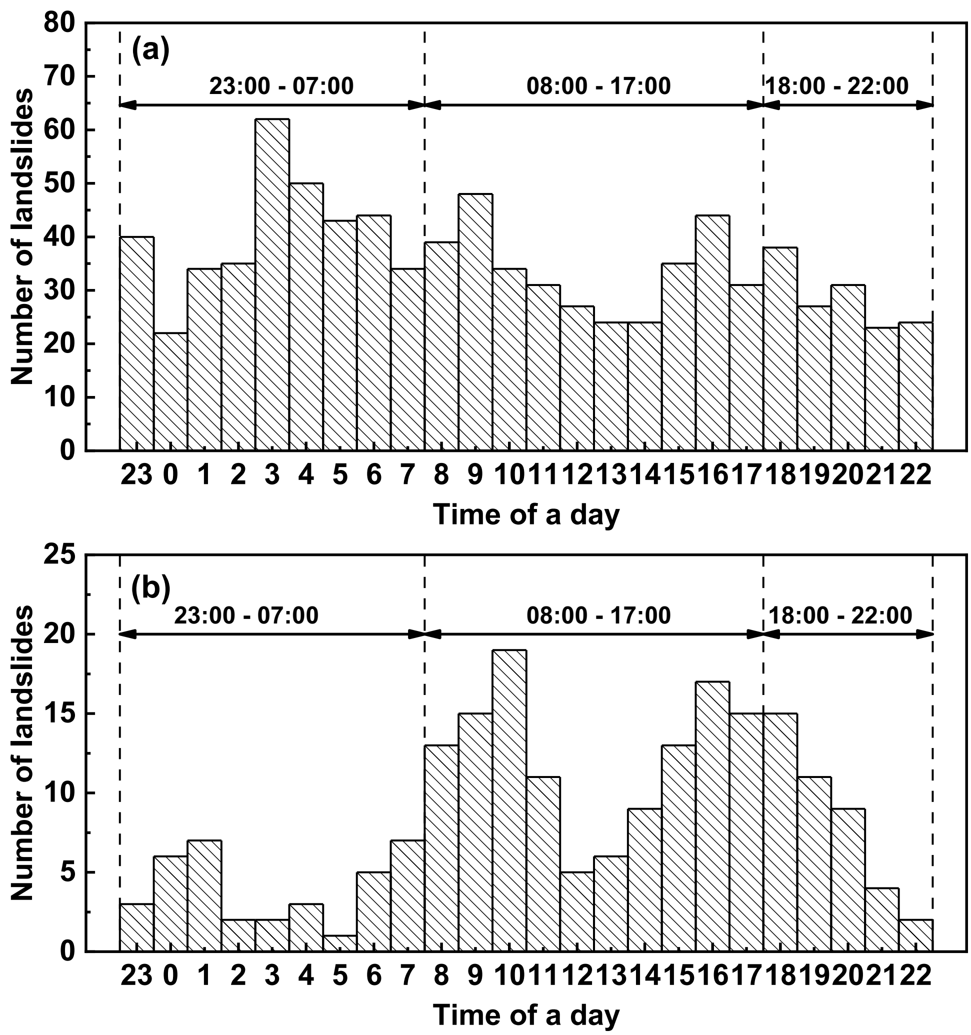
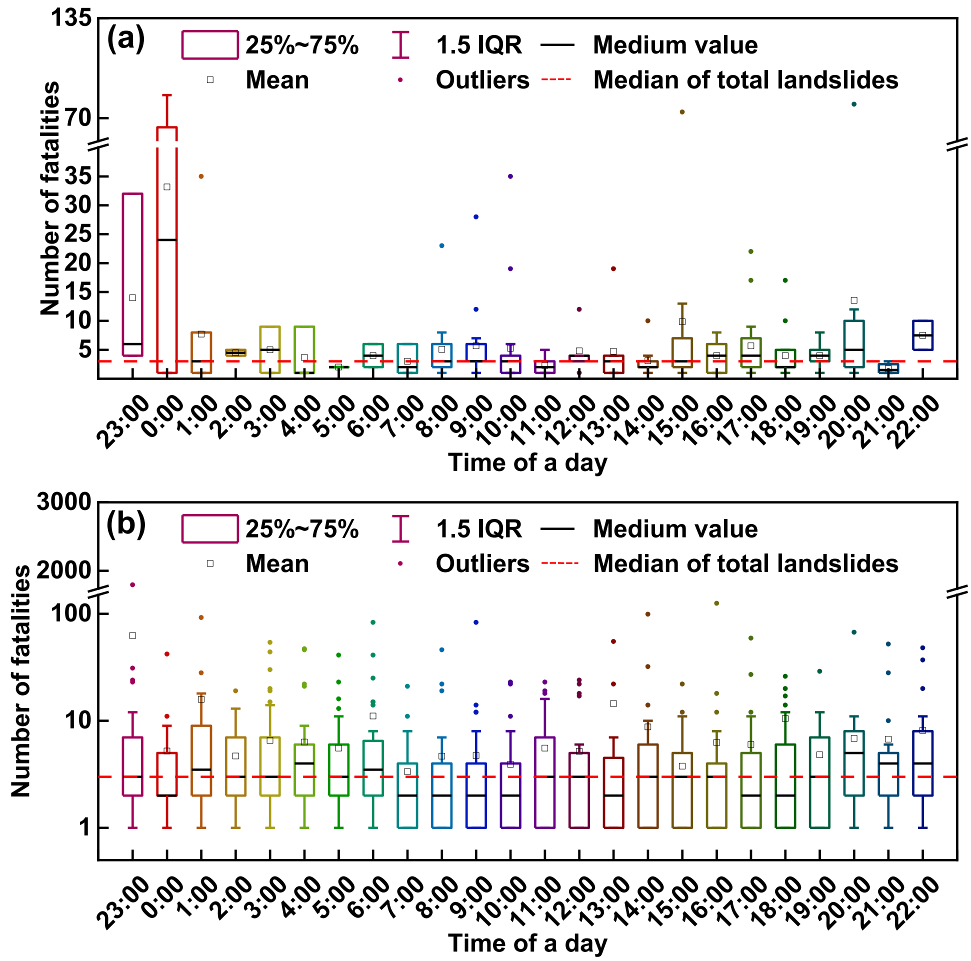


Fig. 12 Distribution of number at different times of the day: **a** natural landslides and **b** anthropogenic landslides

Fig. 13 Distribution of number of fatalities at different times of the day: **a** anthropogenic landslides; **b** natural landslides



government successively promulgated several laws and regulations to regulate mining activities, thus controlling the landslide events induced by mining. Meanwhile, hill-cutting processes were gradually standardized and forbidden, consequently controlling the landslides triggered by unregulated hill cutting. As shown in Fig. 11c, the number and proportion of landslides triggered by hill cutting showed a markedly decreased trend.

Landslides on municipal solid waste (MSW) slopes occurred from time to time in recent years (Fig. 11d). For instance, a catastrophic landslide occurred in Hengtaiyu Industrial Park, Guangming New District, Shenzhen, Guangdong Province, on December 20, 2015. This landslide covered an area of approximately 380,000 m^2, burying or destroying 33 buildings and causing 77 deaths. Therefore, assessing and controlling the risks of such slopes made of MSW is very urgent and necessary.

Comparison of the daily distributions of anthropogenic and natural landslides

The daily distributions of the number of anthropogenic and natural landslides were statistically analyzed (Fig. 12). The landslides triggered by anthropogenic factors have marked temporal characteristics and mainly occurred during working hours (8:00–12:00 and 15:00–18:00). This was because human activities had certain adverse effects on slope stability when working on slopes. The landslides triggered by natural factors occurred evenly at all times of the day, and the number of landslides triggered by natural factors during midnight (23:00–7:00) was slightly larger than that during the working period (8:00–17:00) and in the evening hours (18:00–22:00). This was partly because the constructed database only incorporated landslides that caused deaths, and the probability of landslides threatening human life would be higher at midnight than those during working hours and evening hours.

The fatalities at different times of the day of anthropogenic and natural landslides were also studied. The median number of fatalities for these two types of landslides was 3, and their difference in the number of fatalities was mainly because of the impact of the different times of the day on the number of fatalities. As shown in Fig. 13a, the median number of fatalities for anthropogenic landslides between 16:00–20:00 and 22:00–6:00 the next day was greater than the median number of fatalities from all landslides. However, for naturally triggered landslides, the median number of fatalities from the landslides that occurred from 19:00 to 6:00 the next day was greater than or equal to the median number of fatalities from all naturally triggered landslide events (Fig. 13b). The opposite was true for landslide events that occurred between 7:00 and 18:00. Landslides that occurred at midnight often caused greater casualties because people were often asleep and it was more difficult for them to detect landslide signals and take action than during the daytime. For anthropogenic landslides, the relatively large number of fatalities was often caused by landslides that occurred from 16:00 to 20:00. This was because people tended to relax after finishing a day's work or failed to detect signals of landslides in darkness. Landslides triggered by natural or anthropogenic factors had different characteristics as regards their distributions and the number of fatalities at different times of the day.

Influencing factors of anthropogenic landslides

The number of anthropogenic landslides and the number of fatalities over time were analyzed to determine their controlling factors. As shown in Fig. 14, the number of fatal landslides triggered by human activities gradually increased from 2000 to 2007. There was a turning point in 2008 when the number dropped sharply compared with that in 2007. Thereafter, it increased from 2008 to 2011. This trend was roughly the same as that of the GDP growth rate from 2000 to 2020 (National Bureau of Statistics of China). Landslide events with fatalities over 64 were excluded (considered outliers), which had a substantial impact on the trend analysis. It can also be drawn from the figure that the trends of the number of fatalities caused by anthropogenic landslides was also roughly consistent with that of the GDP growth rate. The area in gray (Fig. 14) indicated that the GDP growth rate gradually decreased. The years of rapid GDP growth were usually accompanied by a large number of human activities. These activities modified natural slopes through construction, mining, and quarries, among others, which greatly increased the risks of landslides.

Further analysis of the correlation between the number of fatal landslides and the number of fatalities and the GDP growth rate was conducted in Statistical Product Service Solutions (SPSS) which is a comprehensive and flexible statistical analysis and data management tool and also one of the most popular statistical packages which can perform highly complex data. The corresponding *P* values in the *T*-tests were all less than 0.01 (listed in Table 6), and the correlation coefficients were 0.832 and 0.751, respectively. These further illustrated the strong correlation between the GDP growth rate and the number of anthropogenic landslides and the number of fatalities from anthropogenic landslides.

The relationships between the urbanization rate and the proportion of anthropogenic landslides in the total fatal landslides and the proportion of the fatalities from anthropogenic landslides in the total fatalities from landslides were also analyzed using the *T*-test in SPSS. Similarly, special landslide events with fatalities of over 64 people were eliminated. The relationship between the proportion of fatal anthropogenic landslides and the urbanization growth rate (Fig. 15). The urbanization growth rate in the last 20 years was in a state of fluctuation, but it tended to decrease overall. The proportion of the number of anthropogenic landslides and the proportion

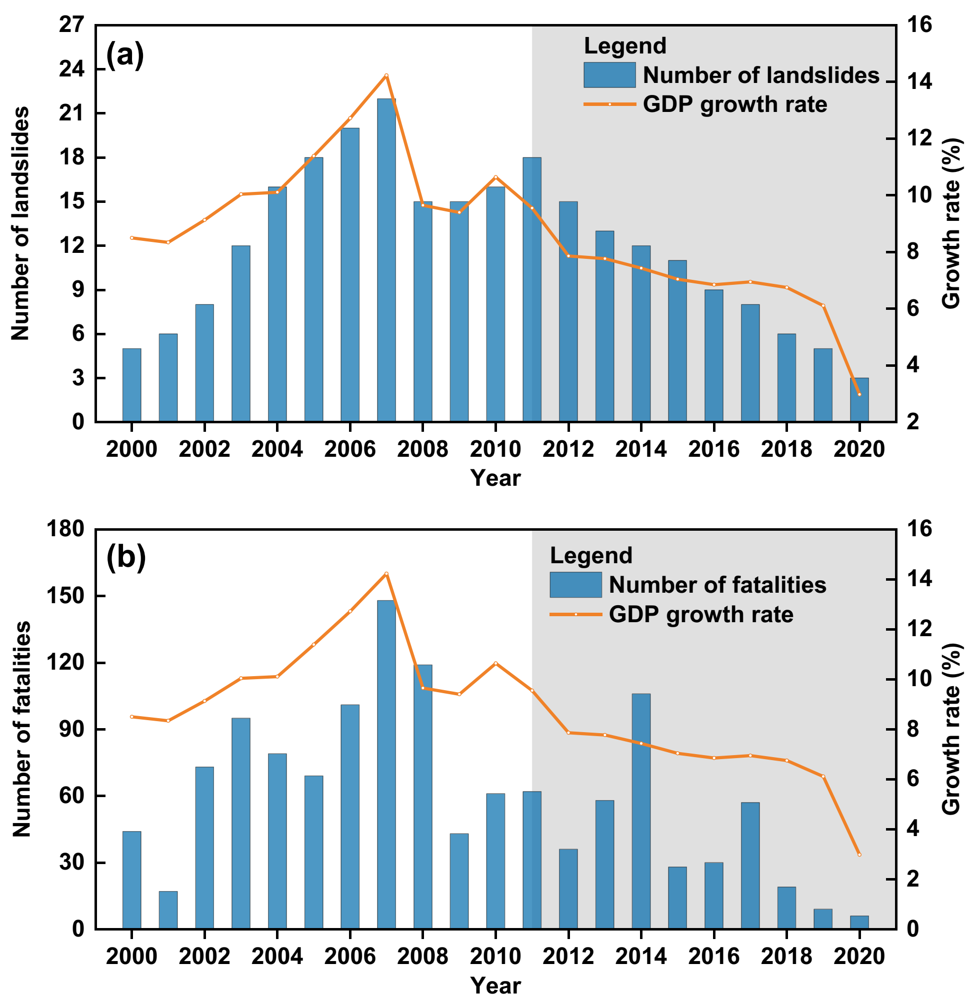


Fig. 14 Yearly variations of GDP growth rate with relation to landslides and fatalities: **a** number of anthropogenic landslides; **b** number of fatalities of anthropogenic landslides

Table 6 Correlation between the annual GDP growth rate and the number of fatal anthropogenic landslides

Items	Correlation coefficient	*P* value
Number of anthropogenic landslides	0.832	0
Number of fatalities of anthropogenic landslides	0.751	0.00009

of the number of fatalities from anthropogenic landslides also fluctuated but decreased overall, and the trend was roughly the same as that of the urbanization growth rate.

The results of the correlation analysis are shown in Table 7. The *P* values between the proportion of fatal landslides triggered by human activities and the proportion of the number of fatalities and the urbanization growth rate were 0 and 0.038, respectively. The correlation coefficients were 0.832 and 0.466, respectively. There was a good correlation between the urbanization growth rate and the proportion of the number of anthropogenic landslides. It also showed that the urbanization growth rate and the proportion of the number of fatalities from anthropogenic landslides were related but not strongly.

Affected populations

The number of affected people from 2000 to 2020 was evaluated year by year, as listed in Table 8. The number of affected people was the highest in 2010 and 2008 in 20 years at 201,225 and 197,417, respectively. The affected population in the seven geographic regions of China was also calculated. The number of people affected by landslides from 2000 to 2020 is listed in Table 8. As shown in Fig. 16, the number of people affected in each region constantly fluctuated but generally showed an initially increasing and eventually decreasing trend. On the national scale, this trend was more obvious. The reason for this trend was that people from rural areas migrated to urban areas during the urbanization progress in China, and people who lived in landslide-prone areas such as mountainous areas turned to live in towns and gradually stayed away from the threat of landslide hazards.

Vulnerability assessment

Human vulnerability to landslides on the regional and national scales was calculated using Eq. 1 and listed in Table 9. The human vulnerability values in North China in 2008 and in East China in 2020 were the highest at 0.244 and 0.1986, respectively. Human vulnerability for some years was zero in North and Northeast China. For instance, no landslide occurred in Northeast China for 12 years

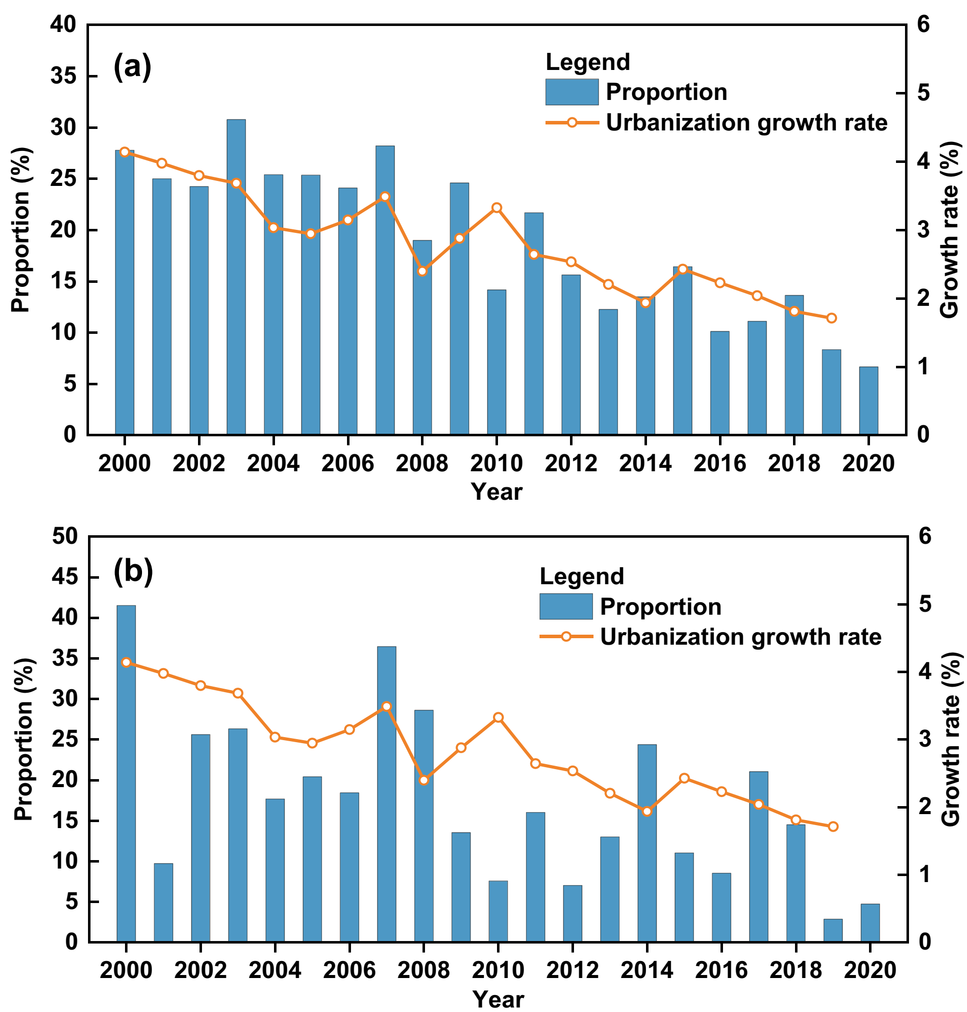


Fig. 15 Yearly variations of growth rate of urbanization rate with relation to landslides and fatalities: **a** the proportion of anthropogenic landslides; **b** the proportion of fatalities of anthropogenic landslides

Table 7 Correlation between the annual urbanization growth rate and the proportion of fatal anthropogenic landslides

Items	Correlation coefficient	*P* value
Proportion of number of anthropogenic landslides	0.831	0
Proportion of number of fatalities of anthropogenic landslides	0.466	0.03829

discontinuously. Compared with those of the other regions, the climate in North and Northeast China is dry and has little rainfall. Their topography and landform are also not conducive to landslides. The terrain of Northeast China is mainly plain, hilly, and mountainous (surrounded by mountains on three sides), with the largest Northeast Plain in the middle, whereas the terrain of North China is mainly plateau, with the Inner Mongolia Plateau and the Loess Plateau accounting for a large proportion of the area.

The socioeconomic component of vulnerability is the dominant reason why economically disadvantaged populations suffer greater human losses in landslides (Pollock and Wartman 2020). With the Heihe–Tengchong economic line (named after Hu Huanyong (Ding et al. 2021), a Chinese demographer who first identified the demarcation in a research paper in the mid-1930s, the imaginary line divides China into two parts that have vast demographic, environmental, and political significance as the boundary of China's eastern and western sections), the human vulnerability values of its western and eastern sections are 0.0211 and 0.0157, respectively. The western section's economy is worse than that of the eastern section, and the human vulnerability of the western section is higher than that of the eastern section.

Table 8 Estimated affected population and number of fatalities from 2000 to 2020 in China

Year	Affected population	Number of fatalities
2000	20,645	274
2001	32,793	226
2002	39,940	277
2003	52,826	332
2004	70,170	486
2005	141,067	258
2006	115,462	513
2007	98,327	383
2008	197,417	746
2009	56,756	338
2010	201,225	2,889
2011	80,603	311
2012	123,045	440
2013	128,933	648
2014	88,002	424
2015	123,297	387
2016	52,708	351
2017	100,707	348
2018	23,757	114
2019	32,749	260
2020	52,220	135

As illustrated in Fig. 17, human vulnerability had been slowly decreasing since 2000. Effective evacuation could significantly decrease human vulnerability to landslides and was an important contributor to this trend. Moreover, people with experience or knowledge of landslides have a greater ability to evacuate (Zhang and Zhang 2014). From 2000 to 2020, the local government and people's ability to cope with the hazards and mitigate the risks of landslides gradually improved since the publicity of scientific landslide prevention, making it easier for people to escape from landslides. Also, with the further study of early landslide warnings, more landslides had been successfully predicted, which prolonged the time to escape for the affected people. Thus, the success rate of evacuation of affected people had been greatly improved.

However, the human vulnerability to landslides in 2010 was the largest in the past decade. The Zhouqu debris flow event occurred in 2010, which directly led to the death of more than 1800 people, resulting in an unusually sudden increase in the number of fatalities and human vulnerability in 2010. Therefore, the social economy, topography and climate conditions, people's accumulation of landslide experience, and social propaganda of landslide knowledge, among others, are closely related to human vulnerability to landslides.

Discussion

The results presented above show the potential of the developed database. However, the database still has several limitations:

1. The landslide records presented in this study were biased in space and time as a whole inventory. This was mainly due to the relatively low data availability when going many years back in time, where some fatal landslide records may be absent. This study focused on human vulnerability to landslide events that occurred from 2000 to 2020 for the same reason that the incompleteness of records will cause great interference for vulnerability quantification. Almost all landslides that can be recorded were large-scale catastrophic landslides of high vulnerability; besides, a very important factor for quantification of landslide vulnerability was population density. The data on population density before 2000 were still not accurate enough. However, for the classification and spatiotemporal trend, landslides before 2000 had also been studied to objectively explain the characteristics of the corresponding landslides. Consid-

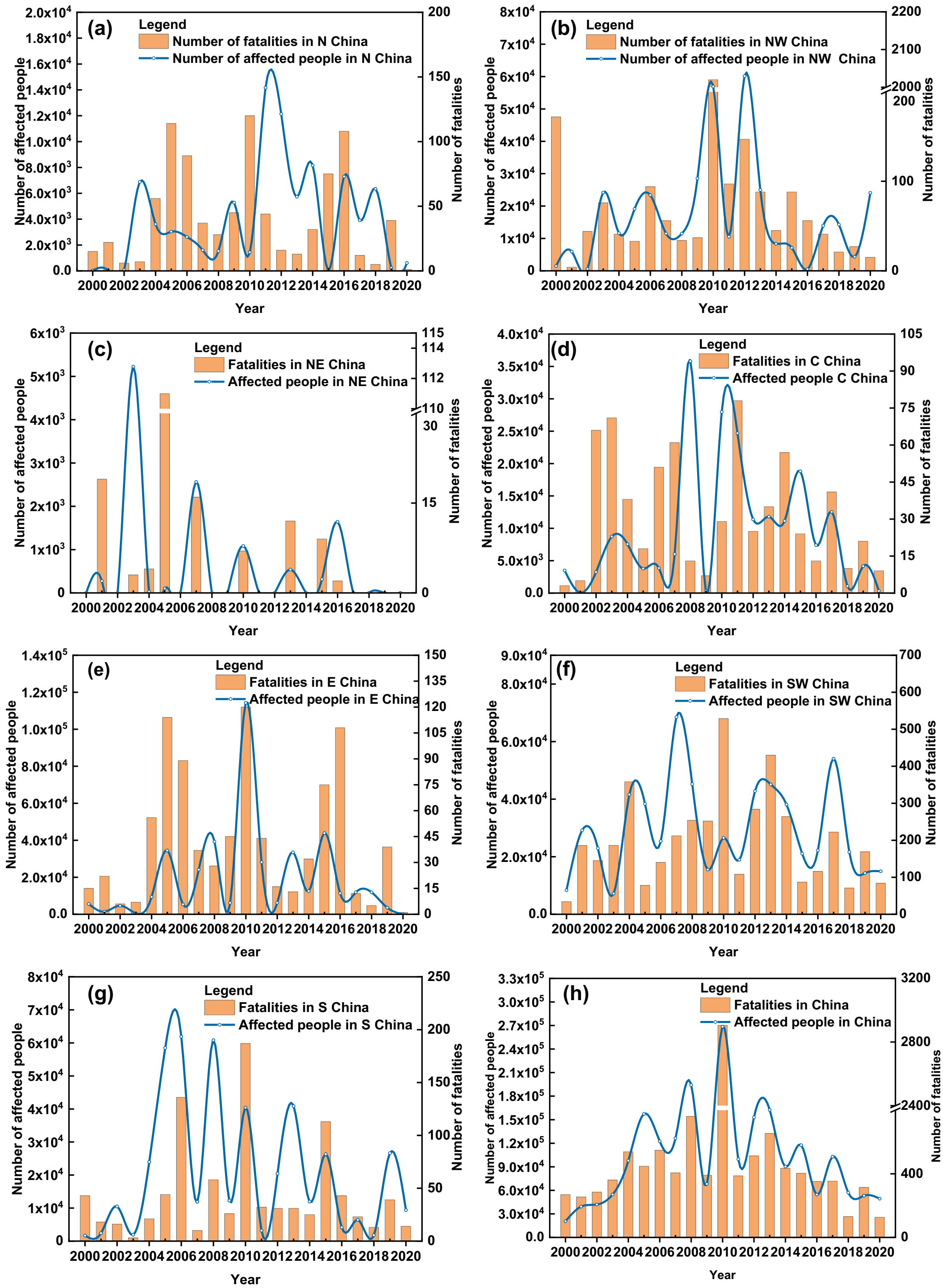


Fig. 16 Affected population from 2000 to 2020 in different regions: **a** North China; **b** Northwest China; **c** Northeast China; **d** Central China; **e** East China; **f** Southwest China; **g** South China; **h** China

ering the difficulty in obtaining landslide trigger and fatality data, these analyses of the human vulnerability caused by fatal landslides may have a certain degree of shortcoming. More complete data needs to be collected for further analysis.

2. Although a trend of increase in the number of small and medium-sized fatal landslides and the decrease in the average number of fatalities could be observed in the constructed database, it was also to some extent due to the

Table 9 Human vulnerability to landslides in various regions from 2000 to 2020

Year	NW	N	NE	C	E	SW	S	China
2000	0.1167	0.0884	-	0.0009	0.0027	0.0041	0.0257	0.0131
2001	0.0007	-	0.0692	0.0684	0.0156	0.0064	0.0075	0.0065
2002	0.0744	0.1084	-	0.0204	0.0013	0.0063	0.0015	0.0068
2003	0.0031	0.0022	0.0006	0.0081	0.0132	0.0259	0.0016	0.0066
2004	0.0035	0.0055	0.1373	0.0050	0.0059	0.0086	0.0009	0.0055
2005	0.0017	0.0162	1.0000	0.0048	0.0033	0.0020	0.0008	0.0028
2006	0.0040	0.0145	-	0.0132	0.0167	0.0055	0.0022	0.0045
2007	0.0049	0.0087	0.0062	0.0101	0.0015	0.0031	0.0008	0.0032
2008	0.0030	0.2440	-	0.0004	0.0007	0.0056	0.0010	0.0039
2009	0.0013	0.0045	-	0.0214	0.0073	0.0162	0.0021	0.0057
2010	0.0355	0.0090	0.0065	0.0010	0.0011	0.0200	0.0046	0.0108
2011	0.0092	0.0020	-	0.0032	0.0016	0.0057	0.0100	0.0039
2012	0.0024	0.0008	-	0.0022	0.0026	0.0066	0.0015	0.0034
2013	0.0035	0.0078	0.0223	0.0030	0.0004	0.0095	0.0008	0.0040
2014	0.0054	0.0015	-	0.0051	0.0026	0.0069	0.0021	0.0048
2015	0.0124	0.1103	0.0285	0.0013	0.0017	0.0041	0.0043	0.0034
2016	0.1116	0.0019	0.0012	0.0018	0.0095	0.0052	0.0103	0.0065
2017	0.0029	0.0038	-	0.0033	0.0010	0.0041	0.0036	0.0034
2018	0.0015	0.0017	-	0.0095	0.0004	0.0033	0.0072	0.0023
2019	0.0062	0.0871	-	0.0051	0.0109	0.0118	0.0015	0.0059
2020	0.0006	0.0066	-	0.0273	0.1986	0.0056	0.0015	0.0026

incompleteness of landslide records and should be justified by more data.

3. The observation period of 20 years may not be long enough to average out the effect of landslides triggering weather events although some trends were observed. Data on landslides of a larger time scale should be collected and a database of extreme events should be built for further study of the relationship between the weather and the number of landslides and fatalities.
4. It was hard to consider the exact influence extent of each landslide previously because the landslides were analyzed both on the national and regional scales. In this study, it was assumed that if a landslide occurred in a pixel of 30arcs, all the people in this pixel were affected. The scale, mobility, and influence zone of every single landslide were not calculated as they were almost impossible to achieve for thousands of landslides.

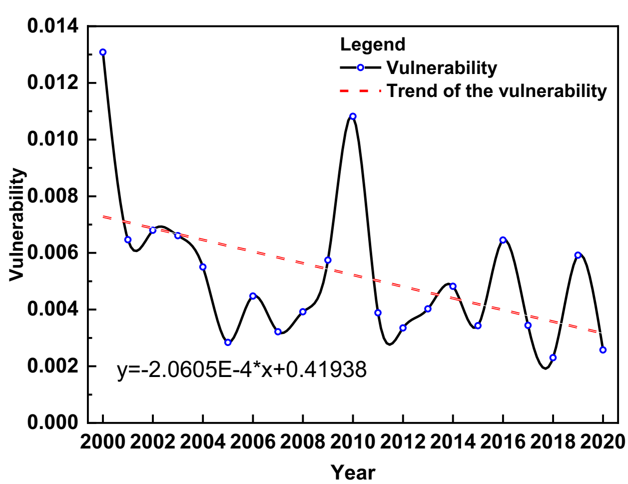


Fig. 17 Annual vulnerability of human affected by landslides in China

Conclusions

A landslide database was presented in this study. A total of 1470 fatal landslide events that occurred in China from 1940 to 2020 were recorded, which caused 14,394 fatalities. This paper described the ratios of different types of fatal landslides, analyzed the spatiotemporal distribution characteristics of fatal landslide events and fatalities, analyzed and compared anthropogenic and natural fatal landslides, revealed the relationship between the GDP and urbanization growth rates and anthropogenic landslides for the first time, and finally calculated the number of affected people and quantitatively evaluated the human vulnerability to fatal landslides.

Such studies would help to evaluate the human vulnerability of landslides and their potential consequences in China, and around the globe. The following conclusions can be drawn from this study:

1. Among these fatal landslides, 60.1% were slides, 23.3% were flows, 14.5% were falls, and 2.1% were classified as other landslides, which caused 42.9%, 43.4%, 10.7%, and 3.0% of the total fatalities, respectively. Of these fatal landslides, 68.9% were triggered by rainfall (among which 3.5% were triggered by rainstorms accompanied by typhoons), 11.2% were triggered by human activities, 1.5% were triggered by other factors, and the triggers of the remaining 11.2% of the landslides remained unknown because of the lack of detailed reports or documents. The landslides triggered by these different factors caused 76.6%, 18.1%, 3.3%, 1.7%, and 0.2% of the total fatalities, respectively.
2. The fatal landslides in China were mainly distributed in the Loess Plateau, Sichuan Basin, and Yunnan-Guizhou Plateau and mainly occurred in 13 provinces. Yunnan Province had the greatest number of fatal landslides at 201. Gansu Province ranked first in the number of fatalities caused by fatal landslides among all provinces. Of the seven geological regions, Southwest China always had the largest number of fatal landslides from 2000 to 2020 and the largest number of fatalities in most years. There were 57 and 1413 landslides before and after 2000 in the constructed database, respectively. For the temporal trend, the number of fatal landslides and the number of fatalities in China fluctuated over the past 20 years. The proportion of super-large landslides with fatalities over 30 gradually decreased over the years, and the average number of fatalities caused by landslides gradually decreased. Fatal landslides usually occurred in the rainy seasons between April and September. A good correlation was observed between the monthly average rainfall and the number of fatal landslides per month in each region through Spearman's rank correlation analysis.
3. It can be deduced that legal mining caused the largest number of fatal landslides in the analysis of the 270 fatal anthropogenic landslides. Landslides triggered by the failure of tailings dams and waste dumps caused the top two largest average numbers of fatalities successively, demonstrating the great significance of risk assessment and control of such artificial slope sites. Natural landslides were evenly distributed throughout the day, whereas most anthropogenic landslides occurred during working hours. The median number of fatalities for these two types of landslides was 3 but varied with different times of the day. The number of landslides and fatalities from anthropogenic landslides both grew with an increasing GDP growth rate. The proportion of the number of anthropogenic landslides in all landslides both varied in a similar pattern with the increasing urbanization growth rate. However, the urbanization growth rate and the proportion of the number of fatalities from anthropogenic landslides were related but not strongly. The GDP and urbanization growth rates were introduced as two influencing factors of anthropogenic landslides.
4. The affected populations of the seven geological regions in China from 2000 to 2020 were evaluated year by year, which constantly fluctuated but generally initially increased and then eventually decreased. This trend was more obvious on a national scale. The results of the vulnerability assessments on the regional and national scales showed that the human vulnerability to landslides in the seven geological regions and in China had been slowly decreasing since 2000. This demonstrated the importance of evacuation knowledge propaganda and early landslide warnings. This study innovatively introduced a quantitative assessment method of human vulnerability to landslides using the constructed database and revealed its trend in China.

Author contribution

Conceptualization: Shuai Zhang, Yunmin Chen, Yao Tang; draft preparation and editing: Shuai Zhang, Can Li, Yao Tang; data collection, analysis, and investigation: Can Li, Jingyu Peng, Yiling Zhou, Shuairong Wang.

Funding

This study was funded by National Natural Science Foundation of China (Grant No. 51988101, Grant No. 52278376), the National Key R&D Program of China (Grant No. 2019YFC1806001, Grant No.2018YFC1802301).

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

References

Aristizábal E, Sánchez O (2020) Spatial and temporal patterns and the socioeconomic impacts of landslides in the tropical and mountainous Colombian Andes. Disasters 44(3). https://doi.org/10.1111/disa.12391

Blahut J, Balek J, Klimeš J, Rowberry M, Kalina J (2019) A comprehensive global database of giant landslides on volcanic islands. Landslides 16(10):2045–2052. https://doi.org/10.1007/s10346-019-01275-8

Chang M, Zhou Y, Zhou C, Tristram I, Hales C (2020) Co-seismic landslides induced by the 2018 M_w 6.6 Iburi, Japan, Earthquake: spatial distribution, key factors weight, and susceptibility regionalization. Landslides (1). https://doi.org/10.1007/s10346-020-01522-3

Corominas J, Westen CV, Frattini P, Cascini L, Smith JT (2014) Recommendations for the quantitative analysis of landslide risk. Bull Eng Geol Env 73(2):209–263. https://doi.org/10.1007/s10064-013-0538-8

Cruden DM, Varnes DJ (1996) Landslide types and processes. In: Turner AK, Schuster RL (eds) Landslides investigation and mitigation. Transp Res Board, Washington DC, Special Rep 247:36–75

Damm B, Klose M (2015) The landslide database for Germany: closing the gap at national level. Geomorphology 249(15):82–93. https://doi.org/10.1016/j.geomorph.2015.03.021

Devoli G, Strauch W, Chávez G, Høeg K (2007) A landslide database for Nicaragua: a tool for landslide-hazard management. Landslides 4(2):163–171. https://doi.org/10.1007/S10346-006-0074-8

Ding JH, Cheng C, Zhang WJ, Tian Y (2021) The ideological origins and geographical demarcation significance of Hu Huanyong Line. Acta Geographica Sinica 76(6):1317–1333. https://doi.org/10.11821/dlxb202106001

Díaz SR, Cadena E, Adame S, Dávila N (2020) Landslides in Mexico: their occurrence and social impact since 1935. Landslides 17:379–394. https://doi.org/10.1007/s10346-019-01285-6

European Commission (1994) The temporal occurrence and forecasting of landslides in the European community. Cordis. https://cordis.europa.eu/project/id/EPOC0025

Fan X, Westen C, Qiang X, Gorum T, Dai F (2012) Analysis of landslide dams induced by the 2008 Wenchuan earthquake. J Asian Earth Sci 57:25–37. https://doi.org/10.1016/j.jseaes.2012.06.002

Foster C, Pennington C, Culshaw MG, Lawrie K (2012) The national landslide database of Great Britain: development, evolution and applications. Environmental Earth Sciences 66(3):941–953. https://doi.org/10.1007/s12665-011-1304-5

Froude MJ., Petley DN (2018) Global fatal landslide occurrence 2004 to 2016. Nat Hazards Earth Sys Sci Discussions 1-44. https://doi.org/10.5194/nhess-18-2161-2018

Ghosh T, Bhowmik S, Jaiswal P, Ghosh S, Kumar D (2020) Generating substantially complete landslide inventory using multiple data sources: a case study in northwest Himalayas, India. J Geol Soc India 95(1):45–58. https://doi.org/10.1007/s12594-020-1385-4

Gorum T, Fidan S (2021) Spatiotemporal variations of fatal landslides in Turkey. Landslides (2). https://doi.org/10.1007/s10346-020-01580-7

Guzzetti F (2000) Landslide fatalities and the evaluation of landslide risk in Italy. Eng Geol 58(2):89–107. https://doi.org/10.1016/S0013-7952(00)00047-8

Harp EL, Jibson RW (1996) Landslides triggered by the 1994 Northridge, California, earthquake. Bull Seismol Soc Am 86(1B):S319–S332. https://doi.org/10.1016/S0013-7952(00)00047-8

Huang RQ (2009) Some catastrophic landslides since the twentieth century in the southwest of China. Landslides 6(1):69–81. https://doi.org/10.1007/s10346-009-0142-y

Hungr O, Leroueil S, Picarelli L (2014) The Varnes classification of landslide types, an update. Landslides 11(2):167–194. https://doi.org/10.1007/s10346-013-0436-y

Kirschbaum DB, Adler R, Hong Y, Hill S, Lerner-Lam A (2010) A global landslide catalog for hazard applications: method, results, and limitations. Nat Hazards 52(3):561–575. https://doi.org/10.1007/s11069-009-9401-4

Komac M, Hribernik K (2015) Slovenian national landslide database as a basis for statistical assessment of landslide phenomena in Slovenia. Geomorphology 249(15):94–102. https://doi.org/10.1016/j.geomorph.2015.02.005

Li G, Lei Y, Yao H, Wu S, Ge J (2017) The influence of land urbanization on landslides: an empirical estimation based on Chinese provincial panel data. Sci Total Environ 595:681–690. https://doi.org/10.1016/j.scitotenv.2017.03.258

Li W, Huang R, Tang C, Xu Q, Western C (2013) Co-seismic landslide inventory and susceptibility mapping in the 2008 Wenchuan earthquake disaster area, China. J Mt Sci 10:339–354. https://doi.org/10.1007/s11629-013-2471-5

Lin L, Lin Q, Wang Y (2017a) Landslide susceptibility mapping on a global scale using the method of logistic regression. Natural Hazards & Earth System Science 17:1411–1424. https://doi.org/10.5194/nhess-17-1411-2017

Lin Q, Wang Y (2018) Spatial and temporal analysis of a fatal landslide inventory in China from 1950 to 2016. Landslides 15:2357–2372. https://doi.org/10.1007/s10346-018-1037-6

Lin Q, Wang Y, Liu T, Zhu Y, Sui Q (2017b) The vulnerability of people to landslides: a case study on the relationship between the casualties and volume of landslides in China. International Journal of Environmental Research and Public 14:212. https://doi.org/10.3390/ijerph14020212

Marc O, Gosset M, Saito H, Uchida T, Malet J (2019) Spatial patterns of storm - induced landslides and their relation to rainfall anomaly maps. Geophys Res Lett 46(20). https://doi.org/10.1029/2019GL083173

Martha TR, Roy P, Jain N, Khanna K, Mrinalni K, Kumar KV, Rao PVN (2021) Geospatial landslide inventory of India—an insight into occurrence and exposure on a national scale. Landslides 18(6):2125–2141. https://doi.org/10.1007/s10346-021-01645-1

Michael-Leiba M, Baynes F, Scott G, Granger K (2005) Quantitative landslide risk assessment of Cairns, Australia. In T. Glade, M. Anderson, M. Crozier (Eds.), Landslide Hazard and Risk. John Wiley & Sons, West Sussex, pp 621–642. https://doi.org/10.1002/9780470012659.ch21

Nadim F, Kjekstad O, Peduzzi P, Herold C, Jaedicke C (2006) Global landslide and avalanche hotspots. Landslides 3:159–173. https://doi.org/10.1007/s10346-006-0036-1

Owen LA, Kamp U, Khattak GA, Harp EL, Keefer DK, Bauer MA (2008) Landslides triggered by the 8 October 2005 Kashmir earthquake. Geomorphology 94(1–2):1–9. https://doi.org/10.1016/j.geomorph.2007.04.007

Pascal L, Bilberto Z, Etienne B, Laurence A (2013) Supervised method of landslide inventory using panchromatic spot5 images and application to the earthquake-triggered landslides of pisco (Peru, 2007, M_w 8.0). Remote Sens 5(6):2590–2616. https://doi.org/10.3390/rs5062590

Peng JY, Zhang S, Han YY, Bate B, Ke H, Chen YM (2021) Soil heavy metal pollution of industrial legacies in China and health risk assessment. Sci Total Environ 151632. https://doi.org/10.1016/j.scitotenv.2021.151632

Petley DN (2012) Global patterns of loss of life from landslides. Geology 40:927–930. https://doi.org/10.1130/G33217.1

Pollock W, Wartman J (2020) Human vulnerability to landslides. GeoHealth 4(10):e2020GH000287. https://doi.org/10.1029/2020GH000287

Qi S, Xu Q, Lan H, Zhang B, Liu J (2011) Spatial distribution analysis of landslides triggered by 2008.5.12 Wenchuan Earthquake, China. Eng Geol 116(1–2):95–108. https://doi.org/10.1016/j.enggeo.2010.07.011

Rodrguez CE, Bommer JJ, Chandler RJ (1999) Earthquake-induced landslides: 1980–1997. Soil Dyn Earthq Eng 18(5):325–346. https://doi.org/10.1016/S0267-7261(99)00012-3

Rosser B, Dellow S, Haubrock S, Glassey P (2017) New Zealand's National Landslide Database Landslides 14(6):1949–1959. https://doi.org/10.1007/s10346-017-0843-6

Rupp S, Damm B (2020) A national rockfall dataset as a tool for analysing the spatial and temporal rockfall occurrence in Germany. Earth Surf Proc Landforms 45(7). https://doi.org/10.1002/esp.4827

Shen P, Zhang LM, Chen HX, Gao L (2017) Role of vegetation restoration in mitigating hillslope erosion and debris flows. Eng Geol 216:122–133. https://doi.org/10.1016/j.enggeo.2016.11.019

Tiwari B, Ajmera B, Dhital S, Sitoula NR (2017) Landslides Induced by the 2015 Gorkha Earthquake. Workshop on World Landslide Forum. Springer, Cham, pp 819–827

Valenzuela P, Domínguez-Cuesta MJ, García MAM, Jiménez-Sánchez M (2017) A spatio-temporal landslide inventory for the NW of Spain: BAPA database. Geomorphology 293:11–23. https://doi.org/10.1016/j.geomorph.2017.05.010

WorldPop, Center for International Earth Science Information Network (CIESIN), Columbia University (2018) Global High Resolution Population Denominators Project - Funded by The Bill and Melinda Gates Foundation (OPP1134076). https://doi.org/10.5258/SOTON/WP00670

Xu C, Shyu J, Xu X (2014a) Landslides triggered by the 12 January 2010 Port-au-Prince, Haiti, M_w=7.0 earthquake: visual interpretation, inventory compiling, and spatial distribution statistical analysis. Nat Hazards Earth Sys Sci 14(7):1789-1818. https://doi.org/10.5194/nhess-14-1789-2014a

Xu C, Tian Y, Shen L, Ma S, Chen X (2018) Database of landslides triggered by 2015 Gurkha (Nepal) M_w 7.8 earthquake. Seismol Egol 40(5):1115. https://doi.org/10.5194/nhess-14-1789-2014

Xu C, Xu X, Shyu J (2015) Database and spatial distribution of landslides triggered by the Lushan, China M_w 6.6 earthquake of 20 April 2013. Geomorphology 248(1):77–92. https://doi.org/10.1016/j.geomorph.2015.07.002

Xu C, Xu X, Shyu J, Zheng W, Wei M (2014b) Landslides triggered by the 22 July 2013 Minxian-Zhangxian, China, M_w 5.9 earthquake: inventory compiling and spatial distribution analysis. J Asian Earth Sci 92:125–142. https://doi.org/10.1016/j.jseaes.2014.06.014

Zhang S, Li C, Zhang LM, Peng M, Zhan LT, Xu Q (2020) Quantification of human vulnerability to earthquake-induced landslides using Bayesian network. Eng Geol 265:105436. https://doi.org/10.1016/j.enggeo.2019.105436

Zhang S, Liu Y, Bate B, Peng DL, Li C, Zhan LT (2021b) Quantitative human risk analysis of 2015 Shenzhen dump failure considering influence of urbanization. J Mt Sci-Engl 18:1439–1457. https://doi.org/10.1007/s11629-020-6260-7

Zhang S, Lv YH, Yang HB, Han YY, Peng JY, Lan JW, Zhan LT, Chen YM, Bate B (2021c) Monitoring and quantitative human risk assessment of municipal solid waste landfill using integrated satellite–UAV–ground survey approach. Remote Sens 13. https://doi.org/10.3390/rs13224496

Zhang S, Zhang LM (2014) Human vulnerability to rapid shallow landslides: fleeing process and modelling. Landslides 11(6):1115–1129. https://doi.org/10.1007/s10346-014-0468-y

Zhang S, Zhang LM, Li XY, Xu Q (2018) Physical vulnerability models for assessing building damage by debris flows. Eng Geol 247:145–158. https://doi.org/10.1016/j.enggeo.2018.10.017

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Shuai Zhang · Can Li · Jingyu Peng · Yiling Zhou · Shuairong Wang · Yunmin Chen · Yao Tang (✉)
Department of Civil Engineering, Zhejiang University,
Hangzhou 310058, China
Email: yaotang@zju.edu.cn

Shuai Zhang · Yunmin Chen · Yao Tang
MOE Key Laboratory of Soft Soils and Geoenvironmental Engineering, Zhejiang University, Yuhangtang Road 866#,
Hangzhou 310058, China

Shuai Zhang
Email: zhangshuaiqj@zju.edu.cn

Yunmin Chen
Email: chenyunmin@zju.edu.cn