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A public Cloud-based China's Landslide Inventory Database (CsLID): development, zone, and spatiotemporal analysis for significant historical events, 1949-2011

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Abstract: Landslide inventory plays an important role in recording landslide events and showing their temporal-spatial distribution. This paper describes the development, visualization, and analysis of a China's Landslide Inventory Database (CsLID) by

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utilizing Google's public cloud computing platform. Firstly, CsLID (Landslide Inventory Database) compiles a total of 1221 historical landslide events spanning the years 1949-2011 from relevant data sources. Secondly, the CsLID is further broken down into six zones for characterizing landslide cause-effect, spatiotemporal distribution, fatalities, and socioeconomic impacts based on the geological environment and terrain. The results show that among all the six zones, zone V, located in Qinba and Southwest Mountainous Area is the most active landslide hotspot with the highest landslide hazard in China. Additionally, the Google public cloud computing platform enables the CsLID to be easily accessible, visually interactive, and with the capability of allowing new data input to dynamically augment the database. This work developed a cyber-landslide inventory and used it to analyze the landslide temporal-spatial distribution in China.

Keywords: Landslide; Inventory; Zone; Distribution; Cloud computing

Introduction

Landslides are mass movement of rocks or soils induced by external factors such as rainfall, earthquake, and flood (Keefer 2002). The formal definition of landslide is the movement of a mass of rock, earth or debris down a slope (Cruden 1991). Climate variability, weather extremes, tectonic stress, and human impacts are some of the causal factors that make landslides one of the most frequent and severe natural hazards across the globe. The world atlas of natural hazards demonstrates that every year landslides cause large economic losses as well as casualties (Jelínek et al. 2007). Global hot spots of high probability of landslides are mainly located in the Rocky Mountains, the Pacific Rim, the Alps, the Himalayas and South Asia (Hong et al. 2007). Due to landslides' impact on human life and society economy, research into landslide hazard and risk assessment has assumed great importance on disaster management and environmental engineering in the last decade.

China is a country with hilly and mountainous areas covering 69% of total land area. Over 90,000 potential threats of landslides exist in 70 cities and villages in the south and northwest of China and 10 percent of Chinese people are threatened by landslides (Huang and Li 2011; Liu et al. 2012; Zhou et al. 2005). In the period of 2004-2010, 32,322 people were killed in landslides all over the world, of which 6860 fatalities occurred in China excluding the fatalities in 2008 Wenchuan earthquake (Petley 2012). Moreover, over 60,000 landslides occurred in valleys after 2008 Wenchuan earthquake (Xin 2010). In 2010, 22,329 landslides occurred in mainland China and Gansu mudslide caused 1501 people dead and 264 lost (http://cn.chinagate.cn/povertyrelief/2011-02/14/content_21915453.htm). As such, it is important to evaluate the time, location, number of fatalities and economic losses caused by the landslides. Developing a systematic inventory of landslide events is very necessary to provide a reference for landslide hazard management.

Landslide events globally are usually archived in the databases of news reports. Many website-based hazard databases also record and describe near real-time significant landslide events, for example, ICL (International Consortium on Landslide, http://iclhp.org), USGS (United States Geological Survey, http://landslides.usgs.gov/recent), ILC (International Landslide Centre; University of Durham, http://www.landslidecentre.org), EM-DAT (International Disaster Database, http://www.em-dat.net), AGU Landslide Blog (http://blogs.agu.org/landslideblog/), and the real-time landslide website jointly created by NASA and University of Oklahoma (http://eos.ou.edu/).

Several research groups have also developed landslide inventories at the global (Kirschbaum et al. 2010) and national scale (Chau et al. 2004; Guzzetti et al. 1999; Van Den Eeckhaut and Hervás 2012). However, these cyber landslide databases emphasize textual description, and few landslide inventories contained spatiotemporal information important for scientific studies.

In line with this research gap, the primary objective of this study is to develop a digitized retrospective and prospective China Landslide Inventory Database (CsLID). The new CsLID includes two objectives: (a) compile an open database for querying, sharing, updating and visualizing the significant landslides in the period of 1949-2011; and (b) reveal the pattern of landslide spatiotemporal distributions and their impacts in different zones of China. We expect this new development will contribute to the landslide susceptibility mapping and spatiotemporal evaluation in China.

1 Landslide Spatiotemporal Database Development

1.1 Data sources

After the founding of the People's Republic of China (PRC) in 1949, China began relevant researches on landslide-related areas. In 1950s, landslide events were tracked mainly from the reports of construction of infrastructure, such as roads, rails, reservoirs and power stations in mountainous areas. In 1960s and 70s, landslide records were commonly listed in the local statistical yearbook. Some scholars used the records and conducted preliminary research into deformation and formation mechanisms (Huang and Li 2011). From the 1980s to the present, the government put great emphasis on tracking landslide occurrence. Many systematic web databases were constructed, for instance, GGDQD (Geostress and Geological Disaster Querying Database; http://www.geomech.ac.cn/geo0503/), CRN (China Risk Network; http://www.irisknet.cn/), CGEIN (China Geological Environmental Information Network; http://www.cigem.gov.cn/).

Although landslide records in general became more detailed and comprehensive (Coe et al. 2004), three problems still lay ahead in the application of these data sources (Guzzetti et al. 1994; Che et al. 2012; Peruccacci et al. 2012). Firstly, most of the data were unmapped events that came from eyewitness accounts and had incomplete information on time of occurrence, location, fatalities and economic losses. Particularly, most of eyewitness accounts lack the accurate longitude and latitude. Secondly, the data is inadequate in some sparsely populated areas because of either less attention from the government or government restrictions on data-sharing. Finally, the data in different scales has significantly varying accuracies in different regions and provinces.

In this paper, significant landslide events have two aspects: spatiotemporal information and representation. Spatiotemporal information includes complete time of landslide occurrence and accurate location. Representation shows the landslide event is important and highlights to reflect the extent of some landslide impact. Therefore, we collected 1221 significant landslide events from 1949 to 2011. The landslide events are from different sources according to different periods (Table 1).

Table 1 Landslide data sources based on different periods in China

Period	Source
1949, 1950s	Official documents
1960s,1970s	News reports, statistical yearbooks
1980- 2011	Web databases: http://www.geomech.ac.cn/geo0503/; http://www.irisknet.cn/?action-category-catid-1705; http://www.cigem.gov.cn/

1.2 CsLID database definition, compilation, and visualization

1.2.1 Definition of CsLID landslide events

In the CsLID database, we define several attributes to describe the landslide events:

a. Identification (ID)

Each record of event is shown as a point on the map with a unique landslide ID between 1949 and 2011. In general, some landslides may re-occur in the same area. We select a landslide with complete records as the landslide event.

b. Time (YYYY/M/D)

The attribute represents the time of landslide occurrence as the form 'Year-Month-Day'. We state the time is only the start time of landslide without regard to the end time.

c. Province

'Province', as the first level of administrative division in China, describes the scope of landslide occurrence. Landslide location can reveal which province landslide occurred at.

d. Location

This entry records the geographic coordinates of landslides, including longitudes and latitudes in the decimal degree form. Considering the late research on landslide susceptibility analysis with 1km spatial resolution, the accuracy of location is set to be 0.01°.

Table 2 The 1221 collected landslide events in China

ID	Time (YYYY/M/D)	Province	Location		Cause	Fatalities	Direct Losses (Yuan)	Indirect Losses (Yuan)	Class
			Longitude	Latitude					
1	1949/5/4	Qinghai	101.80	36.60	Loess	280	N/A	N/A	5
2	1949/7/1	Liaoning	123.90	41.80	Human	N/A	300 million	N/A	1
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
1221	2011/9/29	Chongqing	105.43	29.42	Rainfall	N/A	0.8 million	N/A	1

e. Cause

The record lists the reasons causing landslide. Landslide is induced by one or more triggering factors like rainfall, earthquake, snow melt, flood, and human activity. Therefore, the entries sometimes list multiple factors.

f. Fatality

The attribute records the number of people confirmed dead not including missing and injured. The fatality number is from final official government statistics and reports. In addition, a very small part of data is not accurate because of complex induced factors or staggering number. For instance, the fatalities of landslides by 2008 Wenchuan earthquake are unclear and some papers just indicated that landslides triggered by the earthquake killed more than 20,000 people (Yin et al. 2009). Therefore, we use some ranges as the inaccurate data. 'NaN' means we don't collect the fatality information.

g. Direct economic losses (unit: yuan)

The direct economic losses include two parts: expenses incurred and property losses. Expenses incurred are the direct expenses on the landslide activity; property losses are the total cost from affected people's property. The data is recorded from local government statistical results. The unit is yuan (RMB). 'NaN' represents we don't collect the direct economic loss information.

h. Indirect economic losses (unit: yuan)

Indirect economic losses are the losses except direct economic losses, and represent secondary damage, such as cutting back or suspending products, lost working days and resource losses. The unit is yuan (RMB). 'NaN' represents we don't collect the indirect economic losses information.

i. Class

Landslide class is related to landslide fatality. Usually, high-class landslide may cause more deaths. This study shows five landslide classes based on fatality: fatality is blank, class = 1; fatality ≤ 3, class = 2; 3 < fatality ≤ 10, class = 3; 10 < fatality ≤ 30, class = 4; fatality > 30, class = 5.

Table 2 shows the beginning and the end landslide events; the other major incidences are expressed by suspension points.

1.2.2 CsLID web service

CsLID is the abbreviation of China's Landslide Inventory based on the methodology of cloud database. Figure 1 shows the structure of cloud-based CsLID. It consists of four parts: 1) data source; 2) cloud; 3) server; 4) clients. Firstly, we collect landslide data from data source. Secondly, we save landslide data to a cloud database called Google Fusion Tables and use Google Maps API to interoperate with Google Fusions Tables. Thirdly, we then publish and recall the landslide data on the web. Finally we provide landslide data to users and gather feedback.

1) Data Source

As mentioned in the previous section, data spans 1221 significant landslide historical records between 1949 and 2011.

2) Cloud

The integrated landslide data is imported into Google Fusion Tables which is a platform for online cloud storage. Google Fusion Tables is a cloud-based web service data management system that includes spatial data storage, sharing, visualization and web-publishing (Gonzalez et al. 2010). Moreover, it allows the developers to extend its user-defined functionality by utilizing Google

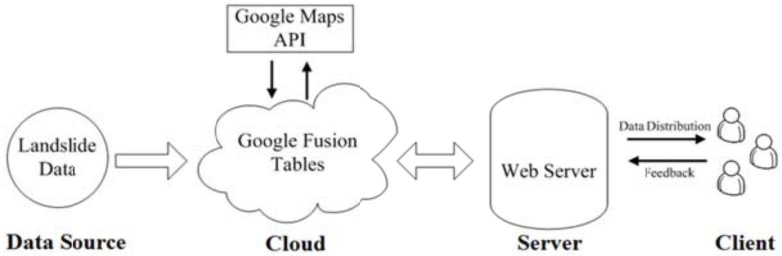


Figure 1 CsLID structure flow.

Fusion Tables with Google Maps API (Application Programming Interface) to programmatically perform structured query language (SQL) querying on tables via hypertext transfer protocol (HTTP) requests. We imported the 1221 collected landslide records (format '*.csv') into Google Fusion Tables (Figure 2).

3) Server

Google Fusion Tables has strict data access rules. The public is not allowed to alter the data or create new data. When we integrate crowd-sourcing in the future, the Google provided key will be used to insert data into our existing Fusion Table. This key is stored on our server which is protected by the University level firewall and assigned with minimum access permission for apache web server application. The web server can deal with requests and responses between the cloud and clients. Meanwhile, it also plays an important role in protecting the Google Fusion Tables on the cloud from being accidentally modified by clients.

4) Clients

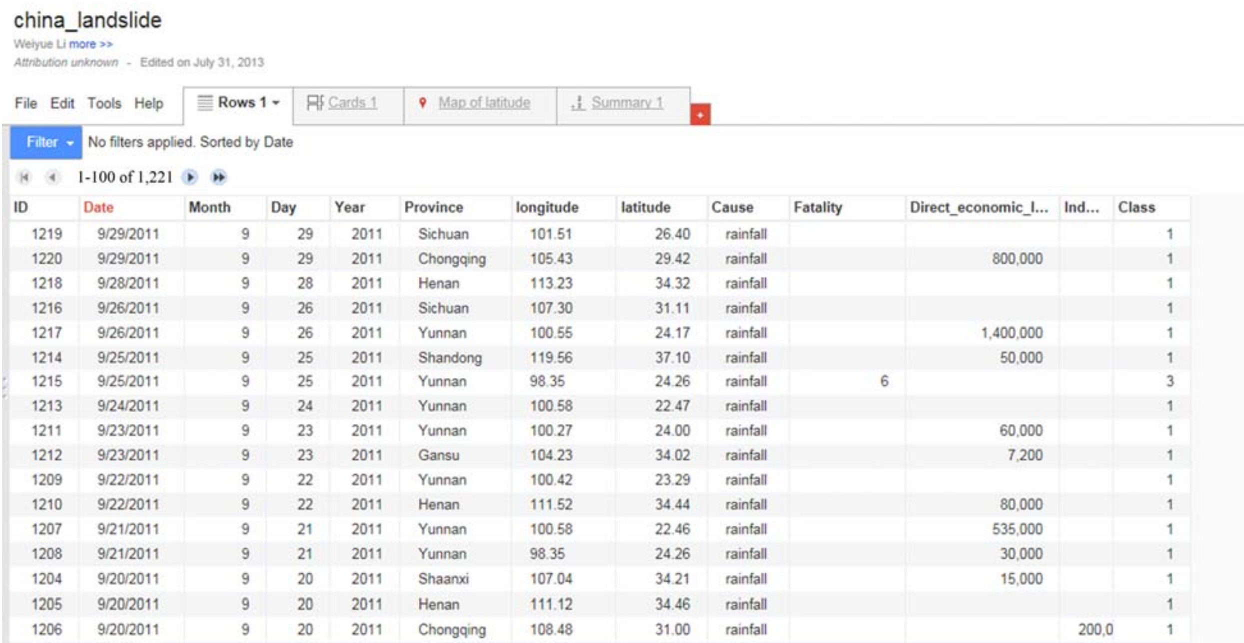
CsLID supplies some functions: visualization, statistics, query, etc. Clients can obtain landslide data and give feedback to the web service.

CsLID is currently running at http://eos.ou.edu/hazards/landslide/. The 'China' column consists of two parts: Map and Statistics.

2 Spatiotemporal, Causes, and Socioeconomic Analysis of CsLID

2.1 Landslide zones in China

Landslides occur due to complex interactions among many factors. The factors are divided into two categories: internal and external (Wu and Sidle, 1995). The internal factors consist of inherent factors including geology, topography, geomorphology, vegetation and soil and so on. The external factors directly induce the landslides, such as rainfall, earthquake, volcanic eruptions and human activity. Landslide susceptibility from internal factors is used to determine the likelihood of landslide occurrence based on local geological environment. According to 'China's Environmental Geological Zone Maps' (Institute of Hydrogeology and Engineering Geology 1992), China is divided into six districts based on the criteria of geological environment zones. Figure 3 shows the six geological environment zones. The base map is 90m-grid digital elevation model (DEM, from: http://srtm.csi.cgiar.org) map of China. The terrain elevations in China are classified into seven categories at the interval of 500 m. Moreover, the boundaries of zones reflect the features in topography: high elevation in West and low elevation in East (or stair-step shape).



ID	Date	Month	Day	Year	Province	longitude	latitude	Cause	Fatality	Direct_economic_l...	Ind...	Class
1219	9/29/2011	9	29	2011	Sichuan	101.51	26.40	rainfall				1
1220	9/29/2011	9	29	2011	Chongqing	105.43	29.42	rainfall		800,000		1
1218	9/28/2011	9	28	2011	Henan	113.23	34.32	rainfall				1
1216	9/26/2011	9	26	2011	Sichuan	107.30	31.11	rainfall				1
1217	9/26/2011	9	26	2011	Yunnan	100.55	24.17	rainfall		1,400,000		1
1214	9/25/2011	9	25	2011	Shandong	119.56	37.10	rainfall		50,000		1
1215	9/25/2011	9	25	2011	Yunnan	98.35	24.26	rainfall	6			3
1213	9/24/2011	9	24	2011	Yunnan	100.58	22.47	rainfall				1
1211	9/23/2011	9	23	2011	Yunnan	100.27	24.00	rainfall		60,000		1
1212	9/23/2011	9	23	2011	Gansu	104.23	34.02	rainfall		7,200		1
1209	9/22/2011	9	22	2011	Yunnan	100.42	23.29	rainfall				1
1210	9/22/2011	9	22	2011	Henan	111.52	34.44	rainfall		80,000		1
1207	9/21/2011	9	21	2011	Yunnan	100.58	22.46	rainfall		535,000		1
1208	9/21/2011	9	21	2011	Yunnan	98.35	24.26	rainfall		30,000		1
1204	9/20/2011	9	20	2011	Shaanxi	107.04	34.21	rainfall		15,000		1
1205	9/20/2011	9	20	2011	Henan	111.12	34.46	rainfall				1
1206	9/20/2011	9	20	2011	Chongqing	108.48	31.00	rainfall			200,0	1

Figure 2 Landslide records in Google Fusion Tables.

Ⅰ Northeast and North China Plain

This district has a wet sub-humid climate, and the average annual precipitation is between 300 mm and 800 mm. Plains dominate the district and the north and middle parts are surrounded by mountains.

Ⅱ Hilly Areas of South China

This district is located in the southeast of China, and the dominant terrain includes hills and mountains of less than 500 m above the sea level. The average annual rainfall is generally over 1000 mm, and the climate is hot and humid because of the monsoon.

Ⅲ Basin and Plateau Areas of Northwest China

The east boundary of the district is the west piedmont of Greater Khingan. It adjoins the small Tengger Desert in the south and the Loess Plateau in the north. The arid climate results in annual precipitation of less than 250 mm on average. The dominant terrain is plateaus in the east and basins and hills in the west.

Ⅳ Loess Plateau, Shanxi Mountains

It is located in the central of the Yellow River basin, with a temperate continental and semi-arid climate. The typical soil type is loess, and the average annual rainfall is between 300 mm and 700 mm.

Ⅴ Qinba and Southwest Mountainous Areas

This district has a humid climate, and is located in the southwest of South China. Highland and plateaus are the dominant terrain with above 2000 m elevation. This district is located in the highest earthquake and landslide zone in China (Yin et al. 2009).

Ⅵ Tibetan Plateau

This district has a plateau climate and located in the southwest of China with an average elevation of above 3000 m. The typical soil type is permafrost and seasonal freezing thawing.

2.2 Landslide distribution in different zones

Figure 4 (a) shows the spatial distributions of the 1221 landslide events and classification by ten-year interval in China.

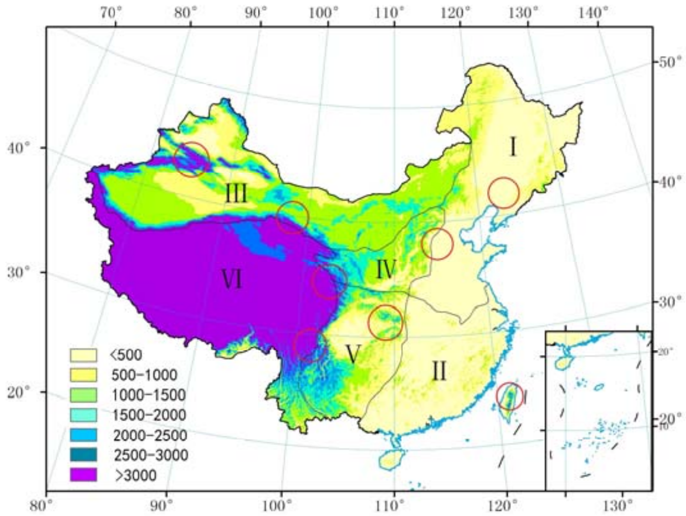
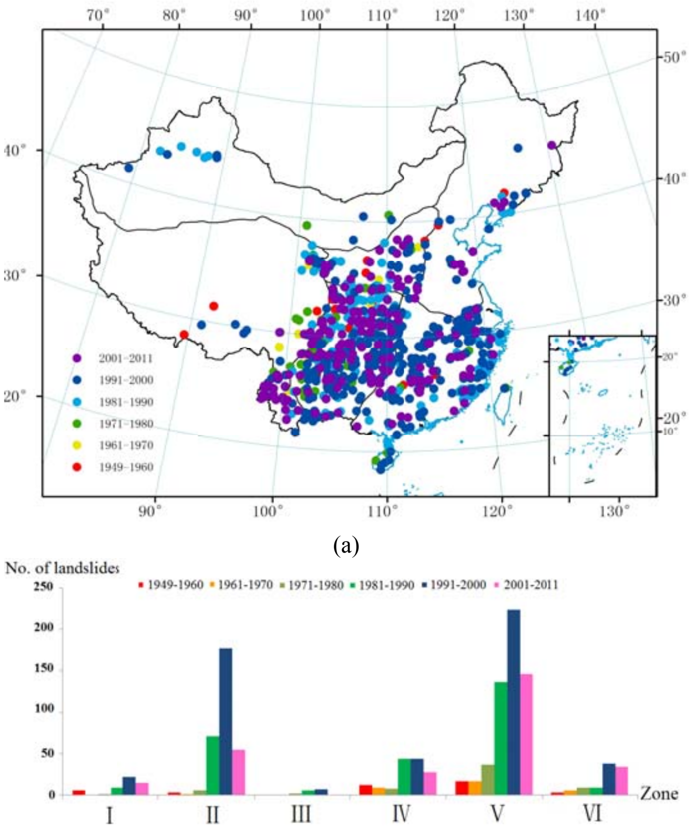


Figure 3 Geological environment zone in China: Ⅰ - Northeast and North China Plain; Ⅱ - Hilly Areas of South China; Ⅲ - Basin and Plateau Areas of Northwest China; Ⅳ - Loess Plateau, Shanxi Mountains; Ⅴ - Qinba and Southwest Mountainous Areas; and Ⅵ - Tibetan Plateau.



(a)

(b)

Figure 4 (a) Landslides distribution from 1949-2011 as recorded in CLI; (b) No. of landslides of zones in different time periods.

The distribution map illustrates that all zones in China are prone to landslides. Most of the landslides are concentrated in the geological environment zone IV, II and V, and spread over the middle, southeast, and southwest of South China. Moreover, part of landslides occurred at the boundaries of different zones.

Figure 4 (b) shows the number of landslide records in different landslide zones for the years 1949-2011. Fewer landslide records are available before 1980 because of fewer reports and inadequate attention from the government. The landslide records increase gradually after the 1980s with the development of economy and include the man-made and natural types of landslides. Among all the six zones, zone Ⅴ has the largest number of landslide records, regardless of the time periods. The frequent occurrence of landslide events in zone V is because of intense tectonic activities, complicated geological structures, and fragmented rock-soil bodies, along with heavy rainfall (Huang 2009).

2.3 Causal analysis of landslides

The landslides in the CsLID were caused by the following factors, including rainfall, earthquake, flood, snow melting, human activities (such as coal extraction, blasting, and excavation), multiple causes (two or more factors) and others (such as soil erosion, reservoir effects). Figure 5 shows the percentages of these factors. Rainfall is the dominant cause, accounting for 88.78%. In contrast, only a few dozen come from earthquake (0.58%) and flood (0.17%). Earthquake and flood as two landslide causes have sudden and complex features and it is difficult to record accurate landslide information. Therefore, the database contains biases due to exclusion of the two external factors. The main reason is that most of landslide events caused by the two external factors include the incomplete landslide records. Earthquake is a sudden event and the time of landslide occurrence may be ambiguous. Flood can cause deaths and economic losses directly, however, it is difficult to distinguish the numbers from the flood-induced landslides. The temporal variation of landslides indicates that the landslide season is between June and September, with peak in July (Figure 6). The most noticeable example is in zone Ⅴ, mainly induced by rainfall. In contrast, the least recorded zone III, mainly deserts or flat areas, does not exhibit seasonality.

Rainfall is the most important factor inducing landslides, especially in the regions where there is heavy rainfall of over 50mm per-day (Liao et al. 2010). Figure 7 shows the distribution of rainfall and heavy rainfall inducing landslides. Most of them concentrate on the southwest (i.e., zone Ⅴ) and coastal areas of South China (caused by storms and typhoons).

2.4 Fatalities and economic losses analysis

The CsLID also contains information on

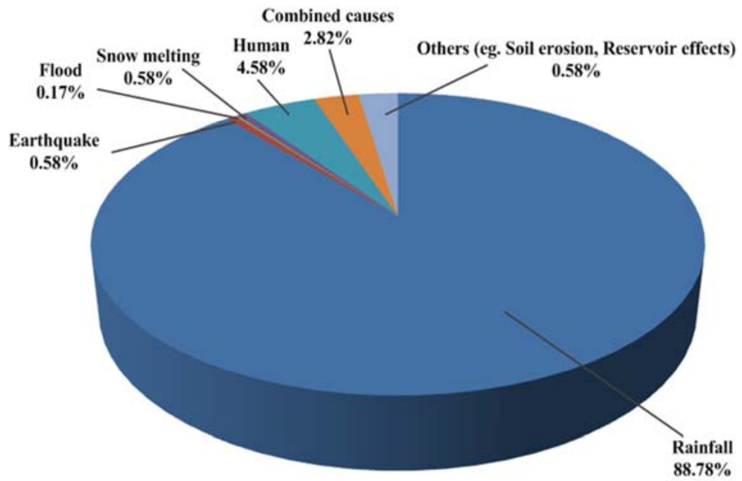


Figure 5 The percentages of landslide-inducing factors as indicated by the inventory.

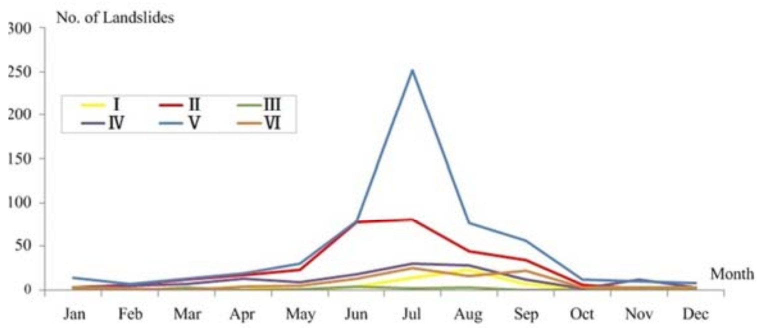


Figure 6 Monthly landslide occurrences in different zones.

fatalities and economic losses caused by landslides. The landslide records are divided into 5 classes according to the fatalities. Figure 8 shows the distributions of different classes. Class 5 represents the area where the landslides killed over 30 people. Most of the serious landslides are located in the southwest (zone Ⅴ) and the coastal areas (zone Ⅰ and Ⅱ) of South China. Among them, Wenchuan earthquake within zone Ⅴ in 2008 (Preliminary estimates indicate there are about 20,000 deaths directly caused by earthquake-induced landslides (Yin et al. 2009)) and Gansu Zhouqu debris flow (between zone Ⅳ and Ⅴ) in 2010 (the fatalities 1765) are included. Figure 9 shows the classes of landslide fatalities distribution in different zones. By the statistical method, the number of class 4 and 5 is higher than the number of class 2 and 3 in zone Ⅴ. It means that the zone Ⅴ is more likely to cause large-scale landslide and high fatalities.

The exact figures of economic losses are not available for each landslide. Economic losses include direct and indirect. In this respect, CsLID is incomplete, and 'NaN' represents the vacant data values. Figure 10 shows both the distributions of the fatalities (over 30 deaths), and direct economic losses (over ¥ 10 million). The results show the large scale landslides which usually bring about economic losses and casualties in the same areas of zone V whereas lower deaths are recorded in the zone Ⅱ.

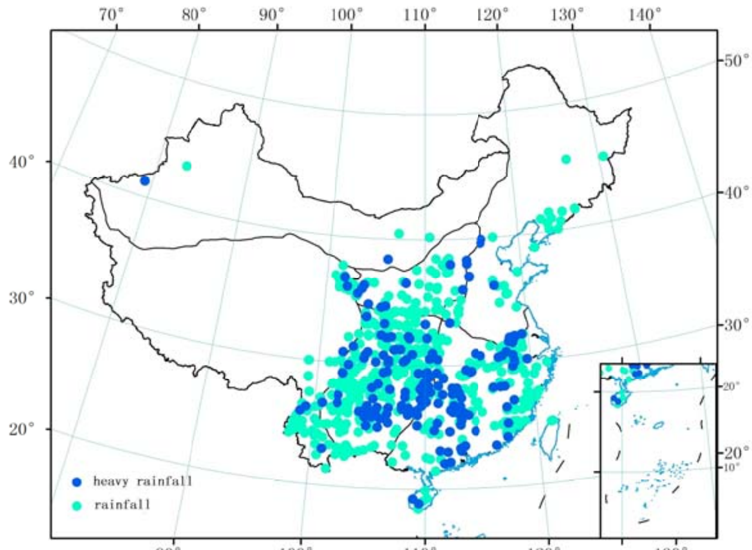


Figure 7 Rainfall-induced landslides in China.

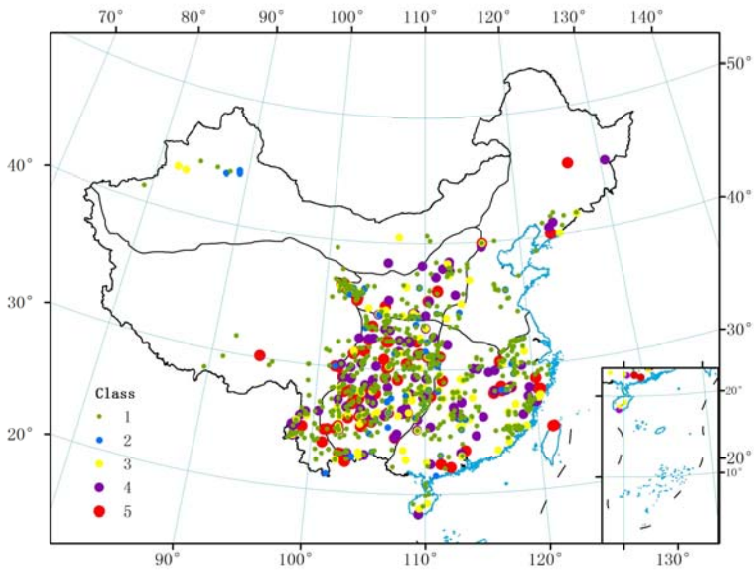


Figure 8 Landslide classification based on the fatalities.

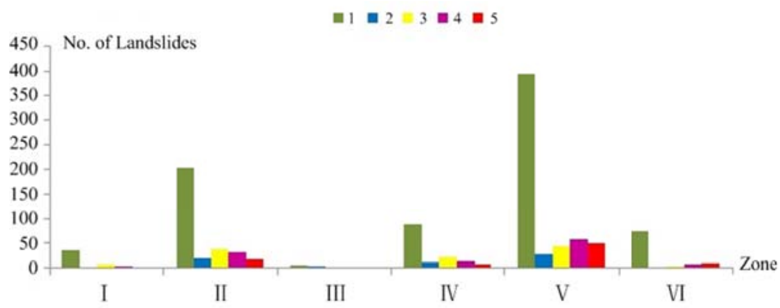


Figure 9 No. of landslides of zones in different classes.

3 Discussion and Conclusion

Mapping the geographic locations of the landslide events, especially the events caused by different factors, is a very challenging task (Kirschbaum et al. 2010). CsLID is just the first step toward this direction by comprehensively analyzing landslide distributions, causes, fatalities and economic losses in China spanning the period of 1949-2011. Out of several sources of uncertainty, population distribution

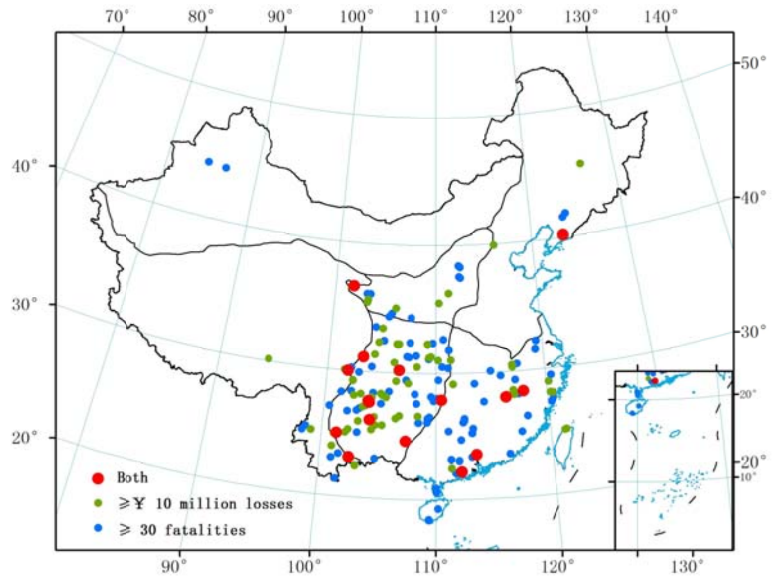


Figure 10 The distributions of fatalities (≥30) and economic losses (≥ ¥ 10 million).

density heavily affects the landslide reports, most likely the data records are incomplete and barely crosses the lower boundary in many sparsely inhabited areas (Kirschbaum et al. 2009). In the densely populated areas, large landslides generally cause more serious casualties and economic losses. Figure 11 also shows landslide density vs. population density in different zones (note that China's population density is available at http://sedac.ciesin.columbia.edu/data/set/gpw-v3-population-density-future-estimates for the year 2010). Most of the landslides are spread over areas with population density of less than 1000 persons per km². Because a large section of the population of China is concentrated in socio-economically more developed areas, people live under more landslide risks in zone I, II and IV. Moreover, the landslides (location: zone Ⅲ-Xinjiang province, time: 1984-6-1, 1986-6-1; location: zone Ⅴ-Sichuan province, time: 1995-6-7) lay in densely populated areas. In sparsely populated zone VI, landslides distribute around the areas with population density less than 400 persons per km².

This study provides a comprehensive platform that collects, catalogs, analyzes, and visualizes China's Landslide Inventory Database (CsLID) from 1949 through 2011, with open access and dynamic addition capability enabled by WebGIS and cloud computing technology. Furthermore, using cloud-based Google Fusion Table tool, CsLID platform provides some unique functions of on-user-demand web service: querying, sharing, updating, visualization, etc. Additionally, users can customize the database by Google Maps API for their actual needs. The CsLID is helpful for the analysis in the spatiotemporal coverage of landslide hazards in China.

Based on the geological environments and terrains, the whole of China is classified into six zones (from zone Ⅰ to Ⅵ) for the purpose of

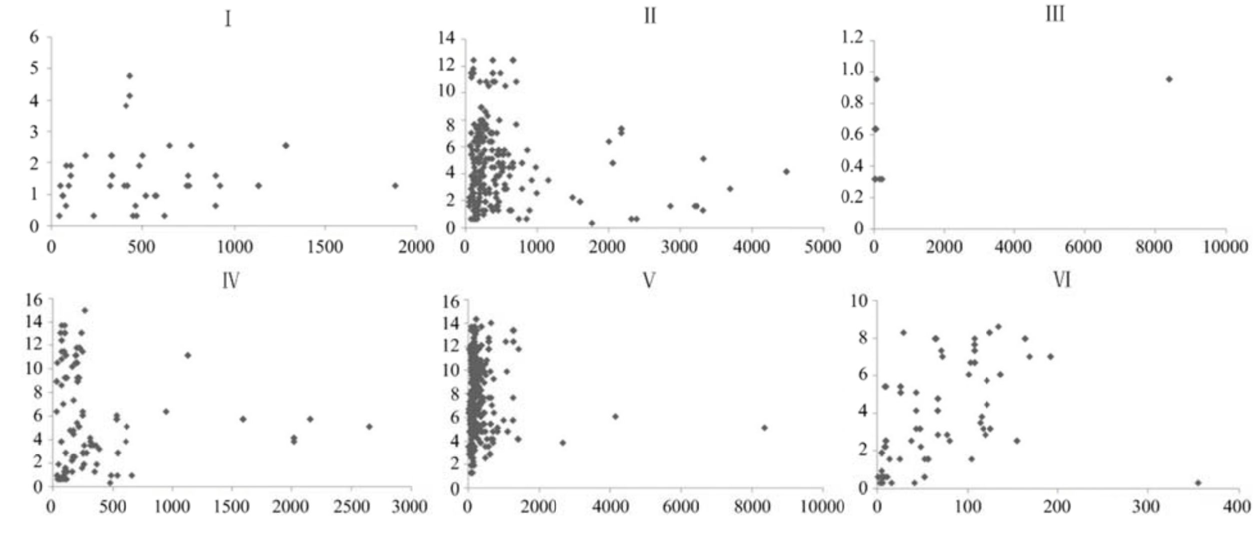


Figure 11 Population densities (horizontal axis, persons per km²) vs. landslide densities (vertical axis, No. of landslides per 10 km²) for each zone.

spatiotemporal analyzing CsLID. The results indicate that the highest percentage of landslide event occurrence, fatalities, and economic losses is located in zone Ⅴ (Qinba and Southwest Mountainous Areas), and the second most impacted area is zone Ⅱ (Hilly Areas of South China). Zone V is mostly prone to landslide disasters due to complex combination and interaction of internal and external factors. Internal factors are those that have decisive effects on landslides, including geology, geomorphology, topography, soil property, vegetation cover, etc. External factors are those that can trigger landslide occurring, such as rainfall, earthquake and floods.

The relationship of inducing factors and the monthly temporal distribution of landslides is further investigated. Of all the significant landslide events, 88.78% occurrences are rainfall-induced landslides. This clearly indicates that rainfall-induced landslides are the most common type and poses the greatest threat in China. The rainstorm-dominated landslide causative factor also explains that the landslide occurrence has a strong seasonal pattern spanning the rainstorm season from May to Sept with peak in July. However, the landslide events induced by earthquakes and floods are less. It is because earthquake and flood are sudden processes and it is difficult to acquire accurate information about them, particularly time of occurrence, latitude and longitude. Therefore, the landslide database may overestimate the proportion of rainfall-induced landslides.

With regard to the analysis of the population density vs. landslide density, the results indicate that most landslides are located in the areas with less than 1000 person per km^2. This work makes contributions to the landslide susceptibility and hazard assessment in China. In conclusion, Google public cloud computing platform enables the CsLID as easily accessible is interactively visual, and the database is dynamically augmentable. This new type of platform has the promise to provide a paradigm shift in hazard database development, visualization, and crowdsourcing new initiatives.

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