Landslide hazard probability and risk assessment at the community level: A case of west Hubei, China

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Abstract. Small communities living in mountainous terrain in Hubei province are often affected by landslides. Previous studies by the China Geological Survey focused on the 1:100,000 scale. Therefore, a more detailed assessment, especially at the community level, is urgently required by local governments for risk management. In this study, we conducted a more detailed semi-quantitative landslide and risk assessment at the community level using a scale of 1:10,000. We applied the probabilistic method to assess landslide spatial, temporal, and size probabilities, while the hazard and risk assessment were considered for four return periods (5, 10, 20, and 50 years) and two size scenarios (landslide volume). The spatial probability from susceptibility mapping with an accuracy of 84% indicates that the major controlling factors are Quaternary deposits and weathered eluvium from Ordovician limestones. This study revealed that most building areas in hazard maps are at the foot of major slopes with very high hazard probabilities, and so, we computed the potential loss of life and property for each slope. The results reveal that 1530 people and 18.00 million USDworth of property were at risk of landslides within a 50 years return period and a landslide volume of 50,000 m^3. The longer the return period is, the higher the hazard probability is. Compared with the classic inverse gamma and power law distribution of landslide magnitude and frequency, the function by the ordinary least square method is more suitable for landslide size probability analysis of the study area. According to these methods, the proposed procedure of landslide risk assessment proves more useful than the existing data from the 1: 100,000 scale in west Hubei, China.

Keywords: Risk management; spatial probability; temporal probability; size probability; element-at-risk; vulnerability

1 Introduction

Risk analysis and assessment in China is an effective means of reducing casualties and economic losses induced by landslides. Although theory and techniques applied worldwide are available (Van Westen et al., 2005; Lee et al., 2007; Neuhäuser and Terhorst, 2007; Erener et al., 2016; Huang et al., 2017; Jiménez-Perálvarez et al., 2017;Van Westen and Greiving., 2017), these are not yet well utilized in west Hubei, China, where the current research was undertaken. To date, very little scientific work is documented at the community level for the study area. Mountainous communities in the area are exposed to landslides because of high rainfall and urbanization. Annually, road construction and anthropogenic modifications at the community level (e.g., excavations in search of building materials), the degree of urbanization, and subsequent population growth have promoted the frequency of landslides, with immense risk to the communities, causing death and unaccountable property loss. According to the Chinese geological disaster notification report (2017), for example, around 850 disasters occurred in 2017 in Hubei province, China, causing 23 deaths and about 254 million RMB (equal to ~ 36.29 million USD (US Dollar) by November 2019 conversion) of economic losses. Quantifying landslide risk and developing a reduction strategy remains a challenging issue.

Currently, guidelines for landslide risk zoning and land use planning with the framework, definitions, and recommendations are available for clearly defined scales (Fell et al., 2008a). Also, research work highlighting landslide risks at a community level has recently been conducted, and some of the result reached are available to the public (Erener and Düzgün, 2012; Abdulwahid and Pradhan, 2016;Chen et al., 2016a; Liu et al., 2016;McAdoo et al., 2018;Paliaga et al., 2019). Paliaga et al. (2019), for example, used a spatial multi-criteria analysis technique to propose geo-hydrological risk mitigation measures in a small but densely-populated catchment, with descriptive parameters involving the extent of urban development and elements at risk. In Spain, a quantitative assessment of landslide risk for the road network of the Basque Country was used for calculating hazard probability and expected consequences (Mavrouli et al., 2019).

Our objective in this study is to conduct a community level landslide hazard probability and risk assessment of an area with limited landslide data and damage records. Despite these limitations, in this study, we attempted to quantify the landslide risk for the Yuyangguan community, in Hubei province, China. The probabilistic method was used to assess landslide spatial, temporal, and size probabilities. Landslide hazard and risk assessment are considered for four return periods and two magnitude scenarios. From these, we propose risk reduction strategies that stakeholders can use for risk management and control.

2 Study area and data

The study area, Yuyangguan community (N 30°03′- 330°15′, E 110°08′- 8110°08′), is in Wufeng County, western Hubei province, China (Fig. 1). It covers an area of about 34 km^2 with 15 villages, including Sanfangping, Dafangping, and Caojiaping. This area has been inhabited since 750 years ago, but intense urbanization development involving the construction of national-class roads only in 2012. The area was selected for this study because of frequent landslides responsible for tremendous damage in recent years. The residential area is surrounded by steep slopes, with elevations ranging from 180 to 680 m.a.s.l. The climate is typical monsoonal with annual average precipitation of about 1500 mm.

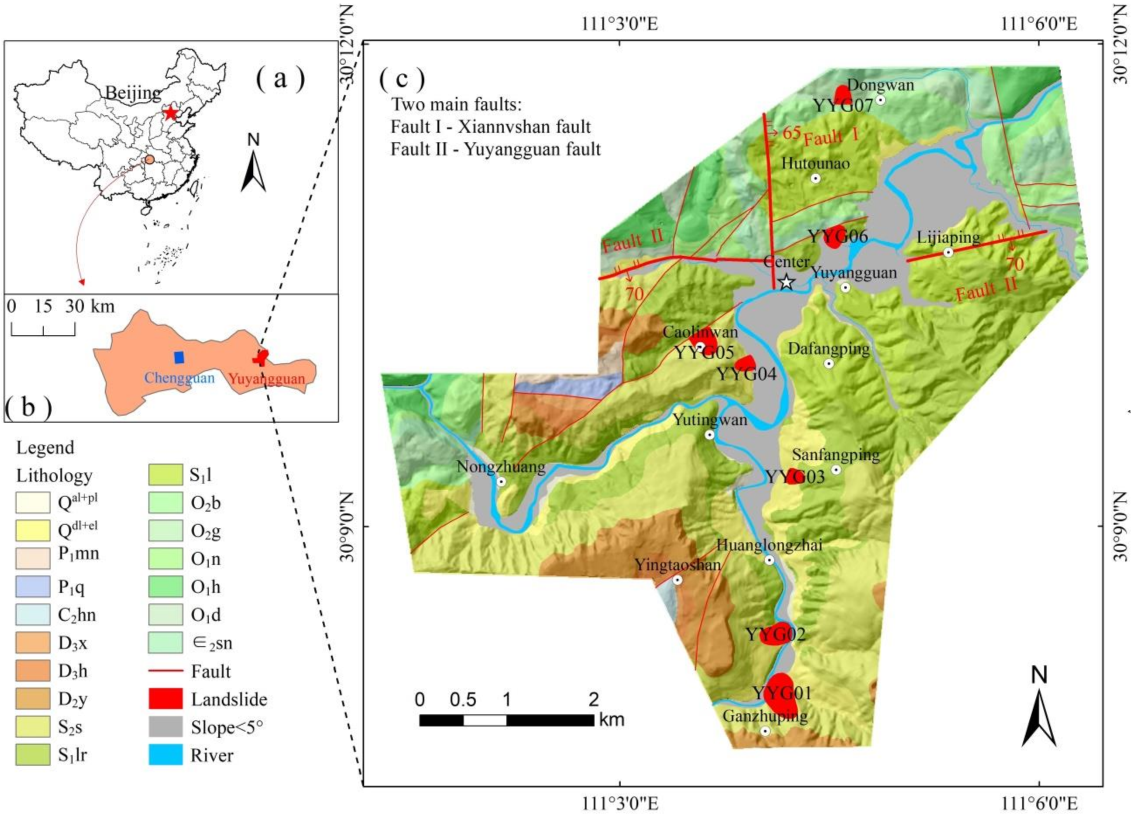


Fig. 1. a) Inset showing a colored map of China, (b) inset representing the county hosting the Yuyangguan and neighboring Chengguan communities, and c) the distribution of lithologies units and recorded landslides in the case community. (The lithology codes in the legend are described in Table I)

The main lithological units outcropping in the study area comprise Ordovician (O_2g) limestones and shales, Silurian (S_2s) sandstones and shales, Devonian sandstones with coal layer, Permian sandstones, and recent deposits. The S_2s sandstones dominate the rock types along the community slopes, and intense weathering explains the low mass strength of the bedrock. Consequently, weathered S_2s and O_2g rocks are the primary sources of landslides, with the records and bedrocks presented in Table II.

The Xiannvshan (Fault 1 in Fig. 1) and Yuyangguan (Fault II in Fig. 1) faults of the Changleping tectonic belt constrain the bulk architecture of the area. The Xiannvshan fault, striking approximately 340°N–345°W and dipping 60°–70° NE is a transpressional fault terminating at the center of the community. The fault is a seismically active belt, exemplified by the Panjiawan earthquake (Ms = 4.9) of 1961 and the Zigui earthquake (Ms = 3.3) of 1972. Conversely, the Yuyangguan fault, striking E–W and dipping 60°–70°S is a transtensional fault. Rocks associated with the Yuyangguan fault comprise 20–50 m wide of cataclasite and brecciated mylonite, with several secondary faults merging into it, and, together, go through the center of the Yuyangguan community. According to the China Earthquake Administration, the studied area is in a weak seismic activity region with a basic earthquake intensity of VI and the 50-year 10% probability exceedance of the peak ground acceleration is 0.05 g. No historical record is available for earthquake-induced landslides in the area.

Rainfall and anthropogenic activities contribute significantly to triggering mass movements, mainly landslides. In the rainy season of 2013, a slope along the main road collapsed, breaking and causing lengthy traffic jams and transportation problems (Fig. 2). A landslide occurred in a new residential quarter of the community on January 3, 2013, due to an unstable foundation pit after a one-day excavation (Fig. 3). These two landslides are examples, with more landslide records prepared from aerial photograph interpretations and validated by field investigations.

Table I. Characteristics of lithology distributed among Yuyangguan.

Lithology code	Characteristics of lithology
Q^{al+pl}	Gravel, pebble, and drift stone, with a small amount of sand.
Q^{dl+el}	Clay intercalated with gravel, mainly distributing in the gentle slope area of the bank slope.
P_1mn	The top marl, the middle thin layered manganese-bearing siliceous limestone.
P_1q	Upper Carboniferous Tumorous Limestone, Lower Chernite Nodules, and Chernite Strip Limestone.
C_2hn	Upper thick-layered limestone, dolomitic limestone, lower dolomite, sometimes conglomerate.
D_3x	Upper sandstone and shale interbedded, middle thick-layered marl, lower sandy shale with oolitic hematite.
D_3h	Thin, medium-thick silty shale, fine-grained quartz sandstone, bottom shale.
D_2y	Thick quartzite and quartz sandstone with a small amount of carbonaceous shale and mudstone shale.
S_2s	Thick- to thin-layered quartz sandstone, siltstone and silty shale, and mudstone shale at the lower part.
S_1lr	Shale with siltstone and thin marl.
S_1l	Muddy shale, sandy shale with siltstone, silty shale, and carbonaceous shale.
O_2b	Medium-thick-layered bioclastic turtle limestone.
O_2g	Microcrystalline limestone with a medium thickness.
O_1d	Thick to thin layers of tumorous limestone interbedded with shale.
O_1h	Thick and massive coarse-grained bioclastic limestone and limestone.
O_1n	Medium- and thick-layered limestone, dolomite and shale with limestone at the bottom.
$Є_2sn$	Massive and thick-layered dolomite with dolomitic limestone.

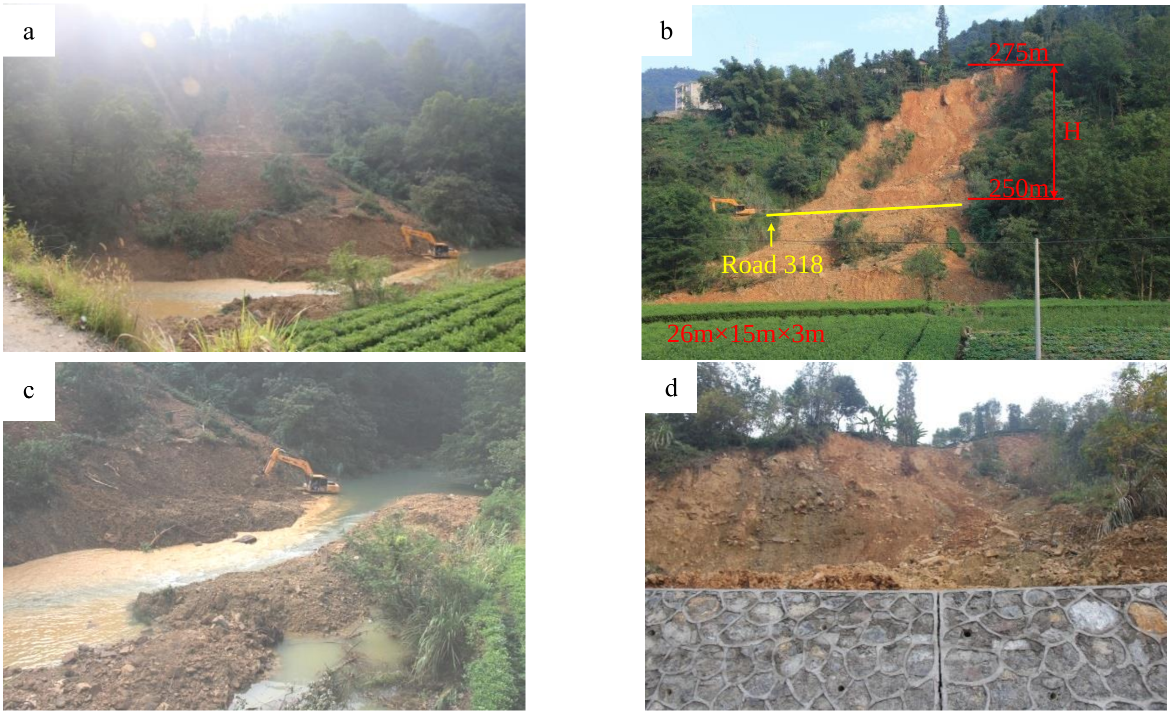


Fig. 2. Landslide YYG01 occurred in the rainy season of 2013, causing damage on the national road (G318) in Yuyangguan. (Travel distance = 57 m). a) An overview of the landslide YYG01, b) left side of the loose landslide body, c) river blockage caused by the landslide YYG01, and d) the retaining wall.

Fig. 3. Landslide YYG03 caused by slope incision in a residential quarter of Yuyangguan.

Table II shows all historical landslide data from 1976 to 2013 in areas dominated by Quaternary deposits. Besides the landslide inventory database, other datasets collected for landslide risk mapping include:

- A 10 m × 10 m resolution digital elevation model (DEM) generated from a topographic map obtained using an unmanned aerial vehicle (UAV). The DEM allowed the extraction of the slope, elevation, aspect, and curvature data using the surface analysis tool in ArcGIS (a geographic information system for working with maps and geographic information, http://www.esri.com/software/arcgis/arcgisonline; Fig. 4a, 4b, 4c, and 4d).
- A Geological map at 1:50,000 scale (Fig. 1) used to extract datasets, including lithology, faults, and slope structure. The slope structure map (Fig. 4e) was generated using the standard and stratigraphic altitude advocated by Cruden (1991). The land use map provided the distribution of rivers and roads (Fig. 4h, 4i).
- Landslide inventory databases of the case community (named Yuyangguan) and a neighboring community (named Chengguan) were utilized in this study to analyze the size probability in hazard assessment (See Table II). We used the hazard database of the neighboring community for the following reasons: (1) the landslides in the case community are limited for probability analysis, and (2) the two communities are similar in geomorphology, geology, climate, and landslide types. The location of the Chengguan community is displayed in Fig. 1b, and administratively, the two communities are in Wufeng County. Both communities belong to the same structural belt named Changleping anticline fold that extends in a nearly E–W direction and comprising the Silurian and Ordovician rocks. Previous landslides in these communities involve shallow and soil slope movement of weathered bedrock. The factors triggering the landslides are rainfall and slope cutting, associated with urbanization development.
- A building footprint map (Fig. 5) was interpreted and checked in the field by the authors, with most buildings on or at the toe of the first slope zones, with an elevation of up to 350 m.a.s.l. The entire built area is 757, 000 m^2, with data on the economic value of buildings obtained from the Department of Lands and Resources of Hubei province (See Table III).
- Census data was obtained by integrating the information derived from the China population data (2010) (http://www.stats.gov.cn/tjsj/pcsj/rkpc/6rp/indexch.htm) and sampling survey (Fig. 6), amounting to a population of 45,914 in the area.

Table II. Historical landslides investigated in the field by the authors

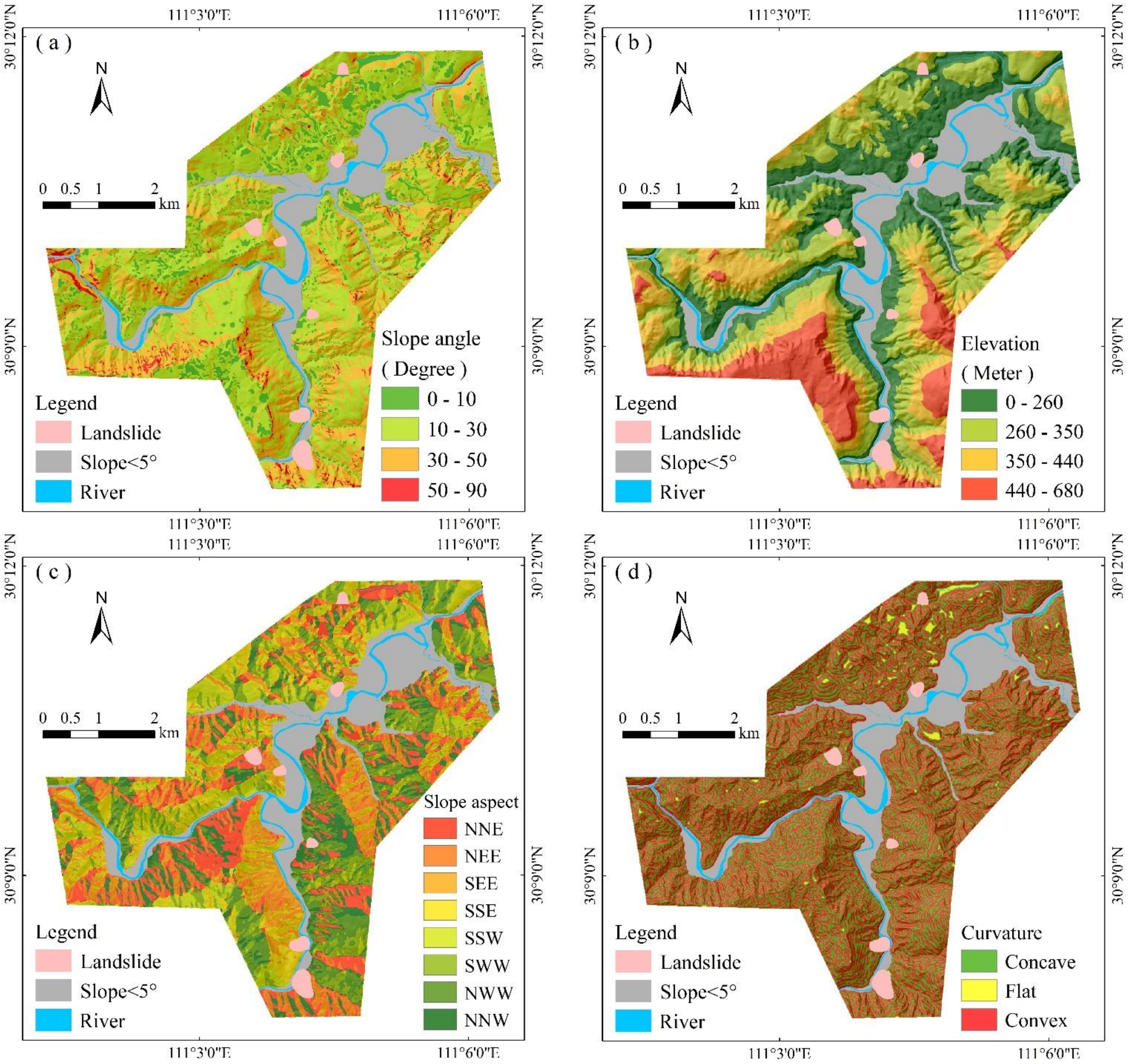
Date (Month/Year)	Landslide ID	Coordinates		Material	Bedrock	Volume (×10 000 m^3)	Area (×10 000 m^2)	Triggering factors
		X	Y					
Seven landslides were located in Yuyangguan community.								
06/1981	YYG02	506615	3335500	Soil	$S_1 lr$	49.8	4	R & SC
01/1989	YYG05	505788	3338880	Soil	$S_2 s$	10.4	3.5	R
12/2007	YYG06	507320	3340080	Soil&rock	$O_1 d$	8	1.6	R & SC

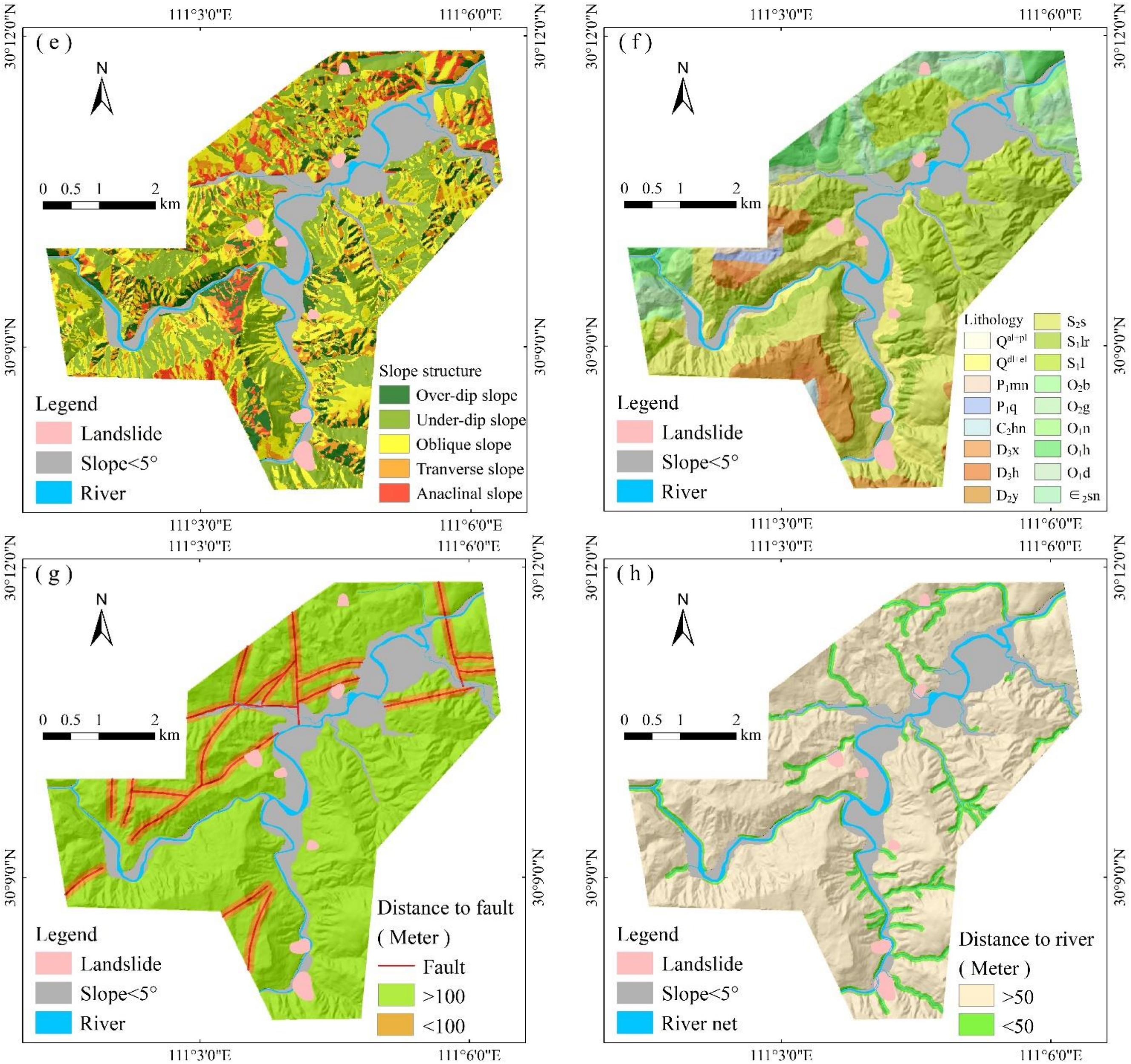
06/2010	YYG07	507381	3341680	Rock	O_1d	22.2	2.2	R & SC
05/2013	YYG04	506275	3338610	Soil	S_2s	10.7	1.5	R & SC
07/2013	YYG01	506692	3334830	Soil	S_2s	147.6	5.9	R
01/2014	YYG03	506828	3337320	Soil	S_1l	20.9	1.7	R & SC
Nineteen landslides were located in Chengguan community.								
06/1967	CG08	468193	3341670	Soil	O_2b	79.5	5.3	R
07/1969	CG09	468331	3341980	Soil&rock	O_2b	16.8	2.4	R
07/1969	CG17	468119	3342020	Soil	S_1l	4	0.5	R
06/1991	CG19	467889	3341710	Soil	S_1l	4.32	0.54	R
07/1991	CG03	467576	3340630	Rock	O_2b	1.92	0.48	R
06/1992	CG06	468072	3341460	Rock	O_2b	34.5	2.3	R
06/1992	CG11	468841	3342740	Soil	S_1l	7	0.5	R
06/1992	CG12	468354	3342720	Soil	S_1l	9.6	1.2	R
07/1994	CG13	467816	3342670	Soil	S_1l	4.55	0.65	R
07/1994	CG14	467888	3342520	Soil	S_1l	8.2	0.82	R
07/1996	CG16	468188	3342070	Soil	S_1l	3.6	0.6	R
07/1997	CG07	468295	3341510	Soil	O_2b	14.3	1.1	R
02/1998	CG15	467956	3342230	Soil	S_1l	8	0.8	R
07/2002	CG05	467830	3340990	Soil	O_2b	55.9	4.3	R & SC
08/2005	CG04	467659	3340830	Rock	O_2b	5.04	0.56	SC
07/2007	CG18	467707	3341990	Soil	S_1l	13.2	1.1	R
05/2009	CG01	466943	3339730	Soil	S_1l	5.4	0.45	R

03/2012	CG10	468597	3342480	Soil	O_2b	3.18	0.53	R
04/2012	CG02	467038	3339980	Soil	S_1l	1.05	0.21	R

R-rainfall; SC- Slope cut. The code of Bedrock is listed in Table I.

Projected Coordinate System is Xian_1980_3_Degree_GK_Zone_37 with projection of Gauss_Kruger.




(e)
111°3'0"E
111°6'0"E
30°12'0"N
30°9'0"N
N
0 0.5 1 2 km
Legend
Landslide
Slope<5°
River
Slope structure
Over-dip slope
Under-dip slope
Oblique slope
Tranverse slope
Anaclinal slope
(f)
111°3'0"E
111°6'0"E
30°12'0"N
30°9'0"N
N
0 0.5 1 2 km
Legend
Landslide
Slope<5°
River
Lithology
Q^{al+pl}
Q^{dl+el}
P_1mn
P_1q
C_2hn
D_3x
D_3h
D_2y
S_2s
S_1lr
S_1l
O_2b
O_2g
O_1n
O_1h
O_1d
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(g)
111°3'0"E
111°6'0"E
30°12'0"N
30°9'0"N
N
0 0.5 1 2 km
Legend
Landslide
Slope<5°
River
Distance to fault
(Meter)
Fault
>100
<100
(h)
111°3'0"E
111°6'0"E
30°12'0"N
30°9'0"N
N
0 0.5 1 2 km
Legend
Landslide
Slope<5°
River net
Distance to river
(Meter)
>50
<50

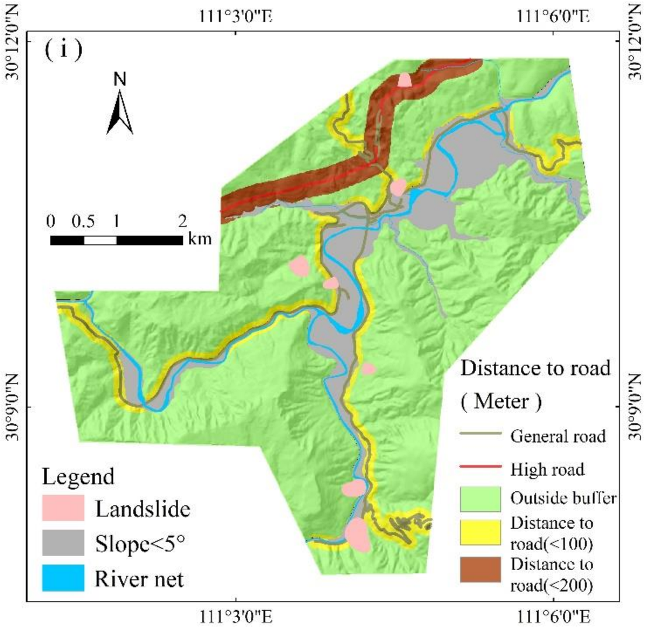


Fig. 4. Thematic maps for landslide susceptibility mapping: (a) slope, (b) elevation, (c) slope aspect, (d) curvature, (e) slope structure, (f) lithology, (g) distance to fault, (h) distance to river, and (i) distance to road.

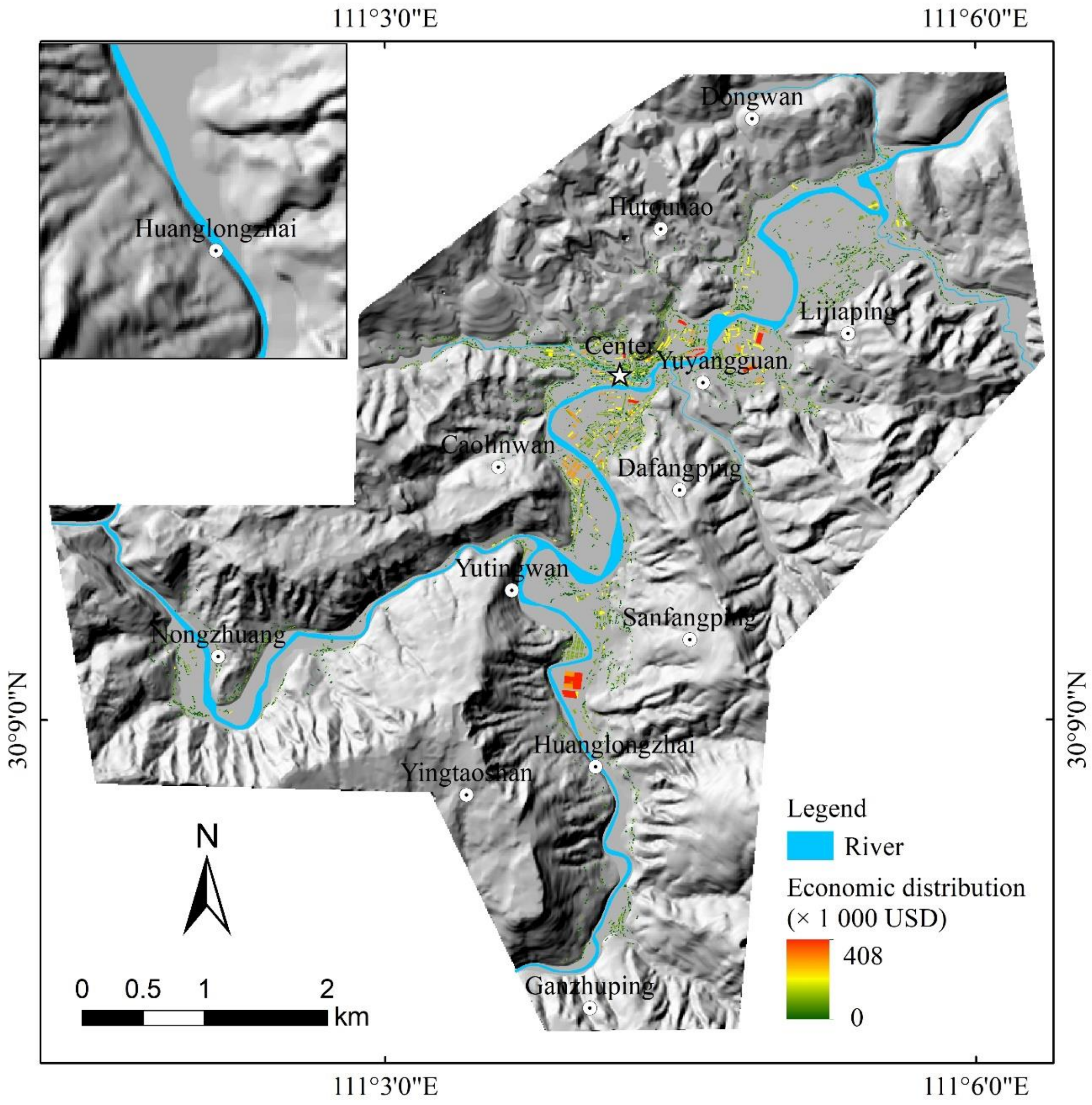


Fig. 5. Building footprint map with economic values for the Yuyangguan community.

Table III. The economic value of buildings in Yuyangguan community (the department land and resource in Hubei province, 2016).

Typology	1 000 USD/ m^2	Number of floors
Reinforced	21.84	20–32
Reinforced concrete	9.31	6–20
Masonry	5.60	2–6
Wooden	0.70	1–2

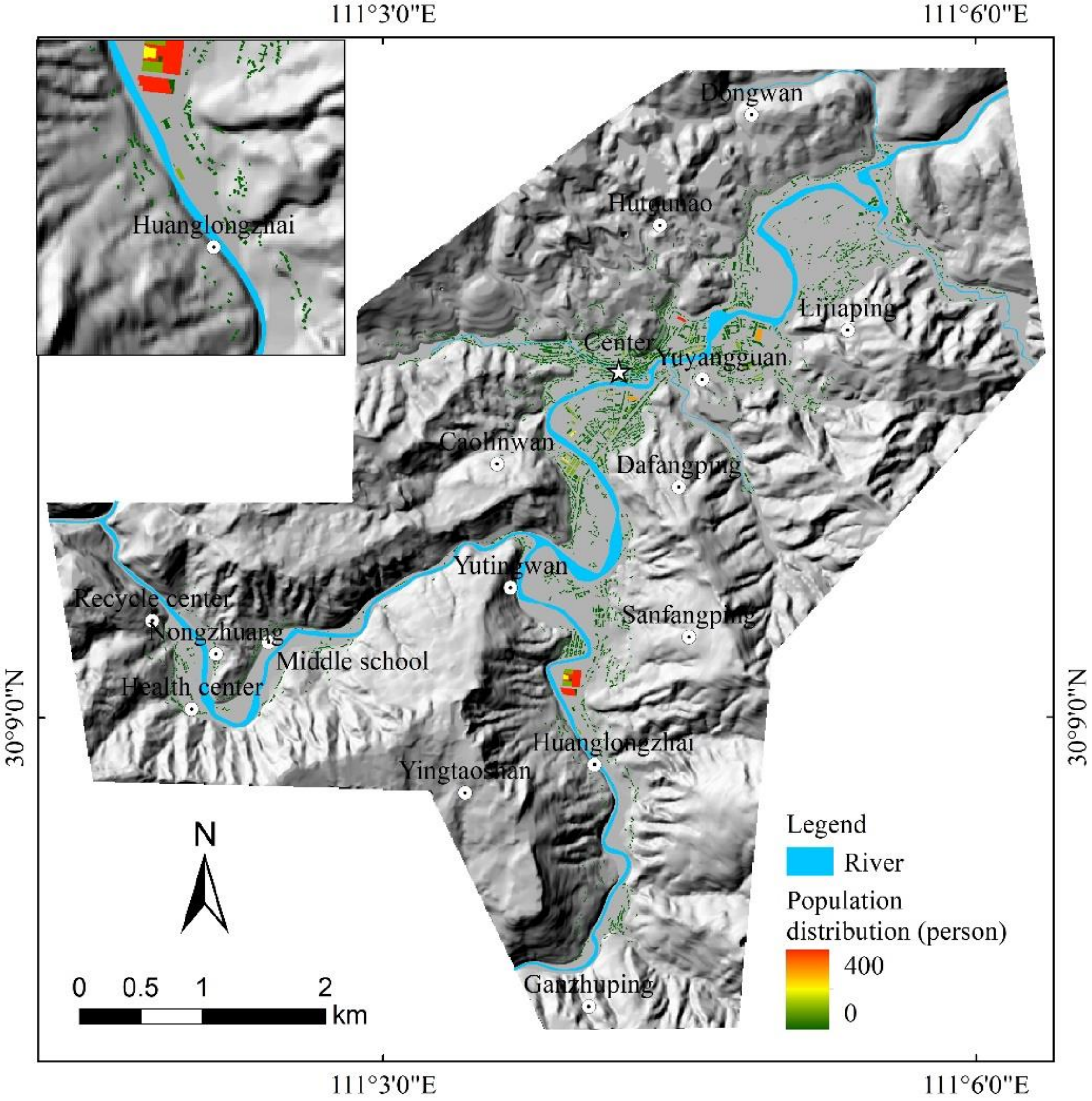


Fig. 6. Population distribution map of the Yuyangguan community.

3 Methodology

This section summarizes the methods employed for semi-quantitative risk analysis for landslides at a community level. Initially, the slope unit-based hazard probability was calculated by integrating spatial, temporal, and size probabilities. We generated eight hazard probability maps involving four return periods (5, 10, 20, and 50 years) and two size scenarios. For each map, we determined the landslide potential influencing area semiquantitatively by calculating the traveling distance of the slope unit. Subsequently, the element-at-risk map was interpreted from the image data, population census data, and sampling survey. The vulnerability map was created by assimilating assets and landslide influencing areas. Values in the vulnerability map were semiquantitatively determined for buildings and people in the buildings. The combination of hazard maps, vulnerability maps, and element-at-risk maps produced the risk value for each slope unit, contributing to the final risk maps of the population and buildings in the study area. The flowchart of the methodology is depicted in Fig.7.

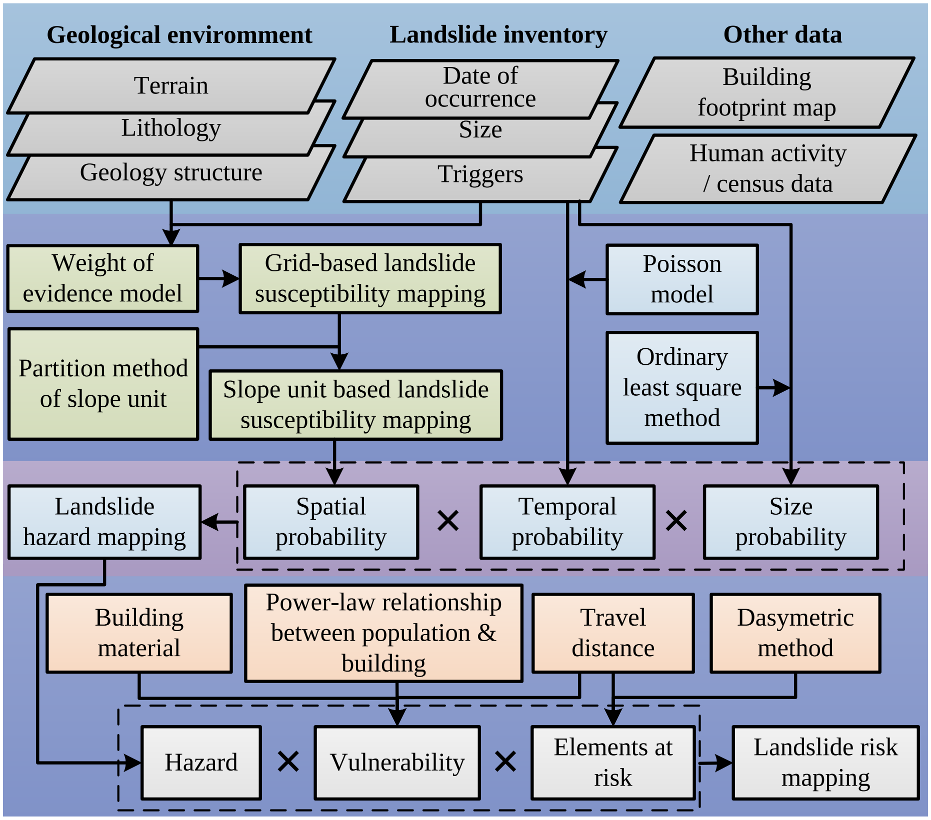


Fig. 7 Flowchart of the methodology for landslide hazard risk assessment

3.1 Landslide hazard from spatial, temporal, and size probability analysis

Hazard assessment is an essential step in landslide risk assessment. For the community level, this is achievable through the deterministic model (Gokceoglu and Aksoy, 1996; Qiao et al., 2019), given enough engineering geology data. For the study area, soil or rock strength parameters were unavailable to use the deterministic method. We, therefore, used three probabilities (spatial, temporal, and size) to resolve questions on where and how potential landslides will occur with absolute magnitude in a given time (Guzzetti et al., 2005) using the expression:

$$H = P(S) \times P(N_L) \times P(A_L) \quad (1)$$

where H represents the hazard probability, $P(S)$ is the spatial probability, $P(N_L)$ is a temporal probability, and $P(A_L)$ is size probability.

3.1.1 Spatial probability

Spatial probability, based on the concept of susceptibility, assesses the locations where a mass movement exists or may potentially occur. Landslide susceptibility mapping (LSM) is now widely used by researchers (Ayalew et al., 2004; Fell et al., 2008b; Van Westen et al., 2008; Guzzetti et al., 2012). In this study, morphometric and geo-environmental factors, including altitude, slope, aspect, curvature, slope structure, distance to rivers, and proximity to roads, were chosen as variables. The morphometric factor maps were derived from the DEM with a 10 m×10 m resolution obtained by a UAV. Geo-environmental factors, such as lithology and faults, were prepared and transformed from shapefiles to grid-based maps using a 1:10 000 scale geological field map from the China Geological Survey (http://www.cgs.gov.cn/). Detailed processing steps in ArcGIS are provided in Catani, Casagli, Ermini, Righini, and Menduni (2005). The commonly applied weight of evidence (WoE) method was used to assess landslide susceptibility in this study. This is a probabilistic model considering evidence factors of landslides, based on the conditional independence hypothesis (Hong et al., 2017). In the WoE method, W^+ and W^- were used as the weights where the evidence was present or absent, respectively, and the contrasts (differences between W^+ and W^-) were used as the weight for the morphometric and geo-environmental factors.

The effectiveness of the LSM was tested using the Receiver Operating Characteristics (ROC) curve (Metz, 1978; Zezere et al., 2017), with the area under the ROC curve used to assess the success rate.

The above grid-based LSM data were then converted into a slope unit-based susceptibility map. The susceptibility value of each slope was calculated from the average value of the susceptibility of the grids within the slope. The slope unit was subdivided using the hydrology analysis method in the ArcGIS platform. The slope unit-based spatial probability map was classified into five classes, including very high, high, moderate, low, and very low.

3.1.2 Temporal probability

Landslide temporal probability $P(N_L)$ is evaluated by assuming that slope failures are independent random point-events in the time domain (Crovelli, 2000;Guzzetti et al., 2006). In this study, the Poisson model (Crovelli, 2000) was adopted for constructing temporal probability. It is the exceedance probability of landslide occurrence during a given period (see Equation (2)), meaning, the probability of experiencing one or more landslides during a given time, and derived as:

$$P(N_L) = 1 - e^{-T/RI}, RI = t / N \quad (2)$$

where T is the return period, e.g., 1, 10, 20, and 50 years, recurrence interval *(RI)* is the historical mean recurrence interval for each slope unit, t is the temporal interval of the landslide database, and N is the number of landslides recorded in each slope. If the historical landslide database is incomplete, N on a slope unit with a very high susceptibility class in the LSM is assigned as 1.

3.1.3 Size probability

Landslide size probability is calculated based on the relationship between landslide volume and cumulative frequency. Guzzetti et al. (2005) used the probability density function of the landslide area to predict the probability of a specific landslide area in each slope unit. Stark and Hovius (2001) found that landslides in New Zealand and Taiwan fitted with a double Pareto probability distribution, and two differences in our study will improve the application. The first is that the present study seeks the most suitable distribution for the case study area. Therefore, we compared the distributions stated previously and introduced another type using the ordinary least square (OLS) method in the Matlab software, with the best fit used for probability calculation. The second is that landslide volume is an acceptable indicator for risk control practice in the study area. Therefore, we converted the landslide size probability distribution from area to volume using the volume–area relationship simulated by the OLS method. For this, we used the historical landslides in the database of the study area in Table II. The hazard database of the Chengguan community was implemented because of the landslide records limitation, but the geo-environment and hazards in both communities are similar. Meanwhile, the two size scenarios were determined from the distribution of landslides volume in the case study area.

3.2 Data preparation for elements-at-risk

The next step was determining the elements at landslide risk. This study focuses on residential buildings and people within. The building footprint map (see Fig. 5) was interpreted from the 2013 UAV image data. The building structure (reinforced, reinforced concrete, masonry, and wooden) and numbers of floors are involved in the building map database. To express the risk in monetary values, we used the economic value of the buildings (see Table III) obtained from the Department of Lands and Resources in Hubei province. These data were converted to building values by multiplying the unit economic values, footprint areas, and the number of floors. Data for the population in buildings were obtained by integrating the information from the China population census data (2010) and the sampling survey. The average number of people per building was calculated by applying a Dasymetric Mapping Approach (a methodology for generating a surface-based representation of the population;Mennis, 2003), that contributes to the data of the population in each building. To assess the element-at-risk, the building footprint map was then combined with the potential landslide influence area at the community level. The influence area of each slope was semi-quantitatively determined by calculating the travel distances by the following formula (Hungr et al., 2005):

$$log(H/L) = A + B \times logV \qquad (3)$$

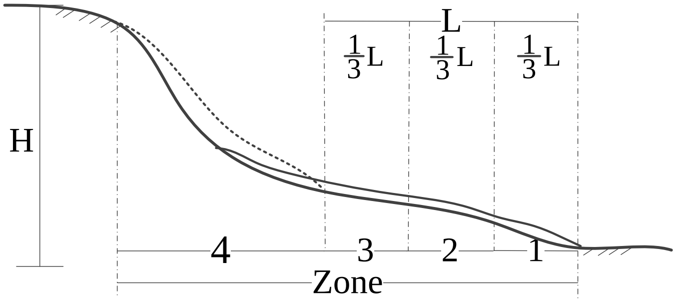
where L is the travel distance; H is the slope height; V is slope volume; and A and B are constants. These constants are referred from Corominas (1996).

3.3 Vulnerability analysis and risk assessment

Quantitative vulnerability analysis is still a challenge in landslide risk assessment (Chen et al., 2011;Peduto et al., 2017). Physical vulnerability assessment is performed in a large or local scale area (Fell et al., 2008b;Li et al., 2010;Quan Luna et al., 2011). In this study, the physical vulnerability was semi-quantitatively determined for buildings, using two indicators. The first indicator relates to building structures, such as reinforced, reinforced concrete, masonry, and wooden, while the second indicator is the landslide travel distance. The assumption is that vulnerability is 1.0 for the buildings on the slope and it decreases from the toe of the surface rupture to the farthest travel distance. We, therefore, propose vulnerability values for different types of buildings (see Table IV).

Table IV. Vulnerability value of buildings impacted by landslides (proposed by authors)

	Influence area			
	Zone 1	Zone 2	Zone 3	Zone 4
Reinforced	0.1	0.3	0.5	1
Reinforced concrete	0.2	0.5	0.7	1
Masonry	0.3	0.7	0.9	1
Wooden	0.4	0.9	1	1



(L is travel distance; H is slope height)

The vulnerability of the population in buildings follows a power–law relationship with building vulnerability (Li et al., 2010) as follows (see Equation (4)):

$$V_p = 0.0014 \times e^{6.07 \times V_b} \tag{4}$$

where V_p is the vulnerability of population in buildings and V_b is the vulnerability of a building..

A landslide risk map was then generated in ArcGIS based on the concept defined by IAEG and Varnes (1984) as “the expected number of lives lost, persons injured, damage to property, and disruption of economic activity due to a particularly damaging phenomenon for a given area and reference period” . The conceptual equation for risk is:

$$R = H \times V \times E \tag{5}$$

where *R* is the expected loss for some return period, and *H* is the landslide probability of some return period with a given size scenario. In the present study, *V* is the physical vulnerability of buildings or the population in the buildings and *E* is the quantification of the exposed elements at risk. Using Equation 5, the risk curve is fitted by plotting the probability versus potential loss, with the annual risk calculated from the area under the risk curve (Van Westen, 2002).

4 Results

This section provides the results of the case study to illustrate the application of the proposed framework and methodology in Section 3.

4.1 Landslide susceptibility assessment

In assessing landslide susceptibility, we investigated the elevation, slope, aspect, curvature, lithology, slope structure, distance to fault, rivers, and roads. The weights and contrasts values from the WoE method for LSM of Yuyangguan are presented in Table V. According to the contrast values explained in Section 3.1 for lithology, the Ordovician limestones and shales (O_2g) and Quaternary eluvium (Q_4^{dl+el}) are the top two units, implying that these units are susceptible to erosion. Under this background, heavy rainfall in the area accelerates erosion, and thus, triggering landslides.

General road construction is of secondary importance, with a contrast value of 0.95. Data in Table V also reveals generally significant morphometric factors in the study area. For aspect and elevation, the contrast values are elevated on the north-facing slopes with an elevation from 0 to 260 m.a.s.l, but low on the south-facing slopes with an elevation above 350 m.a.s.l. For the slope, the steeper the slope is, the higher the landslide probability is, with the contrast value for slopes ranging from 10° to 30° of 0.19, indicating a relatively high landslide probability.

The grid-based susceptibility map was converted to a slope unit-based map with 701 slope units in total. The slope unit-based susceptibility map was ordered into five classes, ranging from very low to very high (Fig.8). The performance from the map reveals an accuracy of 84%, using the ROC curve. The landslide susceptibility is very high for the north-facing slopes along the main road, especially where Q_4^{dl+el} and O_2g rocks are present. These results correspond well with the contrast values presented in Table V.

Table V. The weight and contrast values by Weight of Evidence model for landslide susceptibility mapping of Yuyangguan, west Hubei, China

Factors	Classes	Area of domain %	Landslide area %	W^+	W^-	$C=W^+-W^-$	$S^2(W^+)$[a]	$S^2(W^-)$[b]	$S(C)$[c]	$C/S(C)$[d]
Slope	0–10	11.03	3.66	−1.11	0.08	−1.19	0.01	0.00	11.04	−13.15
(degrees)	10–30	55.76	67.48	0.19	−0.31	0.5	0.00	0.00	27.44	13.84
	30–50	30.77	28.86	−0.07	0.03	−0.09	0.00	0.00	26.53	−2.45
	50–90	2.44	0	0	0.02	−0.02	–	0.00	–	–
Elevation	0–260	30.99	51.21	0.51	−0.35	0.86	0.00	0.00	29.24	25.15
(meters)	260–350	35.75	43.11	0.19	−0.12	0.31	0.00	0.00	28.99	9.07
	350–440	19.81	5.68	−1.26	0.16	−1.42	0.01	0.00	13.60	−19.36
	440–680	13.44	0	0	0.15	−0.15	–	0.00	–	–
Aspect	Plan area	2.32	0.14	−2.79	0.02	−2.81	0.20	0.00	2.23	−6.29
(degrees)	NNE(0～45°)	12.08	10.06	−0.19	0.02	−0.21	0.00	0.00	17.63	0.00
	NEE(45～90°)	10.86	17.23	0.47	−0.08	0.54	0.00	0.00	22.05	12.00
	SEE(90～135°)	11.48	7.06	−0.49	0.05	−0.54	0.00	0.00	15.03	−8.11
	SSE(135～180°)	12.51	7.44	−0.52	0.06	−0.58	0.00	0.00	15.40	−8.96
	SSW(180～225°)	12.25	7.2	−0.54	0.06	−0.59	0.00	0.00	15.17	−8.99
	SWW(225～270°)	12.16	5.88	−0.73	0.07	−0.8	0.00	0.00	13.81	−11.09
	NWW(270～315°)	12.18	15.59	0.25	−0.04	0.29	0.00	0.00	21.21	6.17
	NNW(315～360°)	14.17	29.39	0.74	−0.2	0.94	0.00	0.00	26.56	24.97
Lithology	Q^{al+pl}	0.78	0.06	−2.61	0.01	−2.62	0.50	0.00	1.41	−3.70
	Q^{dl+el}	8.08	50.95	1.91	−0.63	2.54	0.00	0.00	28.83	73.28
	P_1mn	0.58	0	0	0.01	−0.01	–	0.00	–	–
	P_1q	0.75	0	0	0.01	−0.01	–	0.00	–	–
	C_2hn	0.26	0	0	0	0	–	0.00	–	–
	D_3x	0.63	0	0	0.01	−0.01	–	0.00	–	–
	D_3h	1.24	0	0	0.01	−0.01	–	0.00	–	–

	D_2y	7.16	0	0	0.08	−0.08	−	0.00	−	−
	S_2s	22.07	27.61	0.23	−0.07	0.3	0.00	0.00	26.15	7.88
	S_1lr	21.34	11.99	−0.58	0.11	−0.7	0.00	0.00	19.06	−13.26
	S_1l	15.18	0	0	0.17	−0.17	−	0.00	−	−
	O_2b	4.54	0	0	0.05	−0.05	−	0.00	−	−
	O_2g	3.33	9.37	1.06	−0.07	1.12	0.00	0.00	16.89	18.94
	O_1d	3.83	0.03	−4.9	0.04	−4.94	1.00	0.00	1.00	−4.94
	O_1h	4.71	0	0	0.05	−0.05	−	0.00	−	−
	O_1n	4.69	0	0	0.05	−0.05	−	0.00	−	−
	Є$_2sn$	0.84	0	0	0.01	−0.01	−	0.00	−	−
Curvature	Concave	48.71	51.94	0.07	−0.07	0.14	0.00	0.00	29.25	4.11
	Straight/flat	0.87	0.03	−3.42	0.01	−3.43	1.00	0.00	1.00	−3.43
	Convex	50.42	48.03	−0.05	0.04	−0.09	0.00	0.00	29.26	−2.54
Slope structure	Over-dip	9.88	12.28	0.22	−0.03	0.25	0.00	0.00	19.19	4.78
	Under-dip	5.8	2.39	−0.89	0.04	−0.93	0.01	0.00	8.98	−8.32
	Oblique	15.19	6.71	−0.82	0.1	−0.92	0.00	0.00	14.70	−13.49
	Transverse	32.32	33.29	0.03	−0.02	0.05	0.00	0.00	27.59	0.00
	Anaclinal	36.82	45.33	0.21	−0.15	0.36	0.00	0.00	29.14	10.47
Distance to fault (meters)	>100	84.96	88.47	0.04	−0.27	0.31	0.00	0.00	18.72	5.80
	<100	15.04	11.53	−0.27	0.04	−0.31	0.00	0.00	18.72	−5.80
Distance to rivers (meters)	>50	89.57	87.26	−0.03	0.2	−0.23	0.00	0.00	19.50	−4.46
	<50	10.43	12.74	0.2	−0.03	0.23	0.00	0.00	19.50	4.46
Distance to road (meters)	Outside buffer	83.76	69.63	−0.19	0.64	−0.82	0.00	0.00	26.84	−22.09
	General road(<100)	9.73	21.59	0.81	−0.14	0.95	0.00	0.00	23.95	22.85
	Highroad(<200)	6.52	8.79	0.3	−0.02	0.33	0.00	0.00	16.55	5.44

The total area of the community is 29.14 square kilometers.

Total landslide area is 3740 pixels.

[a] Variance of W^+

[b] Variance of W−

[c] Standard deviation of contrast

[d] Studentized value of contrast

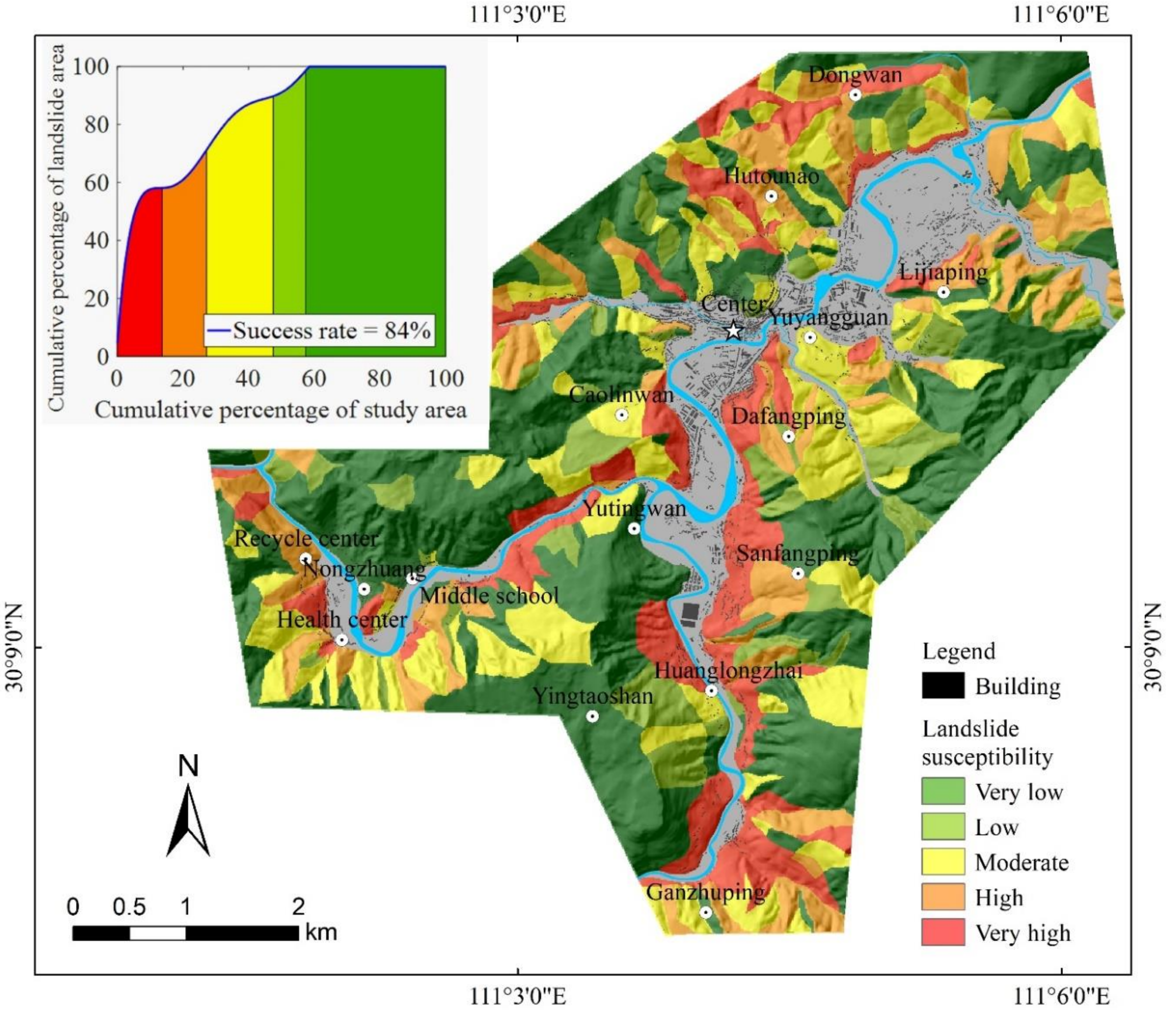


Fig. 8. Slope unit-based LSM at the community level, converted from the grid-based LSM using the weight of evidence method for Yuyangguan, west Hubei, China

4.2 Landslide hazard probability

The landslide hazard involves spatial, temporal, and size probabilities. The landslide data for Yuyangguan presented in Table II covers the 33 years from 1981 to 2013. For each slope unit, the historical mean RI is calculated using Equation 2. Assuming that the past is an indicator of the future, landslides in the study area may be modeled over the next 50 years, based on the past 50 years.

Four landslide temporal probability maps are displayed in Fig. 9 for four return periods (5, 10, 20, and 50 years). The map for 50 years, for example, shows the highest probability for the slope units experiencing landslide events among the four maps. Slope units with high and very high probability values (> 0.5) cluster on the first slope zones around the community.

The probability values on the slopes increase from the return period of 5 years. For example, the enlarged windows in maps of Fig. 9 demonstrate that the slope in Huanglongzhai village experienced a very low probability in the 5 years to a high class in the 50 years return period.

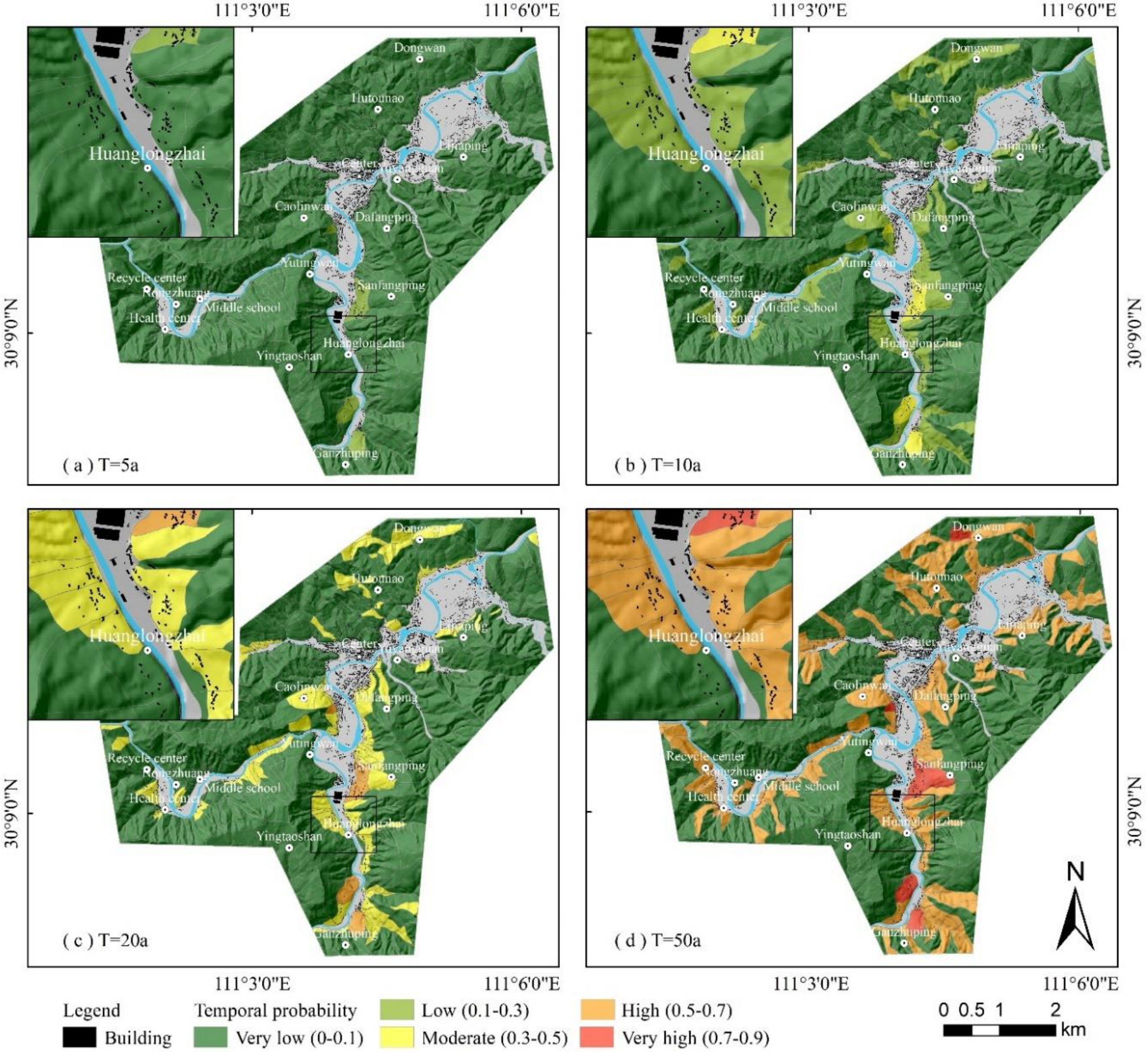
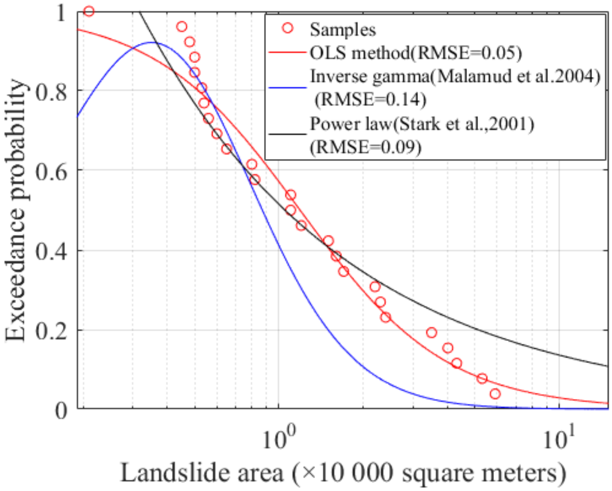


Fig. 9. Landslide temporal probability maps based on the Poisson model, showing the exceedance probability of landslide occurrence in each slope unit for four return periods (5, 10, 20, 50 years).

The landslide probability distribution curves are created using three different fitting functions, as displayed in Fig. 10. In comparison to the inverse gamma and the power law distributions, the function by OLS method shows the best fit, with the lowest root mean square error of 0.05. This indicates that the landslide frequency distribution function by the OLS method is the most appropriate technique to apply in Yuyangguan. The volume–area relationship is analyzed in Fig. 11a with an Rsquared value of 0.915. This indicates that converting the size probability distribution from landslide area data to volume is feasible in the study area. Meanwhile, two size scenarios are determined from the cumulative frequency curve (Fig. 11b) based on a landslide volume of 50,000 m^3 and 100,000 m^3. The number of landslides begins to increase rapidly in Fig. 11b when the volume is greater than 50 000 m^3, representing a probable threshold value of landslide hazard volume, while landside volume greater than 100,000 m^3 represents the maximum for the landslides, as shown in Fig. 11b. The value of 100,000 m^3 is a standard threshold for landslide classification provided by the China Geology Survey and a widely accepted value in the landslide hazard risk control in China.



OLS method: $p=\dfrac{1}{1+a_1 A_L^{\,2a_2}}$

Inverse gamma:

$$p(A_L;\rho,a,s)=\frac{1}{a\Gamma(\rho)}\left[\frac{a}{A_L-s}\right]^{\rho+1} * \exp\left[-\frac{a}{A_L-s}\right]$$

Power law: $p=a_3 A_L^{-a_4}$

where p is the probability, A_L is the landslide area, a =1.89, a_1 =0.75, a_2 =0.83, a_3 =0.51, a_4 =0.58, ρ =2.42, and s =-0.20

Fig. 10. Magnitude-frequency relationships simulated by the ordinary least square (OLS) method, inverse gamma, and power law for landslide in west Hubei. The samples are presented in Table II, and involve the Chengguan database except for the study area.

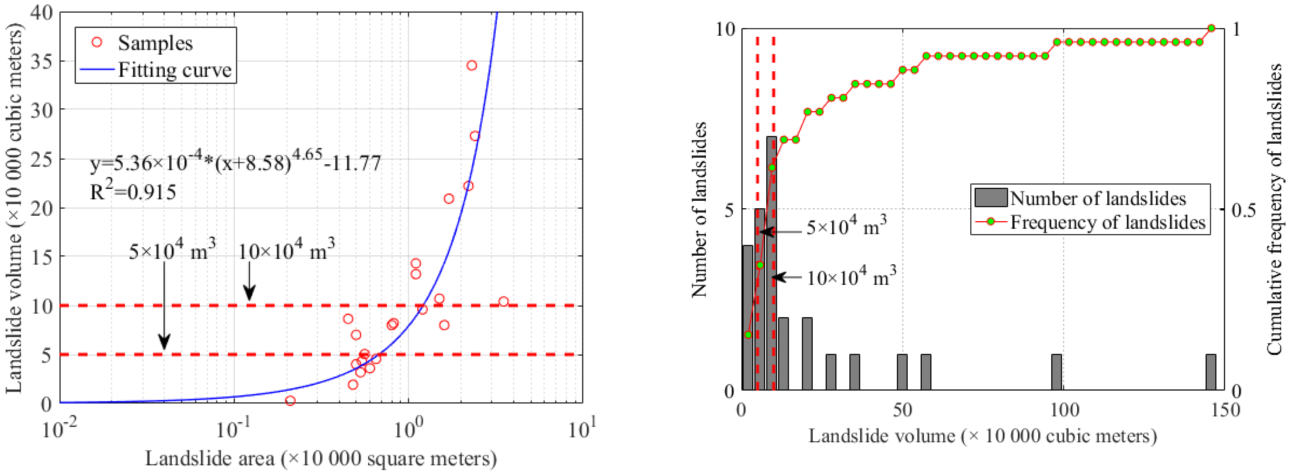


Fig. 11 (a). Relationship between landslide volume and area ($R^2 = 0.915$) used to convert magnitude-frequency relationships for the area to landslide volume. (b) Frequency distribution of landslide volume. The samples are presented in Table II, involving the Chengguan database, except for the study area.

Integrating the spatial probability in Fig. 9, temporal probability in Fig. 10, and the magnitude-frequency relationships in Fig. 11, eight hazard maps were produced using Equation 1. Through these maps, we demonstrate the hazard probability for each slope unit for four return periods (5, 10, 20, and 50 years) and landslide sizes equal or greater than 50,000 m³ and equal or greater than 100,000 m³. For example, Fig. 12 shows the four landslide hazard maps for the four return periods and the landslide size scenarios equal to or greater than 50 000 m³. In these maps, the landslide hazard probability values comprise five categories from very low (0.0–0.1) to very high (0.4–0.5). The maps for the 50 years return period show very high hazard probabilities for most building areas in the community at the bottom or near slopes. Conversely, buildings located in the community center are in areas from low to very low hazard probability class.

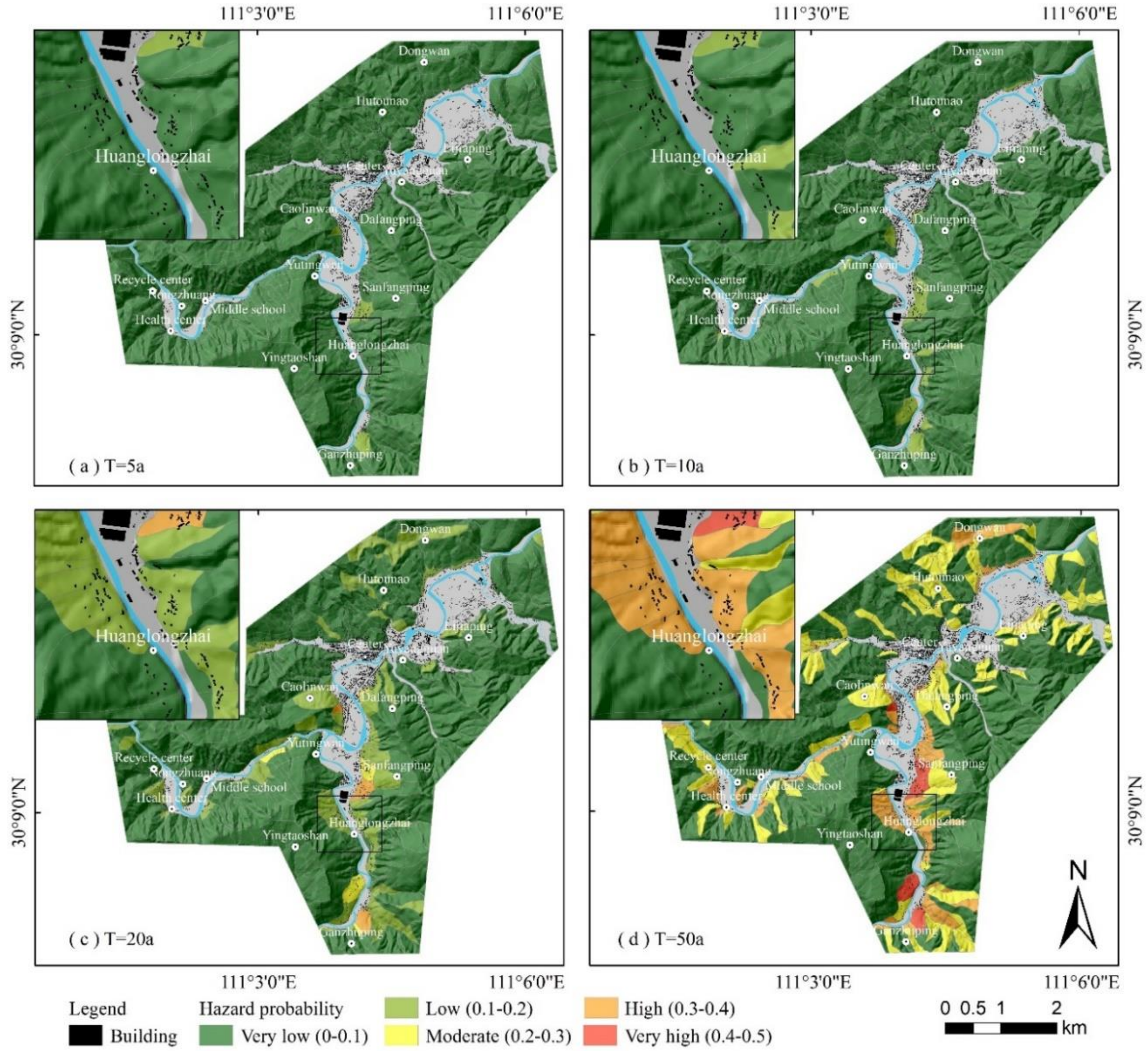


Fig. 12. Landslide hazard maps for four return periods (5, 10, 20, and 50 years) and the landslide sizes scenario equal to or greater than 50 000 m³. The maps were generated by integrating the spatial probability in Fig. 8, temporal probability in Fig. 9, and the magnitude-frequency relationships in Fig. 10.

4.3 Element-at-risk and vulnerability assessment

We assume that the buildings and population in the buildings are exposed to the slopes with high and very high-class probability in the hazard maps. Therefore, the element-at-risk maps for buildings and the population generated from the data in Section 2 and methodology in Section 3.2 are consistent with the four return periods and two size scenarios of the landslide hazard probability maps.

Data in Table VI shows no exposure for the return periods of five years and ten years, while for the 50 years return period and 50,000 m^3 size scenario, 570,000 m^2 of hosing areas and 14,257 persons are exposed to landslide risk. The data also highlight the potential for damaged building areas and the number of persons in the buildings for return periods of 20 years to 50 years. The vulnerability value is indirectly calculated by Equation 4 in Section 3.3. In the size scenario of landslide, for the volume equal to or greater than 50,000 m^3, a sharp increase in exposure exists for built areas and population, with the exposure exceeding double from 20 years to 50 years. Similar results emerge for the size scenario of landslide volume equal to or greater than 100,000 m^3. Comparing the two size scenarios, we find that the number exposed for the 100,000 m^3 volume is lower than that for 50,000 m^3. The building areas exposed to landslides in the 20 years return period is 8.76%, whereas for the 50,000 m^3 volume, whereas it is 5.86% for the 100,000 m^3, probably due to the lower hazard probability in the later scenario. A similar tendency is observed for the population in buildings, with about 30% exposed to landslide for the 50 years return period.

Accordingly, eight vulnerability maps for buildings and eight vulnerability maps for the population in the buildings are created for the four return periods and two size scenarios. For example, Figs. 13 and 14 show the resulting vulnerability maps for buildings and the population in buildings for the four return periods and when the landslide volume is equal to or greater than 50,000 m^3. Most exposed buildings are located on slopes with high or very high hazard probability, including the Caolinwan, Dafangping, and Sanfangping villages. The buildings and population in buildings in these central communities are not exposed to slope hazard because of the very low class (0–0.1) of landslide probability.

As presented in Table IV in Section 3.3, we assigned a vulnerability value of 1.0 to buildings on slopes. This causes buildings outside the flat areas in the community to display very high vulnerability values in Fig. 13, involving five categories ranging from very low to very high. For the 50 years return period and 50,000 m^3 size scenario, 18% of built areas exhibit very high-class vulnerability. The vulnerability value for the population was then assigned according to Equation 4 in Section 3.3 from the building vulnerability result. The very-high class population vulnerability shown in Fig. 14 was over 0.5, with the area representing about 10% of the people exposed, concentrated in the slope influence areas of Dafangping, Caolinwan, and Sanfangping or on the slopes with the very-high class hazard probabilities displayed in Fig. 12.

Table VI. Exposure and risk of buildings and population for landslide under four return periods (5, 10, 20, and 50 years) and two size scenarios (landslide volume equal to or greater than 50 000 m^3 or 100 000 m^3) by using the methodology in Section 3.2 and 3.3. (Number in brackets is in percentage)

Size scenario		landslide volume equal to or greater than 50 000 m^3				landslide volume equal to or greater than 100 000 m^3			
Return Period(years)		5	10	20	50	5	10	20	50
Exposure	Population	0	0	4073(8.87%)	14257(31.05%)	0	0	2724(5.93%)	13746(29.94%)
	Building area(×10 000m^2)	0	0	16.3(8.76%)	57(30.64%)	0	0	10.9(5.86%)	55(29.57%)
Risk	Casualties (person)	0	0	771(1.68%)	1485(3.23%)	0	0	584(1.27%)	1235(2.69%)

	Economic losses (×1000 USD)	0	0	8627(3.69%)	16613(7.10%)	0	0	6593(2.82%)	13360(5.71%)
Annual Risk	Casualties (person)	59(0.13%)				47(0.10%)			
	Economic losses (×1000 USD)	661(0.3%)				513(0.23%)			

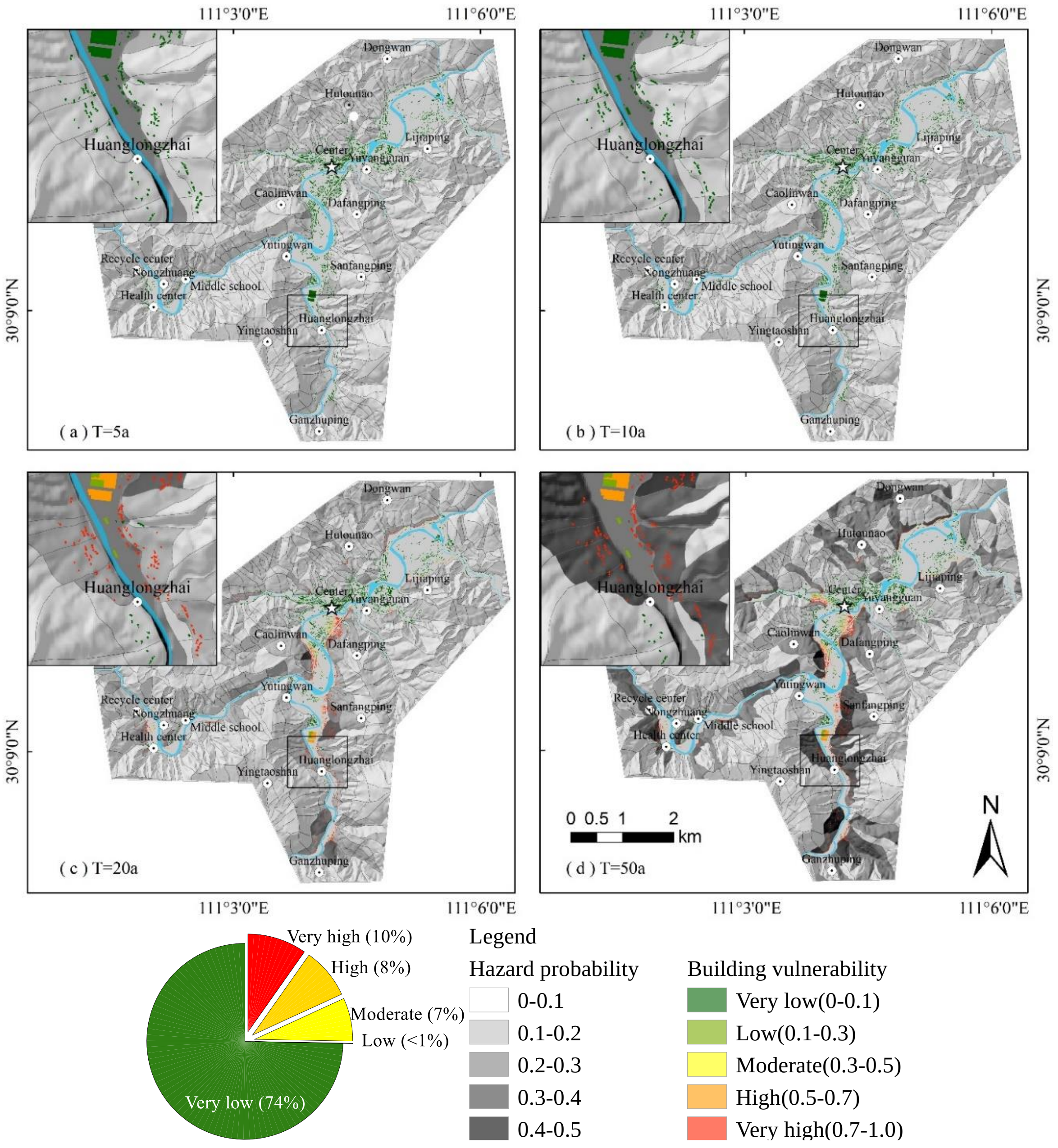


Fig. 13. Buildings exposed to landslides, vulnerability distribution map for four return periods (5, 10, 20, and 50 years), and size scenario of landslide volume equal to or greater than 50,000 m³.

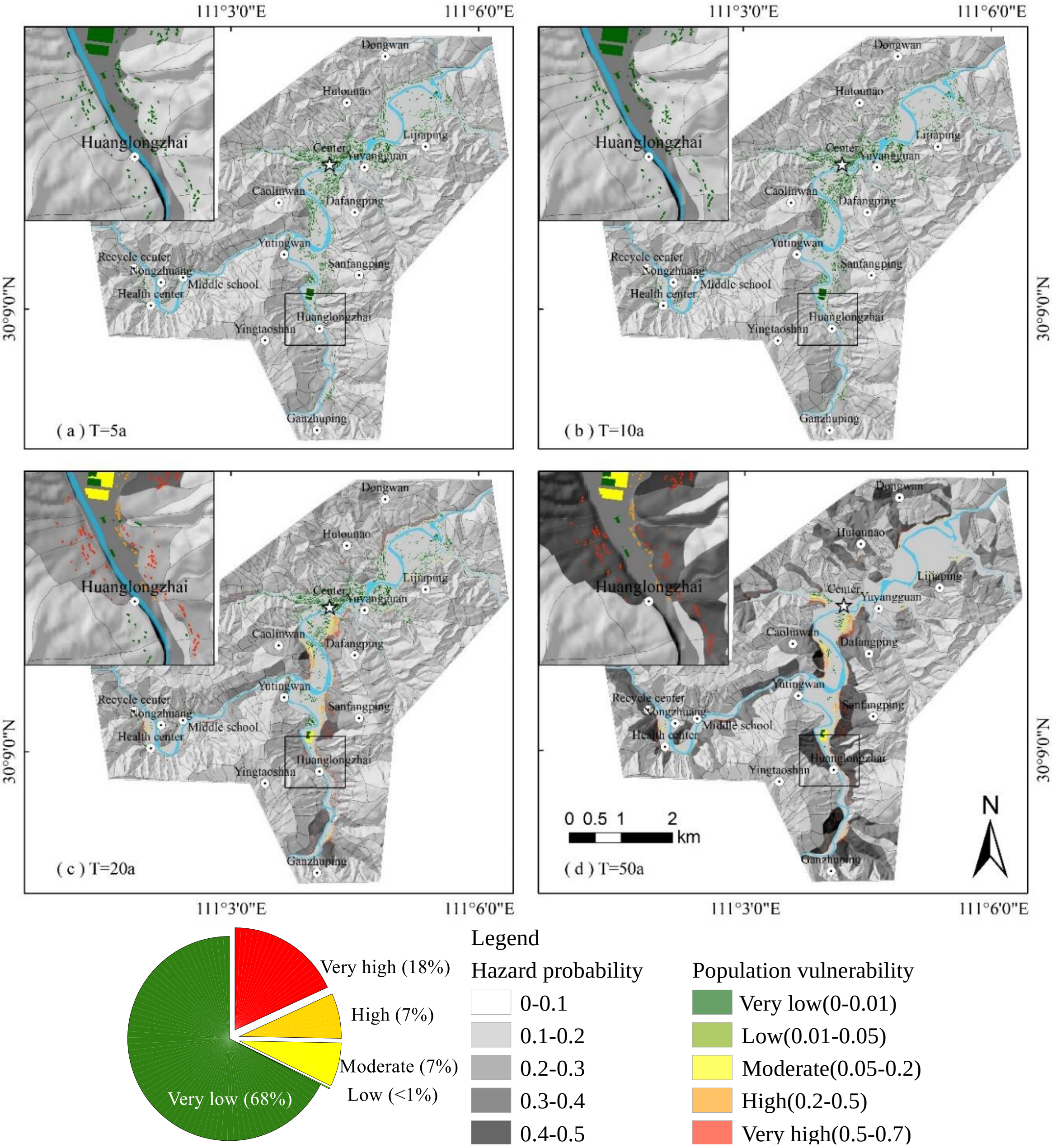


Fig. 14. Population exposed to landslides and vulnerability distribution map four return periods (5, 10, 20, and 50 years) and size scenario of landslide volume equal to or greater than 50,000 m³.

4.4 Risk assessment

Landslide risk maps are then generated from the eight hazard maps, eight vulnerability maps, and the values of the elements-at-risk by Equation 5. An example of a risk map for the population loss is shown in Fig. 15. The map for the 50 years return period, for example (see Fig. 15d), shows that potential loss is concentrated in the urban and densely-populated areas along the Yuyangguan River, especially at the toe of the slope of the Caolinwan, Dafangping, and Sanfangping villages.

The final population and buildings risks for four return periods and two size scenarios are presented in Table VI. Accordingly, no potential losses emerge for the 5 and 10 years return periods. The absence of risk for the 5 years return period is proven by the fact that no casualties or economic losses have been reported in the Yuyangguan community since 2014. For the volume equal to or greater than 50,000 m^3, however, the potential casualties are 771 persons, representing 1.68% of the total population in the community. The economic losses are estimated at 8.57 million USD for the 20 years return period, amounting to 3.7% of economic values associated with buildings. As presented in Table VI, the risk is expected to double in the next 50 years return period. For the volume equal to or greater than 100,000 m^3, the potential loss is lower, with 1.27% of the population exposed to landslides, amounting to a decrease of 0.41% relative to the size scenario of 50,000 m^3.

5. Discussion

5.1. Discussion on landslide susceptibility map

The landslide susceptibility results demonstrate that lithology is the most important controlling factor. Q_4^{dl+el}, weathered Guniutan O_2g limestone, and weathered S_2s sandstone exhibit the top three weight values in lithology contribution in the susceptibility map. This is consistent with findings inform the fieldwork. The residual deposit and eluvium are composed of clay and gravels that are characterized by low strength and cover the main areas with intensive human activities in the Yuyangguan community. For the O_2g bedrock, its high strength makes it less vulnerable to a landslide. However, in the field, we found two groups of surface joints in the O_2g, and this helps to explain why the YYG07 landslide occurred (see Table II). Field observations also reveal that most landslides occurred in S_2s sandstones and shales. However, the weight value (0.3) of S is lower than those of Q_4^{dl+el} and O_2g. This is because the area covered by the S_2s formation is much larger than the area of Q_4^{dl+el} and O_2g (see Fig. 1). Therefore, high landslide probability for slopes in O_2g limestone must be considered, and attention should be devoted to slopes where historical landslides are not too much now.

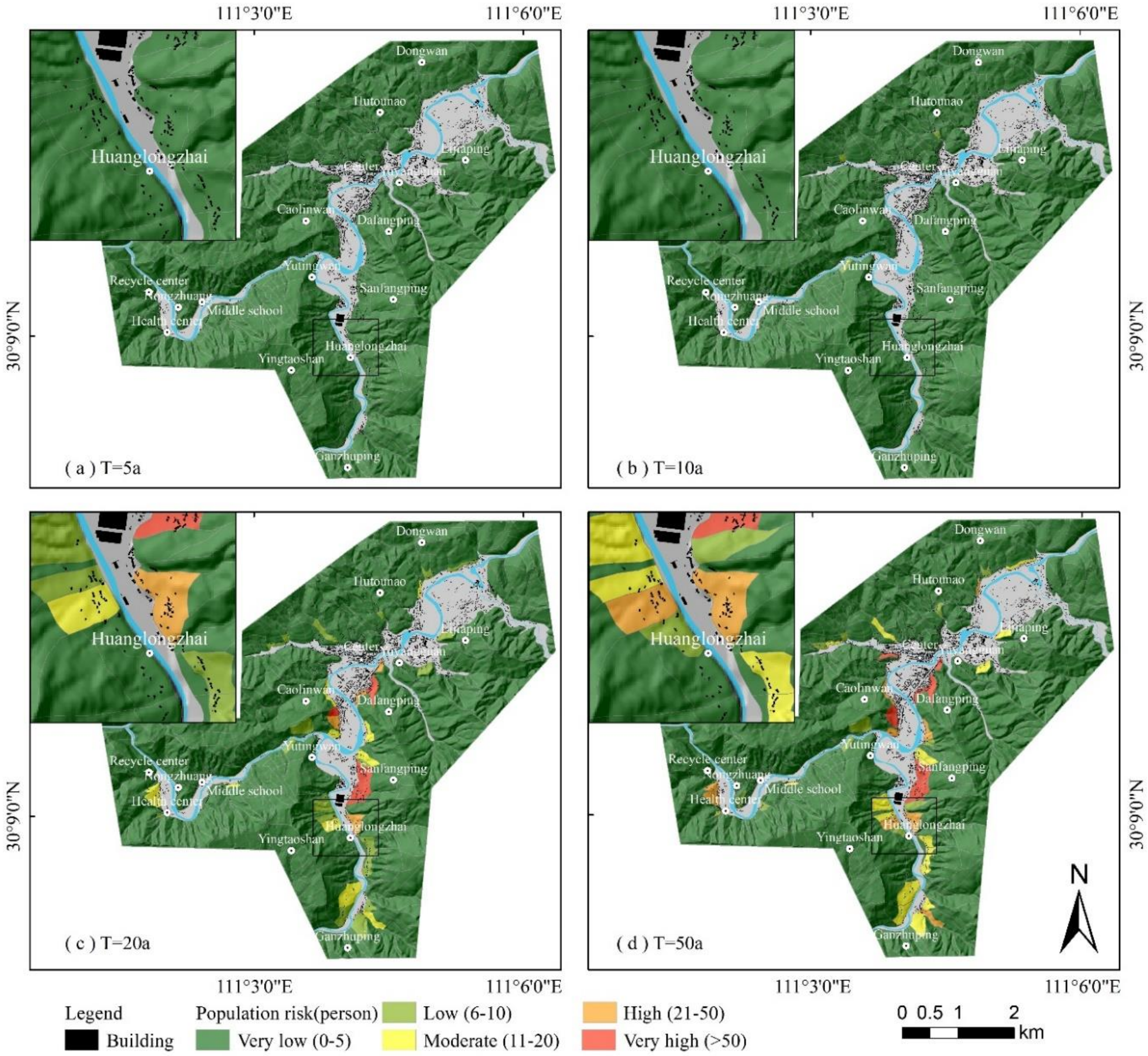


Fig. 15. Example of a risk map for population loss for four return periods (5, 10, 20, and 50 years) and the landslide size scenario equal to or greater than 50,000 m³.

5.2. Discussion on landslide hazard assessment

Landslide hazard maps are generated for four return periods (5, 10, 20, and 50 years) and two size scenarios. Theoretically, the definition of hazard scenarios, as stated by Chen et al. (2016b), should be based on the analysis of landslide occurrences and triggering events. Due to incomplete information on landslide dates in the community, it is challenging to establish the relationship between landslide return period and triggering factor (rainfall in this case study). However, we observed that no landslide has occurred in the Yuyangguan community since 2014, which is consistent with the hazard result for the 5 years return period (see Fig. 12a). This means that the temporal probability approach using the Poisson model is suitable for landslide hazard assessment when the landslide database is missing the occurrence date and triggering event (e.g., rainfall) data.

In the size probability analysis, the landslide probability distribution is the key for quantifications. We found that the classical distribution model (Stark and Hovius, 2001; Malamud et al., 2004) failed to produce an excellent fitting performance in this study. The difference in the landslide size between Malamud's and our landslide database accounts for this inconsistency. No small landslides (<1 000 m^3 in Malamud's research) are present or recorded in the Yuyangguan community, and the simulation equation (in Fig. 10) is suitable for landslide risk assessment in this study. In the future, however, comparison with classical models should be undertaken, and other factors, such as triggers and landslide types, consider using a complete database or one with more landslide events.

5.3. Other limitations in risk results

Uncertainties exist in the final risk maps due to some other factors, such as element-at-risk data and its vulnerability or resilience. In this study, the data for buildings and population in buildings at risk are derived from empirical calculations for the landslide influence area. Further studies considering landslide material, pore water pressure, and ground surface characteristic besides slope height and volume used in this paper will be conducted by numerical modeling.

Meanwhile, the risk results cannot be tested because of a lack of historical damage data in the area, which is a common difficulty in China and other areas (Ghosh et al., 2011;Chen et al., 2016b). Damage data is also crucial for vulnerability analysis. We considered building typology and location from the landslide to assess the physical vulnerability based on local experts' opinions. However, the resilience of the element-at-risk contributes to a reasonable decrease in vulnerability. The mobility of persons and their characteristics (e.g., age, education, and physical disability) and disaster prevention capability of the government are not considered in the community. In the future, physical vulnerability curves for buildings and the population will be constructed for the area.

From susceptibility to risk assessment, in general, we assumed that landslides will occur under the same condition as historical landslides. However, morphometric and geo-environmental conditions will change with time. For example, the slope degree, elements-at-risk, and land use cover may change because of new infrastructures, or the number of historical landslides will increase due to heavier rainfall. Future studies will be necessary, considering the changing conditions for more accurate results and more practical applications. So far, the series of maps represent a basis for landslide risk control and land use planning in the Yuyangguan community. Risk control measurements can be planned on each slope unit using a matrix combining landslide hazard probability and risk maps. For example, risk management on slope units with very high-class hazard probability and very high-risk can be suggested as requiring relocation or engineering works. The precondition is that more detailed geotechnical investigation and comprehensive analysis be complemented. This achievement can be used by professionals on engineering geology. The slopes with high-class hazard probability and mid-class risk are suggested for monitoring, considering the importance of safety for the surrounding population, roads, or other elements at risk. Meanwhile, the results of the four return periods and two size scenarios are useful for multi-temporal land use planning, including short-term (5 years), mid-term (10–20 years), and long-term (50 years). The annual risk value on each slope is useful for the cost-benefit analysis of risk decisions. This kind of achievements can be applied for government decision makers.

6. Conclusion

We conducted a semi-quantitative risk assessment for landslides at the community level based on the definition of landslide risk provided by Varnes and the IAEG (1984). In our case study, we focused on the potential damage of buildings and loss of life for the population in the buildings. We generated a susceptibility map, eight hazard maps, eight vulnerability maps, and eight risk maps for four return periods (5, 10, 20, and 50 years) and two size scenarios (equal to or greater than 50,000 m^3 and equal to or greater than 100,000 m^3). The landslide susceptibility result was tested, and it yielded a success rate of 0.84, highlighting the important contribution of Q_4^{dl+el} and the Guniutan O_2g limestone. The approach for generating hazard maps, which involved integrating three probabilities (spatial, temporal, and size probabilities), proved applicable in the case study area. In the size probability calculation, the use of a normal distribution function for landslide requires caution, with a better fitting function suggested when small landslide data are scarce in an area. Also, the landslide influence area was empirically determined at a community level using simple data (slope height and volume) in the absence of geotechnical parameters. However, for a more accurate vulnerability assessment, numerical modeling on landslide travel distance is suggested because the resulting intensity parameters, such as velocity and depth, are essential input data for vulnerability quantification. Besides the presented limitations, we believe that the proposed risk maps can help local stakeholders for establishing periods of risk planning for the community, including short-term (in 5 years), mid-term (10–20 years), and long-term (50 years) strategies, or provide reference for the cost-benefit analysis for each slope unit from the quantified annual risk values.

Data availability.

We thank China Geological Survey for the data presented in this study, since data is unavailable unless permission is granted.

Author contribution.

Yin, Chen, Xu, Lian, and Li supervised the field work and collected the complicated data. Chen and Fu discussed the plan for this article, designed and implemented all the experiments. Fu compiled all data and prepared the draft including figures in the article. Chen and Woldai revised the article while Du and Zhou provided support on methods.

Competing interests.

The authors declare that they have no conflict of interest.

Special issue statement.

This research article is part of the special issue “Advances in extreme value analysis and application to natural hazards.” The article is not associated with a conference.

Acknowledgment

We want to thank the editor and two anonymous reviewers for their constructive comments, which helped us improve the quality of the manuscript. Also, the research was supported by the National Natural Science Foundation of China (Grant No. 41877525 and No. 41641012), and the Research Foundation of Guidelines for Geological Hazards in Mountainous Towns in Wuling Area, D5.7.3, China Geological Survey. The authors high appreciate the support.

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Point-by-point response to the reviews

Dear Referee 1,

Thank you for your professional comments on our manuscript. These comments are all valuable and helpful for revising and improving our manuscript. Please note that the revised manuscript has been attached in the supplement file. The main corrections in the manuscript and the point-by-point responses to your comments are as following (the page number and line number in this letter refer to **the revised manuscript**):

Specific comments:

(1) It needs to present in more details the work on the field done by the authors to analyze the different causes of landslides (lithology, slopes, etc…). The authors present only 2 examples (Figures 2 and 3) with field analysis.

In particular they do not talk enough about Chengguan area which represents the most historical cases in their database. Their approach seems to illustrate more the Chengguan area than Yuyangguan area indeed. That should be more highlighted in this manuscript. In addition, the Chengguan area shall be more detailed in terms of similarities to context with the Yuyangguan area (geology, geomorphology, climate, etc.) to support the analysis with both.

Related to this topic of historical landslides: Figure 1: the location of Chengguan community does not sufficiently precise in regard to the location of Yuyangguan community. What is Wufeng (Fig.1b) with respect to Yuyangguan? It is not clear enough for the reader. Figure 1 and Table II: the localization of historical landslides is not provided on the figure 1. In addition and the coordinates of each landslide in the table II should be added maybe.

Responses: Thank you very much for your comments. Due to the page limitation of the manuscript, we only show two landslides (Fig.2 and 3). These two are typical for the study area. Landslide in Fig. 2 represents slope instability by rainfall and Fig. 3 by slope cutting.

Our case study area is Yuyangguan community, and the objective of the manuscript is to assess landslide risk for this community. Why we use the database of Chengguan is because the number of landslides in Yuyangguan is limited and not satisfying to calculate size probability. And also, it is because that the geology background and landslide type in Chengguan are similar to in the case community (Yuyangguan). So we didn’t describe the details in Chengguan but just use the historical landslide data. We have complemented the statements from Line 97 to Line 105. Sorry for the confusion.

In Figure 1, we pointed out the location of Chengguan. Sorry for the mistaken label (Wufeng) in Fig.1a, we have corrected it. We added the coordinates of each landslide in table II.

(2) This analysis on the field of historical cases is used to discuss and support the landslide susceptibility result in the paragraph 5.1 (Discussion on landslide susceptibility map). However the authors should develop also: a. the description with more details about the observed lithology on the field (like the most important controlling factor); b. the structural control (fault, joints) plays also a potential part in the cause of some landslides (aggravating factor). It is not sufficiently discussed if we note the presence of numerous faults in the study area indicated on the Figure 1c.

Other point related to this topic, the authors have not mentioned the potential earthquake source (other triggering factors). If it’s not relevant in this zone then it must at least mentioned and discarded. Related to this point, the tectonic context should be added in the presentation of the geological context too brief in the manuscript.

Response: It is a good comment, thank you! The observed lithology was described in line 63 to 67 and Table I. As to the geological structures, they influence the stability of slopes especially of rock slopes. As illustrated in Fig.1c, there are two landslides closing to the faults among seven landslides in red colors on the map. The majority of investigated landslides are soil or debris landslides in Table II, among which seven landslides are relatively small scales. It indicated that the fault has no significant impact to the landslides which have already occurred in this area. The manuscript has paid attention to the geological structure. Unfortunately, we lack sufficient discussions. So, we have added a necessary explanation to demonstrate the importance of these factors in the context. Please see line 68 to line 74. Actually, for regional-scale assessment, it is not easy to directly define the structural figures (faults, joints) as the factors such as defining the dip angle of faults or joints, etc. unless for a site-specific slope instability assessment. However, the manuscript has already designed an alternative index, distance to fault, to present the structures as in Fig.4 comprehensively. For the tectonic factor, the studied area is located in a weak seismic activity region according to the assessment by the China Earthquake Administration. There were no historical records of earthquake-induced landslides in that area. More explanation has also been put in the context. Please see line 74 to line 76.

3) Hypothesis from lines from 215 to 216: the assertion “assuming that the past is the future”, landslides in the study area will probably occur with the same amount of landslides over the next 50 years as the past 50 years” is not sufficiently discussed and argued. In particularly the possibility of impacts of climate change (more heavy rains) should be included or at least introduced for the next 50 years like a limit or a next development to this study. This paragraph echoes to lines from

335 to 337 where the authors remind this assumption of a same condition between future and past to cause landslides. They indicate without details some possible changes of conditions but this issue deserves to be developed.

Response: thank you very much for the suggestion. The assumption is very important for hazard probability calculation in this study. We have discussed this limitation in section 5.3. Further study and development are being taken in our research team now. But as you said, we did not sufficiently discuss the limitation. So we added more details about the possible changes in line 367 to line 372.

4) From line 105 to 109: Please develop the explanation lacks of information. It needs to detail more ("Subsequently……in study area")

Response: thank you very much for the comment. We have added more detail information in this part from line 125 to line 129.

5) Line from 319 to 322: Would other factors exist to explain the difference with the classical distribution model (Malamud et al., 2004, Stark and Hovius, 2001)?

Response: thank you very much for the suggestion. As illustrated in the context (line 351 to 352), no small landslides (< 1000 m^2 in Malamud's research) in our study area is the main reason for the difference. Maybe landslide types and triggering factors are the other reasons for this difference. Further studies in comparison should be taken with more landslides events considering these factors. Complementary statements were added in line 352 to line 354.

6) The conclusion should be more developed about limits and potential application of results.

Response: thank you very much for the comment. After carefully checking, we found that the limitations and potential application of results had been sufficiently pointed out in the conclusion part. Thank you for your reminding.

C. Technical corrections

(1) Figure 1: About faults on the figure 1c, could you indicate more information about the type of faults?

Response: thank you very much for the comment. We added the type and name of the fault in Fig.1c. And the more detailed description was added in the context. Please see line 68 to line 76.

(2) Figure 3: add scale into the zoom called “landslide surface”.

Response: thank you very much for the comment. We have added the scale bar into the Figure 3 called “landslide surface”.

(3) Figures 4,11,12,13 and 14: those maps are too small to be readable and impact the quality of this work. The names of villages or localities are difficult to read also.

Response: thank you very much for the suggestion. We have enlarged the figures 4,12,13,14 and 15.

Text:

(1) From line 61 to 62: the main lithological units should be presented in the order of the geological ages.

Response: thank you very much for the suggestion. We have revised and presented the main lithological units in the order of the geological ages. Please see line 63 to line 64.

(2) From line 115 to 155: the methodology should be presented with more of clarity between each paragraph: determination of spatial probability (1), temporal probability (2) and size probability (3).

Response: thank you very much for the suggestion. We have clarified the methodology from line 120 to 159 by the third level section. Please see line 141 to line 170.

(3) Line 199: rewrite and clarify the second part of this sentence “these two geological units can be susceptible to erosion and can quickly accelerate erosion”.

Response: thank you very much for the suggestion. We have rephrased this sentence. Please see line 228 to Line 229.

(4) Line from 204 to 205: rewrite “the value of slope varies from 10° to 30° is 0.19”.

Response: thank you very much for the suggestion. We have rephrased this sentence. Please see line 233 to line 234.

(5) Line from 304 to 305: rewrite, problem with the grammar sentence “This is because that although …, but the area…”.

Response: thank you very much for the suggestion. We have rephrased this sentence. Please see line 332 to line 333.

(6) Line 314: The world compatible or suitable seems to be more adapted than “feasible”.

Response: thank you very much for the suggestion. We have revised this sentence using the word “suitable”. Please see line 345.

(7) Line 318: Bibliographical order according the growing age: 2001 before 2004. Review in the whole document.

Response: thank you very much for the comment. We have reviewed the whole document very carefully and revised them.

We tried our best to improve the manuscript and made some changes in the manuscript. We feel great thanks for your professional review work on our article, and hope that the correction and response will meet with approval.

Sincerely,
Lixia Chen

Dear Referee 2,

Thank you very much for your professional comments on our manuscript. These comments are all valuable and helpful for revising and improving our manuscript. The main corrections in the manuscript and the point-by-point responses to your comments are as following (the page number and line number in this letter refer to **the revised manuscript**):

General comments

First, it is important to clarify that the two versions of the manuscript were reviewed (August 23rd and October 22nd) and I can affirm that the manuscript improved largely in the second version. **My comments refer to the version contained in the document named "nhess-2019-259-AC1-supplement".**

The manuscript contains the results of a solid and detailed research on hazard and risk at a local scale in the Hubei province in China.

In general terms, the ideas of the authors are clear. However, the document presents several grammatically awkward sentences, expressions that should be checked and lacks connections among the sentences. Therefore, proofreading and English editing services are recommended to ensure that the English of the manuscript is up to the publication standard.

Responses: Thank you very much for your comments. We have made great efforts to improve the language as best as we can by proofreading and English editing services, sorry for the grammatically awkward sentences and expressions.

Specific comments:

(1) The term Community-based leads the reader to think that the performed hazard and risk analysis involved members of the local community as part of a participatory methodology. In this case, it seems that you use the term "Community based" to refer to the scale of the analysis, more than the participants of the process. I would suggest to change the title accordingly. For example, in the introduction you used the more appropriate term "community-level", or you could use something like local -level, community scale, or any other term that refers to the scale of your work.

In general, when using the term community, it is not always clear if it refers specifically to the Yuyangguan community, or if it is used to refer to a local scale. This creates confusion among the reader so I would suggest to check the manuscript and clarify this when necessary.

Responses: Thank you very much for your comments and suggestion. We used the term “community-based” in the manuscript to refer to the scale. In Chinese language the term “community-based” can refer to two senses: scale and administration. Sorry for the confusing words from Chinese to English. Community level is a good suggestion. We changed the title as ‘Landslide hazard probability and risk assessment at the community level: A case in west Hubei, China’.

(2) The introduction contains all the necessary information. However, the current order generates confusion among the readers. I would suggest to switch the first and second paragraph and include some connectors. Additionally, the use of the future sentence should be avoided.

Responses: Thank you very much for your comments and suggestion. We re-managed the order of the paragraphs. The future sentence and related language mistakes will be carefully checked and avoided.

(3) Considering that readers might not be familiar with China’s administrative division and geography, the study area description should be complemented with basic geographic and administrative information. It is clear that the area is in the Hubei province, but is not clear in which Prefecture and/or County the communities are located, and what villages the selected communities include. Additionally, it would be interesting to mention when the area started to be inhabited and if there has been any recent intense urbanization development, considering that one of the landslide triggers are man-made actions, such as roads construction.

Responses: Thank you very much for your comments and suggestions. We complement some necessary information about the geography and villages in the selected community. Meanwhile, it is a very good suggestion to state the urbanization of the community, which is very helpful for readers to understand the triggers of the landslides. We revised the first paragraph of section 2 as: The current study area, Yuyangguan community (N 30°03′- 330°15′, E 110°08′- 8110°08′), is located in Wufeng county, western Hubei province, China (Fig. 1). It covers an area of about 34 km^2 and includes 15 villages, such as Sanfangping, Dafangping, Caojiaping etc. The community started to be inhabited about 750 years ago, and intense urbanization development and the national road construction crossing the community began in 2012. The study area was selected due to frequent landslide activities and caused subsequent damages in recent years. The residential area is surrounded by steep slopes, with an elevation of 180 to 680 m.a.s.l. The climate is characterized as a typical monsoonal climate, with an average annual precipitation of about 1500 mm. Please see line 57 to line 62.

(4) Since in some points you focused only in Yuyangguan community and in some others, you complement it with information of and Chengguan community (i.e. line 175), I would suggest to clarify since the beginning what is the goal and scale of the analysis in both communities.

Responses: Thank you very much for your suggestions. The objective of the manuscript is to assess landslide risk for Yuyangguan community. But when we analyze the size probability, it is found that the samples of the historical landslides are not sufficient for statistical analysis in size probability. So, we complement some other samples from the neighboring Chengguan community, considering that historical landslides and geological environment are similar in both two communities. We complete more detailed information about the similarities in Line 101 to line 105.

(5) In the methodology section I suggest to include a figure with a conceptual map of the different components of the hazard and risk analysis process.

Responses: Thank you very much for your suggestions. We will include a figure for the methodology as following attachment of Fig. 7 Flow chart of the methodology for landslide hazard risk assessment.

Technical corrections

(1) The last sentence of the introduction is confusing "This achievement may also be utilized into community scale landslide risk assessment in a mountainous area in Hubei, China." I would suggest you to check the whole paragraph in order to articulate the different sentences, while avoiding repetition.

Responses: Thank you very much for your comments. We checked the whole paragraph and agree with you to avoid repetition. The whole manuscript was improved in language and expressions.

(2) In Fig. 1, please clarify what each inset represents at administrative or geographical level. Inset (b) seems like a province but it looks deformed, and is not clear what the limits of inset (c) correspond to. Maybe you can try by adding thin administrative division lines at prefecture level. Additionally, it is recommended to include a frame in the bigger map to show where the zoom area is located (as done in Fig. 8).

Responses: Thank you very much for your comments and suggestions. Insert (b) is a county called Wufeng, which includes the studied community Yuyangguan. Insert (c) is a zoomed area (the study area of Yuyangguan community) from insert (b). Sorry for the confusing. We added some necessary lines in Fig 1 (please see the attachment of Fig 1).

(3) Line 63, check the phrase "Weathered rocks in Silurian are the primary source of landslides", maybe you mean something like "As a consequence, weathered Silurian rocks are the primary source of landslides."

Responses: Thank you very much for your comments and suggestions. The meaning here is what you understand. We revised this in the manuscript. Please see line 66 to line 67.

(4) Line 64, the sentence "Weathered rocks in Silurian are the primary source of landslides" seems to contradict the affirmation of the introduction regarding that "that Quaternary deposits and weathered eluvium from Ordovician limestone are the two major controlling factors." This confusion is presented again in the first paragraph of the section 5.1.

Responses: Thank you very much for your comment. We observed in the field that the source of majority landslides was from the weathered rocks in Silurian, and only two landslides in Yuyangguan were from weathered limestone in Ordovician. But in susceptibility analysis, we found that the weight of weathered rocks in Silurian is not the highest. It is because that the frequency of landslides in Silurian is lower than it in Ordovician, due to the area of Silurian in the map is much larger than the area of Ordovician. We have clarified the description with more details. Please see line 63 to 64 and line 332 to line 333. Sorry for the confusing.

(5) Line 67, check the phrase "This fault is a seismic activity belt", seems to refer more to "This fault is a seismically active belt"

Responses: Thank you very much for your comment. The phrase in the manuscript will be changed as 'This fault is a seismically active belt'. Please see line 70.

(6) Line 75, check the phrase "Rainfall and human activities contribute significantly to the slope movement", could be something like "Rainfall and human activities contribute significantly to trigger mass movements…"

Responses: Thank you very much for your comment. The phrase in the manuscript was changed as "Rainfall and human activities contribute significantly to trigger mass movements…". Please see line 77.

(7) Line 75, clarify that the mentioned landslides are just examples and connect this to the following paragraph.

Responses: Thank you very much for your comment and suggestion. One more sentence was added in the end of this paragraph: These two landslides are examples, and more landslide records are prepared by aerial photos interpretation and then validated in field investigation. Please see line 80 to line 81.

(8) All maps. Yuyangguan and Chengguan communities should be labelled in all the maps.

Figure 5. Please remove the labels that do not correspond to locations, but to specific buildings, ex. School, health center, etc.

Fig.5, 8, 11 it is not clear why the zoom frame shows the area around Huanglongzhai, instead that Yuyangguan or Chengguan

Responses: Thank you very much for your comment. Because of the non-sufficient description on the studied community, the following figures in the manuscript gave you a confused impression. Figures of 5, 8 and 12 are for the area of Yuyangguan community, the zoom frame in which shows an area with high risk slopes and buildings. Sorry for the confusing and we have revised all the figures in labels after carefully checking.

(9) Table II. I would suggest to organize the landslides by date, in order to allow the reader to have an idea of recurrence.

Responses: Thank you very much for the good suggestion. We gave re-organized the landslides by date. Please see the table II from page 6 to page 8.

(10) Line 148, explain what W- and W+ corresponds to.

Responses: Thank you very much for the good comment. We added the explanation for W^- and W^+. Please see line 151 to line 153.

(11) Line 238. I suggest to support the affirmation “Assuming that the past is the future, landslides in the study area will probably occur with the same amount of landslides over the next 50 years as the past 50 years.” That, considering Climate change, but also the anthropic incidence as landslide trigger. That affirmation depends largely in the history of the area, i.e. if the area has sustained a stable urban development in the last 50 years the affirmation is valid, but if it is not the case, then the affirmation should be supported with strong arguments.

Responses: Thanks for your very good comments. We agree with your idea that the affirmation depends largely in the history of the area. While dealing with the landslide issues, the hazards are increasingly connected with human activities and climate change which are becoming as the active triggering factors. If we purely consider the landslide from controlling geological factors, the sense of “assuming the past is the future” seems to be reliable during short period of decades or centuries comparing to geological time scale. In order to simplify the hazard probability calculation in this study, we used this assumption even it has limitation for the future. Anyway, the expression of the assumption is too deterministic, so we modified the expression softer as “assuming the past reflects the future”. We have also discussed this limitation in section 5.3. More details are added about the possible changes in line 367 to line 372. Of course, further study and development are being taken in our research now following your constructive comments.

(12) Line 253. Please include some arguments to support the decision of using 50 000 cubic meters and 100 000 cubic meters for the size scenarios, since, according to Table II, there have been historic landslides with a considerably larger volume.

Responses: Thanks for your very good comments. We complemented some sentences at the end of the paragraph. Please see line 259 to line 263.

(13) Fig. 10 (b). Correct the label of Number of landslides

Responses: Thanks for your comment. We have corrected the label of ‘Number of landslides’ in Fig.10(b).

(14) Line 322, please check the wording of the last sentence of this paragraph.

Responses: Thank you very much for the comment. We have carefully revised the last sentence of this paragraph in grammar and wording. Please see 320 to 322.

(15) Line 360, maybe you refer to “the number of landslides”, instead than “the number of historical”. Please check.

Responses: Thank you very much for the comment and suggestion. We have added the missing word “landslide”.

(16) Line 364, regarding the affirmation “… risk management on slope units with very high-class hazard probability and very high-risk can be suggested as relocation or engineering works,” the decision to relocate people is a delicate one, and should be taken based in a large array of information, not solely in risk maps of not detailed scale. In this case, I would suggest to review the affirmation and to propose a more detail geotechnical analysis of the very high-class areas, instead than inviting to relocate the people based solely in these results.

Responses: Thank you very much for your comments. We totally agree with you that the decision of relocation or engineering works on slopes with very high-class hazard probability and very high-risk must be considered based on large array of information. The regional risk zonation is informative for planning. But for specific site treatment, it is essential to complement geotechnical analysis which gives strong support for decision-making. So, we have corrected expression in the context. Please see line 372 to line 380.

(17) Line 368. Check the sentence coherence.

Responses: Thank you very much for your comments. We have carefully checked the sentence then deleted it.

We tried our best to improve the manuscript and made changes in the manuscript. We feel great thanks for your professional review work on our article, and hope that the corrections and responses will meet with approval.

Sincerely,
Lixia Chen