

# Community-based landslide hazard probability and risk assessment: A case in west Hubei, China

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**Abstract.** Small communities living in high mountainous terrains, in Hubei Province are often impacted by landslide hazard. Past work by China Geology Survey focused only on hazard assessment at 1:100 000 scales. In this study, we conducted a  
15 more-detailed semiquantitative landslide and risk assessment at a community level and scale of 1:10 000. We applied the probabilistic method to assess the landslide spatial, temporal and size probabilities while the landslide 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 by susceptibility mapping with an accuracy of 84% indicates that Quaternary deposits and weathered eluvium from Ordovician limestone are the two major controlling factors. Most building areas in hazard maps are located at  
20 the foot of major slopes where hazard probabilities are very high. We computed the loss of lives and properties for each slope. The result shows that 1530 people and 126 million RMB economics were at risk of being affected by landslides with a 50-year return period and a landslide volume of fifty thousand cubic meters.

Meanwhile, the longer the return period, the higher the hazard probability is. Compared with the function by ordinary least square method, classic inverse gamma and power law distribution of landslide magnitude and frequency are not suitable for  
25 landslide size probability analysis in the study area. The proposed procedure is proved to be more useful to complement risk assessment on the scale of 100,000 in west Hubei, China.

Keywords: landslide; hazard probability; element-at-risk; risk assessment; community

## 1 Introduction

Guidelines for landslide risk zoning and land use planning with the framework, definitions and recommendations were provided for different clearly defined scales (Fell et al., 2008a). Also, research work highlighting landslide risks at a community-level has recently been tested, and some of the result reached are open for 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, have used a spatial multi-criteria analysis technique (SMCA) to mitigate geo-hydrological risk in a small but densely-populated catchment, with descriptive parameters of 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).

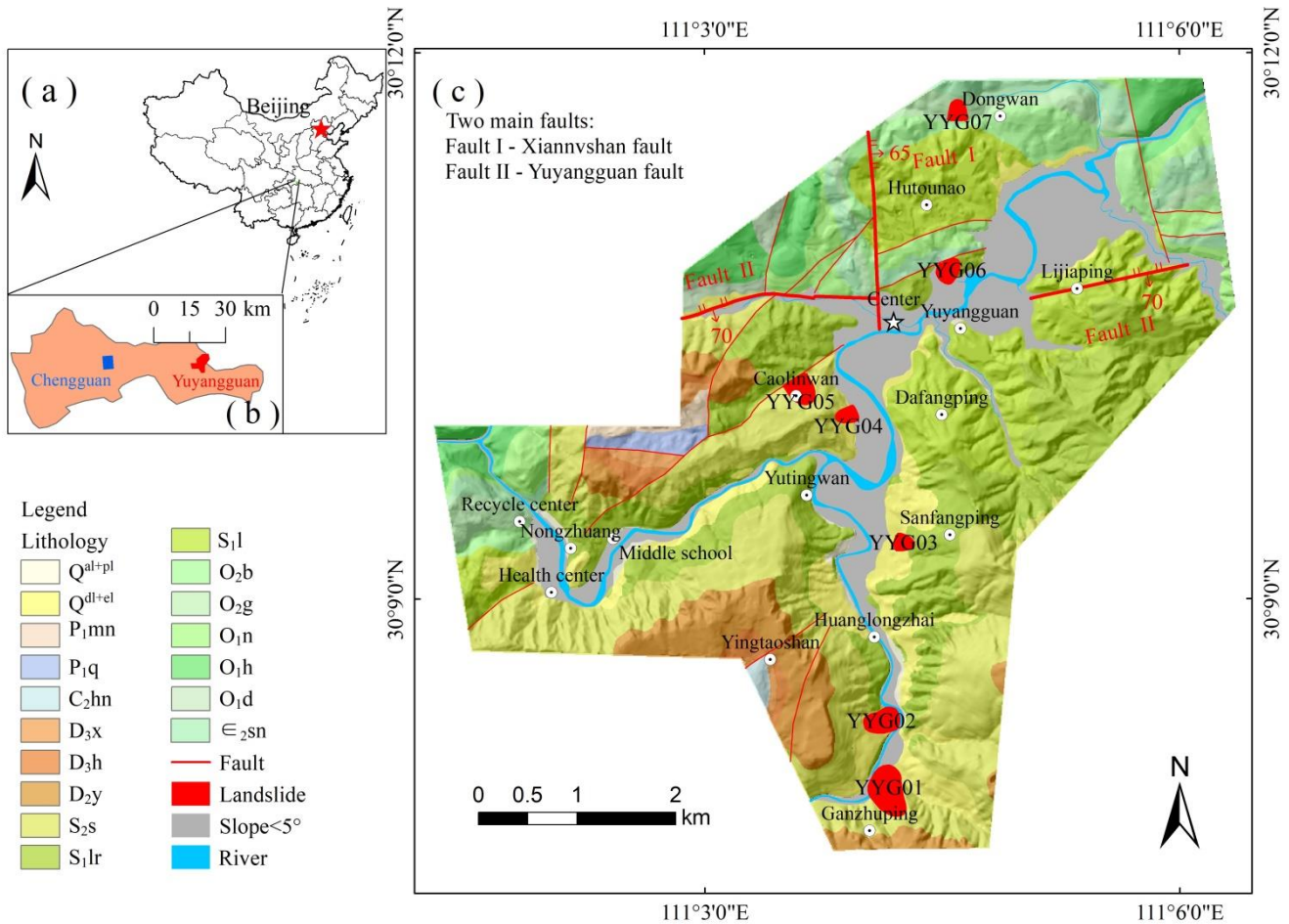
Many investigators in China believe risk analysis and assessment to be an effective means of reducing casualties and economic losses induced by landslides. Theory and technics are available for worldwide application (Van Westen et al., 2005; Lee et al., 2007; Neuhäuser and Terhorst, 2007; Erener et al., 2016; Jiménez-Perávarez et al., 2017; Huang et al., 2017; Van Westen and Greiving., 2017), but not yet well utilized in west Hubei, China, where the current research is undertaken. To date, very little scientific work is documented at the community level. Mountainous communities in this area are prone to landslide hazards, because of rainfall and the degree of urbanisation. Annually, road construction and anthropogenic modifications at the community scale (e.g., excavations in search of building material), the degree of urbanisation and subsequent population growth have accelerated more landslides of immense risk to the communities resulting in death and unaccountable losses in properties. According to the Chinese geological disaster notification report (2017), for example, around 850 disasters occurred in Hubei province, China, causing 23 deaths and about 254 million RMB (equal to ~ 38 million US Dollar, by May 2019 conversion) economic losses. It, therefore, remains a challenging problem to quantify landslide risk and develop reduction strategy.

Our objective in this work is to conduct a community-based landslide hazard probability and risk assessment on an area where limited landslide data and damage records exist. Despite these limitations, in this work, we will try to quantify landslide risk for Yuyanguan community, Hubei province, China. The probabilistic method will be used to assess the landslide spatial, temporal and size probabilities. Landslide hazard and risk assessment will be considered for four return periods and two magnitude scenarios. Upon these, we expect to propose risk reduction strategies to the stakeholders in Yuyanguan town. This achievement may also be utilised into community scale landslide risk assessment in a mountainous area in Hubei, China.

## 2 Study area and data

The current study area, Yuyanguan community, is located in western Hubei province, China (Fig. 1). The study area was selected due to landslides that frequented this area and caused subsequent damages in recent years. It covers an area of about

34 km<sup>2</sup>. 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.



**Fig. 1. a)** Inset showing the map of China with the color **(b)** representing the position of the current study area **(c)** shows the main study area. (Lithology code is described in Table 1)

The main lithological units outcropping in the study area comprise of Ordovician limestone with shale, Silurian sandstone and shale, Devonian with coal layer, Permian sandstone and recent deposits. Silurian sandstone is the dominant rock distributed along the community slopes. Intense weathering causes the bedrock to have low mass strength. Weathered rocks in Silurian are the primary source of landslides.

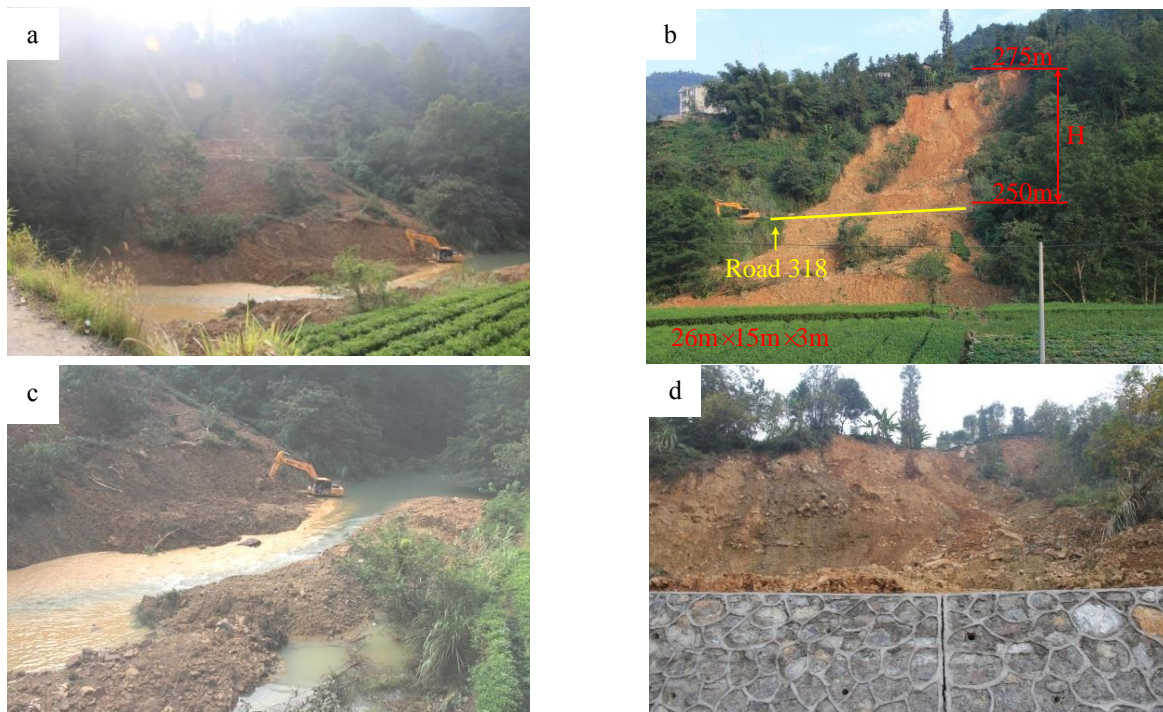
Two main faults constrain the bulk architecture of the area, namely the Xiannvshan fault (Fault 1 in Fig. 1) and the Yuyangguan fault (Fault II in Fig. 1). The Xiannvshan fault, striking approximately N340-345 °W and dipping 60-70 ° to the northeast, is a trans-pressure fault terminating at the center of the community. This fault is a seismic activity belt, represented by Panjiawan earthquake (M<sub>s</sub> = 4.9) in 1961 and Zigui earthquake (M<sub>s</sub> = 3.3) in 1972. The Yuyangguan fault, striking east-west and dipping 60-70 ° to the south, is a trans-tensional fault. Fault rocks of the Yuyangguan fault are

70 composed of 20-50 m width of cataclasite and brecciated mylonite. Several secondary faults merged into the Yuyangguan fault and together go through the centre of the Yuyangguan community. According to the China Earthquake Administration, the studied area is located in a weak seismic activity region with basic earthquake intensity of VI. The 50-year 10% probability exceedance of peak ground acceleration is 0.05 g. There were no historical records of earthquake-induced landslides in the area.

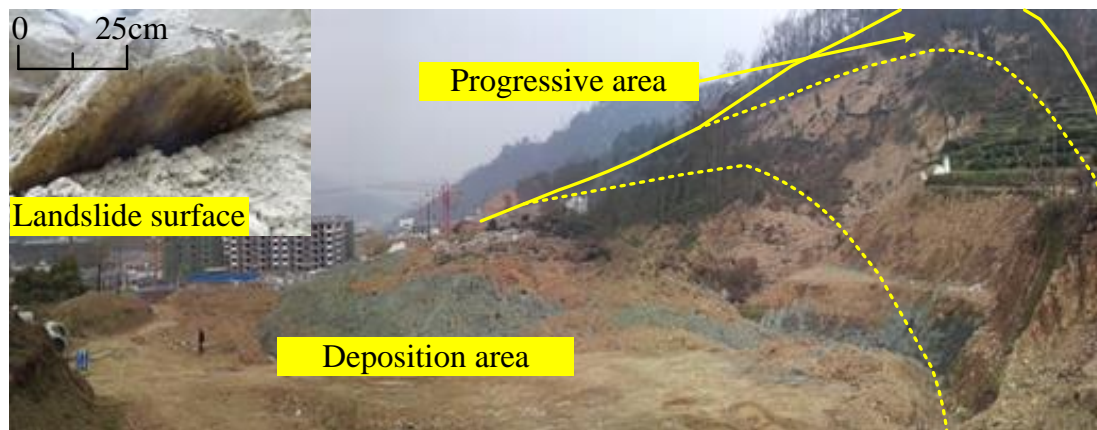
75 Rainfall and human activities contribute significantly to the slope movement, mainly landslides. In the rainy season of 2013, a slope along the main road collapsed breaking and causing long traffic jam and transportation problems (Fig. 2). A landslide in the new residential quarter of the community occurred on the 3rd of January 2013. The foundation pit became unstable after one-day excavation (Fig. 3).

80 **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 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, 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.
$C_{2sn}$	Massive and thick layered dolomite with dolomitic limestone.



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



**Fig. 3. Landslide YYG03 caused by slope cut in the residential quarter of Yuyangguan.**

Landslide database is essential for landslide risk assessment. Seven landslides were interpreted from aerial photos, which were subsequently validated by the authors in the field. All the landslides mapped from 1976 to 2013 happened in areas where Quaternary deposit predominates. 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 slope, elevation, aspect and curvature using the surface analysis tool available in ArcGIS (Fig. 4a, 4b, 4c and 4d).
- A Geological map at 1:50000 scale (Fig. 1) was used to extract datasets such as lithology, faults and slope structure map. The slope structure map (Fig. 4e) was generated using the standard and stratigraphic attitude advocated by Cruden (1991). Land use map was used to provide the distribution of rivers and roads (Fig. 4h, 4i).
- Two landslide inventory databases in the case community (named as Yuyangguan) and a neighbourhood community (named as Chengguan) were involved in this study to analyse the size probability in hazard assessment. We used the hazard database of the neighbourhood community because (1) the number of landslides in the case community is limited for probability analysis; and (2) these two communities are similar in geomorphology, geology, climate and landslide types. The location of Chengguan community is shown in Fig. 1b.
- Building footprint map (Fig. 5) was interpreted and checked in the field by the authors. The majority of the buildings are located on or at the toe of the first slope zones with elevation up to 350 m.a.s.l. Entire build-up area is 18 610 000 m<sup>2</sup>; Data on the economic value of buildings was obtained from the department land and resource in 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). Total population is 45914 persons.

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

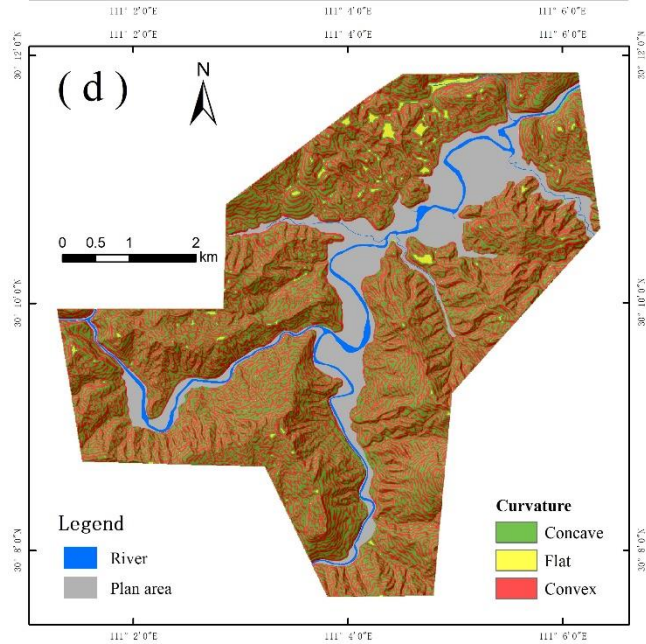
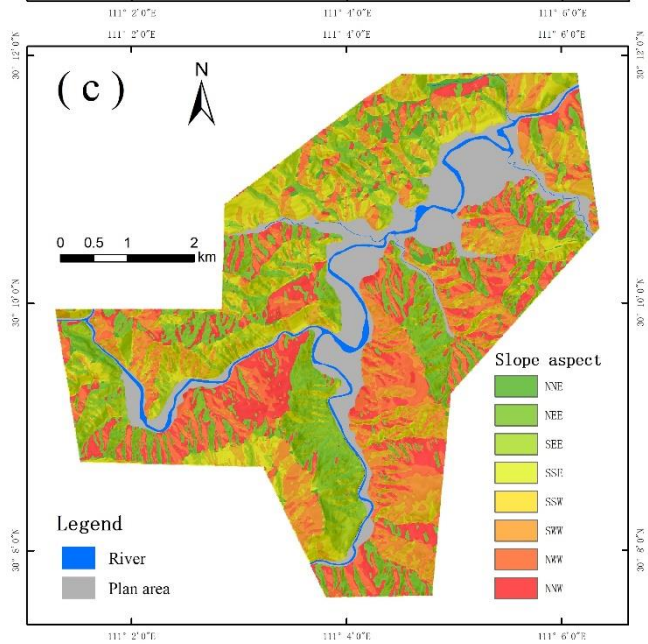
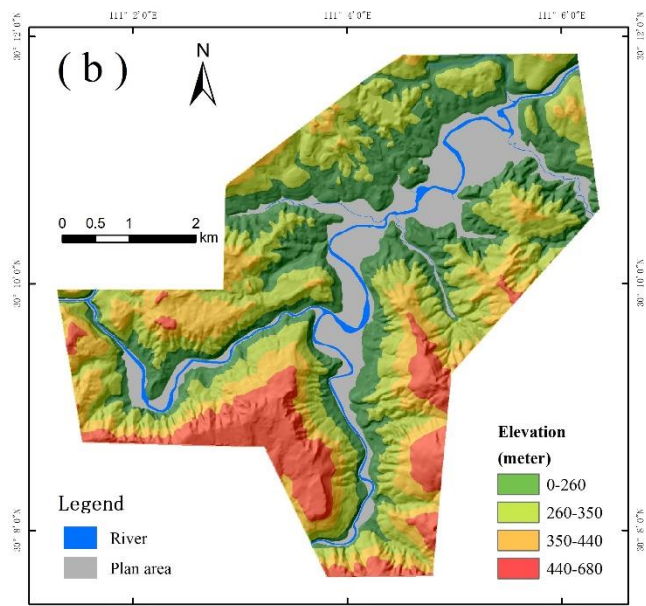
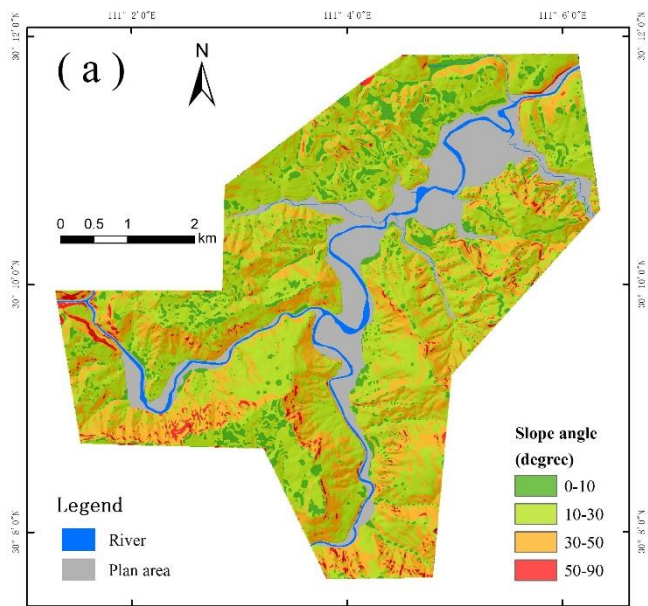
Landslide ID	Coordinates		Material	Bedrock	Volume (×10 000 m <sup>3</sup> )	Area (×10 000 m <sup>2</sup> )	Date (Year.month)	Triggering factor
	X	Y						
Seven landslides were reported in Yuyangguan community								
YYG01	506692	3334830	Soil	S <sub>2s</sub>	147.6	5.9	2013.7	R
YYG02	506615	3335500	Soil	S <sub>1lr</sub>	49.8	4	1981.6	R & SC
YYG03	506828	3337320	Soil	S <sub>1l</sub>	20.9	1.7	2014.1	R & SC
YYG04	506275	3338610	Soil	S <sub>2s</sub>	10.7	1.5	2013.5	R & SC
YYG05	505788	3338880	Soil	S <sub>2s</sub>	10.4	3.5	1989.1	R
YYG06	507320	3340080	Soil&rock	O <sub>2g</sub>	8	1.6	2007.12	R & SC
YYG07	507381	3341680	Rock	O <sub>2g</sub>	22.2	2.2	2010.6	R & SC
Nineteen landslides were reported in Chengguan community								
CG01	466943	3339730	Soil	S <sub>1l</sub>	5.4	0.45	2009.5	R
CG02	467038	3339980	Soil	S <sub>1l</sub>	1.05	0.21	2012.4	R
CG03	467576	3340630	Rock	O <sub>2b</sub>	1.92	0.48	1991.7	R

CG04	467659	3340830	Rock	<i>O<sub>2b</sub></i>	5.04	0.56	2005.8	SC
CG05	467830	3340990	Soil	<i>O<sub>2b</sub></i>	55.9	4.3	2002.7	R & SC
CG06	468072	3341460	Rock	<i>O<sub>2b</sub></i>	34.5	2.3	1992.6	R
CG07	468295	3341510	Soil	<i>O<sub>2b</sub></i>	14.3	1.1	1997.7	R
CG08	468193	3341670	Soil	<i>O<sub>2b</sub></i>	79.5	5.3	1967.6	R
CG09	468331	3341980	Soil&rock	<i>O<sub>2b</sub></i>	16.8	2.4	1969.7	R
CG10	468597	3342480	Soil	<i>O<sub>2b</sub></i>	3.18	0.53	2012.3	R
CG11	468841	3342740	Soil	<i>S<sub>1l</sub></i>	7	0.5	1992.6	R
CG12	468354	3342720	Soil	<i>S<sub>1l</sub></i>	9.6	1.2	1992.6	R
CG13	467816	3342670	Soil	<i>S<sub>1l</sub></i>	4.55	0.65	1994.7	R
CG14	467888	3342520	Soil	<i>S<sub>1l</sub></i>	8.2	0.82	1994.7	R
CG15	467956	3342230	Soil	<i>S<sub>1l</sub></i>	8	0.8	1998.2	R
CG16	468188	3342070	Soil	<i>S<sub>1l</sub></i>	3.6	0.6	1996.7	R
CG17	468119	3342020	Soil	<i>S<sub>1l</sub></i>	4	0.5	1969.7	R
CG18	467707	3341990	Soil	<i>S<sub>1l</sub></i>	13.2	1.1	2007.7	R
CG19	467889	3341710	Soil	<i>S<sub>1l</sub></i>	4.32	0.54	1991.6	R

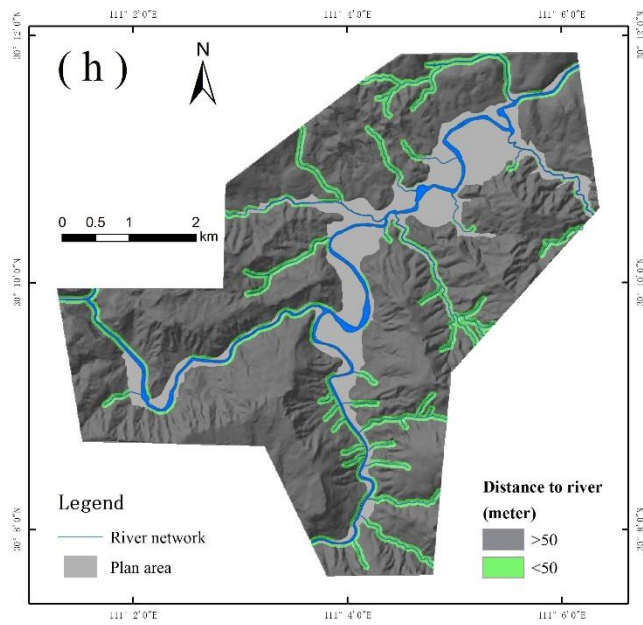
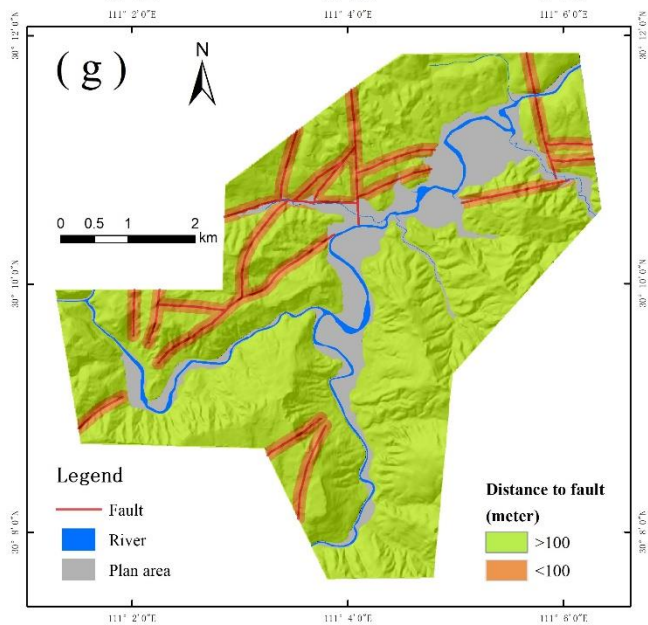
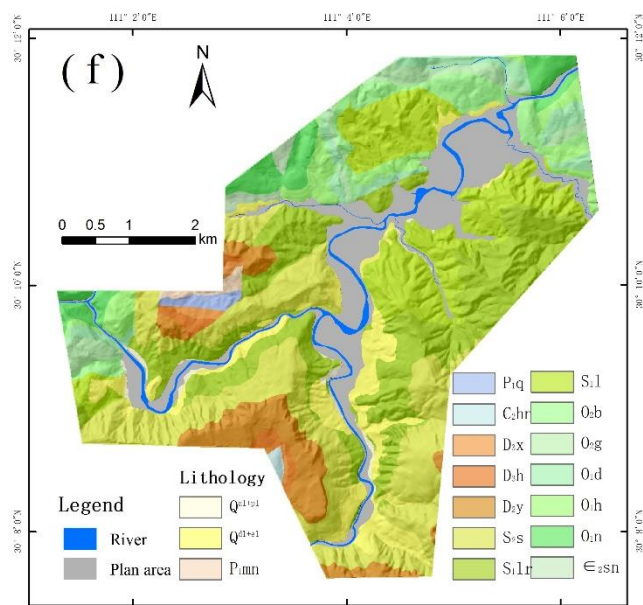
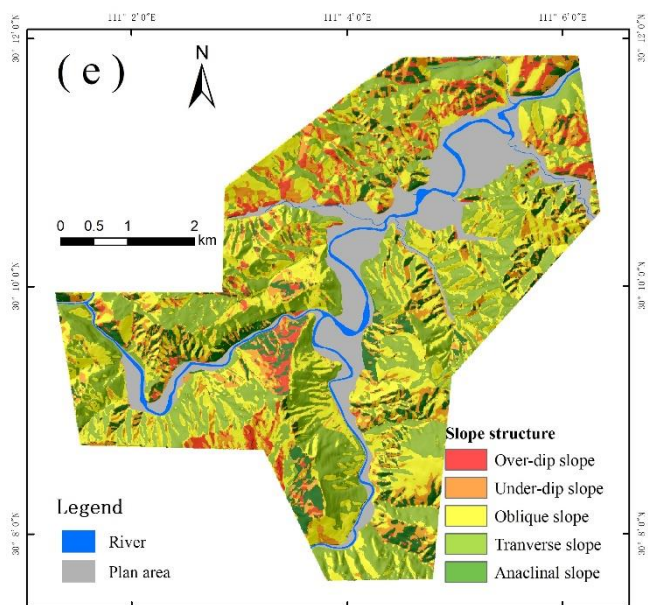
R-rainfall; SC- Slope cut. The code of Bedrock is listed in Table I.

Projected Coordinate System is Xian\_1980\_3\_Degree\_GK\_Zone\_37 with the projection of Gauss\_Kruger.

Note: Database of Chengguan community is complemented for hazard probability analysis because (1) the number of landslides in the case community is limited for probability analysis; and (2) these two communities have similar in geomorphology, geology, climate and landslide types







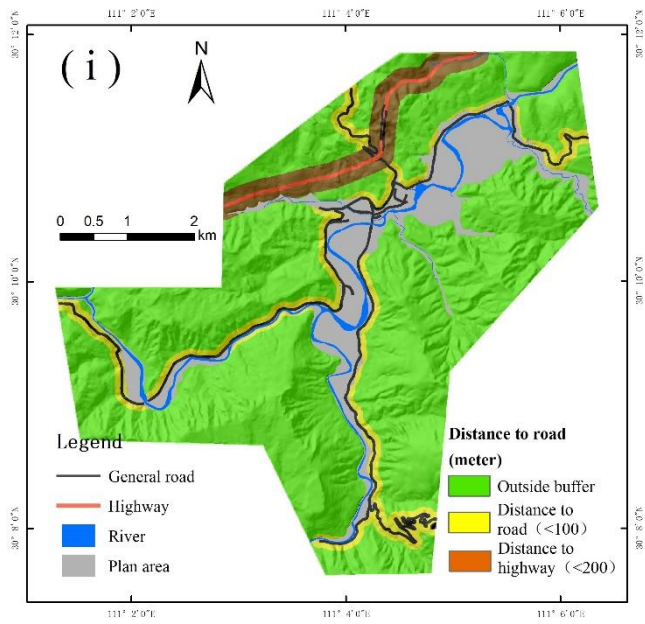


Fig. 4. Thematic maps for landslide susceptibility mapping. (a): Slope, (b): Elevation, (c): Slope aspect, (d): Curvature, (e): Slope structure, (f): Lithology, (g): Distance to fault, (h): Distance to river, (i): Distance to road.

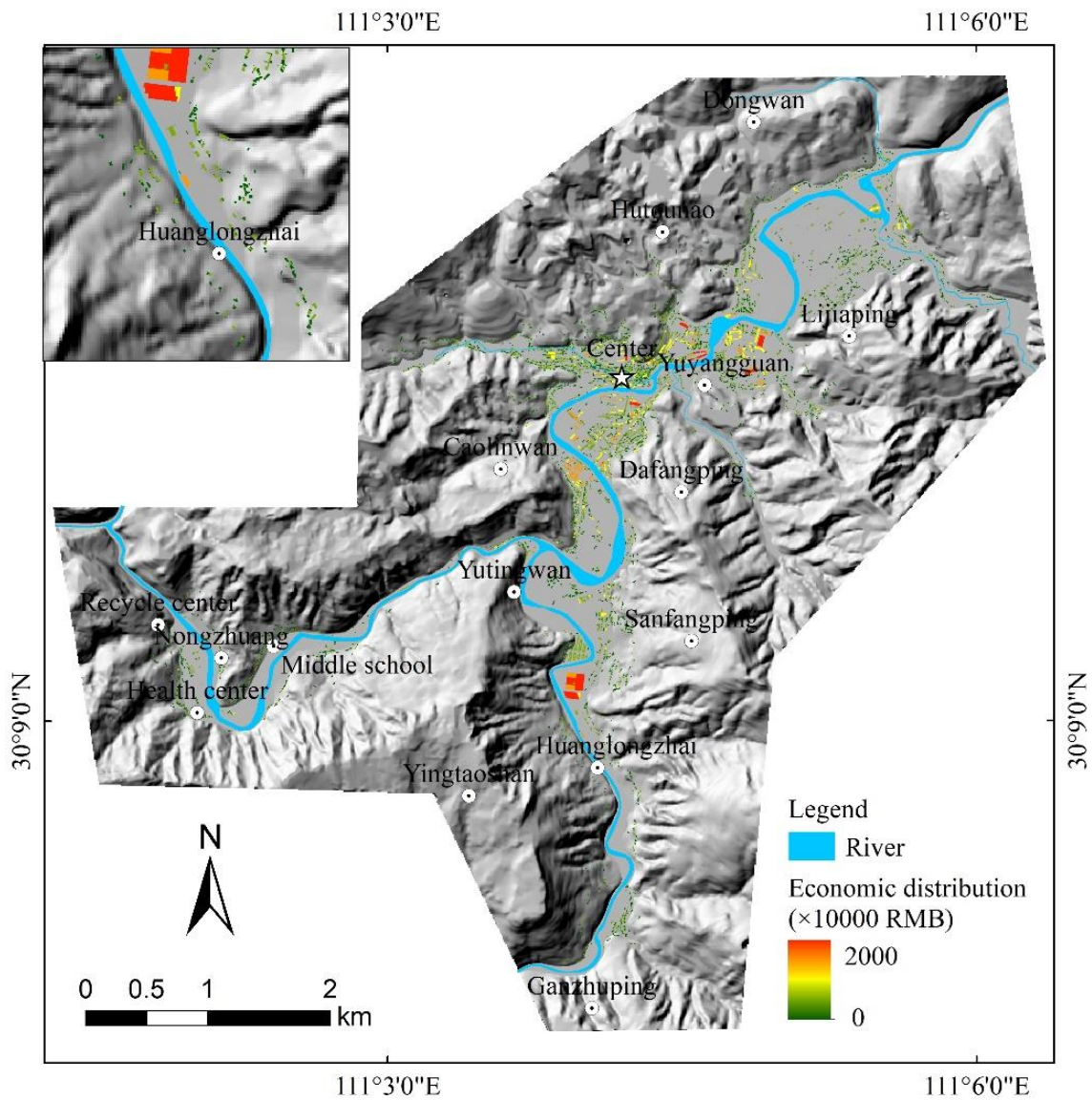


Fig. 5. Building footprint map with economic values.

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

Typology	1 000 RMB/ m <sup>2</sup>	Numbers of floor
Reinforced	3.12	20-32
Reinforced concrete	1.33	6-20
Masonry	0.8	2-6
Wooden	0.1	1-2

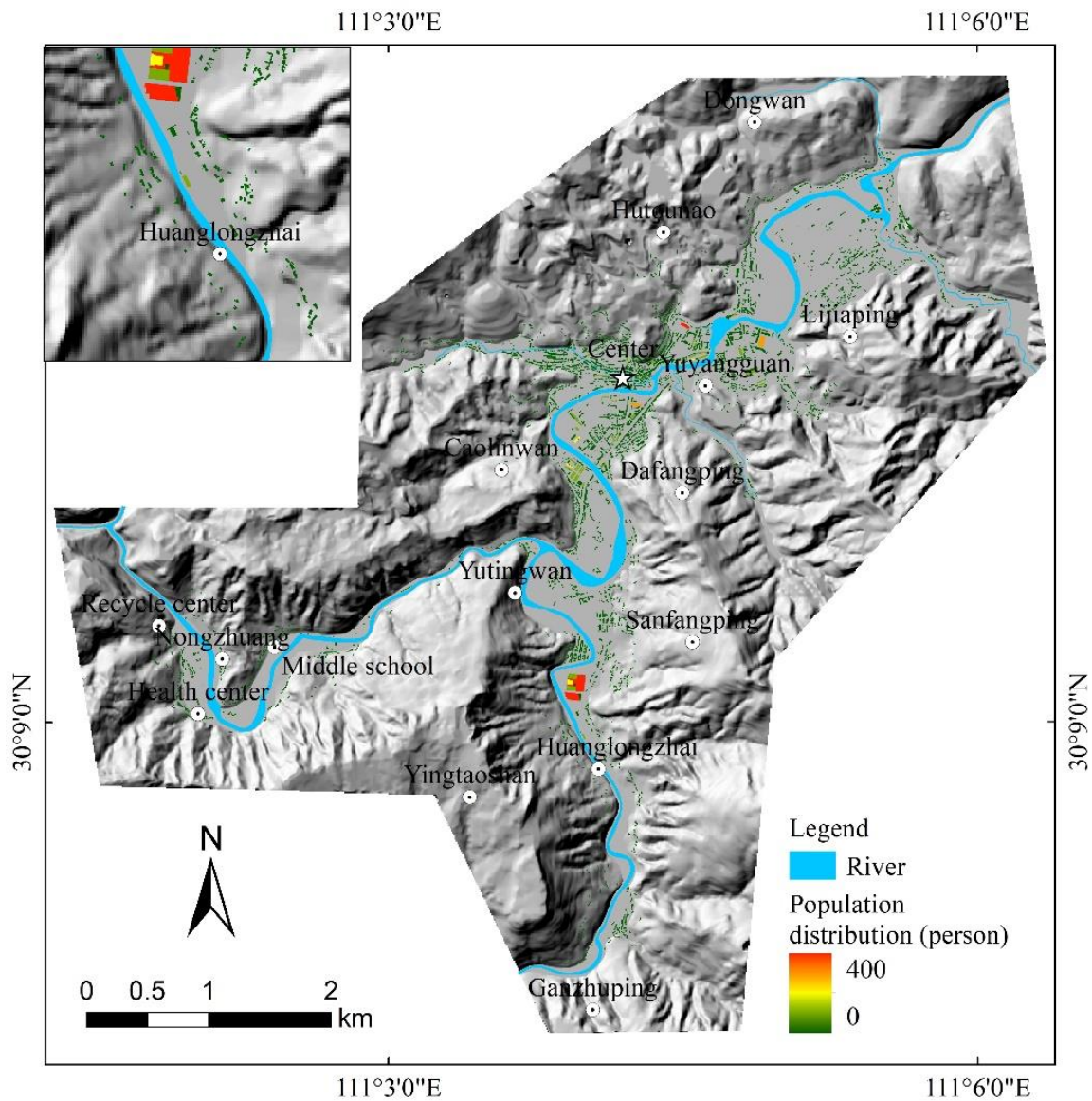


Fig. 6. Population distribution map of Yuyangguan community.

### 3 Methodology

This section explains the method used to conduct a semiquantitative risk analysis for landslides at a community scale. As a start, the slope unit based hazard probability was calculated by integrating spatial, temporal and size probabilities. We generated eight hazard probability maps, considering 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 travelling 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 area. Values in vulnerability map were semiquantitatively determined for buildings and people inside the buildings. The combination of hazard maps, vulnerability maps and element-at-risk maps leads to the risk value for each slope unit, which contributes to the final risk maps of population and buildings in the study area.

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

Hazard assessment is an essential step in landslide risk assessment. For the community scale, this can be achieved by applying the deterministic model (Gokceoglu and Aksoy, 1996; Qiao et al., 2019) if detailed engineering geology data is enough. For the study area, soil or rock strength parameters are not available if using the deterministic method. However, we can use three probabilities (spatial, temporal and size) to answer the question of where and how potential landslides will occur with absolute magnitude in a given time (Guzzetti et al., 2005).

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

Where  $H$  represents hazard probability;  $P(S)$  is 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 various researchers (Ayalew et al., 2004; Fell et al., 2008b; Van Westen et al., 2008; Guzzetti et al., 2012). In this paper, morphometric and geo-environmental factors were chosen as variables. These include altitude, slope, aspect, curvature, slope structure, distance to rivers, and proximity to roads. These Morphometric factor maps were derived from the digital elevation model (DEM), with resolution  $10 \times 10$  m obtained by Unmanned Aerial Vehicle (UAV). Geo-environmental factors such as lithology and faults were prepared and transformed from shapefile to grid-based map, using the 1:10 000 scaled geological field map obtained from Bureau of China Geological Survey (<http://www.cgs.gov.cn>). The detailed processing steps in ArcGIS are explained in the paper of Catani, Casagli, Ermini, Righini, & Menduni (2005). The most common and widely applied weight of evidence (WoE) method was used to assess landslide susceptibility in this paper. It is a probabilistic model considering evidence factors of landslides, based on conditional independence hypothesis (Hong et al., 2017). In WoE method, the contrast (difference of  $W^+$  and  $W^-$ ) was used as a weight for each morphometric or geo-environmental factor. The effectiveness of LSM was tested using the Receiver Operating Characteristics (ROC) curve (Metz, 1978; Zezere et al., 2017). The area under the ROC curve is used to assess the success rate.

The above grid-based LSM was then converted into a slope unit based susceptibility map. Susceptibility value in each slope was calculated from the average value of susceptibility of the grids inside the slope. The slope unit was subdivided using the

hydrology analysis method in ESRI ArcGIS platform (<http://www.esri.com/software/arcgis/arcgisonline>). The slope unit based spatial probability map was classified into five classes: very high, high, moderate, low, and very low.

### 3.1.2 Temporal probability

Landslide temporal probability  $P(N_L)$  is evaluated based on the assumption that slope failures can be viewed as independent random points-event in the time dimension (Crovetli, 2000;Guzzetti et al., 2006). In this study, the Poisson model (Crovetli, 2000) was adopted to construct temporal probability. It is here an exceedance probability of landslide occurrence during a given period (see equation (2) ), which means the probability of experiencing one or more landslides during a given time.

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

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

### 3.1.3 Size probability

Landslide size probability is calculated based on the relationships between landslide volume and cumulative frequency. Guzzetti et al. (2005) used the probability density function of the landslide area to predict the probability of one 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. Two differences in our study will improve the application. The first one is that the present research is to find the most suitable distribution for the case study area. Therefore, we compared the above distributions and tried other type using Ordinary Least Square (OLS) method in Matlab software. The best-fitted one was then used for probability calculation. The second one 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 in this paper, using the volume-area relationship simulated by the OLS method. For this, we used the historical landslides in the database from the study area and the Chengguan community in Table II. Meanwhile, 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 is to determine the elements at landslide risk. This study focuses on residential buildings and people inside these buildings. The building footprint map (see Fig. 5) was interpreted from the image data of UAV in 2013. Building structure (reinforced, reinforced concrete, masonry, 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 buildings (see Table III) obtained from the Department of Land and Resource in Hubei Province. This data was converted to building values by multiplying unit economic values, footprint area and the number of floors. Data of population inside buildings were obtained by integrating the information from China population census data (2010) and sampling survey. The average number of people per building

185 was calculated by applying a Dasyetric Mapping Approach (a methodology for generating a surface-based representation of the population) (Mennis, 2003), which contributes to the data of the population inside each building. In order to assess the element-at-risk, the building footprint map was then intersected with the potential landslide influence area at the community level. The influence area of each slope was semiquantitatively determined by calculating the travel distances by the following formula (Hung et al., 2005).

190 
$$\log(H / L) = A + B \times \log V \quad (3)$$

Where  $L$  is travel distance;  $H$  is slope height;  $V$  is slope volume;  $A$  and  $B$  are constants, 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 can be performed in 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 semiquantitatively determined for buildings using two indicators. The first indicator relates to building structures such as reinforced, reinforced concrete, masonry and wooden. The second indicator is the landslide travel distance. The assumption is that vulnerability is 1.0 for the buildings on the slope, and decreases from the toe of surface rupture to the farthest travel distance. We proposed a set of vulnerability value for buildings with different types (see Table IV).

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**Table I. 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 inside the buildings follows a power-law relationship with building vulnerability (Li et al., 2010), as follows (see equation (4)):

$$V_p = 0.0014 \times e^{6.07 \times V_b} \quad (4)$$

205 Where  $V_p$  is the vulnerability of population inside buildings;  $V_b$  is the vulnerability of buildings.

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 of risk is:

$$R = H \times V \times E \quad (5)$$

210 Where  $R$  is the expected losses in some return periods;  $H$  is the landslide probability in some return period with a given size scenario. In the present study,  $V$  is the physical vulnerability of buildings or populations inside buildings.  $E$  is the quantification of the exposed elements at risk. Using Equation 5, the risk curve can be fitted by plotting the probability versus potential loss and the annual risk can then be calculated using the area under the risk curve (van Westen, 2002)

## 4 Results

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

### 4.1 Landslide susceptibility assessment

In assessing landslide susceptibility, we have looked into the elevation, slope, aspect, curvature, lithology, slope structure, distance to fault, rivers and roads. The weight and contrast value by WoE method for LSM of Yuyangguan is shown in Table V. As can be seen in this Table, the contrast values explained in section 3.1 for lithology shows that the  $O_2g$  and  $Q_4^{dl+el}$  are the top two units. **This implies that these two lithological units are susceptible to erosion. Under this background, rainfall in the area can quickly accelerate the erosion and thus trigger landslides.**

225 General road construction contributes secondary importance, with the contrast value of 0.95. Table V also indicates that the morphometric factor in the study area is generally significant. In the case of aspect and elevation, the contrast value was high on the north facing slopes with elevation from 0 to 260 m.a.s.l, but low on the south-facing slopes with elevation above 350 m.a.s.l. In the case of the slope, the steeper the slope is, the higher the landslide probability. **The contrast value of slope ranging from  $10^\circ$  to  $30^\circ$  is 0.19**, which indicates a relatively high landslide probability.

230 The grid-based susceptibility map was converted to a slope unit based map with 701 slope units in total. As shown in Fig. 7, the slope unit based susceptibility map was ordered into five classes ranging from very low to very high. The performance of this map shows an accuracy of 84% using the ROC curve. The landslide susceptibility in this study area is very high on 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 value shown in Table V.



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

Factors	Classes	Area of domain %	Landslide area %	W <sup>+</sup>	W <sup>-</sup>	$C = \frac{W^+}{W^-}$	S {W <sup>+</sup> } <sup>a</sup>	S {W <sup>-</sup> } <sup>b</sup>	S(C) <sup>c</sup>	C/S (C) <sup>d</sup>
Slope (degrees)	0--10	11.03	3.66	-1.11	0.08	-1.19	0.01	0.00	11.04	-13.15
	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 (meters)	0--260	30.99	51.21	0.51	-0.35	0.86	0.00	0.00	29.24	25.15
	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 (degrees)	Plan area	2.32	0.14	-2.79	0.02	-2.81	0.20	0.00	2.23	-6.29
	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 <sup>al+pl</sup>	0.78	0.06	-2.61	0.01	-2.62	0.50	0.00	1.41	-3.70
	Q <sup>dl+el</sup>	8.08	50.95	1.91	-0.63	2.54	0.00	0.00	28.83	73.28
	P <sub>1mn</sub>	0.58	0	0	0.01	-0.01	-	0.00	-	-
	P <sub>1q</sub>	0.75	0	0	0.01	-0.01	-	0.00	-	-
	C <sub>2hn</sub>	0.26	0	0	0	0	-	0.00	-	-
	D <sub>3x</sub>	0.63	0	0	0.01	-0.01	-	0.00	-	-
	D <sub>3h</sub>	1.24	0	0	0.01	-0.01	-	0.00	-	-
	D <sub>2y</sub>	7.16	0	0	0.08	-0.08	-	0.00	-	-
	S <sub>2s</sub>	22.07	27.61	0.23	-0.07	0.3	0.00	0.00	26.15	7.88
	S <sub>1lr</sub>	21.34	11.99	-0.58	0.11	-0.7	0.00	0.00	19.06	-13.26
	S <sub>1l</sub>	15.18	0	0	0.17	-0.17	-	0.00	-	-
	O <sub>2b</sub>	4.54	0	0	0.05	-0.05	-	0.00	-	-
	O <sub>2g</sub>	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	-	-
	$\epsilon_{2sn}$	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
	Stright/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
	Obique	15.19	6.71	-0.82	0.1	-0.92	0.00	0.00	14.70	-13.49
	Tranverse	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 are is 29.14 square kilometers.

Total landslide area is 3740 pixels.

<sup>a</sup>Variance of  $W^+$

<sup>b</sup>Variance of  $W^-$

<sup>c</sup>Standard deviation of contrast

<sup>d</sup>Studentized value of contrast

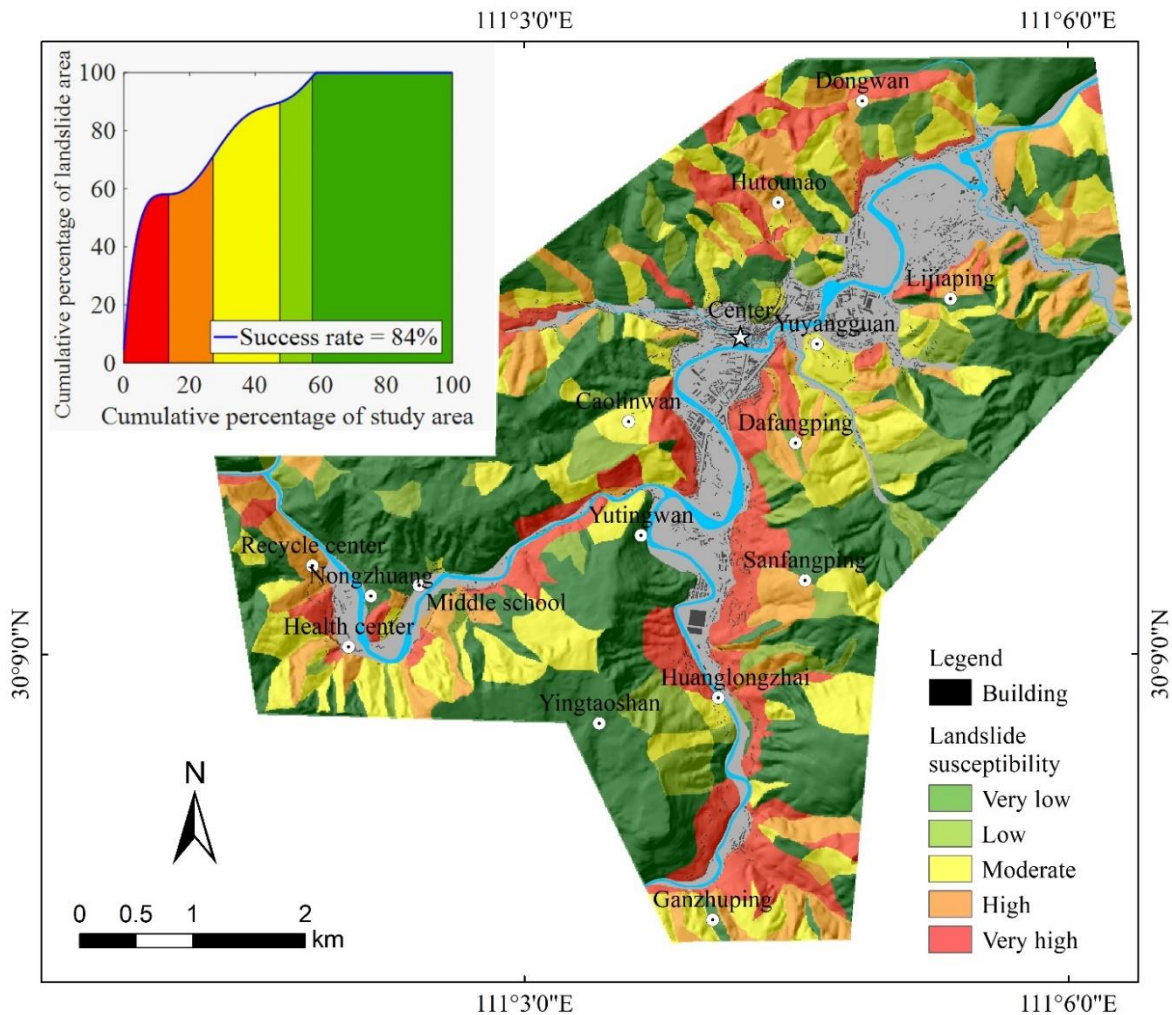


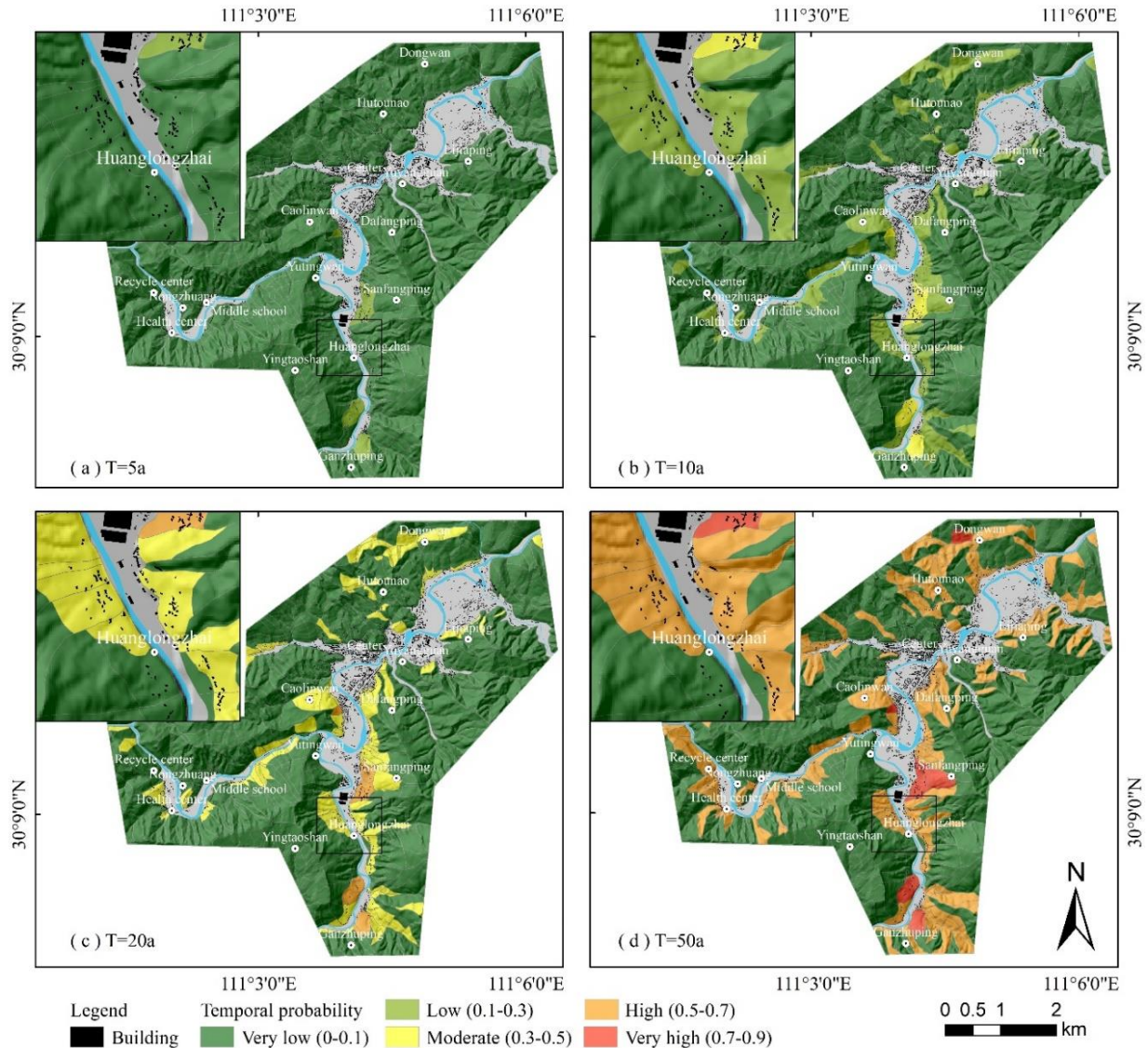
Fig. 7. Slope unit based landslide susceptibility map (LSM) at the community level, converted from the grid-based LSM using the weight of evidence method for Yuyangguan, west Hubei, China

235 **4.2 Landslide hazard probability**

Landslide hazard involves spatial, temporal and size probabilities. The landslide database of Yuyangguan shown in Table II, covers the temporal interval of 33 years starting from 1981 to 2013. For each slope unit, the historical mean recurrence interval (*RI*) was calculated using Equation 2. 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.

240 Fig. 8 shows four landslide temporal probability maps for four return periods (5, 10, 20, 50 years). The map for 50 years, for example, indicates the probability of the slope units experiencing landslide events is the highest among the four maps. Slope units with high and very high probability value (greater than 0.5) mostly cluster on the first slope zones around the

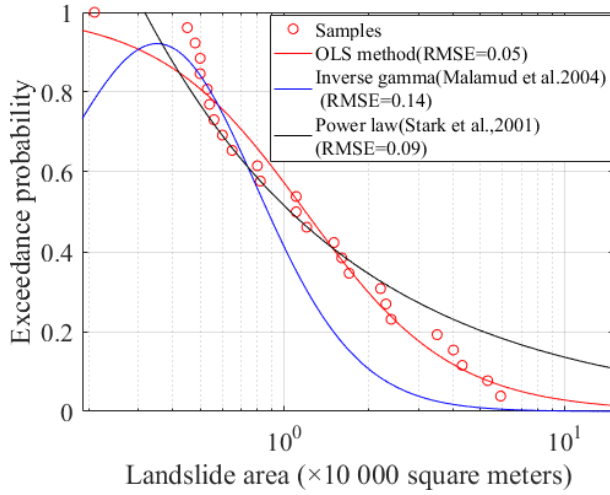
community. The probability value on these slopes increases from the return period of 5 years. For example, Enlarged window in maps of Fig. 8 shows that the slope in Huanglongzhai village experienced a very low probability in 5-year to a high class in a 50-year return period.



**Fig. 8. Landslide temporal probability maps by using the Poisson model, showing the exceedance probability of landslide occurrence in each slope unit during four return periods (5, 10, 20, 50 years).**

The landslide probability distribution curves are created using three different fitting functions, shown in Fig. 9. In comparison to the inverse gamma and the power law distributions, the function by OLS method shows the best fitting degree, with the smallest root mean square error (RMSE) of 0.05. This indicates that landslide frequency distribution function by the OLS method is the most appropriate technique to apply in Yuyangguan. The volume-area relationship is analysed in Fig. 10a

250 with R-square 0.915. This indicates that the way of converting 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 in Fig. 10b in terms of landslide volume: 50 000 cubic meters and 100 000 cubic meters.



$$p = \frac{1}{1 + a_1 A_L^{2a_2}}$$

OLS method:

Inverse gamma:

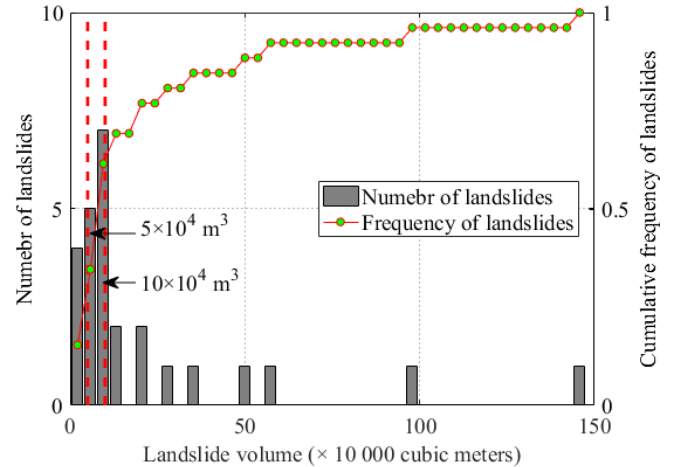
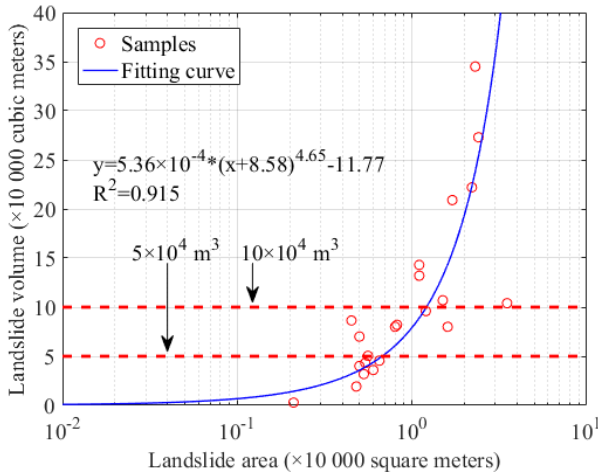
$$p(A_L; \rho, a, s) = \frac{1}{a\Gamma(\rho)} \left[ \frac{a}{A_L - s} \right]^{\rho+1} * \exp \left[ -\frac{a}{A_L - s} \right]$$

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

Where,  $p$  is probability;  $A_L$  is landslide area;  $a = 1.89$ ,  $a_1 = 0.75$ ,  $a_2 = 0.83$ ,  $a_3 = 0.51$ ,  $a_4 = 0.58$ ;

$$\rho = 2.42, s = -0.20$$

**Fig. 9. Magnitude-frequency relationships simulated by Ordinary Least Square method, Inverse gamma, and Power law for landslide in western Hubei. Samples are from Table II, which involves the Chengguan database except for the study area.**



**Fig. 10. (a) Relationship of landslide volume and area ( $R^2=0.915$ ), which will be used to convert magnitude-frequency relationships in terms of area to landslide volume. (b) Frequency distribution of Landslide volume. Samples are from Table II, which involves Chengguan database except for the study area.**

Integrating the spatial probability in Fig. 7, temporal probability in Fig. 8 and the magnitude-frequency relationships in Fig. 9 by using Equation 1, we then obtain eight hazard maps. In these maps, we demonstrate the hazard probability for each slope unit for four return periods (5, 10, 20, 50 years) and two different landslide sizes equal or greater than 50 000 m<sup>3</sup> and equal or greater than 100 000 m<sup>3</sup>. As an example, Fig. 11 shows the four landslide hazard maps for four return periods and the landslide sizes scenario equal to or greater than 50 000 m<sup>3</sup>. In these maps, landslide hazard probability values were classified into five categories from very low (0.0-0.1) to very high (0.4-0.5). The map for 50 years returns period shows that most building areas of the community located at the bottom or near the slopes with very high hazard probabilities. Additionally, buildings located in the community centre are in low to very low hazard probability areas.

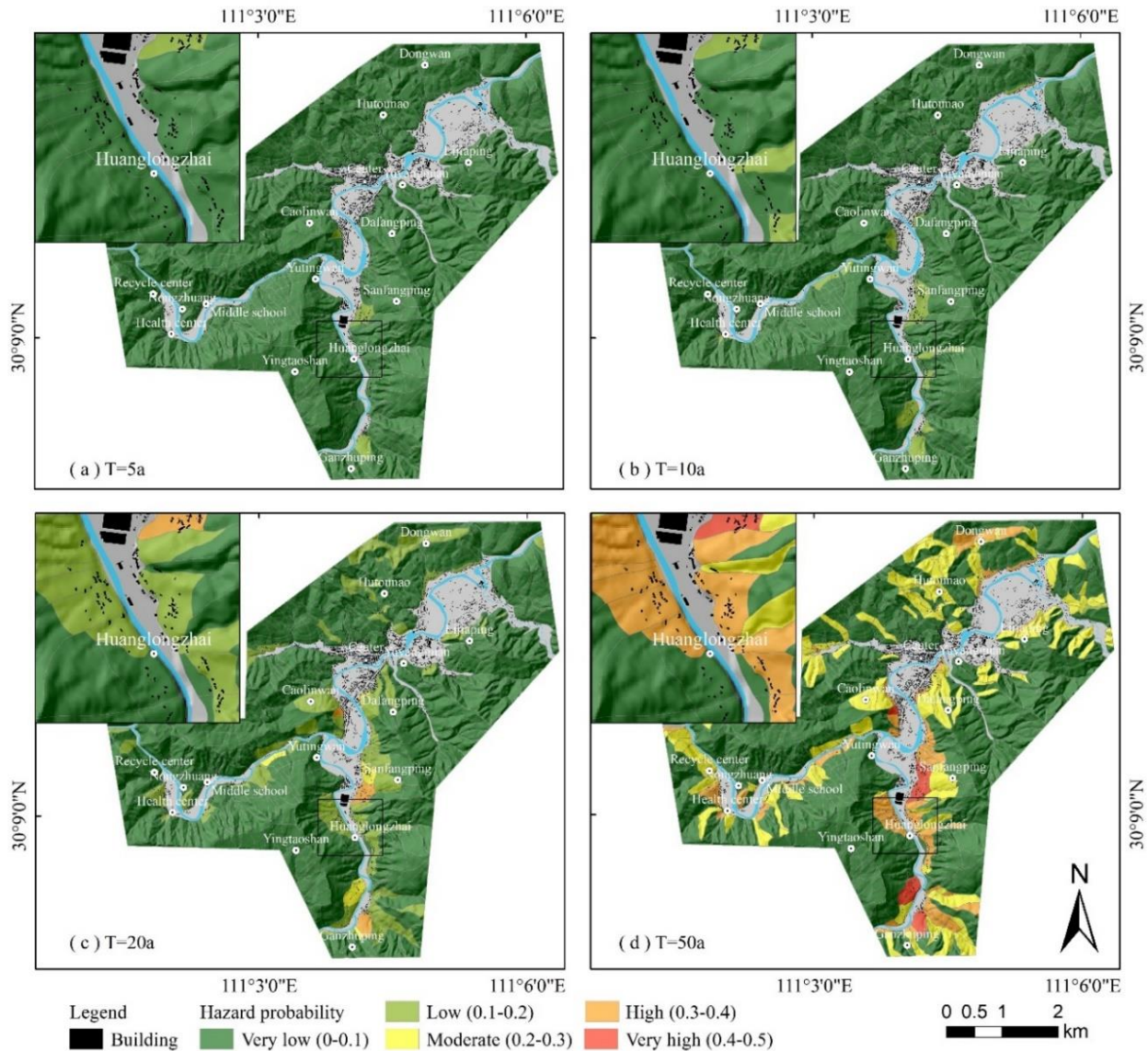


Fig. 11. The Landslide hazard maps for four return periods (5,10,20,50 years) and the landslide sizes scenario equal to or

greater than 50 000 m<sup>3</sup>. The maps were generated by integrating the spatial probability in Fig. 7, temporal probability in Fig. 8 and the magnitude-frequency relationships in Fig. 9.

### 4.3 Element-at-risk and vulnerability assessment

We assume that the buildings and population inside the buildings are exposed to the slopes with high and very high-class probability in hazard maps. Therefore, the element-at-risk maps for buildings and 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 landslide hazard probability maps.

Table VI shows that in the return periods of five years and ten years, there is no exposure, while in the case of 50 years return period and 50 000 m<sup>3</sup> size scenario there are 570 000 m<sup>2</sup> build-up areas and 14 257 persons identified to be exposed to landslide risk. The table also indicates the tendency of potentially damaged building areas and the number of persons within the buildings from the return period of 20 years to 50 years. The vulnerability value was indirectly calculated by equation 4 in Section 3.3. In the size scenario of landslide, volume equal to or greater than 50 000 m<sup>3</sup>, a sharp increase of exposure exists both for built-up areas and populations. The exposure over doubled from 20 years to 50 years. This result also exists for the size scenario of landslide volume equal to or greater than 100 000 m<sup>3</sup>. Comparing the two different size scenarios, we find that the number of exposure of 100 000 m<sup>3</sup> volume is smaller than that of 50 000 m<sup>3</sup>. There are 8.76 per cent building areas exposed to landslide in 20 years return period. However, the value decreased to be 5.86% in size scenario of 100 000 m<sup>3</sup>, which is due to the lower hazard probability in size scenario 100 000 m<sup>3</sup>. The same tendency also exists for the populations inside buildings. About 30 per cent population will be exposed to landslide in the 50 years return period.

Accordingly, eight vulnerability maps for buildings and eight vulnerability maps for populations inside buildings are created for the four return periods and two size scenarios. For example, Fig. 12 and Fig. 13 show the four resulting vulnerability maps for buildings and population inside the buildings under four return periods and the case of landslide volume equal to or greater than 50 000 m<sup>3</sup>. The majority of exposed buildings are located on the slopes with high or very high hazard level, such as Caolinwan, Dafangping, Sanfangping villages. The buildings and population inside the buildings in these community centres are not exposed to slope hazard, thanks to the very low class (0-0.1) of landslide probability hazard.

As discussed in Table IV of Section 3.3, we assigned the vulnerability value to be 1.0 for buildings located on slopes. This causes the buildings outside the flat areas in the community show very high vulnerability value in Fig. 12. The vulnerability map shown in Fig. 12 was classified into five categories ranging from very low to very high. In the case of 50 years return period and 50 000 m<sup>3</sup> size scenario, there are 18% building areas with very high-class vulnerability. Vulnerability value of populations was then assigned according to Equation 4 in section 3.3 based on the building vulnerability result. The very-high class population vulnerability shown in Fig. 13 was over than 0.5, the area of which is about ten percent of the exposed people and mainly concentrates in the influence area of slopes in Dafangping, Caolinwan, Sanfangping or on the slopes which have the very-high class hazard probability assessed in Fig. 11.

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

Size scenario		Volume >=50 000 m <sup>3</sup>				Volume >=100 000 m <sup>3</sup>			
		Return Period(years)		5	10	20	50	5	10
Exposure	Population	0	0	4073(8.87%)	14257(31.05%)	0	0	2724(5.93%)	13746(29.94%)
	Building area(×10 000m <sup>2</sup> )	0	0	16.3(8.76%)	57(30.64%)	0	0	10.9(5.86%)	55(29.57%)
	Casualties (person)	0	0	771(1.68%)	1485(3.23%)	0	0	584(1.27%)	1235(2.69%)
Risk	Economic losses (×10 000 RMB)	0	0	6039(3.69%)	11629(7.10%)	0	0	4615(2.82%)	9352(5.71%)
Annual	Casualties (person)	59(0.13%)				47(0.10%)			
Risk	Economic losses (×10 000 RMB)	463(0.3%)				359(0.23%)			



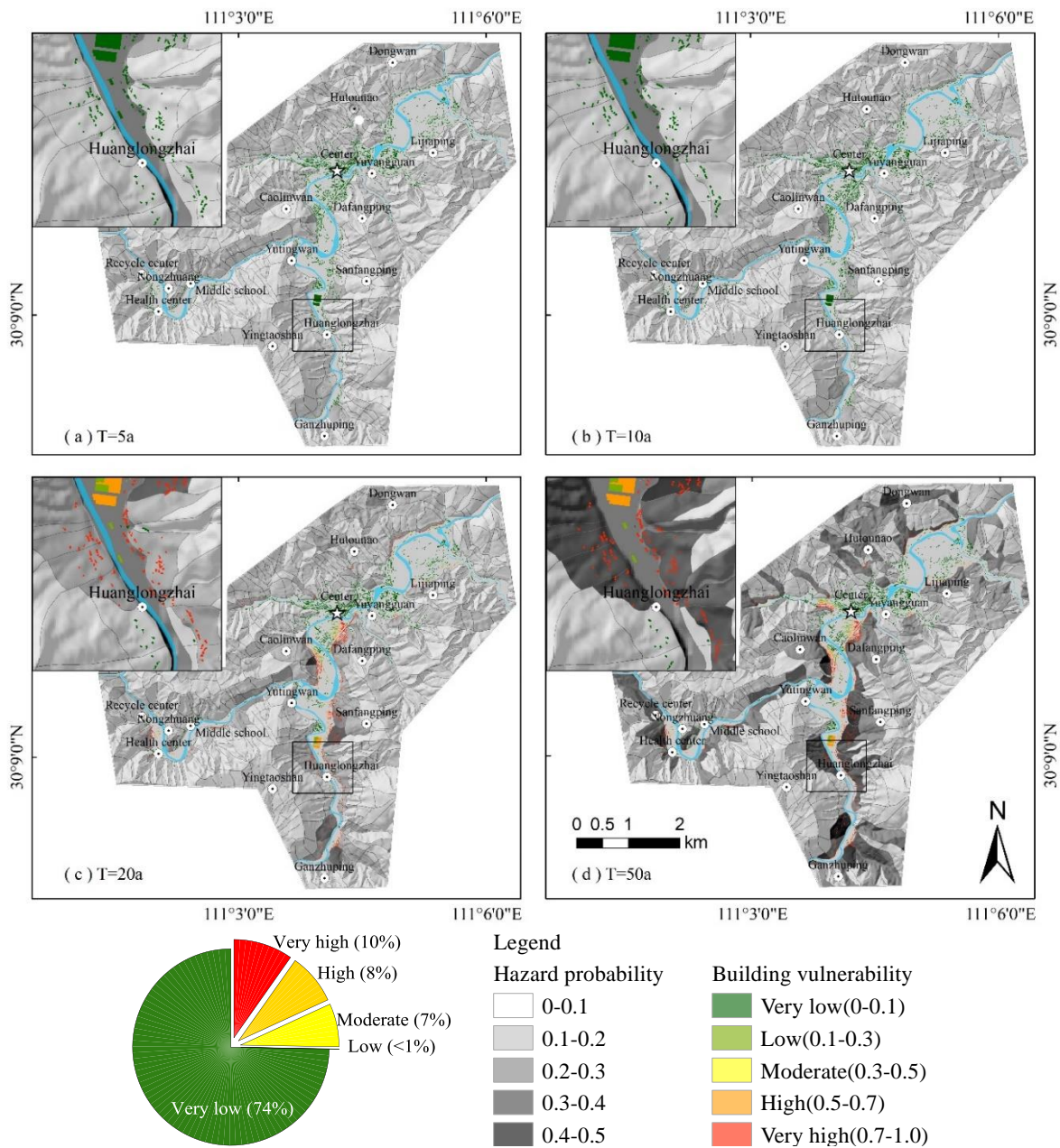


Fig. 12. Buildings exposed to landslides and vulnerability distribution map for four return periods (5,10,20,50 years) and size scenario of landslide volume equal to or greater than 50 000 m<sup>3</sup>.

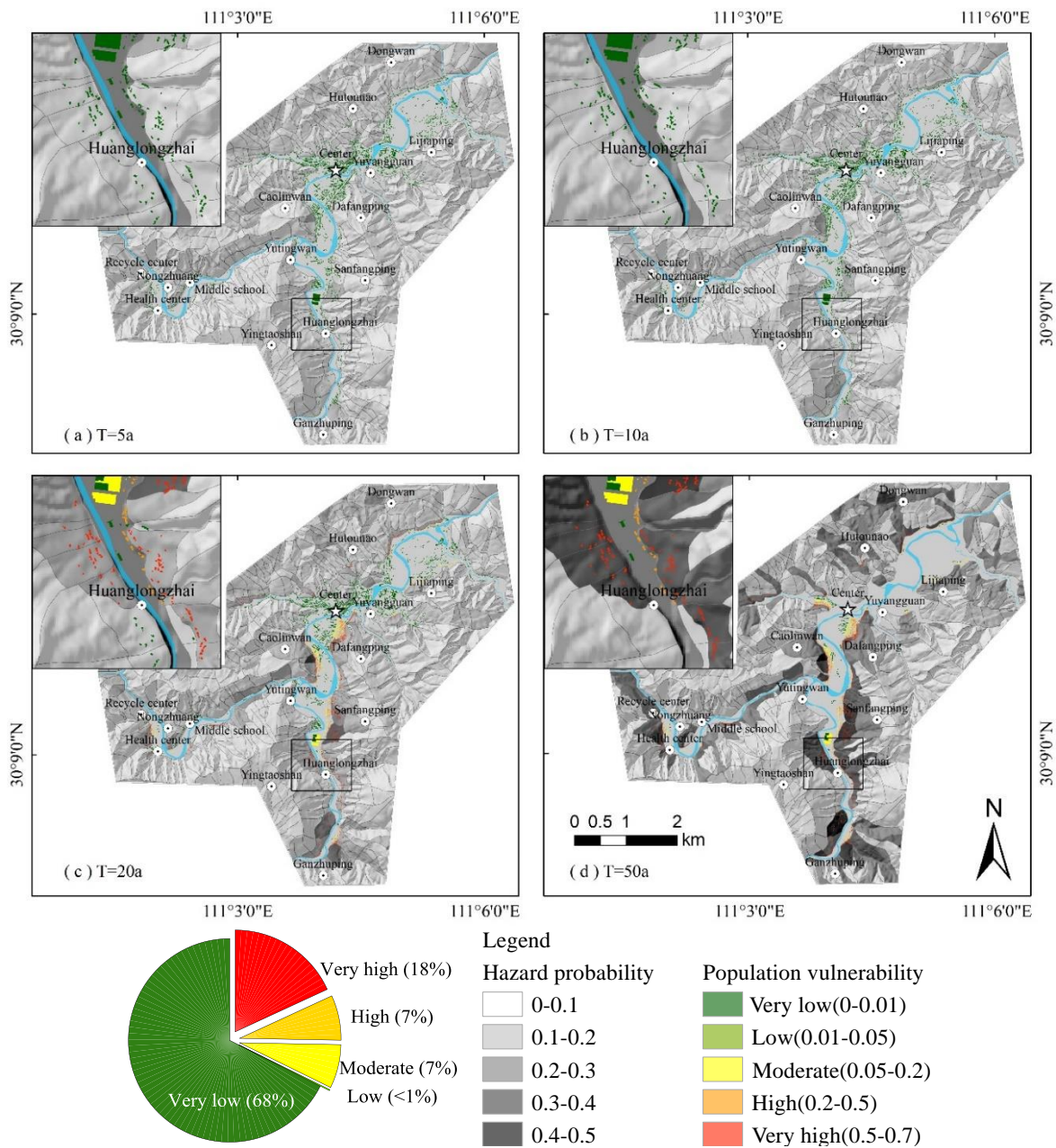


Fig. 13. Population exposed to landslides and vulnerability distribution map four return periods (5, 10, 20, 50 years) and size scenario of landslide volume equal to or greater than 50 000 m<sup>3</sup>.

#### 4.4 Risk assessment

300 Landslide risk maps were generated from the eight hazard maps, eight vulnerability maps and the value or amount of elements-at-risk by equation 5. An example of a risk map for the loss of population is shown in Fig. 14. The map created for 50 years return period for example (see Fig. 14d) shows that potential loss was concentrated in the urban and densely-populated areas along the Yuyangguan River, especially at the toe of the slope of Caolinwan, Dafangping, Sanfangping villages.

305 Table VI presents the final population and buildings risks for four return periods and two size scenarios. Accordingly, there are no potential losses in five and ten return years. The result of no risk in 5 year return period can be proved by the fact that no casualties or economic losses are reported in Yuyangguan community since 2014. For the case of volume equal to or greater than  $50\,000\text{ m}^3$ , however, the potential casualties are 771 persons, 1.68% of the total populations in the community. The economic losses are calculated as about 60 million RMB in 20 years return period, about 3.7% of buildings economic

310 values. As shown in Table VI, the risk is expected to be double in the next 50 years return period. In the case of volume equal to or greater than  $100\,000\text{ m}^3$ , the potential loss will be lower. For example, there is 1.27% of the populations exposed to landslides, 0.41% lower than that in size scenario of  $50\,000\text{ m}^3$ .

### 5. DISCUSSION

#### 5.1. Discussion on landslide susceptibility map

315 Landslide susceptibility result shows that lithology is the most important controlling factor. Quaternary eluvium ( $Q_4^{dl+el}$ ) and Guniutan limestone from Ordovician ( $O_{2g}$ ) has the top two weight values in the susceptibility map. It is consistent with the findings in fieldwork by the authors. Residual deposit and eluvium is the composition of clay and gravels, which is with low strength and is the main areas with intensive human activities in Yuyangguan community. As to the bedrock  $O_{2g}$ , it is with high strength and not vulnerable to have a landslide. But in the field, we found two groups of joint surface in  $O_{2g}$ , which are

320 the vital in understanding why the YYG07 landslide occurred (see Table II). We can also find in the field that the majority of landslides occurred in Silurian sandstone and shale. However, the weight value (0.3) of  $S$  is lower than the value of  $Q_4^{dl+el}$  and  $O_{2g}$ . **This is because the area of Silurian formation is much larger in Yuyangguan community (see Fig. 1).** Therefore, we should take the things in mind that slopes in Ordovician limestone can have a much high landslide probability and we should pay attention to the slopes although historical landslides are not too much now.

325

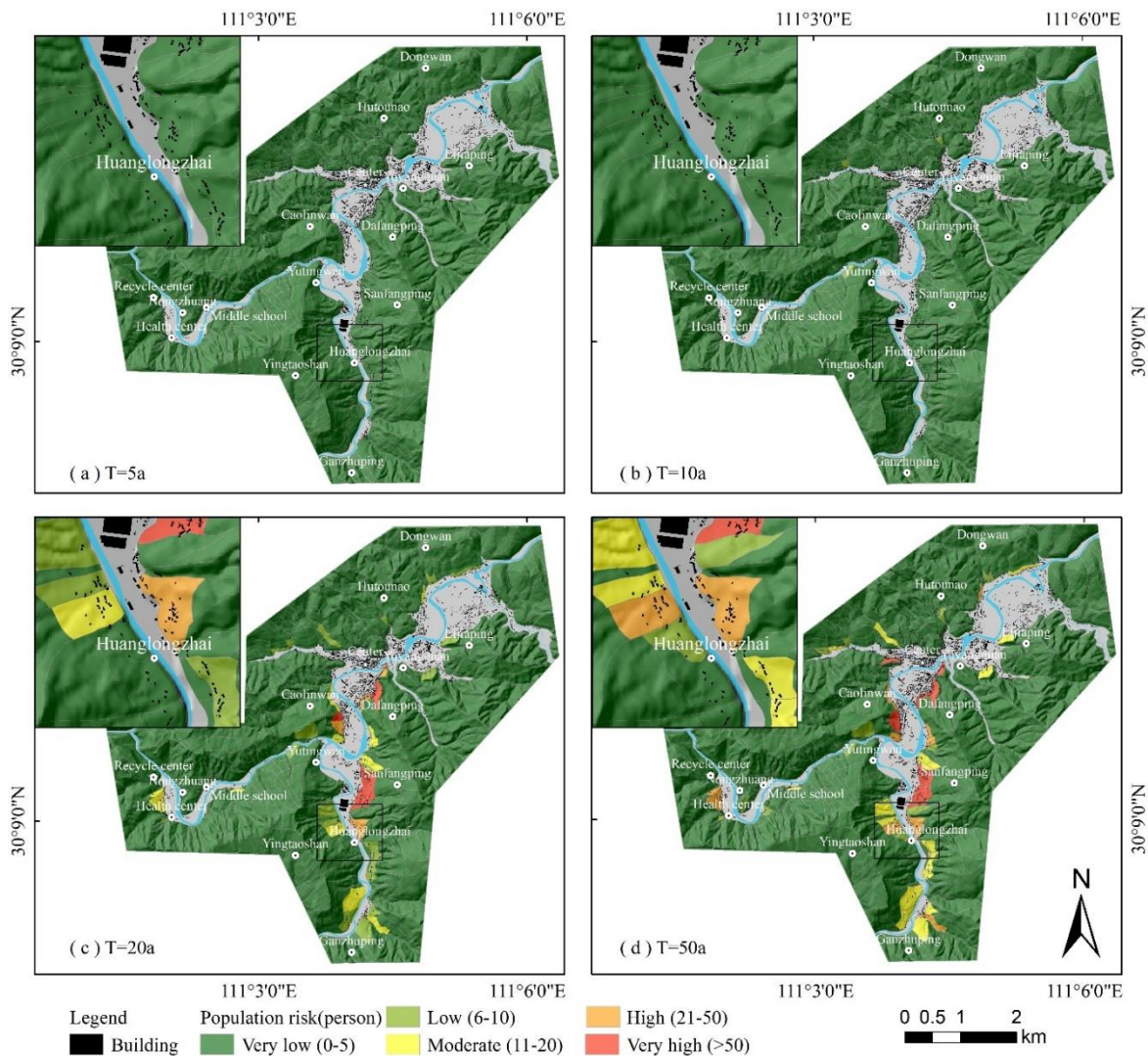


Fig. 14. Example of a risk map for the loss of population for four return periods (5, 10, 20, 50 years) and the landslide size scenario equal to or greater than 50 000 m<sup>3</sup>

## 5.2. Discussion on landslide hazard assessment

330 Landslide hazard maps are generated for four assumed return periods (5, 10, 20, and 50 years) and two size scenarios. Theoretically, the definition of hazard scenarios as described by Chen et al. (2016b) should be based on the analysis of landslide occurrences and triggering events due to the incomplete information on landslide date in the community, it is challenging to build the relationship between landslide return period and triggering factor (rainfall in this case study). However, we find that since 2014 no landslide occurred in Yuyangguan community, which is consistent with the hazard

335 result in 5-year return period (see Fig. 11a). It means that the way of temporal probability using the Poisson model is **suitable**  
for landslide hazard assessment when a landslide database incomplete with detail occurrence date and triggering event  
data(such as rainfall).

In 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) did not show an excellent fitting performance in this  
340 study. The difference in landslide size between Malamud's and our landslide database is the main reason. No small  
landslides (< 1000 m<sup>2</sup> in Malamud's research) are presented or recorded in Yuyangguan community. The simulated equation  
(in Fig. 9) is suitable for landslide risk assessment in this research. **In future, however, comparison with the classical models  
should still be taken with by considering other factors, such as triggering factors and landslide types, with a more complete  
database or more landslide events.**

### 345 **5.3. Other limitations in risk results**

Uncertainties do exist in the final risk maps due to some other items, such as element at risk data and its vulnerability or  
resilience. In this study, we get the data of buildings and population inside the buildings at risk by empirical calculation for  
landslide influence area. Further study will be taken by numerical modelling considering landslide material, pore water  
pressure and ground surface characteristic besides slope height and volume used in this paper.

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

From susceptibility to risk assessment, we hold the assumption that landslide will occur under the same condition which  
caused historical landslides. However, morphometric, geo-environmental conditions and assets will change in practice. **For  
example, the slope degree, elements at risk and land use cover may be change because of the new-built infrastructures, or the  
360 number of historical will increase due to heavier rainfall. Future studies will be taken in terms of these changes for more  
accurate and practical assessing results.** Despite this, the resulting maps can be referred for landslide risk controlling strategy  
making and land use planning in Yuyangguan community. Risk controlling measurements can be planned on each slope unit  
using a matrix from the combination of 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 relocation or engineering works, while  
365 the slopes with high-class hazard probability and mid-class risk suggested being monitored by GPS or borehole inclinometer.  
Also, the four return periods and two size scenarios can be used for multi-temporal land use planning, such as short term (in  
5 years), mid-term (10-20years) and long-term(50 years). The annual risk value on each slope can be used for cost-benefit

analysis in risk decision. To some extent, it answers the question raised by Guzzetti et al. (2005) that how to combine a large number of hazard maps efficiently for different users.

## 370 **6. CONCLUSIONS**

We conducted a semiquantitative risk assessment for landslides at a community scale based on the definition of landslide risk given by Varnes and the IAEG (1984). In our case study, we focused on the potential loss of building and populations inside buildings. We generated one susceptibility map, eight hazard maps, eight vulnerability maps and eight risk maps for four return periods(5,10,20,50 years) and two size scenarios(equal to or greater than 50 000 m<sup>3</sup> and equal to or greater than 375 100 000 m<sup>3</sup>). The landslide susceptibility result was tested to have a success rate of 0.84 and indicates the important contribution of Quaternary eluvium, Guniutan limestone from Ordovician. The way of generating hazard maps by integrating three probabilities (spatial, temporal and size probability) proved applicable in this case study area. While in size probability calculation, a normal distribution function of landslide should be used carefully and better fitting function is suggested to be found if small landslide data are scarce in the area. Also, landslide influence area can be empirically 380 determined at a community scale by using simple data (slope height and volume) if geotechnical parameters not available. However, for more accurate vulnerability assessment, numerical modelling on landslide travel distance is suggested because the resulting intensity parameters, such as velocity, depth are essential input data for vulnerability quantification. Besides the presented limitations, we believe that the proposed risk maps can tell the local stakeholders how to make different period of risk planning for the total community, such as short term (in 5 years), mid-term (10-20years) and long-term (50 years) 385 strategy, or provide the reference to do cost-benefit analysis for each slope unit from the result of quantified annual risk value.

### **Data availability.**

We thank China Geological Survey for the data for this work. Unluckily, the data is not available unless get the permission from China Geological Survey.

### 390 **Author contribution.**

Yin, Chen, Xu, Lian and Li supervised the field work and collected the complicated data. Chen and Fu discussed the whole plan of this article, designed and implemented all the experiments. Fu prepared all the data and finish the draft, including all figures in the article. Chen and Woldai revised the article. Du and Zhou supported the methods and techniques.

## Competing interests.

395 The authors declare that they have no conflict of interest.

## Special issue statement.

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