J. Mt. Sci. (2018) 15(12): 2730-2740 e-mail: jms@imde.ac.cn http://jms.imde.ac.cn
https://doi.org/10.1007/s11629-017-4798-9

Risk-based evaluation on geological environment carrying capacity of mountain city - A case study in Suide County, Shaanxi Province, China

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Citation: Wang Y, Zhang MS, Xue Q, Wu SD (2018) Risk-based evaluation on geological environment carrying capacity of mountain city - A case study in Suide County, Shaanxi Province, China. Journal of Mountain Science 15(12). https://doi.org/10.1007/s11629-017-4798-9

Abstract: With the rapid development and expansion of the cities in China, the carrying capacity of resource and environment has become a huge concern for local governments. From the perspective of geological environment, geological disasters are the main restraining factor of the development in mountain cities. This study was conducted in Suide County of Shaanxi Province with a risk-based approach as followed: a hazard analysis on geological disasters based on a slope geological survey at a scale of 1:10,000; a consequence analysis based on unmanned aerial vehicle (UAV) aerial survey data; integrating the results of hazard analysis and consequence analysis, a risk zonation and analysis of geological disasters in urban areas were completed considering urban planning, land use planning and the safety of infrastructure and major engineering. Subsequently, taking the acceptable levels of human life and property risks incurred by landslides as the criteria of the evaluation of geological environment carrying capacity, a comprehensive assessment of current and future urban carrying capacity was conducted based on the results of the risk analyses. Accordingly, the prior development zone, the restricted development zone and the prohibited zone were delineated, with corresponding suggestions for future urban development. The technological and methodological system used in the study can be applied to geological environment carrying capacity evaluation of other important mountain cities, which can provide scientific basis for the optimization of land and space.

Keywords: Mountain cities; Risks; Geological environment; Carrying capacity; Evaluation

Received: 13 December 2017
1st Revision: 20 April 2018
2nd Revision: 25 July 2018
3rd Revision: 15 October 2018
Accepted: 03 November 2018

Introduction

On August 8th, 2010, a severe mudslide broke out in the Sanyan and Luojia valleys of Zhouqu County in Gansu Province in northwestern China, which led to 1765 people dead or missing, making it the most disastrous mudslide ever recorded in China. Since the late Qing Dynasty (1823), there were 9 severe mudslides before this one, with 13 deaths in total, the one of the highest toll were in July of 1943 with 7 deaths. They all happened in the same valleys, with the same topography, provenance and precipitation conditions, yet the damage tremendously worsened. Thus, we should definitely reconsider the role of human activities in natural disasters. The risks of disasters induced by population explosion and passages for mudslides being occupied by dense buildings were underestimated; and there is still a lack of knowledge in carrying capacity of geological environment.

Ever since the concept of carrying capacity was first explicitly proposed by Hawden and Paimer in 1921, many studies have been carried out involving carrying capacity of population, land resources, environment, water resources and ecology (Higgins et al.1985; Khanna et al. 1999; William 1992; Willem 1996). They tried to define the carrying capacity from different aspects such as capacity, limit, threshold (Wackernagel and Rees 1997; Heijungs et al. 2010; Lane 2010; Giljum et al. 2011; Fang and Heijungs 2014; Fang et al. 2014), so as to overcome the problem of information incompletion in its indexes. In particular, the concept of planetary boundary (Rockström 2010) was addressed by Rockström in 2009, aiming to establish an "ecological red line" for environmental issues with a global perspective. In the 1940s, Chinese scientists started on the study of carrying capacity on the basis of international experience. Over the past few years, researches towards the theory and methodology of carrying capacity and its assessment became ever heated. They were mainly based on the demarcation of "the three red lines" of ecological pattern to optimize land management, including the red line of cultivated land, the red line of ecological space and the red line of urban development boundary (Fan et al. 2015; Wu et al. 2015; Guan et al. 2016; Xu et al. 2016; Zhang et al. 2016; Fan et al. 2017; Xu et al. 2017; Yang et al. 2017; Zhou and Wang 2017). However, there are still blanks in terms of technical methods and standards for scientifically quantitative evaluation of carrying capacity, such as the disunity of understanding, connotation, research content of the resources and environmental carrying capacity. The evaluation methods are not applicable enough, the selection of index system is subjective, and the evaluation results lack comparability and standards. Existed previous evaluations set the standards more from a geological point of view, without enough consideration of the damages caused by geological and environmental problems, and with rarely comprehensive considerations in project avoidance, engineering transformation and other human influences.

In this study, we focused on the geological environment of Suide County in Shaanxi Province and innovatively considered and modified risk theory (AGS 2000; USDI and USGS 2006; Liu et al. 2006; PGeo et al. 2006; AGS 2007; Tagliavini et al. 2007; Fell et al. 2008; Zhang and Tang 2008; Shi et al. 2009; Wu et al. 2009; Liu and Chen 2010; Hang et al. 2011; Li and Tan 2013; Wang et al. 2015; Tang et al. 2015; Wang and Zhang 2016; Zhang and Wang 2018). It aimed to fulfill the enrichment of risk theory and methodology and support the decision making on identifying "the three red lines". The study considered geological environment risk caused by human production, livelihood and ecological activities to be the evaluation criteria for carrying capacity of geological environment. Based on such consideration, we proposed concepts of risk-based tolerable and ultimate carrying capacity by multi-disciplinary study, and established a risk-based theoretical and methodological evaluation system for carrying capacity of geological environment.

1 Data and Methods

1.1 Study area

Suide County is located in the southeastern Yulin City in northern Shaanxi Province. It lies in the lower reaches of the Wuding River, serving as a transportation hub connecting Shaanxi, Shanxi, Ningxia and Inner Mongolia, and is therefore named the "land wharf" in northwestern China. It covers a total land area of 1853 km^2 with urban built-up area of 12 km^2. It has a total population of nearly 360,000 people and up to 40% of urbanization rate. The ecological environment in

Suide County is fragile due to its vulnerable geological environment, which makes it one of the towns that suffered most from geological hazards in China (Yuan et al. 2017). Suide County sits in the eastern Ordos platform, with weak tectonic activity and only a few gentle and open folds. The Haojiaqiao fault is mainly developed in the urban area. Historically, Suide County is associated with weak earthquakes. After Mesozoic, it mainly showed a strong downward movement and was subjected to large-scale fine-grained clastic deposits. The tectonic movement has been dominated by an intermittent slow rise during the Quaternary of Cenozoic. Based on the development of three terraces of Wuding river, there were 3 or 4 large-scale intermittent rises since the Pleistocene. The neotectonic movement provides a topographical and material basis for the development of geological disasters.

In the study, an aerial survey using a UAV (unmanned aerial vehicle) with scales of 1:10,000 and 1:2,000 was carried out in and around Suide County, engineering geological drilling was also conducted on typical slopes. Combining with the field survey and engineering geological mapping of slopes, a 28.5 km² slope survey was completed. There are 342 landslides, 49 unstable slopes (Figure 1), and 1 debris flow found. Small shallow landslides induced by rainfall, artificial activities and freezing-thawing, etc. are the most frequent disasters in the study area. A slope is the basic landform unit of landslide disasters, in other words the ideal unit for landslide assessments, thus the area was divided into 1050 slope units (Figure 2).

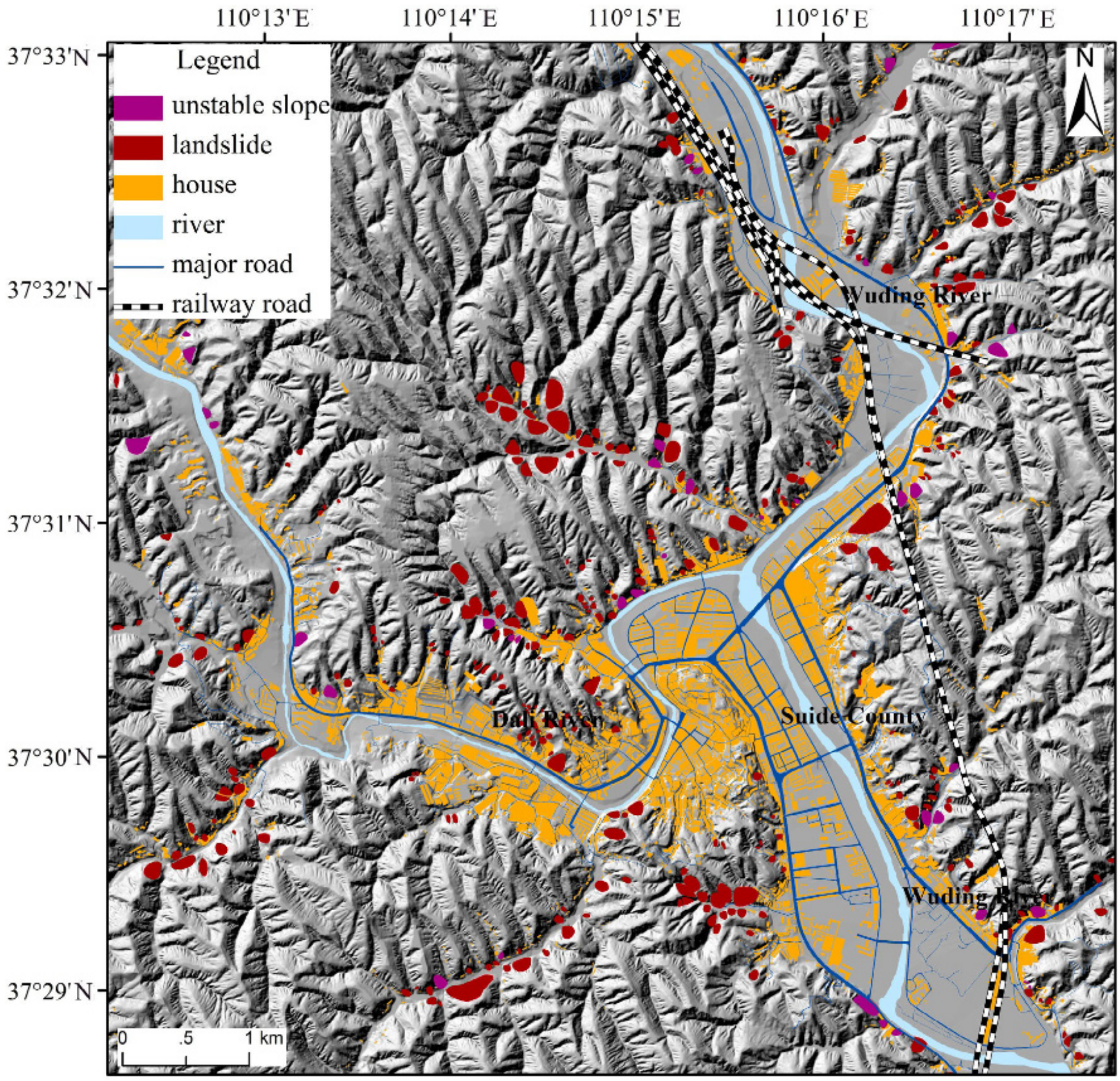

Figure 1 Distribution of collapses and landslides in the urban and planning area of Suide County.

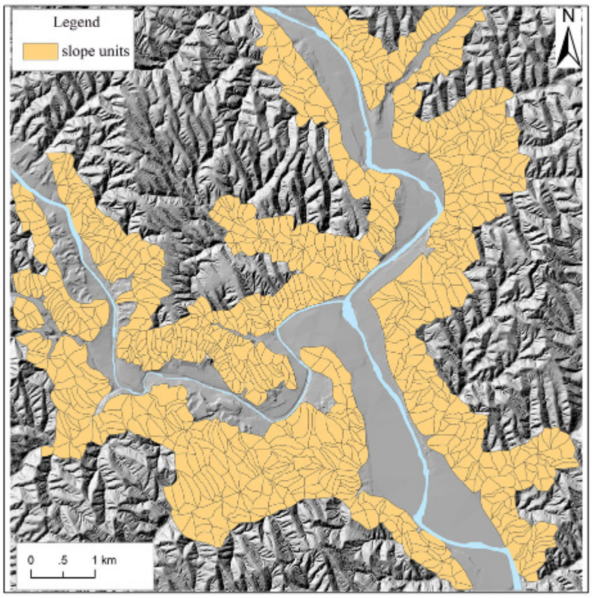

Figure 2 Mapping of slope units in the urban and planning area of Suide County (field survey).

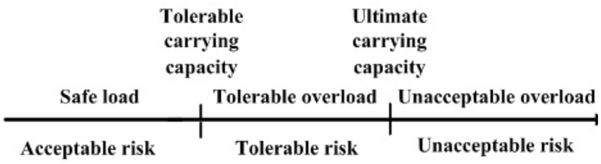

Figure 3 Risk-based geological environment carrying capacity evaluation principles.

1.2 Research data

The research data includes: 1:10,000 UAV aerial survey data in Suide County; field surveys of landslide, unstable slope and artificial slope in Suide County; InSAR-based identification data of geological hazards; 3D laser scanning data of major geological hazards; 1:10,000 geological and geomorphological maps in Suide County; general land use planning database on a village level in Suide County, and the Statistical Bulletin of National Economic and Social Development in Suide County (2017).

1.3 Research method

In the perspective of risk management, the definition of geological environment carrying capacity could be regarded as geo-ecological consequences caused by unreasonably engineered activities. The acceptance levels of human life and property risks incurred by environmental geological problems were regarded as the criteria of carrying capacity of geological environment (Figure 3). A geological environment is considered in safe load when the risk is acceptable, taking the tolerable carrying capacity as its maximum acceptance; it is in tolerable overload when the risk is tolerable, between tolerable and ultimate carrying capacity; it is in unacceptable overload when the risk is unacceptable, exceeding the ultimate carrying capacity (Wang and Zhang 2016).

A risk-based assessment of geological environment carrying capacity includes: (1) Determination of the scope of study. (2) Identification of the geological environmental issues, including unexpected geological hazards such as collapse, landslides and mudslides, etc.; realization of chronic geological hazards such as land subsidence, ground fissures, karst collapse, etc., or environmental engineering geological problems; and awareness of general environmental geological problems such as drying up of aquifers, groundwater pollution, soil pollution, etc. (3) Hazard analysis including identification and classification of potential landslides, collapses, debris flows and the associated frequency estimation. (4) Consequence analysis including identification and quantification of the population at risk, estimation of the spatiotemporal probability of the bearing bodies, evaluation of the vulnerability of the bearing bodies according to life, property and health damage rate. (5) Risk assessment of life, property and health based on the results of hazard analysis and consequence analysis. (6) Single-factor carrying capacity evaluation based on the acceptance levels of the risk. (7) Comprehensive assessment of carrying capacity based on the result of single-factor carrying capacity evaluation of both current and planning carrying capacity.

1.3.1 Hazard analysis of slopes

Hazard analysis grades the possibility of geological disasters of a certain scale in a certain period of time. It is an integrated concept of distribution, scale (intensity) and frequency. Using the Mohr–Coulomb criterion and the Morgenstern–Price model (Feng et al. 2009), the probability of slope instability under different water contents for different slope types was calculated. The parameters selected for the analysis were given in Table 1. Results of slope unit stability under different water content conditions were given in Table 2. The results indicated that with the increase of water content, the area of stable slope units decreases, which means more slopes become unstable.

Table 1 Results of soil rapid shear test under different water content conditions in Suide County.

Parameter type	Water content					
	5%	10%	15%	20%	25%	30%
Cohesion (kPa)	33.87	29.93	27.12	25.0	20.7	18.4
Inner friction angle (°)	24.55	23.85	23.08	21.8	17.2	15.3

Based on the slope instability probabilities at different water contents, the level of hazardousness of each slope unit could be graded as: 1) Very High level, unstable at 0%–15% water content; 2) High level, unstable at 15%–20% water content; 3) Medium level, unstable at 20%–25% water content; 4) Low level, unstable at >25% water content.

1.3.2 Consequence analysis of slopes

The hazard bearing bodies were divided into two categories: buildings & infrastructures and population. However, property and population at no risks of geological hazards were not considered as bearing bodies in this study, since we were focusing on the potential threats of geological hazards. The building & infrastructure includes residential building, residential housing, railways and highways. Population includes direct, indirect and floating population. In this study, the buildings, railway and main roads were extracted from 1:10,000 UAV aerial survey data of the research area, regarded as the main geological hazard bearing bodies.

The vulnerability of the hazard bearing body mainly depends on their structure and their resistance to disasters. According to "Guidelines for landslides susceptibility, hazard and risk zoning for land use planning" (Fell et al. 2008), the vulnerability of the bearing bodies was scored from 0 to 1, where 0 stands for no damage and 1 stands for totally damaged. Additionally, based on field surveys, the types of disaster bearing bodies in Suide County and the planning area and their vulnerability to corresponding risks were given in Table 3.

Consequence analysis ranks the severity of potential undesirable outcomes of geological disasters. It is defined as a function of the bearing bodies (population or economic value) and vulnerability, which is the product of population/economic value and vulnerability. Based on the vulnerability analysis and classification of the bearing bodies, as well as taking the scale and type of hazards and the size of the bearing bodies into account, we ranked potential geological hazards by the level of consequence according to the following principles:

Geological hazards that occurs in major constructions around the town or residential areas with a population of greater than 500 people would be regarded as a Tremendous hazard; occurs in

Table 2 Results of slope unit stability under different water content conditions in Suide County

Water content	Area (km²)		Area ratio (%)		Number		Proportion (%)	
	Stable	Unstable	Stable	Unstable	Stable	Unstable	Stable	Unstable
5%	28.03	0.48	98.32	1.68	355	36	90.79	9.21
10%	27.06	1.45	94.91	5.09	300	91	76.73	23.27
15%	24.95	3.56	87.51	12.49	212	179	54.22	45.79
20%	20.55	7.96	72.08	27.92	81	310	20.72	79.28
25%	14.67	13.84	51.46	48.54	28	363	7.16	92.84
30%	6.68	21.83	23.43	76.57	10	381	2.56	97.44

Table 3 Vulnerability classification of hazard bearing bodies in Suide County and planning districts

Vulnerability level	Hazard bearing bodies						
	Buildings & infrastructure				Population		
	Residential building	Residents housing	Railway	Highway	Direct population	Indirect population	Floating population
Very high	0.9	1.0	1.0	1.0	1.0	0.7	0.6
High	0.6	0.8	0.8	0.8	0.8	0.5	0.4
Medium	0.3	0.6	0.6	0.6	0.6	0.3	0.2
Low	0.1	0.3	0.3	0.3	0.3	0.1	0.0

general buildings around the town or residential areas with a population between 100 to 500 would be a Huge hazard; occurs in residential areas in valleys around the town with a population between 10 to 100 would be a Large hazard; occurs in residential areas in valleys around the town with a population less than 10 people would be a Normal hazard.

1.3.3 Risk estimation of landslides

Risk is a function of hazardousness and consequence.

$$R = f(H, D) \tag{1}$$

In which:

R —— risk

H —— hazardousness from hazard analysis

D —— consequence from consequence analysis

In terms of conditional probability, a landslide risk for properties (i.e. building) can be determined as follows (Fell et al. 2008):

$$R_{(prop)} = P_{(L)} \times P_{(T:L)} \times P_{(S:T)} \times V_{(prop:S)} \times E \tag{2}$$

In which:

$R_{(prop)}$ —— expected annual loss due to landslide

$P_{(L)}$ —— annual probability of occurrence of a landslide of a given magnitude

$P_{(T:L)}$ —— probability of a landslide reaching the bearing body

$P_{(S:T)}$ —— spatiotemporal probability of the bearing body

$V_{(prop:S)}$ —— vulnerability of the bearing body

E—— cost of the bearing body

Single life risk was calculated by the following formula:

$$P_{(LOL)} = P_{(L)} \times P_{(T:L)} \times P_{(S:T)} \times V_{(D:T)} \tag{3}$$

Where:

$P_{(LOL)}$ —— annual probability of loss of life

$V_{(D:T)}$ —— vulnerability of the person

Other definitions are the same as above.

The estimation considered the results of hazard analysis and consequence analysis comprehensively. According to the life risk classification standard, and property and health risk classification standard (Wang and Zhang 2016), the geological disaster risk of Suide County and planning area was then divided into four levels: Very High risk (VH), High risk (H), Medium risk (M) and Low risk (L). The risk assessment results were mapped according to the risk classification.

1.3.4 Evaluation of the carrying capacity of the base period

Based on the risk assessment of slopes, and by using Analysis Tools in ArcToolbox in ArcGIS, we defined Very High risk and High risk areas as unacceptable overloading areas; Medium risk areas as acceptable overloading areas; and Low risk areas as safe areas for carrying capacity. By overlapping the carrying capacity assessment map with the current land use map of cities and towns, we delineated prohibited development zone for unacceptable overloading areas, restricted development zone for tolerable overloading areas, and prior development zone for safe areas.

1.3.5 Evaluation of planning carrying capacity

According to the sliding distance investigation result and the theoretical frequency analysis of rainfall induced landslide in Shaanxi Loess Plateau, we set a 70-meter buffer zone for Very High risk area, a 50-meter buffer zone for High risk areas, a 20-meter buffer zone for Medium risk areas, and no buffer zone for Low risk areas. Combining the results of the slope risk assessment and the landslide buffer zone analysis, all the slopes are in unacceptable overloading state, the landslide buffer zones are in tolerable overloading state, and other areas are safe areas in terms of carrying capacity. By intersecting the carrying capacity assessment map with the land use planning map of cities and towns, we delineated prohibited development zone for unacceptable overloading areas, restricted development zone for tolerable overloading areas, and prior development zone for safe areas.

2 Results and Discussion

2.1 Hazard analysis of slopes

The hazardousness distribution of slope units in Suide County and surrounding areas was mapped in Figure 4. Within a total area of 28.50 km^2, 3.56 km^2 of unstable slopes were marked as Very High risk; 4.40 km^2 of unstable slopes were High risk; 5.88 km^2 of unstable slopes were Medium risk; and 14.67 km^2 of slopes were considered Low risk, among which, 7.99 km² were unstable and 6.68 km² were stable.

2.2 Consequence analysis of slopes

The ranked consequence distribution of slope units in Suide County and surrounding areas was mapped in Figure 5. The slopes with the potential of Tremendous hazard were Gaoshijiao village, Bianshang village, and Liujiawan brickyard; those with the potential of Huge hazard were Shilipu village, Wangjiazhuang village, Wuliwan village, Majiawa village, Xinshichang community and relative courtyard of Post Office; those with the potential of Large hazard are Gaoli brickyard and Longwan village.

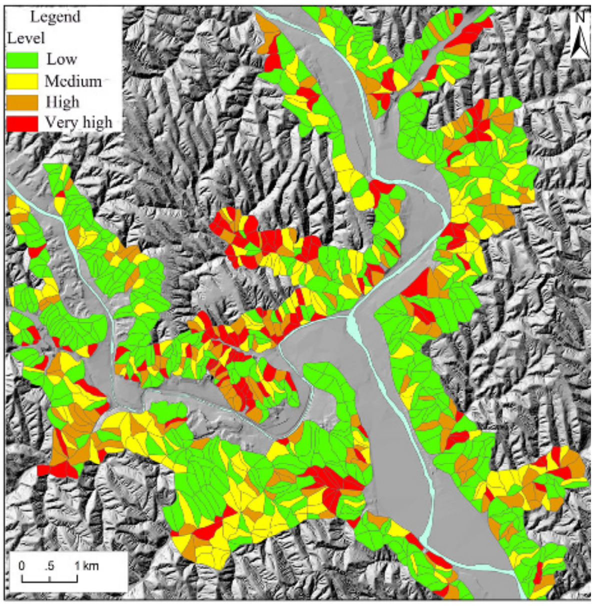

Figure 4 Graded hazardousness distribution in and around Suide County.

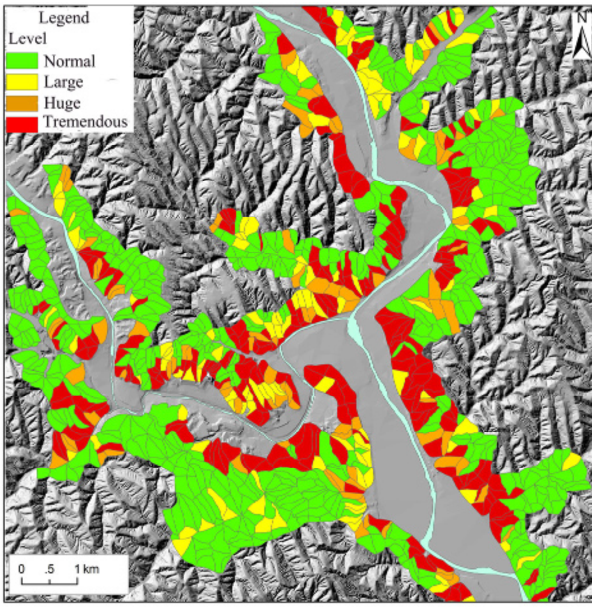

Figure 5 Graded consequence distribution in and around Suide County.

2.3 Risk estimation of landslides

Integrating the results of hazard analysis and consequence analysis, the risk distribution in Suide County and surrounding areas was mapped in Figure 6. Most areas were comparatively safer with smaller risk of landslides, since the study area was covered by 36.48% of Medium risk and 44.93% of Low risk. Nonetheless, nearly a fifth of the area was threatened with relatively higher potential of landslides that requires more attention, covered by 7.96% of Very High risk and 10.63% of High risk.

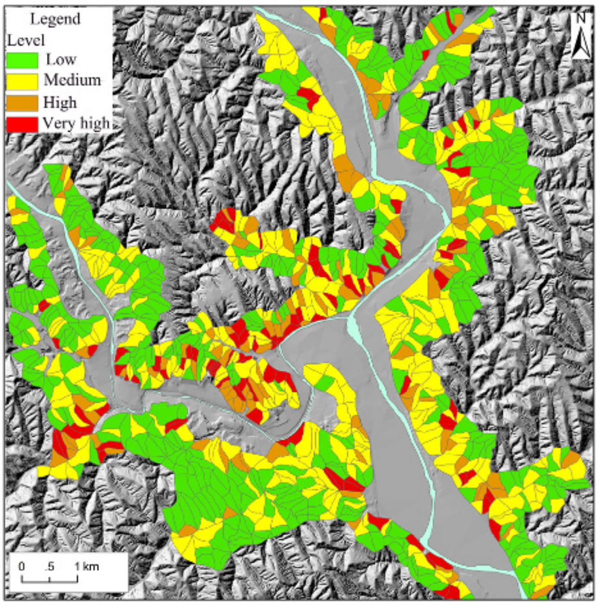

Figure 6 Risk distribution in and around Suide County.

2.4 Evaluation of carrying capacity

It is illustrated in Figure 7 and Figure 8 that the present unacceptable overloading areas and prohibited development zones were mainly distributed on the north bank of Dali river in Suide County, and along Majiawa village to Mujialou on the south bank of Dali river, while the rest sporadically scattered over other areas. The prohibited development zones contain 220 slope units, covering a total of 5.30 km². There are 201 previous landslide sites in the zone, where 889 houses with a total area of 95.55×10⁴ m² were in bad conditions due to landslides, dense population and buildings. It suggested that the population in the area should be watching for steep loess slopes by conducting monitoring and early warning, and if possible, relocate the local inhabitants and houses.

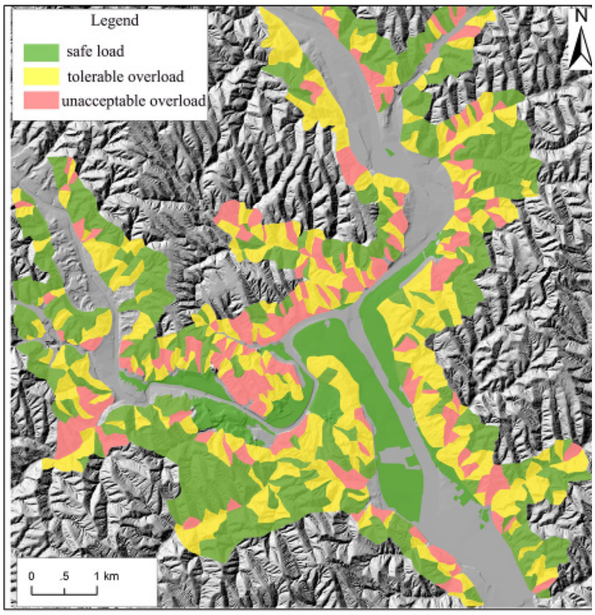

Figure 7 Evaluation diagram of the base period carrying capacity of the central district of Suide County.

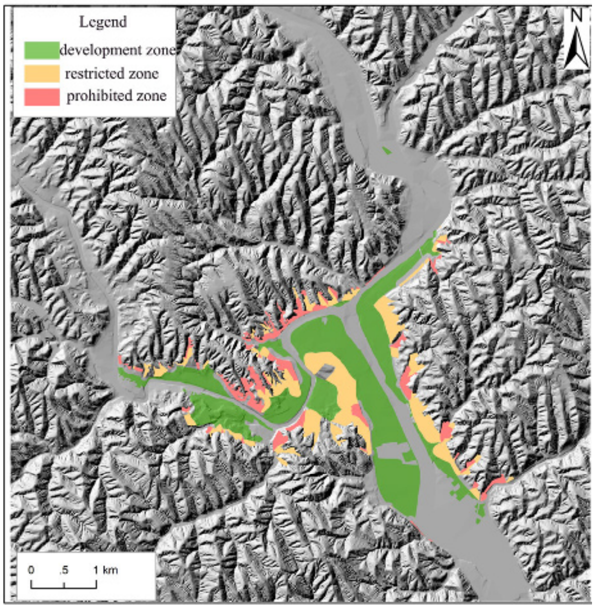

Figure 8 Land use recommendations for the base period in Suide County.

During flood season, patrolling should be strengthened and the engineering measures shall be taken in case of any incident.

The current tolerable overloading areas and restricted development zones were distributed on the slopes along Wuding river and the Dali river. The restricted development zones contain 362 slope units, covering an area of 10.40 m², and at 161 previous landslide sites where 1521 houses with a total area of 104.60×10⁴ m² were at risk. The strengthening of disaster control education and publicity to the local community is advocated, as well as patrolling in flood season.

The current safe bearing areas and prior development zones were distributed in the deep valleys and areas with fewer people. The prior development zones contained 468 slope sections, covering an area of 12.81 km², and there are 29 previous landslide sites where 851 houses with a total area of 2.84×10⁴ m² were exposed. Although these zones were sorted into the low risk areas, there is still possibility of geological hazards. Therefore, promotion of disaster control education and publicity to the local community in the area should be considered, and patrolling in the flood season would be necessary.

As were shown in Figure 9 and Figure 10, for the unacceptable overloading areas, comprehensive prevention and controlling measures of hazards should be taken according to the causes of different

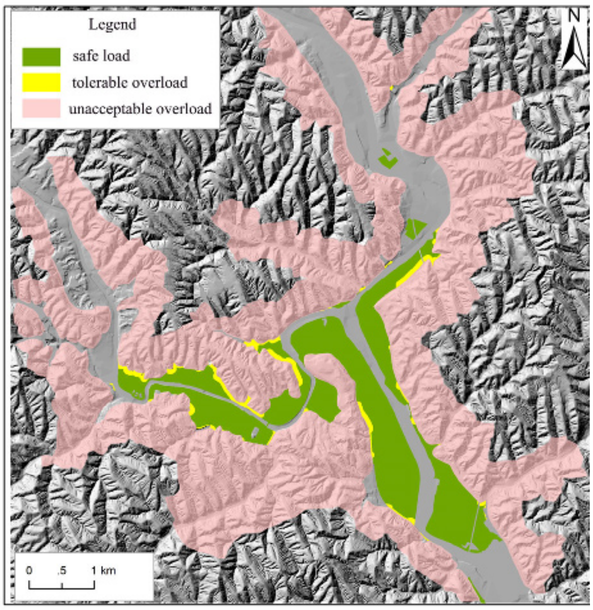

Figure 9 Evaluation of planning carrying capacity of the central district of Suide County in 2020.

geological environment problems. Relevant departments of Yulin city concerning geological disasters should strengthen and improve the monitoring and prevention system on a community level, in conjunction with concerted effort from relevant agencies of the state, province, and city. Moreover, these agencies should cooperate to establish a professional carrying capacity monitoring and early warning network system in Suide County. The tolerable overloading and safe bearing zones in planned 2020 Suide urban area, which were also in the restricted and the prior development zones, covers a total area of 7.56 km^2. According to the national minimum construction land standard which is 60.1 m^2 per person, the allowable population of the central urban area should be 125,800 people, while the planned population is 144,400 by 2020. Therefore, a reduction of 18,600 people was proposed for the coordination of urbanization between land and population, so as to reasonably control the scale and speed of the urban land expansion. In other words, to prevent the towns from blindly expanding construction land and excessively pursuing the process of population urbanization and employment structure transformation.

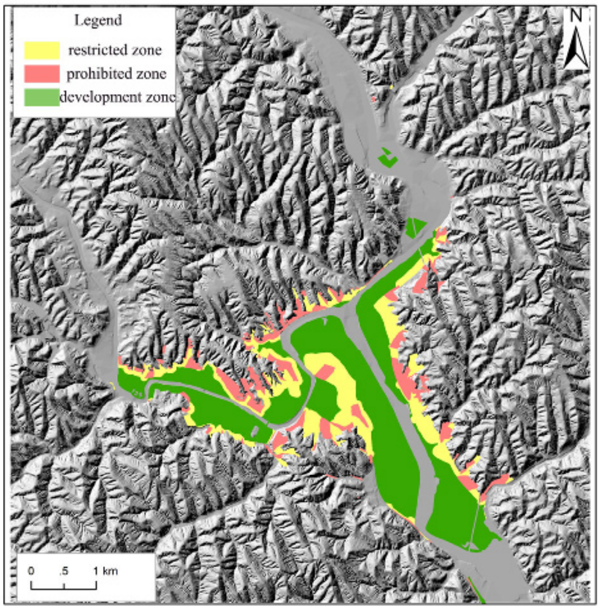

Figure 10 Land use layout for the planned urban area of Suide County, 2020.

3 Conclusion

This study of typical mountain city was located in the Loess Plateau in Suide County of northern Shaanxi Province. Based on field survey results, the main potential risks restricting socioeconomical development were recognized and classified according to different slope structure. The hazardousness of disasters and the vulnerability of bearing bodies were analyzed in terms of characteristics of mass-movements, path of flow and possibility of reaching the bearing bodies. Whereafter, a comprehensive risk evaluation at the scale of 1:10,000 with a defined threshold standard was conducted on this basis. Since the risk of geological hazards is the shared restraining force, this risk-based evaluation system can provide a reference for other important mountain cities.

The carrying capacity evaluation results in Suide County showed that: The area of unacceptable loading was 5.30 km^2, which contained 201 previous landslide sites and 889 houses in danger. The area of tolerable overloading was 10.40 km^2, which included 161 previous landslide sites and 1,521 houses in danger. The area of safe bearing was 12.81 km^2, which included 29 previous landslide sites. A comprehensive evaluation of the carrying capacity of urban areas in the base period and the planning period in Suide County was also conducted and mapped. Suggestions were put, including a proposal of population control of at most 125,800 people in the central urban area of Suide County by 2020. Combining the evaluation result with practical situation of disaster prevention and control in Suide, countermeasures and suggestions were given against different levels of carrying capacity, providing reference for city planners and decision makers.

This study only presented the concept and assessment framework of risk-based geological environment carrying capacity and plays the role of throwing out a minnow to catch a whale. There are still details to look into: the fully integration of risk theory (Zhang and Tang 2008), functional optimization of production/life/ecology theory (Huang et al. 2017), and geological environment theory (Chen 1995); to carry out a detailed and in-depth study to thoroughly understand the essence of resources and environment carrying capacity; and to form a systematic and scientific resources and environment carrying capacity assessment system.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (Grant No.41641011) and the Special Funds of Geological Mineral Resources and Environment Investigation Project (Grant No.DDT20160087). We thank the comprehensive geological investigation team of Guanzhong Basin city cluster from Xi'an Geological Survey Center of China Geological Survey. We acknowledge the leasers and colleagues from the Development Research Center and the Strategy and Intelligence Research Office of China Geological Survey who helped the research, for the inseparable cooperation over the years. We appreciate the valuable suggestions by CHEN Rui-shan from East China Normal University, and we are extremely grateful for the constructive comments from the editor and anonymous reviewers on earlier versions of the manuscript.

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