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Measuring county resilience after the 2008 Wenchuan earthquake

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Abstract

The catastrophic earthquake in 2008 has caused serious damage to Wenchuan County and the surrounding area in China. In recent years, great attention has been paid to the resilience of the affected area. This study applied a new framework, the Resilience Inference Measurement (RIM) model, to quantify and validate the community resilience of 105 counties in the affected area. The RIM model uses cluster analysis to classify counties into four resilience levels according to the exposure, damage, and recovery conditions, and then applies discriminant analysis to quantify the influence of socioeconomic characteristics on the county resilience. The analysis results show that counties located right at the epicenter had the lowest resilience, but counties immediately adjacent to the epicenter had the highest resilience capacities. Counties that were farther away from the epicenter returned to normal resiliency. The socioeconomic variables, including sex ratio, per capita GDP, percent of ethnic minority, and medical facilities, were identified as the most influential socio-economic characteristics on resilience. This study provides useful information to improve county resilience to earthquakes and support decision-making for sustainable development.

1 Introduction

Wenchuan County in Sichuan Province, China and its surrounding counties are a region prone to frequent and destructive earthquakes and their accompanying secondary disasters (Chen et al., 2007). The Wenchuan earthquake that occurred in 2008 is known for its huge destruction and high mortality. The magnitude 7.9 earthquake caused more than 69 227 deaths and property damage of over 845.1 billion RMB (Guo, 2012). Due to the mountainous landscape, low economic development, and poor infrastructure, Wenchuan County and its surrounding regions are extremely vulnerable to earthquakes and secondary disasters such as landslides and barrier lake flood. Although these counties have similar characteristics in many aspects, it is observed that some counties had less damage during earthquakes and recovered more quickly afterwards. According to these observations, two questions are put forward: (1) are some counties more resilient to earthquakes than others; and (2) what socioeconomic characteristics make a county more resilient? The answers to these two questions could help improve the resilience of counties by promoting or controlling certain socioeconomic characteristics.

The ability to survive and recover through disasters is referred to as resilience. There is an extensive literature on definitions (Holling, 1996), frameworks (Bruneau et al., 2003; Cutter et al., 2003) and case studies (Boruff et al., 2005; Cutter et al., 2003, 2010; Reams et al., 2012) of county resilience. However, few convincing approaches measured resilience quantitatively and with validation. The challenges of measuring community resilience to disasters are many. First, due to the diversity on characteristics of disaster, natural and social processes, and definitions of the terms, there is significant controversy on how to identify the main factors. Second, the many subjective factors and inaccurate weights assigned to variables make the measurement model difficult to generalize and apply to other contexts. Third, some study results, which have explored seismic resilience of counties, have seldom been validated (Bruneau et al., 2003; Chang and Shinozuka, 2004). To address some of these issues, Lam and other researchers developed the Resilience Inference Measurement (RIM) model to quantify the community resilience (Lam et al., 2014; Li, 2011). The RIM model has been successfully applied in the Gulf of Mexico region to measure county resilience to coastal hazards (Li, 2011). The RIM model is theoretically sound, enables empirical validation, and can be easily extended to various disasters and different areas (Lam et al., 2014).

The RIM model overcomes several major difficulties in assessing resilience. This study applies the RIM model to analyze quantitatively seismic resilience after the 2008 Wenchuan earthquake. We focus on the quake-prone region in Southwestern China, specifically the hardest-hit counties of Sichuan, Gansu, and Shaanxi provinces by the 2008 Wenchuan earthquake. Due to the limitation on data availability, a total of 105

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counties around the epicenter that had the most serious economic loss caused by the Wenchuan earthquake were selected for this study.

2 Related work

The term resilience is involved in multiple disciplines ranging from engineering, psychology, environment, sociology to geography, and beyond. The original definition of resilience from the Merriam-Webster Dictionary is "the ability to become strong, healthy, or successful again after something bad happens; the ability of something to return to its original shape after it has been pulled, stretched, pressed, bent, etc." Holling (1996) defined resilience in two forms: engineering resilience, which refers to the ability of returning to its original state, and ecological resilience, which indicates the ability to sustain successfully its original state after disturbance. Adger et al. elaborated that resilience includes two elements: the ability to self-organize and the capacity to learn and adapt (Adger et al., 2010). Bruneau et al. (2003) expressed a broad conceptualization of seismic resilience as "the ability of a unit to reduce failure probabilities, consequences from failures, and time to recovery". They further defined resilience for both physical and social systems to consist of four properties: robustness, redundancy, resourcefulness, and rapidity (Bruneau and Reinhorn, 2006). Recently, the concept of resilience is often mixed with other closely related concepts such as vulnerability, adaptability, and sustainability, making the measurement of resilience more complicated.

The different understandings of resilience cause various viewpoints on resilience measurement in many studies. Also, the concept varies when disaster occurs in different natural and socioeconomic environments, which makes it very difficult to select indicators for resilience measurement. Brooks and others (Brooks et al., 2005) presented a set of national-level indicators of vulnerability and capacity to adapt to climate variability using a novel empirical analysis. Based on statistical correlations, 11 variables that had the highest correlations with mortality were selected from a pool of 46 vulnerability variables. These variables were then assigned a weighted score from 1 to 5 by a focus group of experts. By averaging the weighted scores of all selected variables, an aggregated index was obtained to represent vulnerability and capacity to adapt to climate variability. Brooks' approach used expert knowledge as a form of validation; it lacked quantitative validation of the derived index. Cutter et al. (2003) constructed the Social Vulnerability Index (SoVI) to assess social vulnerability to environmental hazards using county-level socioeconomic and demographic data in the United States. The method produced 11 factors from 42 variables to explain 76.4 % of variance based on factor analysis, and created SoVI scores using the factor scores for each county. Cutter et al. (2010) subsequently introduced another set of indicators to derive the Baseline Resilience Index for Communities (BRIC). However, both the SoVI and the BRIC approaches lacked empirical validation of the variable selection and weighting. This shortcoming exists in many studies on resilience measurement. The RIM model gave us an approach to overcome some of the difficult problems discussed above.

In the context of seismic disaster, recent studies that focus on resilience or vulnerability assessment are generally based on loss estimation, particularly economic loss estimated from physical damage to infrastructures (Cho et al., 2001). Bruneau and others (2003) developed a framework to assess seismic resilience from economic losses and the speed of recovery in four resilience dimensions (technical, organizational, social, and economic) of five systems ("global", electric power, water, hospital, and response and recovery systems). Chang and Shinozuka (2004) outlined a more succinct series of measures based on the framework developed by Bruneau et al. (2003) and reframed it in a probabilistic context. However, those factors in the framework often cannot be observed or measured and have to be quantified according to human experience, which leads to bias in the measurement of seismic resilience. Moreover, measurement of socioeconomic status is insufficient in the assessment framework of seismic resilience which is usually based on loss estimation. As influence on life quality caused by seismic disasters draws increasing attention from people, there becomes a need to consider the recovery and adaptive aspect of a community after the disaster. For the reason

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above, and building on the RIM model (Lam et al., 2014; Li, 2011), we aim to assess seismic resilience by choosing the population growth rate as the key indicator of the recovery capability of counties in the area where counties were hit hard in Sichuan, Gansu, and Shaanxi provinces by the 2008 Wenchuan earthquake.

The heavy mortalities and property loss caused by the Wenchuan earthquake have captured extensive public attention. However, relatively few studies have been conducted concerning the earthquake, especially on the community resilience assessment. Most studies were devoted to the physical aspect of the earthquake, such as studies on debris-flow (Tang et al., 2012), landslide (Dai et al., 2011; Gorum et al., 2011; Guo and Hamada, 2013; Tang et al., 2011; Xu et al., 2012), gas emission (Zheng et al., 2013), gravelly soil liquefied (Cao et al., 2011), surface deformation (Fu et al., 2011), and stress evolution (Nalbant and McCloskey, 2011; Shan et al., 2013) of Longmenshan fault zone (Li et al., 2013; Ran et al., 2013) triggered by the 2008 Wenchuan earthquake. Y. Guo (2012) proposed a post-disaster urban resilience design framework focusing on governmental reconstruction. Comparing scenarios of governmental reconstruction with key aspects of urban resilience, Guo explored alternative scenarios of reconstruction and indicated that it is critical to consider the specific post-disaster urban context of the many urban components, elements, networks, dynamics, and capacities so that they can make radical social and spatial changes to cope with future disaster (Guo, 2012). However, Guo's study did not provide a quantitative measure to evaluate urban resilience. There is urgent need to evaluate and quantify seismic resilience of the affected region of Wenchuan earthquake. Our study on resilience assessment of the affected region using the RIM model will fill this void.

3 The Resilience Inference Measurement (RIM) model

In the RIM model, community resilience is defined by three dimensions and two abilities (Lam et al., 2014; Li, 2011). The three dimensions of resilience are (1) the exposure to hazards (such as the number of times a community is hit by earthquake), (2) the

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damage from exposure to hazards (such as property damage), and (3) the recovery (such as population return). The two “abilities”, vulnerability and adaptability, indicate the relationships from exposure to damage and from damage to recovery (Fig. 1). Communities with high vulnerability are those suffering from high damage under low exposure. Similarly, communities with high adaptability recover quickly from high damage. They are represented as the slopes of the lines between exposure and damage and between damage and recovery in Fig. 2. There are four resilience rankings in the RIM framework. From high to low, the framework includes four states: usurper, resistant, recovering, and susceptible. Resilience of community is classified as one of the resilience rankings according to the two abilities (vulnerability and adaptability). In general, susceptible communities have high vulnerability and low adaptability. Recovering communities have average vulnerability and adaptability. Resistant communities have low vulnerability and average adaptability, while usurper communities have low vulnerability and high adaptability (Lam et al., 2014; Li, 2011).

Applying the RIM model involves two statistical procedures. Firstly, K-means cluster analysis was conducted to derive the a priori resilient rankings for the 105 counties (susceptible, recovering, resistant, and usurper). Each observation is regarded as a multidimensional real vector, and K-means cluster analysis segregates the n observations into k sets in order to minimize the within-cluster sum of squares (Hartigan and Wong, 1979):

$$\arg\min_{S} \sum_{i=1}^{k} \sum_{x_j \in S_i} \left\| x_j - \mu_i \right\|^2 . \quad (1)$$

where $X = (x_1, \ldots, x_n)$ is the data matrix of observations, $S = \{S_1, \ldots, S_k\}$ stands for k sets, and μ_i is the mean of points in S_i.

Then, discriminant analysis was used to characterize the a priori resilient groups via a number of socioeconomic indicators. Discriminant analysis is commonly used in constructing a function to distinguish a set of observations according to previously defined groups (Klecka, 1980). Also it can be used to evaluate whether cases are classified as predicted. Given the independent variables (socioeconomic indicators) and dependent variable (K-means groups) for each observation, discriminant analysis derives discriminant functions as a linear combination of independent variables (Klecka, 1980):

$$L = b_1x_1 + b_2x_2 + \ldots + b_nx_n + c \quad (2)$$

where $b = \{b_1, \ldots, b_n\}$ are the discriminant coefficients which maximize the distance between the means of dependent variables; $x = \{x_1, \ldots, x_n\}$ are the independent variables for each observation; and c is a constant.

Based on the derived discriminant functions, classification functions can be computed. The procedure will then re-classify the observations into one of the four groups based on the observation's independent variables (e.g., socioeconomic indicators). This posterior classification from discriminant analysis can be compared with the a priori classification from K-means analysis, and the classification accuracy can be used to indicate how good the set of independent variables are in distinguishing the four groups. If the classification accuracy is high and the statistical assumptions of discriminant analysis are met, the set of classification functions can be used to predict the resilience group membership for observations in other regions. Thus the RIM model for resilience assessment has two main advantages: validation by using the damage data and inferential potential by employing inferential statistics (Lam et al., 2014; Li, 2011).

4 Measuring the resilience

4.1 Study area and data

On 12 May 2008, a magnitude 7.9 devastating earthquake in Wenchuan County (31°00′ N, 103°24′ E) caused more than 69 227 deaths and 845.1 billion RMB in property loss. Six provinces and 15 million people were directly affected by the earthquake. An overwhelming majority of mortality and damage was caused in the area around the epicenter which lies in Sichuan, Gansu and Shaanxi provinces (Fig. 3). In historical records, within a 200 km radius of the Wenchuan earthquake epicenter, an earthquake equal to or above magnitude 7 takes place about every 40 years. In the last century, the other two destructive earthquakes also took place in the region: the 7.5-magnitude earthquake in Maoxian County on 25 August 1933 at 31°54′ N, 103°24′ E, which is about 100 km away from the epicenter of Wenchuan earthquake, and killed about 9000 people, and the 7.2-magnitude earthquake in the boundary between Songpan County and Pingwu County on 16 August 1976 (32°36′ N, 104°06′ E), which is about 190 km from the epicenter of Wenchuan earthquake. The communities and cities in the surrounding region of Wenchuan County are highly exposed to earthquakes with high magnitude and huge destructiveness. Although this region is generally very vulnerable to earthquakes due to the weak economic foundation, less diverse industrial structure, and poor social resources, some counties had better performance (e.g. lost less and recovered more quickly) during and after the disasters. Therefore, finding the factors that made the counties perform better is the key to promote resilience.

Due to the data availability of reported property damage and affecting range of the earthquake, 105 counties near the epicenter of Wenchuan earthquake were selected as the study area, which lie across three provinces, Sichuan, Shaanxi and Gansu (Fig. 3). The study counties were selected according to the following criteria. First, the county was evaluated as the worst-hit area by China Earthquake Administration (2008b). Second, economic loss data for the county is available from a credible source (in this case, the official yearbooks). Third, the county did not have more than 10 % administrative boundary changes between 2000 and 2011. Since the socioeconomic data was collected during this period, significant boundary changes may bias the analysis. For example, about 15 counties in Sichuan Province, such as Songpan, Beichuan, Anxian, and others, had significant administrative boundary changes during 2002–2012. They were not included in the study even though some of them had serious damages from the earthquake.

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As described in the previous section, resilience consists of three dimensions: exposure, damage and recovery. In this study, (1) the exposure indicator is the intensity of the 2008 Wenchuan earthquake (Fig. 4), which is commonly used to quantify the destructiveness of seismic disaster (Eiby, 1966). The intensity distribution of the Wenchuan earthquake was obtained from the U.S. Geological Survey (USGS) (2008a). (2) Since there is very limited official publication of mortality data for the Wenchuan Earthquake at the county level, direct economic loss per capita caused by the earthquake was selected as the damage indicator (Fig. 5), which were collected from Sichuan Yearbook (2009), Shaanxi Yearbook (2009), and Gansu Yearbook (2009) published by the Provincial People's Government (2009a, b, c). (3) The recovery status is estimated by the population growth rates from 2002 to 2011, which were obtained from the provincial statistical yearbooks published by the Provincial Bureau of Statistics (2003a, b, c, 2012a, b, c). It is noted that researchers examining sources of recovery following disturbances have not reached consensus on the best way to measure recovery (Bevington; et al., 2011). Although the recovery status of a county could also be represented by other aspects, such as GDP and income growth, we chose population growth as the recovery indicator because the variable has often been seen to indicate the summative outcome of various aspects of recovery (Chang, 2010; Li et al., 2010). Moreover, population data is relatively easy to find, making comparison and generalization across space and time possible.

The intensity of the 2008 Wenchuan earthquake ranged from 9.14 to 3.0 MMI (Modified Mercalli Intensity scale) in the study area. The original data were in MMI contour-polygon form in intervals of 0.2 intensity units. The MMI original data was first interpolated into raster of 6.72 km pixels (Fig. 4) by the "Topo to Raster" tools in ArcGIS 10. Then we utilized the "Zonal" tools to obtain the average intensity in each county to represent its exposure. The top five counties that had the highest exposure were all in Sichuan province, including Mianzhu City (average intensity: 8.46 MMI) Shifang City (8.21 MMI), Dujiangyan City (8.15 MMI), Pengzhou City (8.07 MMI), and Wenchuan County (7.49 MMII).

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As for the damage indicator, the top five counties that had the greatest economic loss per capita caused by the 2008 Wenchuan earthquake were Wenchuan County (CNY 618 269.23), Lixian County[1] (CNY 538 695.65), Mianzhu City (CNY 276 848.25), Shifang City (CNY 205 311.78), and Maoxian County (CNY 203 669.72); all of them are located in Sichuan province.

We chose population growth rate from 2002 (pre-event status) to 2011 (post-event status) as the recovery indicator for each county in this study (Fig. 6). The top five counties with the highest population growth rates were all from Sichuan province as well, including Yuexi County (31.2 %), Chengdu Metropolitan Area (30 %), Hongyuan County (25 %), Abaxian County (22.95 %), and Wenjiang District (22.33 %). The bottom five counties that had the lowest population growth were Xixiang County (−14.16 %), Wenxian County (−14.06 %), Yangxian County (−12.81 %), Nanzheng County (−12.39 %), and Lixian County (−11.8 %). Population growth rate in Wenchuan County (−9.82 %) was lower than most of the counties in the study area, which reflected that Wenchuan County had difficulty in recovery after the earthquake.

4.2 Clustering resilience groups

Next, K-means cluster analysis was conducted to derive the four resilience groups according to the exposure, damage, and recovery indicators. All the raw data has been converted into z-score before the cluster analysis. Figure 7 plots the groups derived from the K-means analysis and Table 1 shows the number of counties in each cluster. Figure 8 maps the group membership of the 105 counties.

The most severe economic loss occurred in Wenchuan County and Lixian County, which made up the susceptible group. The line graphs (Fig. 7) show that the average economic loss per capita in these two counties was much higher than other groups, despite that they did not have the highest average intensity of the earthquake. Also, these two counties showed the lowest population growth after the earthquake. Both

[1] Without special note, Lixian County is the one which located in Sichuan Province.

counties are located at the epicenter, and are thus expected to have the lowest resilience (Fig. 8). However, it is observed that resilience rose to the highest level in the counties immediately surrounding these two counties. The remaining counties farther away from the epicenter showed average resilience.

4.3 Discriminant analysis

After the cluster analysis, discriminant analysis was carried out to test whether the resilience level of a county can be predicted by its socioeconomic characteristics. Discriminant analysis was also used to validate the accuracy of the a priori groups.

In light of previous vulnerability and resilience research and considering the difference in data definition and availability in China (Cutter et al., 2003; Nelson et al., 2009), 15 socioeconomic variables that describe pre-event conditions of the counties were selected for the discriminant analysis (Table 2). The pre-event condition (Year 2000) should be used, instead of the post-event condition, to indicate how the underlying socioeconomic capacity can withstand disasters. These variables represented the demographic, social, economic, health, and social welfare capitals of each county in the study area. The majority of variables were collected from the 2000 population census published by the National Bureau of Statistics of the People's Republic of China (2001). The national population census was conducted every 10 years and Year 2000 is the closest year before the Wenchuan Earthquake. The other variables were collected from provincial yearbooks near Year 2000 to be consistent with the census variables, including the Provincial Statistical Yearbooks 2002 published by the Provincial Bureau of Statistics (2003a, b, c). Before performing discriminant analysis, the 15 socioeconomic variables were normalized by converting into densities per square mile, per capita, or percentage.

The four a priori groups derived by K-means cluster analysis and the 15 predictor variables were entered into discriminant analysis in SPSS statistical package as grouping variable and independent variables. Using discriminant analysis, three discriminant functions linearly combined predictor variables were obtained. Two of the

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discriminant functions, which explained 70.1 and 24.8 % (accumulating to 94.9 %) of the total variance, respectively (Table 3), were statistically significant, while the third function described the remaining 5.1 %.

The discriminant functions provide probabilities of group membership for each county. According to the probability of group membership, each county was classified into one of the four groups. The group membership predicted by discriminant analysis matched 85.7 % of the a priori groups derived from K-mean analysis, which means that the 15 selected socio-economic variables can discriminate 85.7 % of the 105 counties' resilience level. Only 15 counties were misclassified. The counties' resilience rankings and misclassified counties are shown in Table 4.

5 Results

5.1 Spatial distribution of resilience

The predicted group memberships by the discriminant functions are illustrated in Fig. 9, which shows that 20 of the 105 counties were classified as Group Usurper, and 10 were in Group Resistant, followed by 72 in Group Recovering and the remaining 3 in Group Susceptible. The spatial distribution of county resilience shows a generally spatially contiguous pattern. Counties in the epicenter area (Wenchuan County, Lixian County, and Maoxian County) had the lowest resilience to earthquake among all the study counties. Maoxian County was not classified as Susceptible by K-means analysis but was classified as Susceptible by discriminant analysis based on its socioeconomic variables. Counties east of the epicenter area (such as Pengzhou City, Mianyang Metropolitan Area, Pingwu County, and Shifang City) maintained high population growth despite the earthquake disaster. Counties in Chengdu City and Aba Prefecture generally had higher resilience to earthquake disaster than any other counties, such as Chengdu Metropolitan Area, Longquanyi District, and Wenjiang District. All of the counties in Gansu and Shaanxi province were classified as Group Recovering. In general, counties in Group Susceptible were concentrated in the epicenter area, whereas counties immediately neighboring the three susceptible counties had high resilience rankings belonging in either Usurper or Resistant groups. With a few exceptions, the rest of the counties farther away from the epicenter were classified as Group Recovering by both K-means and discriminant analysis.

Figure 10 shows the distribution of the misclassified counties. Nine of the 15 misclassified counties were in Group Usurper, in which six were downgraded to Group Recovering (Wenxian County, Wudu District, Chaotian District, Jiange County, Mingshan County, and Santai County) and the remaining three were downgraded to Group Resistant (Dayi County, Mianyang Metropolitan Area, and Qionglai City) by discriminant analysis.

5.2 Potency index

The Potency index of each variable can be used to evaluate the discriminant power of indicator variables using all significant discriminant functions, which is often used when there are more than two significant discriminant functions derived (Perreault Jr et al., 1979). The potency index is calculated as:

$$\text{Potency}_i = \sum_{j=1}^{n} l_{ij}^2 \times \frac{e_j}{\text{Sum of all } e_j}, \quad (3)$$

where Potency_i is the potency index of variable i, n is the number of significant discriminant functions, l_{ij} is the discriminant loading of variable i on function j, and e_j is the eigenvalue of function j.

Table 5 ranks the 15 variables by their potency indices. It shows that sex ratio had the greatest influence on resilience, followed by per capita GDP, ethnicity, and medical facilities. Low sex ratio means high female proportion, which is found to be associated with high-resilient counties. By comparing the average value of each variable in each resilience group, we find that counties in Group Usurper and Resistant had (1) higher

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proportion of female, aged 15–64 (RtoPopAge15–64) and urban population (RtoUrbanPop); (2) higher GDP per capita and gross output value of agriculture per square kilometer (GOVFFAF); (3) higher ratio of population with education of senior secondary school and above (RtoEduSecSch); and (4) more savings deposit balance of residents per capita (PCSvgsDpstB). The recovering group had the highest proportion of primary industry and the lowest proportion of population with education of senior secondary school and above (RtoEduSecSch). The susceptible group also included some extreme values of variables, including high proportion of male (SexRatio), high proportion of ethnic minorities' population (RtoEthMinPop), high proportion of secondary industry (PSecIndus), and very low population density (PopDensity).

5.3 Discriminant score and variable loading

The discriminant scores of the counties in the four resilience groups were plotted onto the first two functions in Fig. 11. The plot clearly shows the three groups – Usurper, Recovering and Susceptible – were well separated using the two functions, while Group Resistant mainly overlapped with Group Usurper. In the spatial distribution (Fig. 8), counties in Group Usurper and Resistant were often adjacent areas. The socioeconomic characteristics of the counties were similar in both groups (Fig. 11). That also was the reason that about (6 out of 15) 40 % of misclassification counties were downgraded from Group Usurper to Groups Resistant and Recovering.

To further interpret the association between indicator variables and resilience groups, the loadings of the indicator variables were plotted onto the first two discriminant functions (Fig. 12). From the two plots (Figs. 11 and 12), we can observe the following:

First, the discriminative analysis results indicate that the resiliency of the top two most resilient groups, Groups Usurper and Resistant (blue and green areas in Fig. 8), was highly positively correlated with the following eight factors: GDP per capita, number of hospital beds per 10 000 people, percentage of urban population, gross output value of farming, forestry, animal husbandry and fishery per square kilometer, percentage of population between age 15–64, resident saving deposit balances per capita, percent-

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age of population with education of senior secondary school and above, and ratio of employment. Moreover, counties belonging to the Usurper and Resistant groups were mostly associated with economically developed and highly populated areas such as those in Chengdu City, Mianyang City, and Deyang City. We can interpret that GDP per capita and gross output value of farming, forestry, animal husbandry and fishery per square kilometer are indicators of the economic state of a county. The state of economic health might have helped in longer-term recovery after earthquakes. Better health care might expedite immediate relief from disasters. Counties with higher percentage of urban population and per capita saving deposit balances might be more resilient, as more wealth can help them reduce and recover from damage. Higher percentages of population with education of senior secondary school and above can also promote the resilience of a county. More younger and employed residents also characterize a resilient county.

Second, Group Recovering (yellow areas in Fig. 8) was highly positively correlated with sex ratio and proportion of primary industry, but negatively correlated with number of social welfare home beds per 10 000 persons. We can interpret that high percentage of male exists in economically undeveloped region, where the traditional preference for male babies still dominates. These underdeveloped counties were found to have lower resilience to earthquake disaster. Higher proportion of primary industry with low productivity is often characterized by low income and low density of buildings, which could make the counties more susceptible to hazard. Furthermore, poor social welfare services would indirectly decrease the resiliency of the counties. The objectives of social welfare service are to serve the disadvantaged group of society, and they are generally more fragile and need additional support in the recovery period.

Third, Group Susceptible (red area in Fig. 8) had two counties classified by K-means, Wenchuan County and Lixian County, which are located in the epicenter area. The two counties had been severely impacted by the Wenchuan earthquake, and had more property damages than others. So they were classified as the lowest level, Group Susceptible, by K-means analysis. Moreover, Figs. 11 and 12 show that the Susceptible group is highly positively correlated with percentage of ethnic minorities' population. High percentage of ethnic minorities' population would make a county less resilient to earthquake disaster. High percentage of ethnic minorities' population is mostly associated with the societies of cultural barriers, poor economy, and less-developed education in China. And the local government usually takes a more conservative policy to respond to disasters because of the lack of technical support in the minority area (Shan, 2010).

6 Discussion

This study aimed to measure 105 communities' resilience in the area that was greatly affected by the Wenchuan earthquake in 2008 using a quantitative measurement approach, the Resilience Inference Measurement (RIM) model.

First of all, the results indicate that the two counties (Wenchuan, Lixian) located in the epicenter region had the lowest resilience level. However, the counties immediately surrounding these two counties had the highest resilience. Then the counties farther away from the epicenter return to the lower resilience level again. This finding is somewhat unexpected, as counties closer to the epicenter are expected to recover more slowly. However, the findings can also be interpreted that people that are often exposed to seismic hazards, such as those living near the epicenter, may be more aware of the hazards and hence they may be better prepared and adapted (Chang and Shinozuka, 2004).

Secondly, the potency index has shown that sex ratio had the greatest influence on resilience assessment, followed by per capita GDP, ethnicity, and medical facilities. Low sex ratio means high female proportion, and the assessment result shows that the lower the ratio, the higher the county's resilience. While there is no published evidence, we can interpret that the sex ratio can be treated as a broad indicator of community characteristics, and in China it may mean that counties with high resilience are the more developed, and the more developed counties have better work opportunities and equity education for female, while the traditional preference for male babies is more dominant in the undeveloped counties. This sex-ratio variable is different from the variable of percent of female-headed households often used in the United States, where the latter is often associated with poverty, low-income status, and low resilience (Lam et al., 2009, 2012).

Finally, if the data is available, the effect of governmental policy on post-disaster recovery should be considered for future research. After extreme disasters took place, several funds had been sanctioned for post-disaster reconstruction. For example, the Chinese government invested 654.5 billion yuan in the stricken communities for the post-Wenchuan earthquake recovery and reconstruction, especially in the epicenter area and surrounding counties (2010). It is possible that these funds could partly promote the high resilience of counties surrounding the epicenter area.

7 Conclusion

In this study, we applied the RIM model to assess the county resilience for 105 counties in southwestern China after the 2008 Wenchuan earthquake. We then interpreted community resilience based on the socioeconomic characteristics; evaluated the discriminant power of every indicator, and demonstrated the association between indicators and resilience ranks across the impacted region. We found that counties located right at the epicenter area (Wenchun and Lixian) had the lowest resilience, but counties immediately surrounding the epicenter area had the highest resilience. Counties that were farther away from the epicenter returned to the normal level of resilience. Through discriminant analysis, we found that the 15 selected socioeconomic variables were able to predict the resilience group membership with a reasonably high degree of accuracy (85.7 %). The variables that showed great influence on the resilience were: sex ratio, per capita GDP, percent of ethnic minorities, and average number of hospital beds. This study produced the first quantitative analysis of seismic resilience assessment in the study area. The findings should provide useful benchmark information on community resilience assessment to seismic events in China where socioeconomic conditions are very different from other countries. The assessment results will also provide more decision-making support for policy making regarding disaster resilience.

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Table 1. Number of cases in each cluster.

Cluster	Number of cases
Usurper	26
Resistant	7
Recovering	70
Susceptible	2

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Table 2. Socioeconomic variables for discriminant analysis.

Label	Socioeconomic Variable		Variable Meaning	Unit	Source
Demographic					
PopDensity	Population Density (2002)	Population per square kilometer	Population	Person km^{-2}	YB
SexRatio	Sex Ratio (2002) (female = 100)	The ratio of males to females	Gender	%	YB
RtoEthMinPop	Percentage of Ethnic Minorities Population (2000)	Percent non-Han Chinese population	Ethnicity	%	CS
RtoUrbanPop	Percentage of Urban Population (2000)	Percent of population that live in urban areas	Urban	%	CS
RtoPopAge15–64	Percentage of Population Age 15–64 (2000)	Percent of population between the ages of 15 and 64 years old	Age	%	CS
Social					
RtoEduSecSch	Percentage of Population with Education of Senior Secondary School and Technical Secondary School and above (2000)	Percent of the population with diploma of senior secondary school and technical secondary school and above	Education	%	CS
RtoEmpPop	Employment Ratio (2000)	Percent of the workforce that is employed	Employment	%	CS
Economic					
GDPperCapita	GDP per Capita (2002) (at current prices)	Gross domestic product per capita	Commercial & Industrial Development	Yuan/ person	YB
PPriIndus	Proportion of Primary Industry (2002)	Proportion of the primary industry to GDP	Commercial & Industrial Development	%	YB
PSecIndus	Proportion of Secondary Industry (2002)	Proportion of the secondary industry to GDP	Commercial & Industrial Development	%	YB
GOVFFAF	Gross Output Value of Farming, Forestry, Animal Husbandary and Fishery per Square Kilometer (at current prices) (2002)	Gross value of agricultural output (farming, forestry, animal husbandary and fishery) per square kilometer	Agricultural Activity	10 000 yuan km^{-2}	YB
PCLA	Proportion of Cultivated Land Area (year-end) (2002)	Percent of cultivated land to total area	Agricultural Activity	%	YB
PCSvgsDpstB	Per Capita Savings Deposit Balances of Residents (2002)	Savings deposit balances per capita	Residential Property	Yuan/ person	YB
Health					
NoHospBed	Number of Hospital Beds per 10 000 Persons (2002)	Number of hospital beds per 10 000 persons	Medical Capacity	Unit/ 10 000 person	YB
Social welfare					
NoSWBed	Number of Social Welfare Homes Beds per 10 000 Persons (2002)	Number of social welfare homes beds per 10 000 persons	Social Welfare	Unit/ 10 000 person	YB

Note: The 2000 population census was obtained from the National Bureau of Statistics of the People's Republic of China (CS), and the 2002 socioeconomic data was from the Provincial Statistical Yearbooks 2003 (YB).

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Table 3. Variance explained by discriminant functions.

Function	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
1	1.379	70.1	70.1	0.761
2	0.487	24.8	94.9	0.572
3	0.100	5.1	100.0	0.302

Table 4. County resilience rankings and misclassification.

Province	County	K-means	Discriminant	Misclassification
Gansu	Chengxian	Recovering	Recovering	No
	Huixian	Recovering	Recovering	No
	Kangxian	Recovering	Recovering	No
	Liangdang	Recovering	Recovering	No
	Lixian (Gansu)	Recovering	Recovering	No
	Tanchang	Recovering	Recovering	No
	Wenxian	Usurper	Recovering	Yes
	Wudu	Usurper	Recovering	Yes
	Xihe	Recovering	Recovering	No
Shaanxi	Chenggu	Recovering	Recovering	No
	Foping	Recovering	Recovering	No
	Hantai	Recovering	Recovering	No
	Lueyang	Recovering	Recovering	No
	Mianxian	Recovering	Recovering	No
	Nanzheng	Recovering	Recovering	No
	Xixiang	Recovering	Recovering	No
	Yangxian	Recovering	Recovering	No
	Zhenba	Recovering	Recovering	No
Sichuan	Abaxian	Usurper	Usurper	No
	Anyue	Recovering	Recovering	No
	Baoxing	Usurper	Usurper	No
	Cangxi	Recovering	Recovering	No
	Chaotian	Usurper	Recovering	Yes
	Chengdu*	Usurper	Usurper	No
	Chongzhou	Usurper	Usurper	No
	Cuiping	Recovering	Recovering	No
	Danba	Recovering	Recovering	No
	Dayi	Usurper	Resistant	Yes
	Dazhu	Recovering	Recovering	No
	Dongxing	Recovering	Recovering	No
	Dujiangyan	Resistant	Usurper	Yes
	Ebian	Recovering	Recovering	No
	Ganluo	Recovering	Recovering	No
	Gaoxian	Recovering	Recovering	No
	Gongxian	Recovering	Recovering	No
	Guanganqu	Recovering	Recovering	No
	Gulin	Recovering	Recovering	No
	Hanyuan	Recovering	Recovering	No
	Heishui	Usurper	Usurper	No
	Hejiang	Recovering	Recovering	No
	Hongyuan	Usurper	Usurper	No

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Table 4. Continued.

Province	County	K-means	Discriminant	Misclassification
Sichuan	Huaying	Recovering	Recovering	No
	Huili	Recovering	Recovering	No
	Jiajiang	Recovering	Recovering	No
	Jiange	Usurper	Recovering	Yes
	Jiangyang	Recovering	Recovering	No
	Jiangyou	Resistant	Resistant	No
	Jinchuan	Recovering	Usurper	Yes
	Jingyan	Recovering	Recovering	No
	Jinkouhe	Recovering	Recovering	No
	Jintang	Usurper	Usurper	No
	Jinyang	Usurper	Usurper	No
	Jiuzhaigou	Usurper	Usurper	No
	Junlian	Recovering	Recovering	No
	Kaijiang	Recovering	Recovering	No
	Lezhi	Recovering	Recovering	No
	Lixian	Susceptible	Susceptible	No
	Longquanyi	Usurper	Usurper	No
	Luding	Recovering	Recovering	No
	Lushan	Recovering	Recovering	No
	Luxian	Recovering	Recovering	No
	Maerkang	Usurper	Usurper	No
	Maoxian	Resistant	Susceptible	Yes
	Mianyang*	Usurper	Resistant	Yes
	Mianzhu	Resistant	Resistant	No
	Mingshan	Usurper	Recovering	Yes
	Miyi	Recovering	Recovering	No
	Muchuan	Recovering	Recovering	No
	Nanjiang	Recovering	Recovering	No
	Naxi	Recovering	Recovering	No
	Panzhihua*	Recovering	Resistant	Yes
	Pengan	Recovering	Recovering	No
	Pengxi	Recovering	Recovering	No
	Pengzhou	Resistant	Resistant	No
	Pingchang	Recovering	Recovering	No
	Pingwu	Resistant	Resistant	No
	Pixian	Usurper	Usurper	No
	Pujiang	Usurper	Usurper	No
	Qianwei	Recovering	Recovering	No
	Qingshen	Recovering	Recovering	No
	Qionglai	Usurper	Resistant	Yes
	Quxian	Recovering	Recovering	No

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Table 4. Continued.

Province	County	K-means	Discriminant	Misclassification
Sichuan	Santai	Usurper	Recovering	Yes
	Shawan	Recovering	Recovering	No
	Shehong	Recovering	Recovering	No
	Shifang	Resistant	Resistant	No
	Shimian	Recovering	Recovering	No
	Suining*	Recovering	Recovering	No
	Tongjiang	Recovering	Recovering	No
	Wangcang	Recovering	Recovering	No
	Wenchuan	Susceptible	Susceptible	No
	Wenjiang	Usurper	Usurper	No
	Wutongqiao	Recovering	Recovering	No
	Xiaojin	Usurper	Usurper	No
	Xichong	Recovering	Recovering	No
	Xuyong	Recovering	Recovering	No
	Yanbian	Recovering	Resistant	Yes
	Yanjiang	Recovering	Recovering	No
	Yanting	Recovering	Usurper	Yes
	Yingjing	Recovering	Recovering	No
	Yucheng	Recovering	Recovering	No
	Yuechi	Recovering	Recovering	No
	Yuexi	Usurper	Usurper	No
	Zitong	Usurper	Usurper	No
	Zizhong	Recovering	Recovering	No

* Metropolitan Area.
"No" in the Misclassification column stands for accurate classification.
"Yes" in the Misclassification column stands for misclassification.

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Table 5. Potency index and mean value of each variable in each group derived from discriminant analysis.

Variables	Mean Value				Potency
	Usurper	Resistant	Recovering	Susceptible	index
SexRatio	104.49	106.13	109.54	112.38	0.131
GDPperCapita	8772.65	11173.22	3840.21	6991.78	0.129
RtoEthMinPop	30.65	5.87	4.38	76.55	0.098
NoHospBed	35.20	32.64	20.81	37.72	0.062
GOVFFAF	116.35	94.67	59.76	3.05	0.055
RtoPopAge15–64	70.75	73.15	68.71	68.78	0.046
PSecIndus	32.48	47.51	35.22	54.21	0.043
PPriIndus	25.58	17.82	32.15	17.56	0.042
RtoUrbanPop	31.76	38.47	19.92	18.09	0.033
PCSvgsDpstB	5334.66	5656.38	2857.18	3238.90	0.030
RtoEduSecSch	12.30	12.09	8.41	11.79	0.026
NoSWBed	4.26	9.81	5.26	0.38	0.023
RtoEmpPop	61.55	63.91	62.40	60.92	0.021
PCLA	18.13	17.01	16.48	1.08	0.019
PopDensity	660.60	371.46	342.19	21.46	0.019

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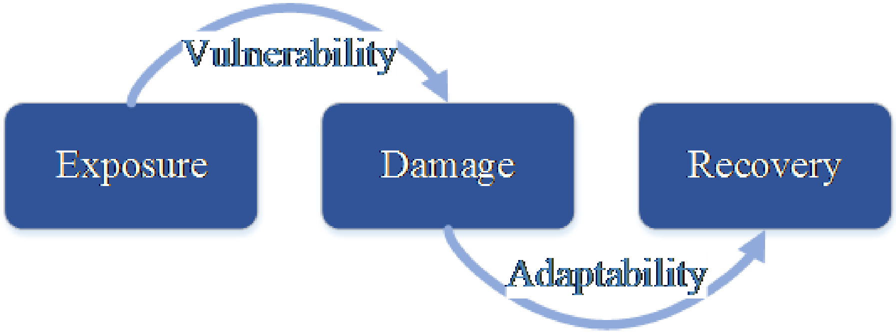

Figure 1. The conceptual framework of the Resilience Inference Measurement (RIM) model (Lam et al., 2014; K. Li, 2011).

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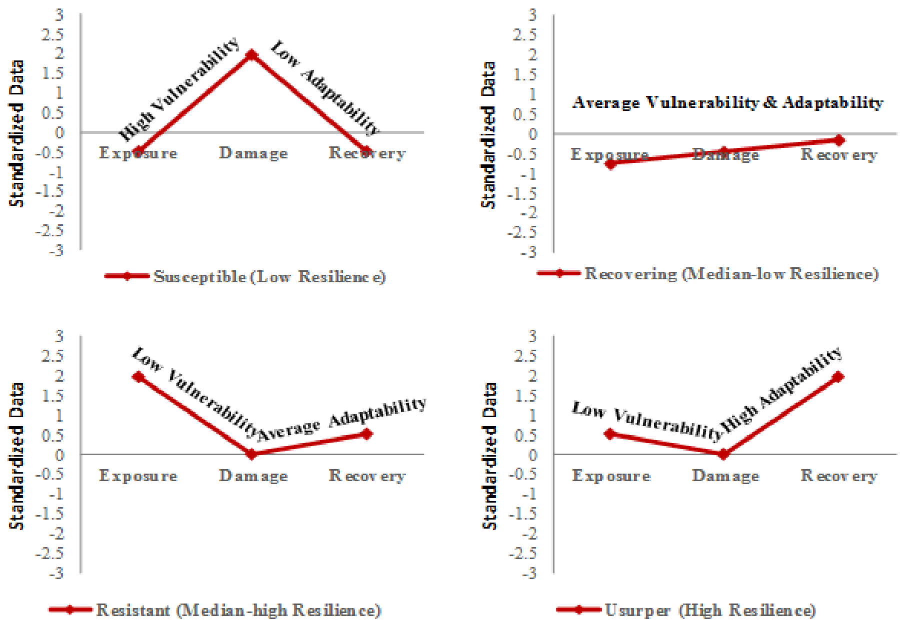

Figure 2. Four states of resilience in the RIM framework. The *y* axis shows the deviations of exposure, damage and recovery from their means (Lam et al., 2014; K. Li, 2011).

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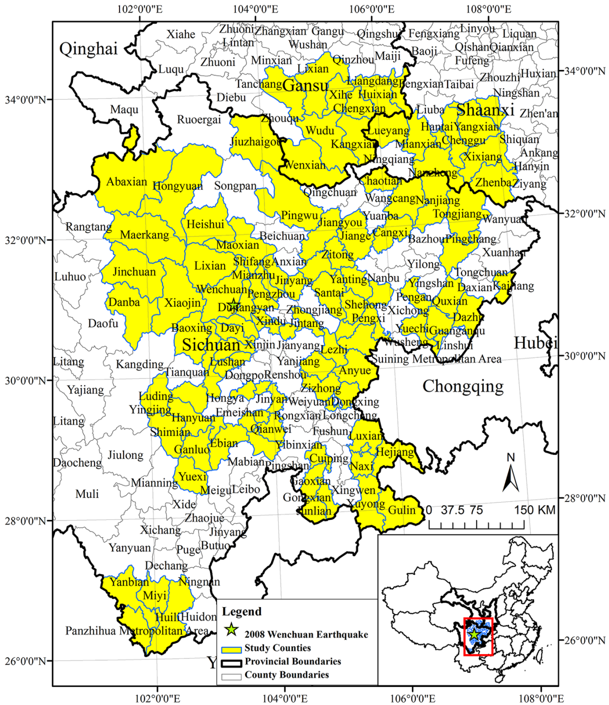

Figure 3. Counties examined in this study.

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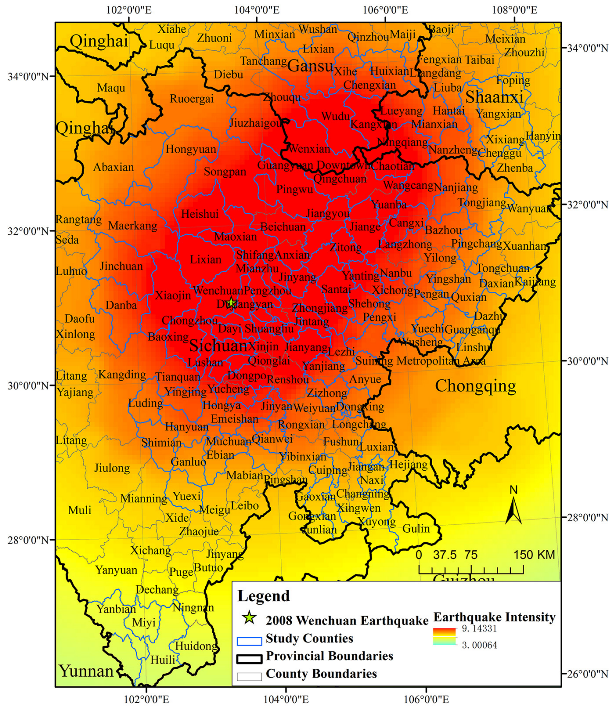

Figure 4. The intensity of 2008 Wenchuan earthquake.

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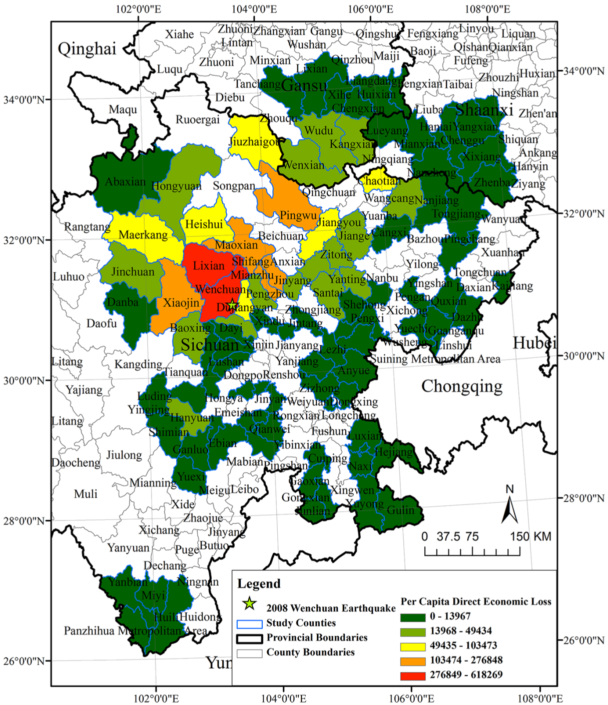

Figure 5. The economic loss per capita by county caused by the 2008 Wenchuan earthquake.

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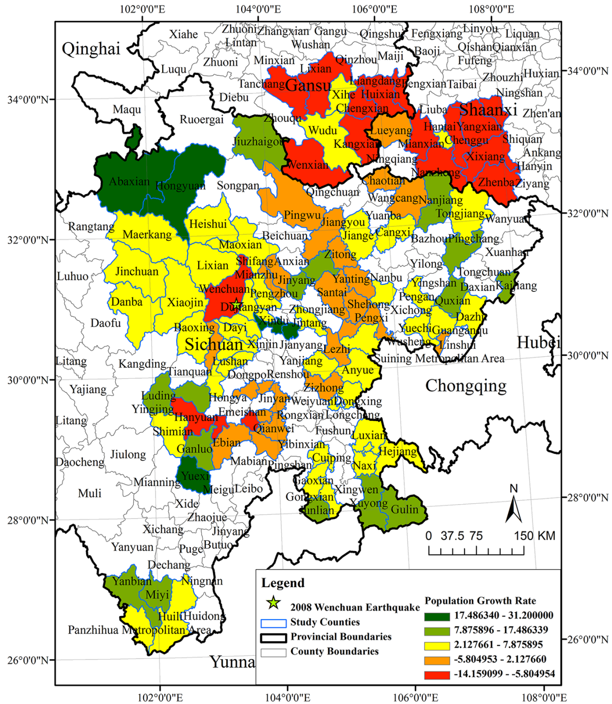

Figure 6. The population growth rate by county from 2002 to 2011.

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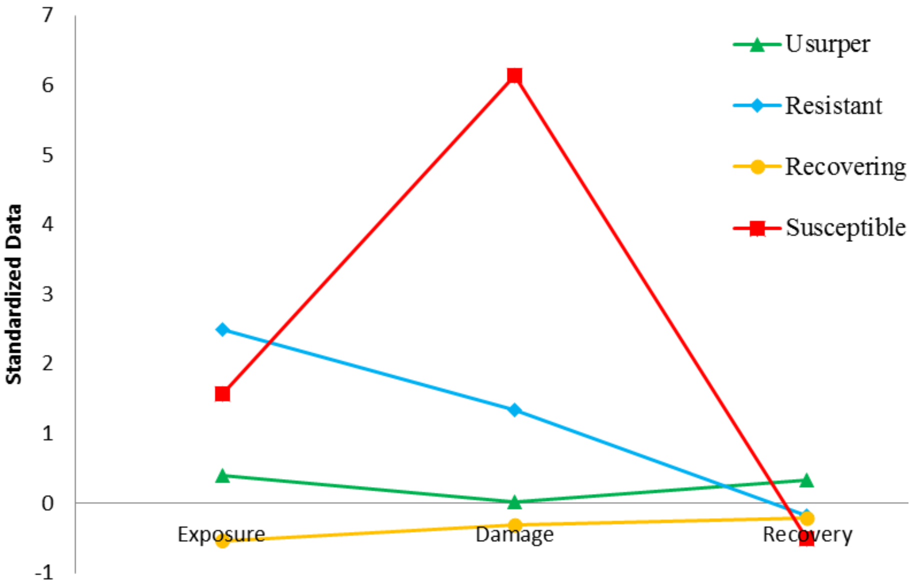

Figure 7. Plot of the four K-means clusters on the three dimensions.

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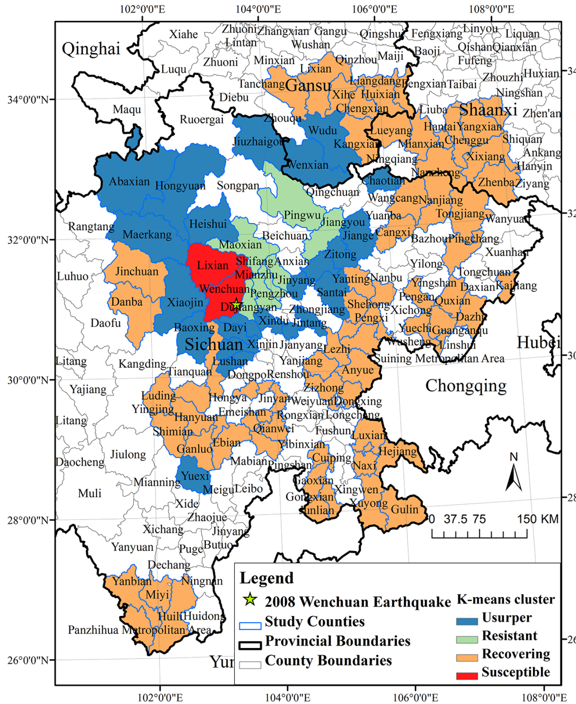

Figure 8. Map of the four resilience groups derived by K-means cluster analysis.

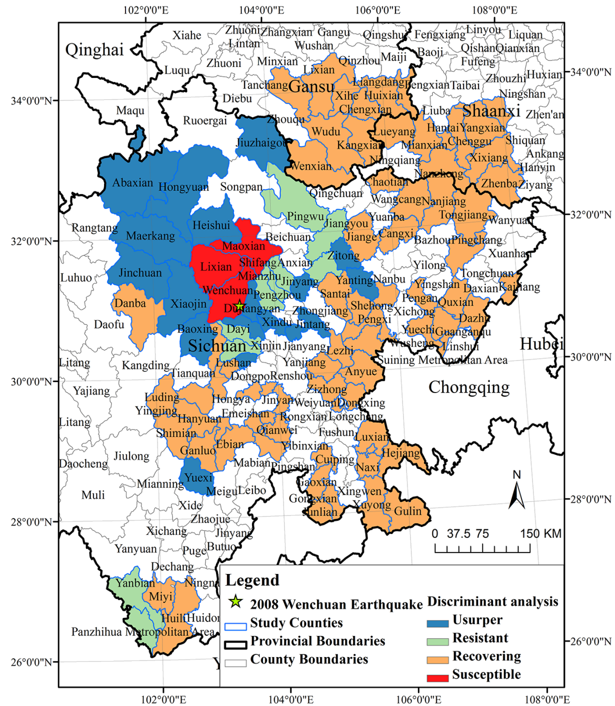

Figure 9. Map of the four resilience rankings derived by discriminant analysis.

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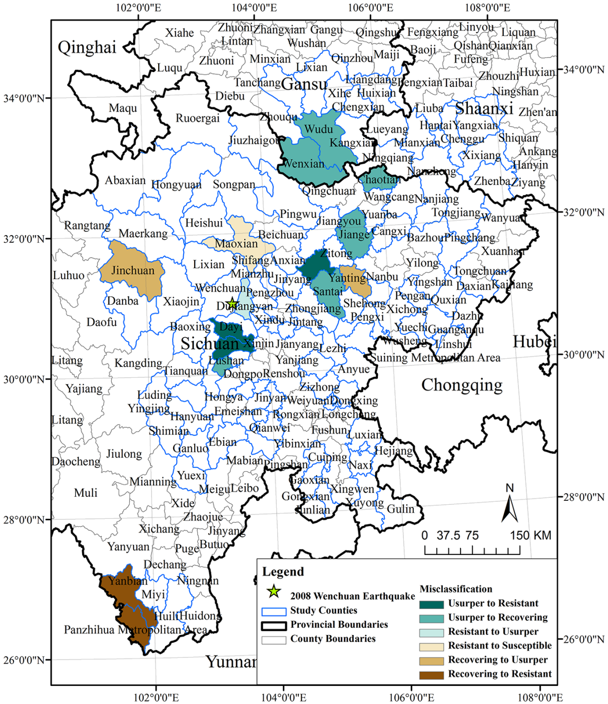

Figure 10. Map of the misclassified counties.

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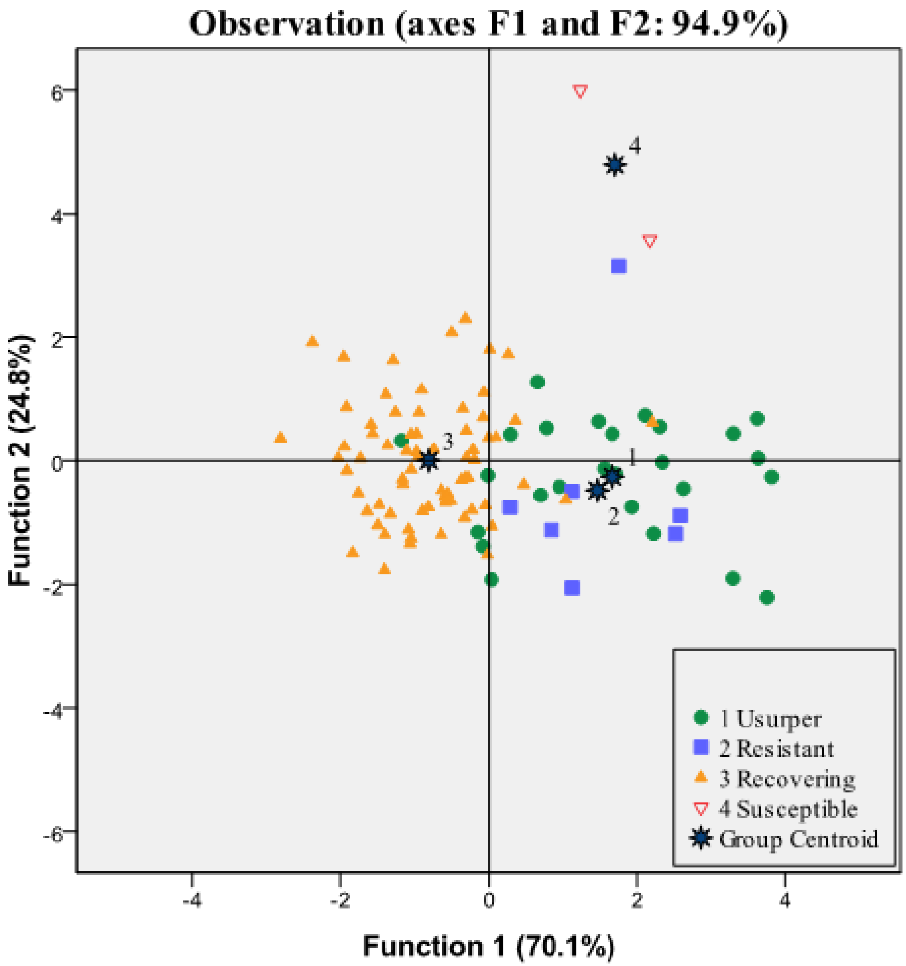

Figure 11. Plot of the four resilience groups on the first two discriminant functions.

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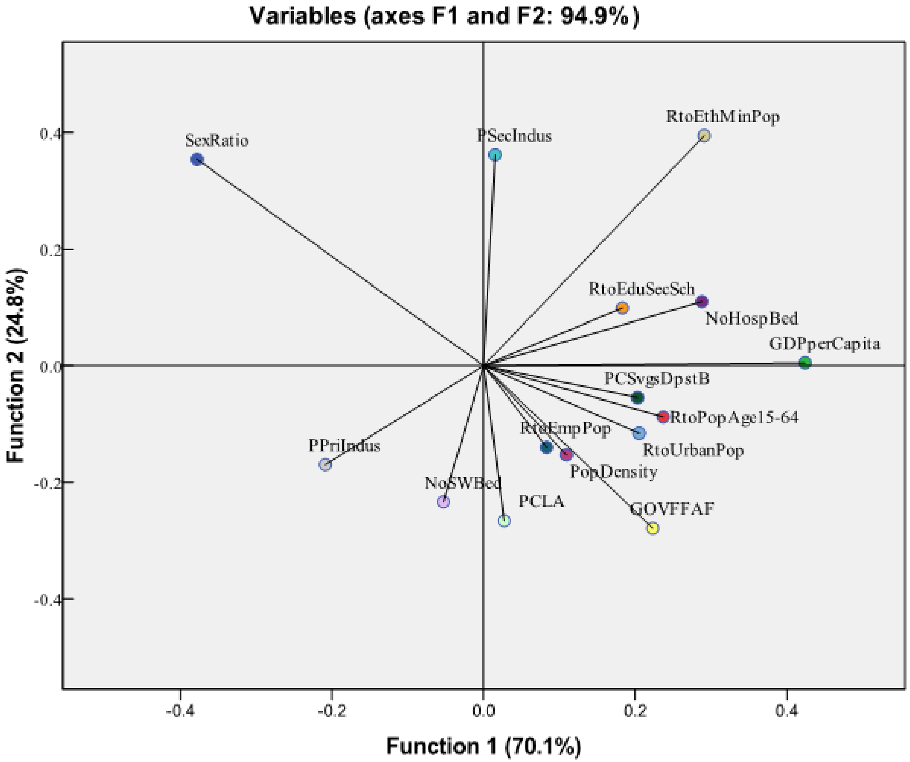

Figure 12. Plot of the 15 variables on the first two discriminant functions.

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