Quantifying some components of resilience by analysing the changes of elements-at-risk in the Wenchuan epicentral area

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March, 2015

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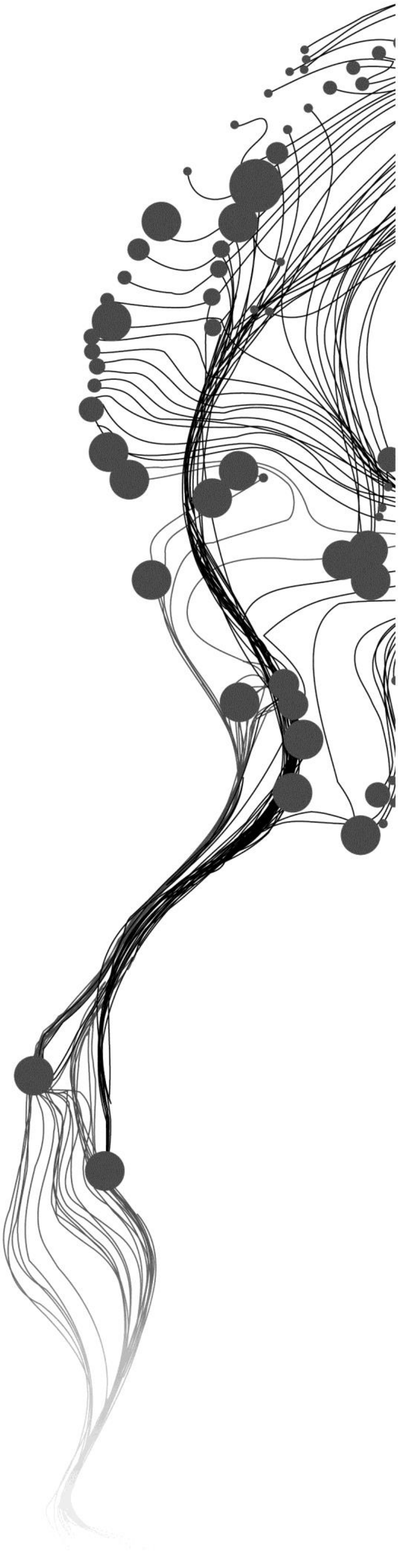

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FENGCHAO GU
Enschede, The Netherlands, March, 2015

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Applied Earth Sciences: Natural Hazards and Disaster Risk Management

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Statement of some small problems in the figures in this thesis:

In Figure 26, page 37, the X axis is "year", and the Y axis is "Number".

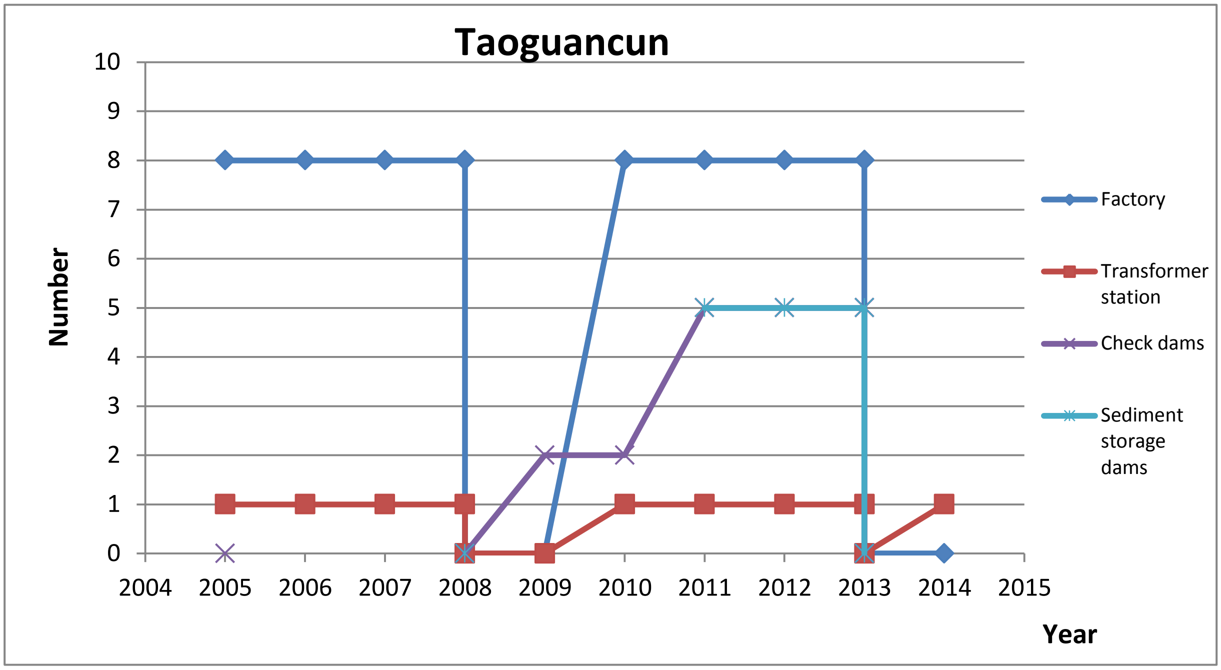

Figure 26. The quantitative changes in Taoguancun.

In Figure 29, page 38, the X axis is "Year", and the "Y" axis is "Number".

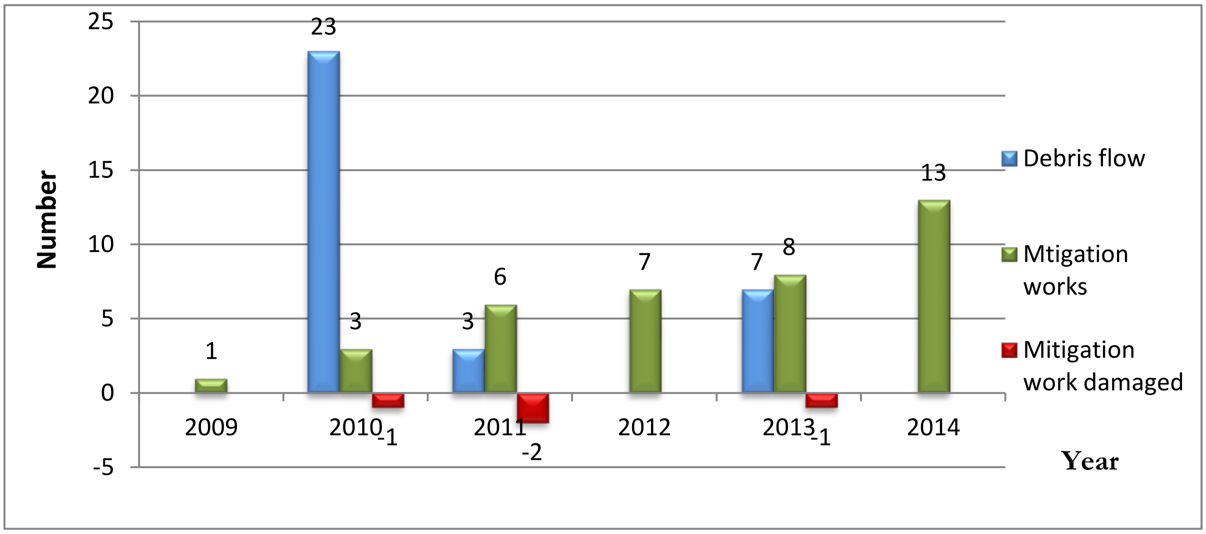

Figure 29. The changes of mitigation works, the occurrence of debris flows through years.

In Figure 31, page 44, the numbers on the right side are missing. The actual one is like below:

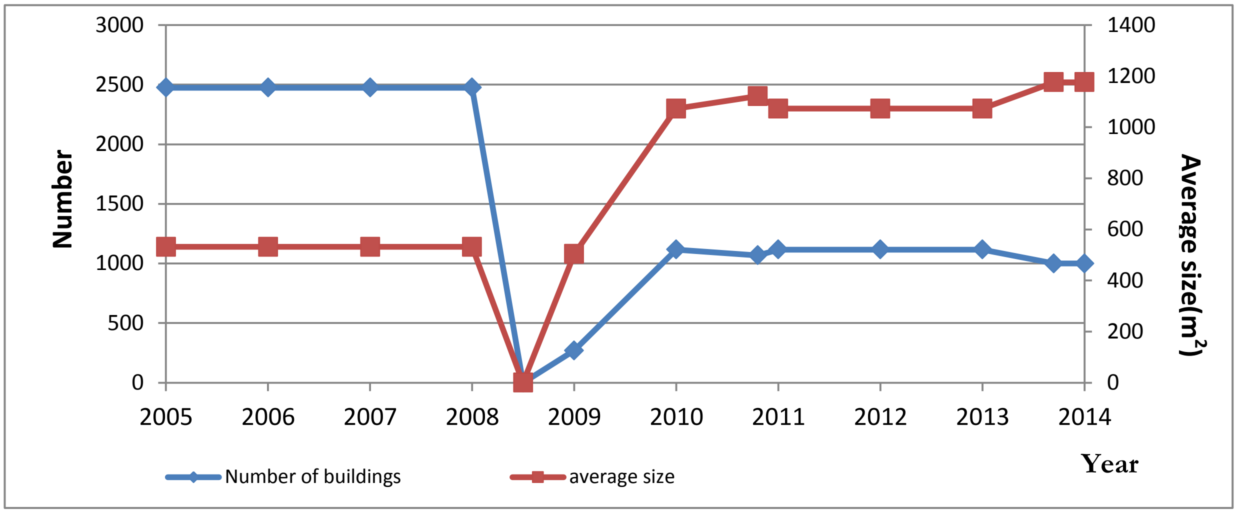

Figure 31.Infrastructural resilience in terms of number of buildings.

In Figure 33-36, page 45-46, the X axis is “Year” for each figure.

ABSTRACT

Resilience is a term used to describe the ability to bounce back from disruption, stress or change. It is a popular but complex concept which can be defined into six dimensions, ecological, social, economic, institutional, infrastructure and community competence resilience. Four properties of community resilience are represented as robustness, redundancy, resourcefulness and rapidity. These 6 dimensions and 4 properties of resilience formed the framework of this research. Large earthquakes may have a devastating impact on a society, and are a good example of showing the earthquake resilience especially in areas that are affected by post-seismic events such as landslides. The level of earthquake resilience depends on a number of components, such as the political background, the risk governance structure, the socio-economic situation, the cultural and religious background, the level of prevention, the level of preparedness, the coping characteristics and the recovery aspects.

The main objective of this research is to quantify some components of resilience by analysing the changes of elements-at-risk (e.g. built-up areas, transportation infrastructure and landslide mitigation works) in the post-earthquake mountainous area affected by the 2008 Wenchuan earthquake. Starting from multi-temporal satellite images and aerial photos from the pre-earthquake situation till 6 years after the earthquake, image interpretation was carried out to map the changes in physical elements-at-risk, such as buildings and transportation infrastructure. In the field data was collected on the attributes of the elements-at-risk and disaster and damage reports caused by the earthquake and the post-earthquake landslides. These were used to generate a multi-temporal database about elements-at-risk. Subsequently both qualitative and quantitative change analysis was carried out. Quantitative changes are analyzed about the number of buildings, the length of functioning roads and bridges, and the number of people. Qualitative changes were analyzed regarding the occupancy types of buildings, types of roads and the structural characteristics of buildings. This research focused on using the results of the quantitative changes of the built environment for different years to represent the "bouncing back" graph which can be considered one component to characterize the general earthquake resilience of the study area. Also the reconstruction planning about industrial changes, cultural preservation and disaster risk reduction are analyzed in terms of the qualitative changes which can show the improvements of landuse planning, building codes and building structures characteristics. The quality of recovery is briefly discussed by companying the landuse type and diversity of livelyhood before and after the earthquake. This research shows that the reconstruction in China is rapid with new reconstruction mechanisms and funding sources, even though the area showed a high robustness, and experienced a large amount of destruction due to the earthquake, but the economic recovery was relatively low, as some of the main sources of the economy (tourism, hydropower, industry) were heavily affected, and it was not possible to reestablish them fast. Post-earthquake landslides and the damage they caused have a major influence on the recovery. Moreover, the limited livelyhood after the earthquake is another factor which affects recovery. The lessons from the Wenchuan earthquake show that secondary hazard assessment should receive more attention in potential earthquake affected mountainous areas, and instead of making rapid reconstruction, more emphasis should be placed on long term hazard and risk assessments after earthquakes. The research also discovered that the resilience of different areas differ substantially on various aspects, such as the industrial adjustment in reconstruction planning. It is important to establish job opportunities in different sectors, as a strong dependency on some sectors (e.g. tourism) might have a negative impact on the long term.

ACKNOWLEDGEMENTS

Sitting in front of this laptop, with many days working on the thesis with stress and anxiety, finally, this is the moment that I can recall the long journey of studying in ITC and doing the thesis, with much thanks to many people.

First, thanks to my first supervisor, Cees. I am like "an empty paper" when starting doing the research. Being used to doing something with a straight line, I am not a creative student. However, I am so lucky that I meet a nice supervisor who always encourages me and supervises me even though sometimes my work is really bad. He is like a big tree during my research journey. Without him, I don't think I can insist on doing my thesis till now. Remember that my research proposal is very draft, both for the idea and the English writing, but he corrected it very carefully. Before the thesis submission, there were some problems with my word file and all his comments were not saved. But he did it again during his lunch time. However, problems again! Then we met together and he made the comments on my laptop the third time. Remember that I had some problems with the images before going to the fieldwork, we met every day for one week and he guided me to solve these problems. Remember that he knew that I was worried about the thesis, and he came to join me during the lunch time to see if I am ok or not. Remember that he encouraged me to not give up after a big denial about what I have kept doing for three weeks. He is like my life mentor and tells me there are a lot of mountains in my life. I will do my best to across over "the mountains" one by one.

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Third, thanks to my friends in ITC, Biao Xiong, Kaixi Xhang, Lixia Chen, Chenciao Tang, Shaoqing Lv, Hadi Bun, Fashuai Li, MengMeng Li, Wentao Yang and so on. Thanks very much with company in ITC and the help you gave me. I have a happy life with studying in ITC though there are a lot of challenges. I am like a little sister with them and when I need help, they are always there. They make me brave, make me feel like I am in a big warm family. I really cherish the time with you, the time that we grow up together, we enjoy the life together and we help each other to overcome the difficulties together. Thanks to my even-aged friends, Gaoyan Wu, Xuan Jiang, Yannan Shi and so on, thanks that we have spent a lot of time sharing the ideas to each other.

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1. INTRODUCTION

In this chapter, the definitions of resilience are reviewed and the two different ways of resilience representation are introduced with the explanation of concepts that are related to resilience. Earthquake resilience is explained with three main earthquake examples, the Japan earthquake, the Haiti earthquake and the Wenchuan earthquake. The approaches of quantifying resilience and the different dimensions and components of earthquake resilience are summarized to come out a new framework to analyze earthquake resilience. In the end, the problem is pointed out and the research objectives and research questions are defined.

1.1. Background

1.1.1. The definition of resilience

Resilience has been a term used to describe the ability to bounce back from disruption, stress or change. It comes from the Latin word “resilio”, meaning “bouncing back”. The first definition of resilience given by Holling (1973) is a measure of “the persistence of a system and of their ability to absorb change and disturbance and still maintain the same relationship between population or state variables.” And then a second and third definition redefined by the same author, place importance on the stability of a system and the buffer capacity and ability to absorb perturbation in a pre-event phenomenon, respectively (Holling, 1986; Holling et al., 1995). However, these sort of resilience were named as Engineering Resilience by Gunderson et al. (2009). From an engineering system view, at the simplest level, the less it is disturbed by an amount of stress , the faster it bounces back from stress and the greater it endures stress, the more resilient the system is. The limitation of engineering resilience is that slow changes and adaptive capacity of system were not taken into account (Martin-Breen & Anderies, 2011).

In the ecology field, Holling (1973) determined two distinct properties of ecological system: resilience and stability. A system can be resilient but with low stability because of the high ability of absorbing changes but may fluctuate greatly after a disturbance. Timmerman (1981) was the first person who talked about resilience of society. In 2002, Walker et al. extended the definition of resilience to three characteristics, the original meaning in Holling (1973), the capacity of self-organization and the capacity for learning and adaptation. Martin-Breen and Anderies (2011) named this as resilience in complex adaptive system, meaning the “ability to withstand, recover from, and reorganize in response to crises”.

In the disaster field, much research had been done to analyze resilience (Klein et al., 2003; Klein et al., 1998; Tobin, 1999). UN-ISDR (2009) define resilience as “the ability of resistance, absorption, adaptation and recovery of a system from the effects of hazard, including preserving and restoring the basic structures and functions”. This depends on the necessary resources and organizing capability for the community before and after a disruptive event. Building disaster resilience can help community to be better prepared to the disasters and recovery fast after the disasters.

1.1.2. The representation of resilience and relative concepts and components

Resilience can be represented in different ways, one of them is to plot a graph as the performance of a system through time (See Figure 1). Different phases are shown in this graph before and after a disruptive event occurs, including the preparation before disasters, impact of disasters and recovery after disasters and long-term impact of disasters.

Cutter et al. (2008) developed a disaster resilience of place (DROP) model for a local or community level (See Figure 2). In this model, community is composed of three parts, social system, built environment and natural system. Without disruptive events, the community is both vulnerable and resilient. After an event, the external abilities, such as coping capacity, absorbability and adaptability, have an effect on the impact of community and the degree of recovery. During the recovery or after recovery, the efficient mitigation works and preparedness before the next disaster decrease the internal vulnerability and increase the resilience of community.

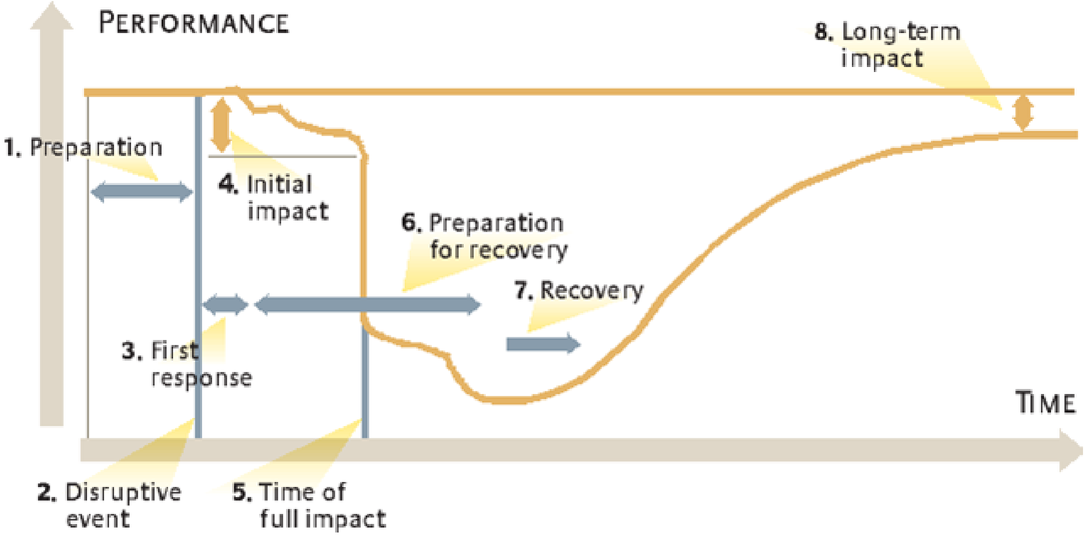


Figure 1. Schematic representation of resilience, as a graph plotting the performance of a society through time, as a function of time. Source: Multi-hazard risk assessment (van Westen et al., 2011).

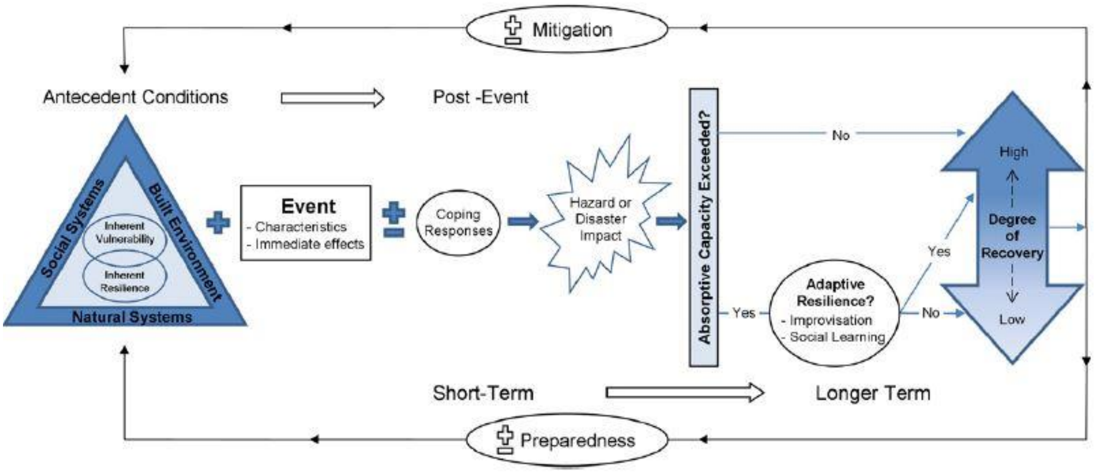


Figure 2. Schematic representation of the disaster resilience of place model. Source: (Cutter et al., 2008).

There are several concepts that related to the earthquake resilience, such as the coping response, absorptivity, adaptability, recovery and vulnerability. The explanations of these concepts are below:

Coping response: Coping response are the actions that community take immediately after an event, this includes efficient evacuation plans and shelter creation, information spreading and emergency response (Cutter et al., 2008).

Absorptivity: Absorptivity is the ability that community or system can withstand the event impacts or disturbance (Cutter et al., 2008). It is used to describe how strong the community or system is.

Adaptability: Adaptability refers to the ability of community or system to adjust in response to climate change or disaster, which can reduce harm or create other beneficial chances (UN-ISDR, 2009). In the Methods for the improvement of vulnerability assessment in Europe (MOVE) framework, adaptation contains two parts: hazard intervention and vulnerability intervention, and it will lead to reduction of hazard, exposure, and susceptibility and improvement of resilience (Vinchon et al., 2011).

Recovery: Recovery is defined as the restoration and improvement of the status of community after the effect of disaster, which includes facilities, livelyhoods and living conditions (UN-ISDR, 2009). Three meanings of disaster recovery were explained by Lindell (2013):

1) the goal of restoration/rehabilitation the community activities
2) the phase that between the end of emergency response and normal activities are archived
3) the process that the goal of returning to normal routines is reached.

The recovery process includes four functions: disaster assessment, short-term recovery, long-term reconstruction and recovery management (Lindell, 2013).

Vulnerability: Vulnerability is related to the characteristics and circumstances of a community or system, these characteristics and circumstances make community or system susceptible to hazard and cause loss (UN-ISDR, 2009). In the MOVE framework, resilience has an influence on susceptibility and fragility and one part of resilience, adaptation, has an effect on hazard and vulnerability (Vinchon et al., 2011). It is difficult to separate the concepts of vulnerability and resilience. Buckle et al. (2001) proposed that vulnerability and resilience were two attributes of objects or system, and they present double helix structure. From the definition of resilience in UN-ISDR (2009) and DROP model (Cutter et al., 2008), there are different ways to improve disaster resilience, for example, improving coping capacity, adaptability and constructing mitigation works, and these measures will have positive effect on reducing vulnerability.

Many types of resilience or the components of resilience and relative variables/indicators are defined from different disciplinary perspectives. Six different dimensions of community resilience with different forms of measurements were summarized, which were ecological resilience, social resilience, economical resilience, institutional resilience, infrastructure resilience and community competence resilience (Cutter et al., 2008; Enemark, 2006; Norris et al., 2008).

- Ecological resilience was related to the ecological system and it can be affected and assessed by several variables, such as the percentage of the land area in the 100-year flood plain, the percentage of green space/ undisturbed land, the percentage of forest land cover and soil erosion (Cutter et al., 2010). Biodiversity, governance, management and plans had an influence on it (Adger et al., 2005; Folke, 2006).
- Social resilience depends on leadership and communication (Ink, 2006), social capital (Breton, 2001), community involvement (Clauss-Ehlers & Levi, 2002) and resource dependency (Adger, 2000). Indicators are, for example, the education equality (the ratio between the number of people with college education and number of people without high school diploma), demographics (age, class, and gender), the communication capacity (the percentage of people with a telephone) and health insurance (Cutter et al., 2010) which were used to measure social resilience.
- Economic resilience links the behavior of individuals, markets and macroeconomy (Rose, 2004). The percentage of homeowners, employment and median household and the income quality and business size had a positive effect on economic resilience. However, the percentage of poverty had a negative influence on resilience (Cutter et al., 2008; Cutter et al., 2010; Norris et al., 2008).
- Institutional resilience focuses on the coping response ability and management, for example, the effective emergency plans and emergency service, disaster risk reduction plans and the zoning and

building standards. Many indicators, the percentage of population covered by the hazard mitigation plans, or the percentage of municipal service (fire and police), and the percentage of the population covered by the Citizen Corps programs, were justified by different researchers (Burby et al., 2000; Cutter et al., 2010; Godschalk, 2007).

- Infrastructure resilience includes the physical system themselves and the dependence/ interdependence between them, for example, lifelines, critical infrastructure and the transportation network. Cutter et al. (2010) used housing type, shelter needed and housing age, the number of hospital beds and the number of public schools as indicators to measure infrastructure resilience.
- Community competence resilience was relevant to the quality of life, health and wellness and counseling service.

Even though resilience related to the whole aspects of a society and a large number of factors are required to measure resilience, there are several major components that can affect earthquake resilience.

1) The political background. Governments, at all levels, play an important role in strengthening the nation's disaster resilience. A strong state/ government can manage disasters or pressures better than a weak government. Moreover, it is also relevant to the form of government. For example, in a centralized government, the emergency response and the recovery plans and regulations are made and issued by the central government and then these are implemented by lower government bodies.
2) The risk governance structure. Disaster risk management refers to the systematic process, which combines administrative directives, organizations, and operational skills and capacities to reduce the impact of hazard (UN-ISDR, 2009). This comprises all forms of activities and elements, which are risk identification and assessment, knowledge management, political commitment and institutional development, early warning system, disaster preparedness and emergency management and recovery and reconstruction. The clarity of these different components and the role of different actors makes sure an effective management and high ability to cope disasters.
3) The socio-economic situation. Disaster prevention and preparedness, for example, the technologically detection and disaster warning systems, are effective ways to improve resilience when an earthquake occurs. However, these require numerous funding and they depend on the level of the wealth of a country. Moreover, a rich country with sound insurance system makes sure the timely and effective financial aid to victims, either from government, international donors or the different insurance companies. Comparing with rich counties, the international aid is the only way for the poor countries to response and recovery from catastrophic disasters and there will be some problems, for instance, the postponement of funding which can affect the rapidity of reconstruction. Furthermore, the educational level, the demographics characteristics, such as age and sex ratio, literacy ratio and population with access to sanitation are all related to the vulnerability of society (Brooks et al., 2005) and society resilience.
4) The level of prevention. Landuse planning has been widely utilized to build community resilience to natural hazard, and hazard/risk assessment should be taken into account in landuse planning. Establishing community-based disaster management structures to disaster risk reduction is also helpful to improve disaster resilience. Furthermore, physical protection and technical measures also make important contribution for community to resist disasters, for instance, safe location selection, structure mitigation measures and knowledge and adoption of building codes.
5) The level of preparedness. Early warning system is one of the major elements for disaster risk management. To make it effective, early warning system should be at local level and capable of disseminating messages to the whole community. The level and quality of communication risk depend on the communication medium, e.g. radio, TV and telephone, and the understandable

signals and meanings. Education and training should also be carried out to help people to manage disasters better. Local schools provide disaster risk reduction courses for children and the training programs and drills can be established for future hazards. For the community, the community plans, emergency sources and services (e.g. facilities, structures and staff) preparation should be made.

6) The coping characteristics. Coping characteristics to disasters are related to the ability of a community to manage emergency response. This includes the safe evacuation route that is identified and the number of emergency shelters that are estimated timely, which combine the damage assessment, entry restriction assessment and the number of affected population assessment. It is also related to the rescue principle and fundraising mechanisms.
7) The recovery aspects. The reconstruction and recovery show how the society system bouncing back and it's a complex process. Hazard assessment, site selection and survey to decide the appropriate site and the design for the types of reconstruction which includes the disaster risk reduction are the three major works for reconstruction. The safe reconstruction area, the mitigation works that are made to reduce the risk, the culture preservation, the main livelihoods after reconstruction, the ecosystem that is protected, repaired and enhanced by reconstruction, the population trend, and the physiological recovery for people, all these have an influence on the quality of reconstruction and recovery, and at the end, determining the community resilience.

Resilience can also be represented as a graph (See Figure 3) considering multi-events may occur after a major disaster. The major event took place at time t_0, then different events occurred at time t_1, t_2 and t_3, and also caused damage to infrastructures. After a long recovery, the infrastructure got fully recovered to original function at time t_4.

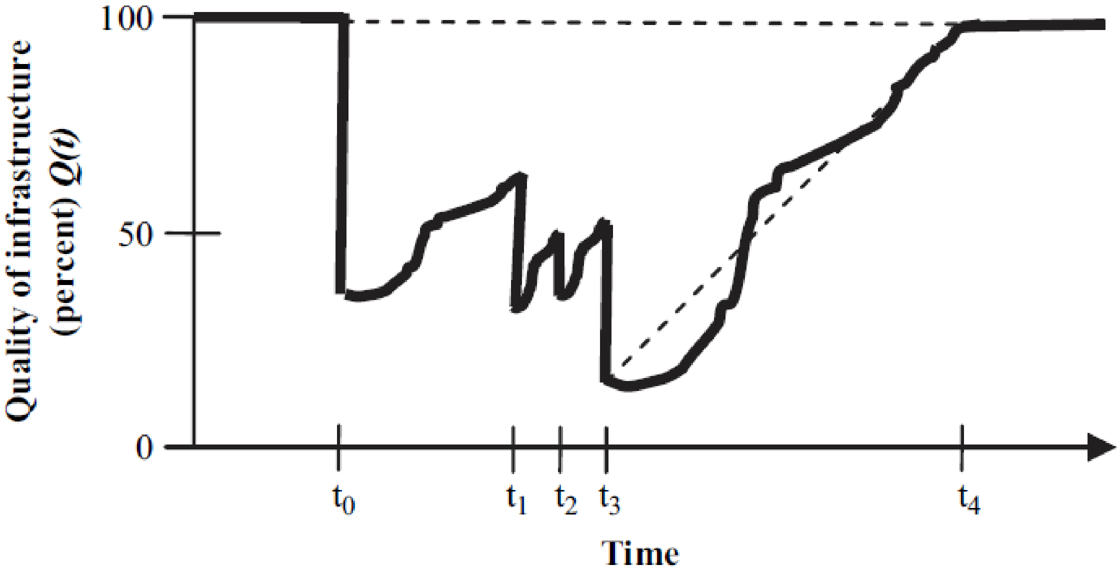


Figure 3. Multi-event resilience graph. Source: (Zobel & Khansa, 2014).

1.1.3. Earthquake resilience

Large earthquakes may have a devastating impact on a society, and are a good example of showing the resilience of a society with the effect of post-earthquake landslides. Social system, built environment and natural system can be affected by a large earthquake, and post-earthquake landslides may cause huge damage and losses to human environments by destroying buildings, infrastructures and traffic lines, which had been reconstructed after the earthquake. In this case, resilience can be represented by the graph with the quality of infrastructure through time (See Figure 3).

On 11 March, 2011, the large earthquake with magnitude (Mw) 9.0 occurred in Japan. Over 3 million people were exposed to severe shaking and this event with the tsunami it triggered caused over 19,000 people died or missing, with more than 295,000 buildings collapsed (Fraser et al., 2012). With high coping capacity and relative high resilience, Japan had shown its ability to withstand the worst earthquake. Strict building codes and effective warning system played a key role in reducing impact and damage during the earthquake. For example, within 8 seconds after the first earthquake waves, the whole country was warned and 27 high-speed "bullet" trains were stopped to avoid derailment. Moreover, the foundation of high resilience was also relative to the wealth, good governance and community characteristics, such as community participation, collective efficacy and trust. Paton et al. (2010) examined the degree of cross-cultural equivalence between Japan and New Zealand in predictors of earthquake preparedness. Two aspects were assessed, which were individual hazard beliefs (outcome expectancies) and the social characteristics (community participation, collective efficacy, empowerment, trust). Paton et al. (2010) concluded that the both communities preferred to take actions to make hazard preparedness if it was assessed to be implemented. However, tsunami was triggered by this earthquake and the double disaster triggered a third crisis at the Fukushima nuclear plant. Tsunamis with 3.3m to 7.2m height in Ibaraki and 1.3m to 7.6m height in Chiba caused devastating damages on the coastal areas (Mimura et al., 2011). Fukushima nuclear plant was damaged and four reactors were destabilized, leading to radioactive particles release and contamination. Even though with relative high earthquake resilience to resist the impact of earthquake, the reconstruction and recovery in Japan after earthquake was slow because of the large destruction, the nuclear crisis and the government's response to the disaster. In the third anniversary of the 3.11 Earthquake, reconstruction minister presented that there was still 270,000 people displaced and the clearing and processing of debris had not finished yet and was expected to be completed by the end the March, 2014.

Haiti earthquake, which occurred in January, 2010, was a catastrophic magnitude 7.0 Mw earthquake with over 230,000 deaths and 8–14 billion dollars in damage (Hayes et al., 2010). It left an estimated 10 million cube of rubbles to be cleared to Haiti country. In ten months after the earthquake, cholera outbreak and hurricane made this traumatic country worse. The Haiti cholera outbreak has killed at least 8,231 Haitians more than 6% of population have had the disease (Roos, 2013). Hurricane Tomas, as well as triggered flooding and mudslides, battered the western Haiti and caused damage to residential houses. Bilham (2010) presented that the buildings in Haiti were doomed by analyzing their engineering structures and materials. There were some obvious mistakes of buildings construction, such as the brittle steel, weak cement mixed with dirty or salty sand and coarse non-angular aggregate, as a consequence, making the buildings more vulnerable to earthquake. Moreover, there is not enough money and resources for earthquake emergency response in this one of the least developed countries. With the poor living conditions, paralyzed government and the promised aid money coming slowly, the recovery of Haiti was in a very slow progress. Six months after the earthquake, 98 percent of the rubble was still uncleared. It was reported that there was still 145,000 people who continued to live in make-shift camps four years after the earthquake. While making reconstruction, Haiti was trying to improve its resilience to earthquake. The plan of installing equipment and improve the seismic hazard map were underway to protect the country and people against further quakes one year after the earthquake. However, the county is exposed to some other problems, such as flooding caused by hurricanes and the poor quality of Haitian's home which was not strong enough to withstand the flood.

The Wenchuan earthquake, which occurred in May 2008, was one of the largest earthquake disasters of the past decade. The devastating earthquake (M_w 7.9) triggered over 56000 landslides (Dai et al., 2011). More than 70,000 people died in this earthquake and the total direct economic loss was about 187.5 billion Euros (Chen & Booth, 2011). The Chinese government reacted very fast to the earthquake, and initiated a large programme for reconstruction, with the construction of temporary shelters completed a few months after the earthquake, and at the end of 2009, 91% of the 3105 reconstruction projects were under construction and 50% had already been completed (Chen & Booth, 2011). The damage assessment and early recovery monitoring within 11 months after the earthquake had been done by Brown et al. (2012). High resolution QuickBird images were obtained for three years before earthquake (2005) and 22 days after the earthquake to apply the damage assessment. Two field visits took place to collect data in 5 month and 11 months after the event. With high resolution images and ground observation, several geo-databases were created for the epicenter of the Wenchuan earthquake which included the buildings, roads, bridges, tents and transitional shelters. Building damage assessment, accessibility assessment, natural environment assessment and internally displace persons assessment were applied to provide geo-referenced observation of damage and recovery across the area. 11 months after the earthquake, the major cities which were affected by the earthquake functioned normally without much evidence of damage, except for two areas where are planned to be memorial sites (Brown et al., 2012). A large number of transitions shelters had been built for housing people and business were flourishing. However, during the years since this earthquake occurred, several hazardous events happened. On 13 August 2010, debris flows from the Wenjia gully destroyed many buildings, roads and bridges in the Qingping area that were reconstructed after the 2008 earthquake. In 2013 a debris flow occurred in QiPan catchment near Wenchuan county, causing 8 deaths and 6 missing, 90% of reconstruction buildings were damaged and 4,400 people were left homeless (Huang, 2014). The Chinese authorities use the term "re-reconstruction planning" for developing the areas that were initially reconstructed after the earthquake but subsequently hit by debris flows.

1.2. Approaches to analyze resilience

Although resilience is a well-known concept in different fields, there are relatively few studies that try to quantify resilience, especially with the effects of multi-events. In general, there are two different types of methods to quantify resilience reported in the literature: the loss model and resilience inference measurement (RIM) model.

Bruneau et al. (2003) developed a conceptual framework based on loss estimation model to measure seismic resilience of community. The performance of any system can be measured as a point at a given time or as a serious change gradually or abruptly over time. Catastrophic event, for example, earthquake, can lead to abrupt change of system performance. In this case, the system failed. In terms of system performance, resilience can be understood as "the ability of the system to reduce the chances of a shock, to absorb a shock if it occurs (abrupt reduction of performance) and recover quickly after a shock (re-establish normal performance)" (Bruneau et al., 2003). Bruneau et al. (2003) presented that resilience could be quantified based on three objectives: 1) failure probabilities reduction 2) consequences reduction from failures 3) time reduction to recovery. Four properties (robustness, redundancy, resourcefulness and rapidity) and four dimensions (technical, organizational, social and economic) of community resilience were described to measure resilience. The explanations of these four terms and four dimensions show below:

Robustness: the strength of a system that can withstand and maintain the original function after the impact of the event. This can be quantified in terms the degree of damage of infrastructure.

Redundancy: the degree of the system in which the elements can be substitutable after the infrastructure function has been damaged.
Resourcefulness: the level of dynamic response capacity, including a series decisions and measures to improve rapidity and/or robustness from the event occur till recovery.
Rapidity: the capacity to rehabilitate/restore and recovery to an acceptable function in a timely manner.

Technical dimension of resilience focuses on the ability of physical system when the system subject to earthquake forces, such as the availability of hospital system, the electric power supply and the water supply. *Organizational* dimension refers to the capacity of organization to manage, make decisions and take actions after a disruptive event, for example, the ability of the emergency organization. *Social and economic* dimensions of resilience consist of capacity and measures that lessen and reduce the consequence of lacking critical services and direct and indirect economic loss.

Chang and Shinozuka (2004) assessed the improvement of resilience based on the framework developed by Bruneau et al. (2003). It was a probabilistic approach about calculating the probability of losses in terms of robustness and rapidity by comparing the actual performance and the standard one with system performance framework. For each dimension of resilience, there is an indicator to measure the system performance. Technical and organizational performance was defined in terms of water system. Technical performance referred to the network physical condition and it was measured by the number of major pumping stations that lost function and the percentage of broken pipes. The organizational performance referred to water service and it was measured by the percentage of population losing water service. Social and economic performances were defined in terms of the community. Social performance referred to the population living at home and it was measured by the percentage of population displaced from home. Economic performance referred to the economic activity and it was measured by the percentage of the gross regional product lost. With the pre-defined performance standards, resilience can be calculated by the probability of meeting the standards and the probability of the earthquake occurrence. The improved resilience was calculated for 3 retrofit cases and 2 earthquake scenarios. This research was useful to guide the mitigation and preparedness efforts and succeeded relating the loss estimation to four dimensional resilience, but there was only one indicator to represent the system performance. Moreover, if failed to take the impact of organizational response and different societal behaviours on the engineering / physical performance.

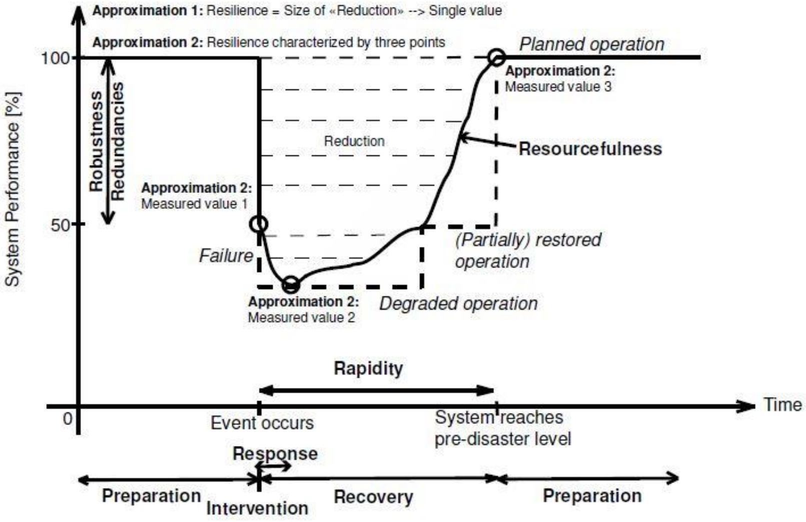


Figure 4. Schematic representation of resilience with failure, degraded operation and disaster impacts. Source: (Dorbritz, 2011)

Dorbritz (2011) used modelling and statistics methods to assess the resilience of transportation system based on the framework of Bruneau et al. (2003). In this study, resilience was defined as the ability to maintain transport service even some severe disasters occur and cause failures of stations or blockades of connections of tracks. The system performance with the fraction of removed nodes and consequences of operation (e.g. rerouted line and/or truncated line) were modelled with software. And then these consequences were related to the four dimensions of resilience: robustness and redundancy (initial reduction of the system), resourcefulness (shape of system performance curve) and rapidity (duration from failure to regained system performance) (See Figure 4). The final disaster resilience can be quantified by measuring the area under the performance curve or by measuring three values: robustness, the minimal value of system performance and rapidity.

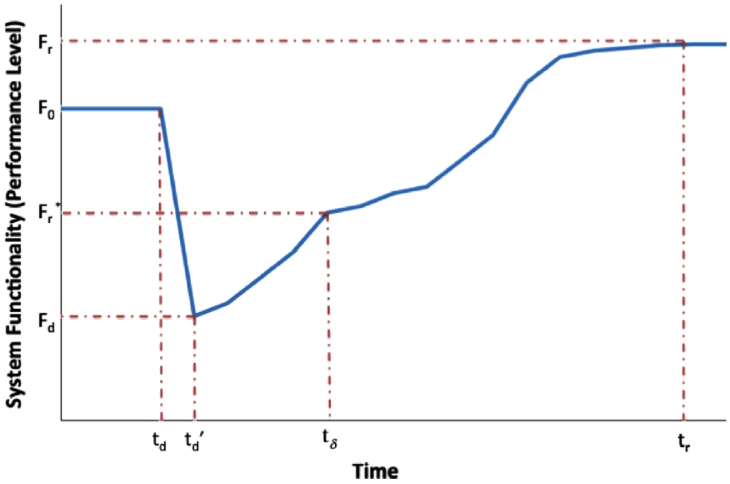


Figure 5. Schematic representation of relationship between system performance and time. Source: Francis and Bekera (2014).

Francis and Bekera (2014) provided a metric and framework for analysing resilience which focus on three resilience capacities: adaptive capacity, absorptive capacity and recoverability. In this research, four resilience factors were defined based on system functionality: the recovery speed Sp (a function of time), the original system performance (Fo), the immediate performance level after disruption (Fd) and the new performance of system after recovery (Fr) (See Figure 5). The three capacities can be calculated by these four factors, for example, absorptive capacity can be represented as Fd/Fo, and adaptive capacity was calculated as Fr/Fo. The author also took fragility (the probability of system failure) and entropy (the subjective probabilities about potential disruptions) into account to measure resilience.

Zobel and Khansa (2014) developed an approach for providing a quantitative measure of charactering predicted resilience taking into account multiple disaster events. The analysis was based on the graph (See Figure 3) and resilience was characterized with a mathematic way for five different scenarios in terms of different degree of impact by earthquake and aftershock (e.g. landslide). For each scenario, the resilience was calculated by the area above the curve and then the tradeoffs between the robustness and the rapidity was characterized with the graphical illustration of loss and recovery time.

All the researches above provided different ideas to quantify resilience based on loss estimation model. However, the factors in the framework can only be quantified by human experience because of the difficulty in measuring and loss estimation is insufficient to measure socioeconomic status in quantifying resilience (Li et al. 2008). A new model, namely, resilience inference measurement model, was developed and used to quantify community resilience in different areas (Li, 2013; Li et al., 2015) . In this model, community resilience was represented by three dimensions and two abilities. The three dimensions were the exposure to hazard, the damage caused by exposure to hazard and the recovery. Vulnerability and adaptability, the two abilities, made these three dimensions associated. Four states of resilience were defined based on the above three dimensions, which were usurper, resistant, recovering and susceptible

(See Figure 6). These four states of resilience were classified in terms of exposure (intensity of earthquake), damage (the direct economic loss) and the recovery (the population growth from pre-earthquake to post-earthquake) by using K-mean cluster analysis. With these priori resilience level and 15 socio-economic variables that described pre-event conditions, discriminant analysis was applied to test if the resilience level can be predicted by these socio-economic characteristics. The result presented that these socio-economic variables had an important influence on resilience. These variables, particularly, the sex ratio, per capital GDP, percent of ethnic minorities and average number of hospital beds, can be used to predict the earthquake resilience. This research succeeded to quantify the earthquake resilience at a county level and proved that the selected socio-economic characteristics can be used to predict the level of resilience. However, the quantitative resilience was static. Moreover, exposure, damage and recovery are related to resilience, but recovery has different dimensions, such as built up environment and economic system, and also resilience is affected by different components and indicators. In this research, quantitative resilience was only determined by the intensity of earthquake, the direct economic loss and the population recovery.

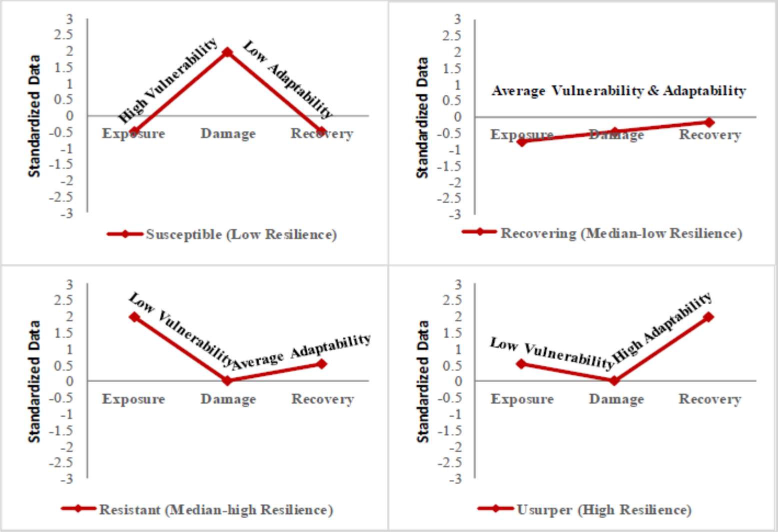


Figure 6. Four state of resilience in the RIM model. Source: (Li et al., 2015).

Even though researchers have tried to measure resilience, it is difficult to quantify. For one reason, it relates to different phases before disaster and after disaster, as shown in the Figure 1 and Figure 2. Moreover, resilience had four different dimensions and properties (Bruneau et al., 2003), this makes it complex to integrate those dimensions. Chang and Shinozuka (2004) failed to integrate the technical dimension with organizational and societal dimensions. Researchers Dorbritz (2011), Francis and Bekera (2014) and Zobel and Khansa (2014)presented several theoretical methods to measure resilience based on its four properties, but when they were used in reality, there were a lot of assumptions which make these complex method simple. RIM model is a way to quantify resilience from a new perspective, which not only focus on infrastructure system, but also consider the socioeconomic characteristics, however, this method didn't show the other phases in Figure 2, except for pre-event, event occur and recovery. And also, the recovery is only presented by population growth rate.

1.3. Framework for analysing resilience in this research

From the literature review in the above section, six dimensions (e.g. economic, social, institutional, infrastructural, ecological and community competence) were defined for earthquake resilience and several indicators for each resilience dimension were presented and justified. Resilience can be quantified and represented in terms of four properties (e.g. robustness, rapidity, redundancy and resourcefulness) with the multi-disaster graph (See Figure 3 and Figure 4).

The categories and the indicators for each dimension of resilience are defined in the framework for analysing resilience in this research which is presented in Figure 7. The categories are the main dimensions of earthquake resilience and the indicators are the components that can be measured to quantify resilience or indicated to analyse resilience. The indicators marked red in Figure 7 are the direct indicators that can be measured from the infrastructure change analysis and population change analysis in this research, for example, the number of buildings and the length of roads to quantify the infrastructural resilience, and the number of people for quantifying the social resilience. The indicators marked with blue in Figure 7 are the indirect indicators that cannot be determined directly in this research, but where the changes analysis, and reconstruction efforts can indirectly say something about their importance. For instance, the employment opportunities and funding are analysed to show the economic resilience, which is based on the different economic sectors (e.g. tourism, agriculture, industry, energy) and the investments during the reconstruction. Moreover, the employment opportunities can also be indicated indirectly in terms of the changes in physical infrastructure. For instance, the destruction of industrial buildings clearly is an indication that there are less opportunities for employment in that sector. And the large ecological system disruption caused by the earthquake and debris flows, leading to less job opportunity and farming space. An indirect indicator for the ecological resilience coming from the analysis of changes is illustrated by the percentage of forest cover which is caused by the co-seismic landslides and the occurrence of debris flows which may hamper the recovery of ecological system for a considerable time period. To mitigate the hazards, several disaster risk reduction had been done during the reconstruction, such as building codes improvement, better landuse planning. These indicators are analysed to show the institutional resilience. Community competence resilience is affected by life satisfaction, which is related to the employments, the income and living environments. Life satisfaction is indicated by the reconstruction efforts, such as tourism, and the debris flow affection during the recovery. There are more indicators to quantify and analyse resilience, which are shown black. However, there is no information about these indicators in this research.

With those above indicators for six dimensions of resilience, each resilience dimension can be represented with the multi-disaster graph, combining the three properties of resilience (See Figure 7). For the infrastructural and social resilience, the quantitative resilience graph can be generated. The economic, ecological, institutional, community competence resilience graph will be presented with descriptive information instead of quantitative analysis.

1.4. Research identifications

1.4.1. Research objectives

The main objective of this research is to quantify some components of resilience (See Figure 7) by analysing the changes of elements-at-risk (built-up areas, transportation infrastructure and landslide mitigation works) in the post-earthquake mountainous area affected by the 2008 Wenchuan earthquake.

Sub-objectives:

1. To create a comprehensive multi-temporal database of elements-at-risk including built-up areas, transport infrastructure (roads, bridges, and tunnels), landslide mitigation constructions, and population in the study area.
2. To quantify the changes of elements-at-risk caused by reconstruction work and post-earthquake landslide events, using a number of approximate measurement scales (e.g. nr of buildings, length of roads, number of people).

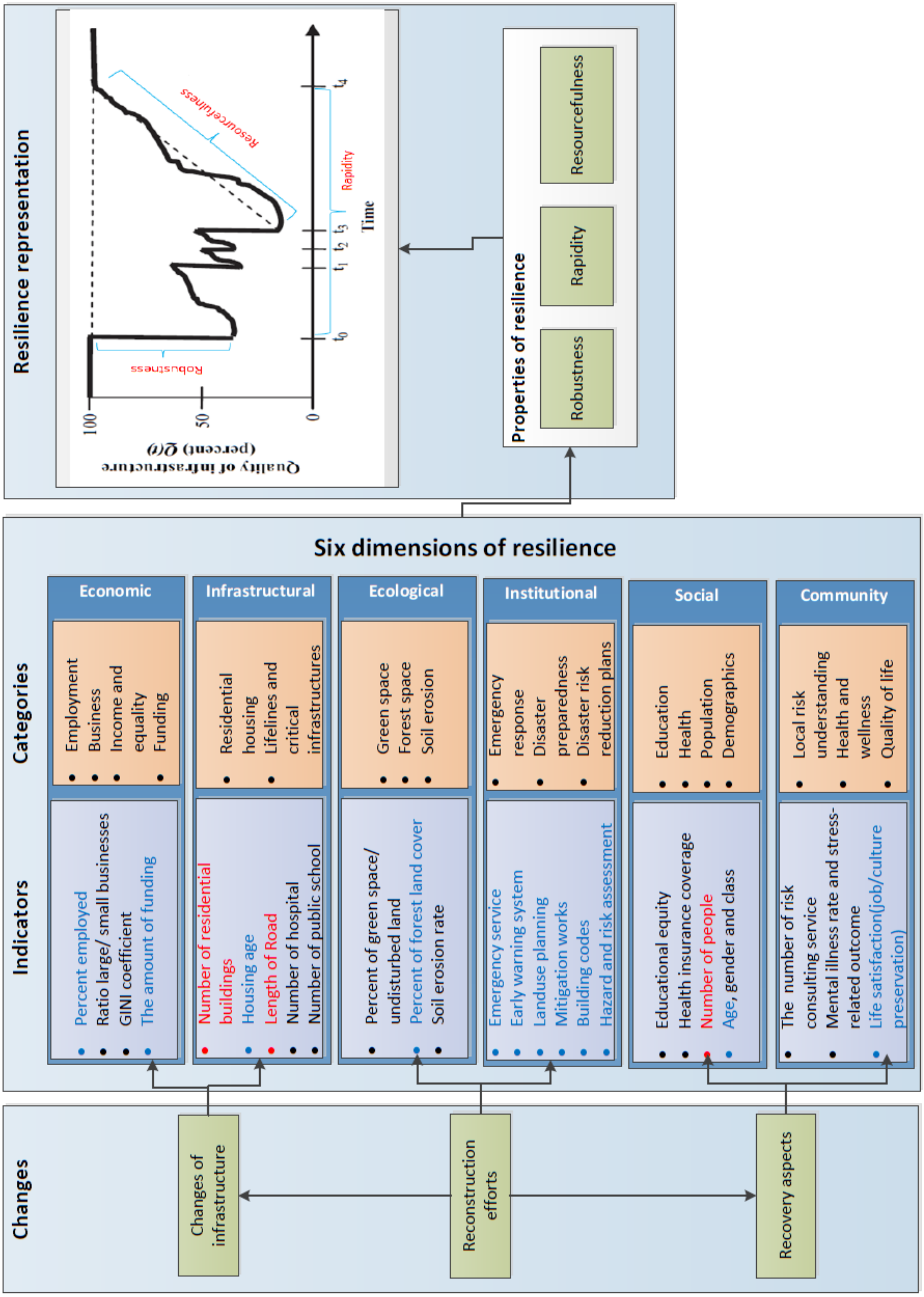


Figure 7. Framework for analysing resilience in this research.

1.4.2. Research questions

- How useful are the yearly available satellite images for monitoring the changes in elements-at-risk?

- How many buildings and infrastructures were destroyed by the 2008 earthquake and the co-seismic landslides?
- How many buildings and infrastructures were reconstructed and how many were destroyed by post-earthquake landslides?
- Is it possible to quantify the number of people based on built-up area characterization? How many people lived in the area before the earthquake, and how many were able to live there in the years after? Is there an increasing or decreasing trend?
- Can we quantify some components of resilience in terms of number of elements-at-risk and mitigation works over a number of years? Which other aspects of resilience could be identified for further studies?
- What can we learn about the resilience of the Chinese society and the communities in the Wenchuan area, from the results of this study?

1.5. Structure of the thesis

Chapter 1—Background. The concept of resilience is defined and the different components and variables are reviewed and summarized. The problem is pointed out and the research objectives and research questions are defined.

Chapter 2—Study area and dataset. The different situations about the study area before the earthquake and after the earthquake are described, with the efforts of earthquake reconstruction. The data that have been acquired, the quality and the data obtained from fieldwork or published articles are explained.

Chapter 3—Methodology. The designed approach to accomplish the research questions and research objectives is explained in this chapter, which includes the image interpretation, database generation, change analysis and earthquake resilience analysis.

Chapter 4—Result and discussion. The outcomes of the processes described above are shown in this chapter with the analysis and discussion.

Chapter 5—Conclusion and recommendations. A brief conclusion of this research is presented and the recommendations for the future study are pointed out.

2. STUDY AREA AND DATASET

This chapter gives a detailed description and illustration about the geomorphology situation and the elements-at-risk distribution for this study area. It is also explained about the damage caused by the Wenchuan earthquake, the reconstruction efforts that were made by the Chinese government and the complicated situation after the earthquake with the occurrence of post-earthquake landslides. Moreover, the satellite images with quality description are described and the data obtained from field work is explained.

2.1. Study area.

The study area, with a size of approximately 500km^2, is located in the epicentre of the Wenchuan earthquake area which is close to Yingxiu town (115 km^2), in Sichuan province, China. The area is situated about 20km east to the epicentre of Wenchuan earthquake (according to USGS data) (See Figure 8). It is located in a mountainous belt which is between the Sichuan Basin and the Western Sichuan Plateau. Rugged mountains and deep valleys are the two characteristics of this study area. After the earthquake, huge amount of loose sediments hanging on the hillslopes provide sufficient source materials for numerous debris flow occurrences during the heavy rainfalls (See Figure 8). The climate type of the study area is humid subtropical with annual average temperature of 12.9℃。 In the south part of the area, the average yearly precipitation is 1134.8mm, and 90% of the precipitation occurs from June to September. In the north part of the area, the average annual precipitation is 725-750mm and most of the rainfall occurs in 5 months, from May till September. In July 8-10, 2013, the daily rainfall was 34.4mm, 32.7mm, 104mm, respectively.

Rapid emergency respond and reconstruction had been made by Chinese government for the study area after it was severely damaged by the Wenchuan earthquake and co-seismic landslides. As early as May 18, six days after the earthquake, the rough number of dwellings required for each county was estimated by State Council. And then, the Ministry of Housing issued instructions to 23 provinces and cities to support the earthquake affected areas with transitional resettlement. The immediate top level government response, open and transparent relief information, the diversity of donors and voluntary contributions made the disaster coping response quickly and effective (Chen & Booth, 2011). Just three months after the earthquake, the State Council issued the *State Overall Planning for Post-Wenchuan Earthquake Restoration and Reconstruction*, which set the goal of completing the reconstruction within three years. Brown et al. (2012) monitored the Wenchuan earthquake reconstruction and recovery and the result showed that the supply of tents and transitional shelters in Yingxiu was rapid and well-organized. The major cities affected by this earthquake functioned normally with no evidence of homelessness around 11 months after the earthquake. At the end of 2009, 91% of the 3105 reconstruction projects were under construction and 50% had already been completed (Chen and Booth 2011).

The area suffered from debris flow disasters almost every year since 2008 (See Table 1). Not only the villages and roads along the valley (See Figure 8 and Table 2) were affected by the debris flows, but also the engineering mitigation works constructed in the study area were damaged and reconstructed (See Table 1). One of the most catastrophic event occurred on August 12-14, 2010. Within 33 hours from 17:00 on the 12th of August, the total cumulative rainfall was 162.1mm with 126.8mm on August 13. Debris flows occurred in most of the catchments in the area of Yingxiu. They blocked the main road from

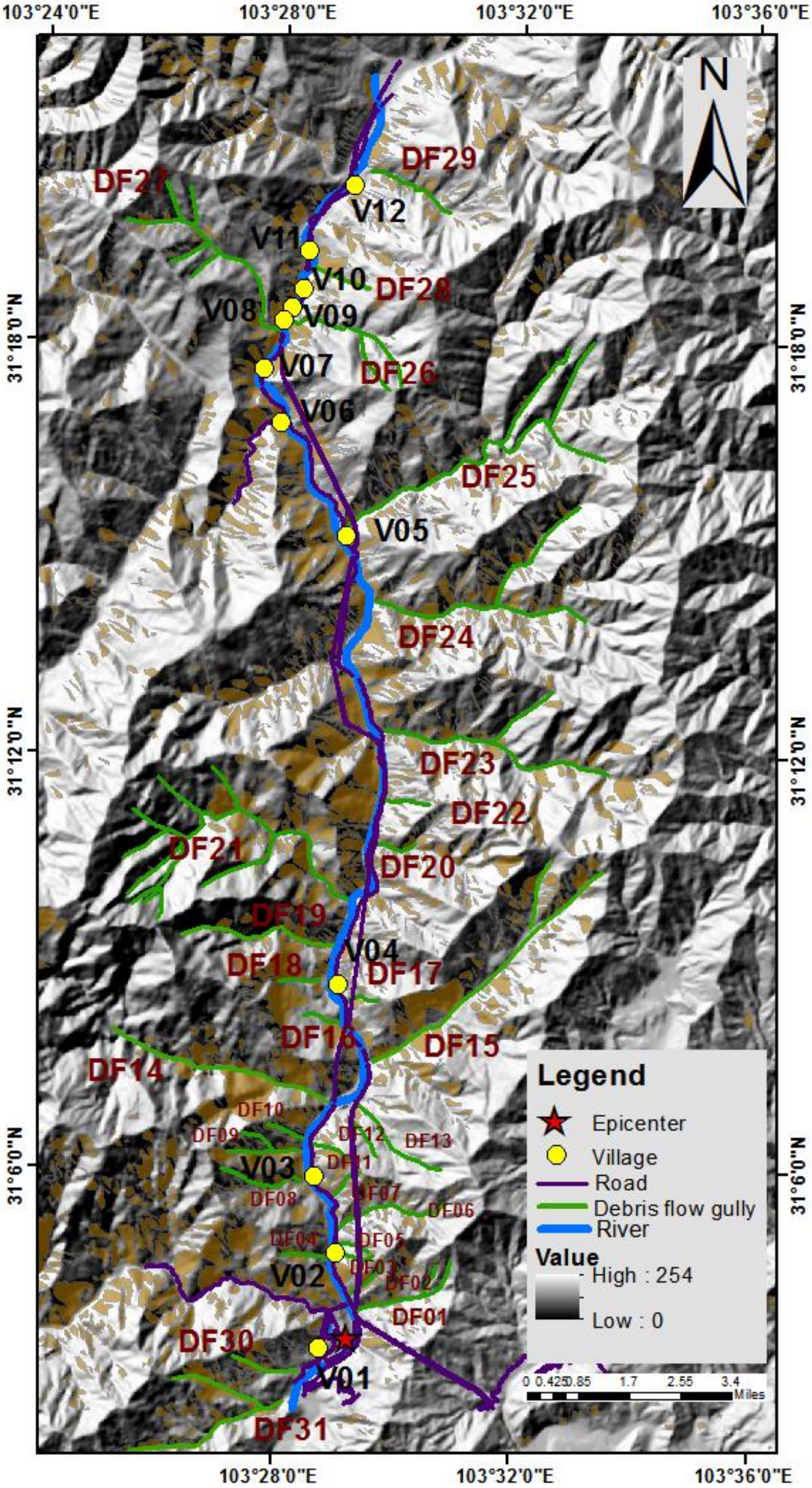


Figure 8. Debris flow gullies distribution and post-earthquake landslide distribution. Debris flow gullies are marked in green and landslides triggered by the Wenchuan earthquake are marked in brown. The codes of the debris flow gullies are also used in Tables 1. The location of the villages and the epicentre of the earthquake are also indicated, the population distribution in terms of villages are indicated in Table 2.

Table 1. List about debris flow occurrence and mitigation works construction and disruption in different years. "DF" represents occurrence of debris flow and MWC with green background represents the mitigation work construction. The "DF" with red background represents the mitigation works disruption caused by debris flow. Source: Reports collection and image interpretation and fieldwork characterization.

Gully code	Gully name	Year					
		2009	2010	2011	2012	2013	2014
DF01	Hongchun		DF	MWC			
DF02	Shaofang		DF	MWC			
DF03	Xiaojia		DF	MWC			
DF04	Baijialin		DF				
DF05	Wangyimiao		DF	MWC			
DF06	Mozi		DF				
DF07	Laohuzui		DF	MWC			
DF08	Douyaping		DF				
DF09	Mayangdian		DF				
DF10	Maliuwan		DF				
DF11	Santaidi		DF	MWC			
DF12	Dagou		DF				
DF13	Dacaotou		DF				
DF14	Ergou		DF				
DF15	Taipinggou		DF				
DF16	Zaojiaowan		DF				
DF17	Heicaotou		DF				
DF18	Xingwenping		DF				
DF19	Yiwanshui		DF				
DF20	Supodian		DF				
DF21	Yeliu		DF				
DF22	Maojiawan		DF				
DF23	Yinxingping		MWC/ DF	DF		MWC	
DF24	Gaojia		MWC/ DF	DF		DF	
DF25	Taoguan	MWC		MWC/ DF		DF	MWC
DF26	Maozi (in Caopo)					DF	MWC
DF27	Huaxi					DF	MWC
DF28	Yangdian					DF	MWC
DF29	Gaodianzi					DF	MWC
DF30	Zhangjiaping					DF	MWC
DF31	Niujuan				MWC	DF	

Yingxiu to Wenchuan (See Figure 9) and the resulted flooding inundated the part of the new re-constructed Yingxiu town. On the same day, a debris flow occurred in Yinxingping catchment causing the main road blocked. After this, the debris flow also occurred in July 2011 and the mitigation works were damaged, which made the reconstruction of mitigation works in 2013. Another catastrophic event occurred on July 10, 2013. With the total cumulative rainfall 119.3mm for 84 hours, around 90% of the study area suffered from debris flows. The new reconstructed road (G213) was buried and damaged, the highway that was completed in 2012 was blocked.

Table 2. Number of buildings, households and people for each village.

Code	Name	Nr_households	Nr_people
V1	Yuzixicun	207	739
V2	Laojiecun	100	310
V3	Douyapingcun	30	80
V4	Yinxing town	392	1544
V5	Taoguancun	120	600
V6	Yangdiancun1	52	220
V7	Yangdiancun2	33	140
V8	Yinjiaba1	30	105
V9	Yinjiaba2	32	112
V10	Yangdiancun3	30	120
V11	Keyuecun3	70	250
V12	Gaodiancun	168	540

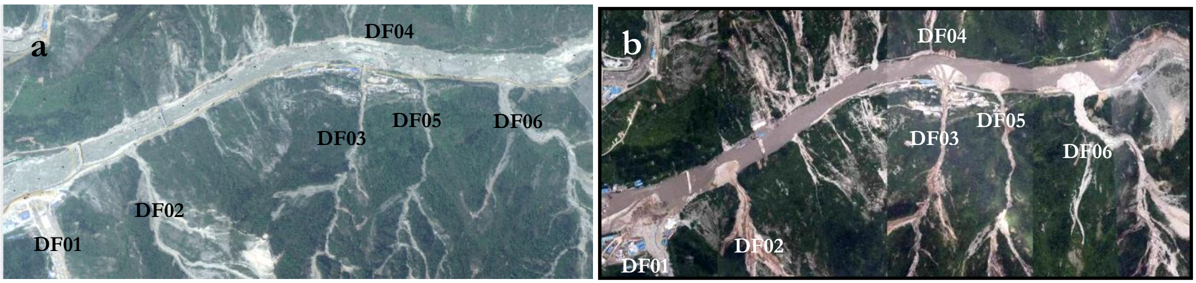


Figure 9. Satellite images before the debris flow (a) and after the debris flow (b).

Confronted with the difficult situation damaged by the major earthquake, the restoration and reconstruction was a challenging work and a lot of reconstruction efforts have been made by the Chinese government and local community for this study area. Culture preservation is one important aspect taken into account during the reconstruction. Most of people who live in the study area are from minority groups. There are two major ethnic groups, Zang people and Qiang people, and they have their own unique ethnic traditions, cultural life and faith. The cultural differences have been respected and the traditional architectures and the minority ethnic elements are preserved and reconstructed after the earthquake (See Figure 10). Industrial adjustment is another design for reconstruction planning. Tourism in Yingxiu had an initial development because of the convenient transportation and the famous tourist attractions nearby. The major earthquake will undoubtedly further increase the advantages for the development of tourism and service. Landuse types in Yingxiu changes from the main residential and town_mixed into multiple types, for example, emergency public service facilities area, secondary hazard affected area, residential area and tourism area. The memorial museum and park, international academic exchange centre for disaster reduction and Business Street with ethnic characteristics are constructed for the tourists and experts. Furthermore, lessons have been learned from the earthquake and the building codes are improved during the reconstruction. The fortification intensity has been improved to VIII and the basic seismic acceleration is 0.20g. Four different types of seismic standards are classified in terms of the occupancy types of buildings.

2.2. Datasets

There are three main components of the dataset, satellite images, attributes of elements-at-risk, disaster reports and relevant loss information. Prior to the field mission, pre-vent and a series of post-event high-resolution optical satellite images (from 2008 till 2013) are obtained for each year. The attributes of elements-at-risk for buildings, roads and bridges are characterized during field work, such as the occupancy types of buildings and types of roads. Disaster reports and the relevant loss information are collected from local people, investigation reports and some published articles.

2.2.1. Satellite images

Multi-temporal satellite images were collected for the study area for each year since pre-earthquake till 2013 (See Table 3 and Figure 11). These images were provided by a European research project, INCREO (Increasing Resilience through Earth Observation) project, which is an EU project in collaboration with the European Space Agency (ESA) under the COPERNICUS programme. The satellite images acquired from multiple sources cover partial or full study area with different resolution. Figure 12 shows the examples of the images acquired for image interpretation with different qualities for small part of Yingxiu town. The resolutions of some images are very high without clouds cover, such as the Digital Globe (0.5m) and Pleiades (0.5m) data. For 2009, there is only one panchromatic image and it will be a little difficult to identify small buildings. The Arial photo mosaic from 2008 was acquired immediately after the earthquake which is very useful to get the earthquake damage information by image interpretation. However, the resolution of this Arial photo (5m) is not as high as enough to make detailed image interpretation, for example, the individual building without damage will be mixed with the collapsed buildings. Cloud cover is another important factor of image quality. Image 2012 has the highest cloud over, which is 55 percent and it covers most of elements-at-risk in Yingxiu town. Even though there are also clouds in the images for 2005 and Arial photo for 2008, the elements-at-risk are not covered by clouds at all. For the images 2010 and 2013, both panchromatic and multi-spectral images were collected, this makes image interpretation easier for much more detailed information about objects. Image acquired in 2005, 2010 and 2011 come from Google Earth and they are already registered in Google Earth for easier changes interpretation and analysis in the next step.

Table 3. Satellite image data acquired.

Year	Source	Resolution (m)	Area covered	Cloud cover (%)	Description
2005	QuickBird	2.4	Partial	3.5	Multi-spectral
2005	QuickBird	2.4	Partial	3.5	Multi-spectral
2005	QuickBird	2.4	Partial	3.5	Multi-spectral
2005	QuickBird	2.4	Partial	3.5	Multi-spectral
2005	Digital Globe	1	Partial	0	Multi-spectral
2008	Arial photo	5	Full	11.9	True colour
2009	SPOT5	2.5	Partial	0	Panchromatic
2010	Digital Globe	1.5	Partial	0	Panchromatic
2010	Digital Globe	6	Partial	0	Multi-spectral
2011	Digital Globe	0.5	Full	0	Multi-spectral
2012	SPOT 5	2.5	Partial	55	Multi-spectral
2013	Pleiades	0.5	Partial	0	Panchromatic
2013	Pleiades	2.0	Partial	0	Multi-spectral

Figure 10. The two different types of traditional buildings for two different ethnic groups.

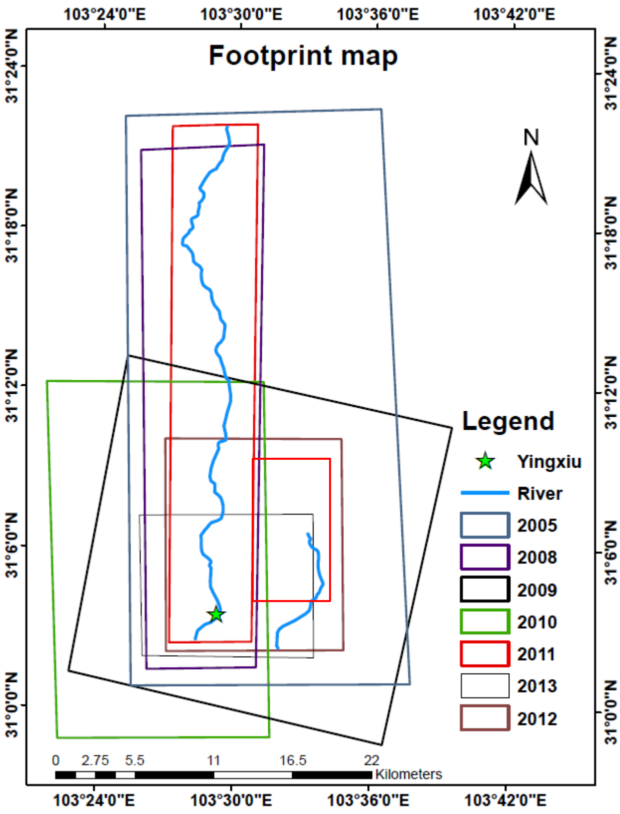


Figure 11. Footprint maps of all images.

Figure 12. The examples of images about part of Yingxiu town with different resolution and different qualities.

2.2.2. Data from field work

Two main components of field work data are the attributes of elements-at-risk and the damage/loss information for the earthquake and post-earthquake landslides and debris flows. The attributes of elements-at-risk are explained in this section and the loss information collected from reports and fieldwork will be shown in the Chapter 4.

The attributes of elements-at-risk were characterized during the field work (See Table 4). For buildings, the occupancy types were defined as "residential", "commercial_mixed", "industrial", tourism", "commercial", "institutional" and "town_mixed". The "commercial_mixed" referred to the buildings that were mixed with "residential" and "commercial". The "town_mixed" occupancy type was defined as the area that was used as town developments based on landuse map for pre-earthquake in Yingxiu town. The number of floors of buildings and the different types of roads were characterized during fieldwork data collection.

Table 4. The detailed information about elements-at-risk for generating the database.Source: (van Westen et al., 2008) with modification.

Type of elements-at-risk	Detailed information
Buildings	Mapping units •Occupancy type of buildings (e.g. residential, commercial_mixed, industrial, tourism, commercial, institutional and town_mixed) •Nr. Buildings •Nr. Floors •Nr. Households or Apartments
Transportation networks	•The type of roads (e.g. national road, highway, tunnel, province road) •Bridges
Population data	By mapping units •The number of people
Mitigation works	•Construction (yes/no)

There are three towns in this study area and two of these three towns (Yingxiu and Yinxing) are composed of 12 villages in Figure 8 and Table 2. The number of people for each village and the total number of people for each town were obtained from the local people and census data (See Table 2 and Table 5). Moreover, the mitigation works construction and destruction were collected form reports and characterized by fieldwork (See Table 1).

Table 5.Total number of people for three towns, Yingxiu, Longchi and Yingxing. Source: Census data.

Town	Year		
	Pre-earthquake	During earthquake	After-earthquake
Longchi	3487	die(36),missing(17)	3234
Yingxiu	14000	die(6566)	6238
Yinxing	2179	die(618),missing(11)	1361

3. RESEARCH METHODOLOGY

This chapter introduces the methodology that is used to quantify some components of earthquake resilience which are defined in Figure 7. The methodology is presented with the flowchart below (See Figure 13). It can be divided into five stages, image interpretation, field work data collection, database generation, change analysis and quantifying and analyzing resilience. Quantitative changes are related to the earthquake resilience directly and the qualitative changes are analyzed to show the reconstruction efforts and the recovery quality. With linking Figure 13 and Figure 7, the different dimensions of earthquake resilience can be simply quantified or analyzed.

The flowchart (Figure 13) shows the methodology that is used in this research. Starting from multi-temporal satellite images pre-processing and image interpretation, the changes of elements-at-risk can be extracted. With fieldwork data collection, the attributes of the elements-at-risk were obtained to generate the multi-temporal database. The number of buildings are estimated with the occupancy type characterization and sampling for some homogenous area. After generating the database of elements-at-risk, the changes of buildings, roads and population can be quantified and used to quantify simplified infrastructural and social resilience. The qualitative changes are analyzed based on the occupancy types, the road types, and the improvement of landuse and building codes. The employment opportunity and life qualify can be indicated by the large number of co-seismic landslides which had a seriously impact on the destruction of ecological system. Even though large amount of money was invested in reconstruction and tourism development which can increase the economic resilience, the less tourists and job opportunity show the relatively low economic resilience. The other dimensions of earthquake resilience can also be analyzed with the indictors in Figure 7, by linking Figure 13 to it.

3.1. Image pre-processing

3.1.1. Image mosaicking

Image mosaicking is the process of stitching multiple images to be seamlessly together or blending numerous overlapped images into a composite image (Goshtasby, 2005). When multiple satellite images cover the same spatial domain in the study area, it is required to combine these images into one larger image by mosaicking. The main objective of mosaicking is to obtain the images for a larger area and maximize cloud-free coverage (Bindschadler et al., 2008; Crawford et al., 2013). The images can be required from the same sensor at different time, or from the different sensor at the same time, however, there must be overlap between these images. In this research, ERDAS IMAGING 2014 is used to do the image mosaicking.

3.1.2. Image enhancement

Image enhancement is one way of adjusting images and improving the quality of an image for more suitable display. The main objective of image enhancement is to highlight the digital information of interest and reduce the effect of the un-useful information. It can be done by increasing the contrast between the target objects and the background information, or called contrast modification/stretching. Contrast modification is just a mapping of brightness values by respecifying the digital number (DN) values (Richards & Jia, 2006). ArcGIS 10.2.2 software is selected to make the image enhancement.

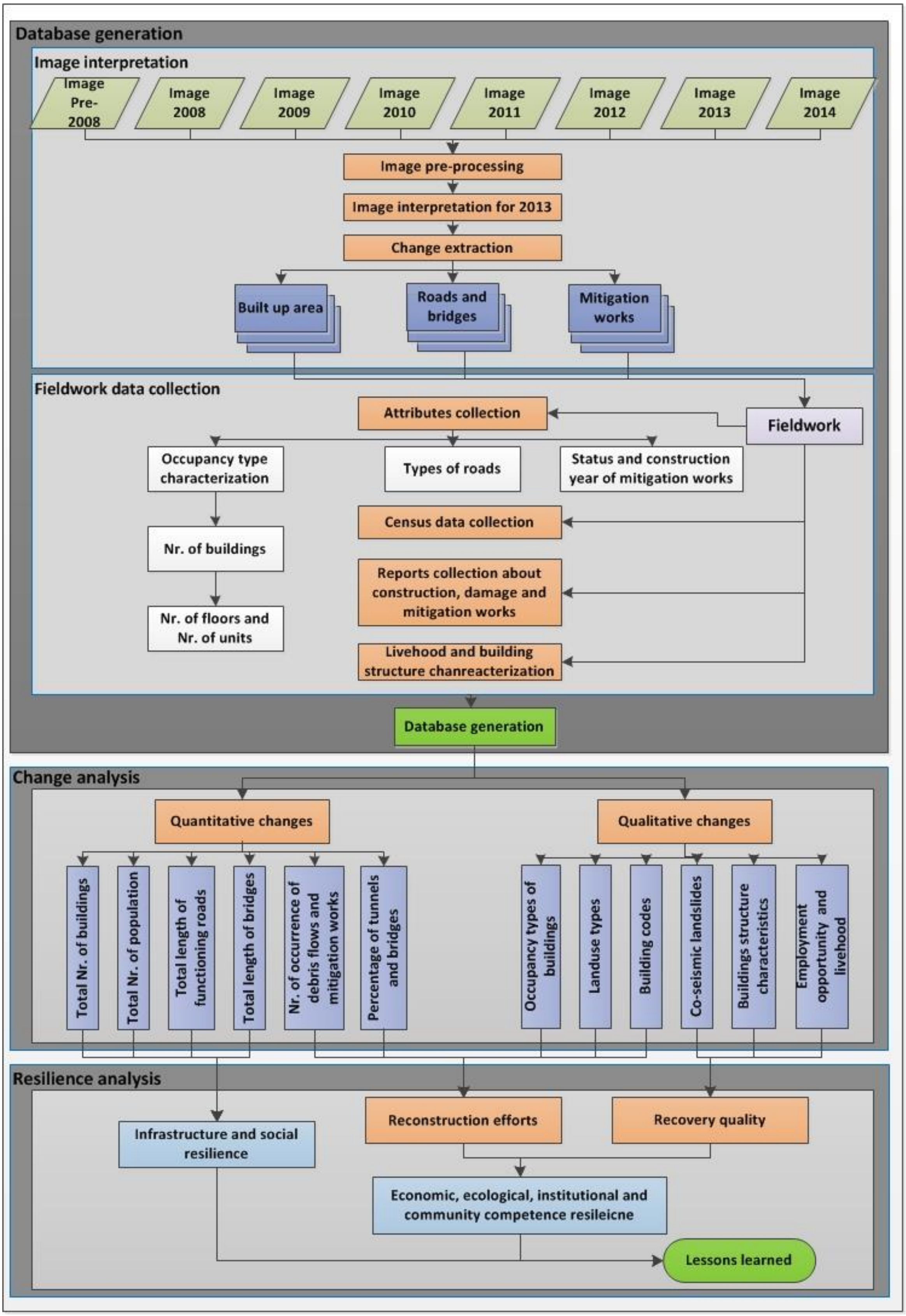


Figure 13. The flowchart describing the methodology of this study.

3.1.3. Image fusion

Image fusion is the process of generating a new image by combining information from two or more images with certain algorithms to enhance viewing, better understanding and acquiring detailed geospatial information (Goshtasby, 2005). Because of the broad range of earth observation satellites, the product of image fusion is valuable to provide increased interpretation capabilities for bringing different characteristics of sensors together into a single image (Campbell, 2002). These characteristics vary in spectral, spatial and temporal resolution. A good example of image fusion is combining optical image with synthetic aperture radar image. This fusion can generate a better understanding of objects observe for integrating the characteristics of reflectivity of target from sun light and the characteristics of the target surface from signal (Pohl & Van Genderen, 1998). Pan-sharpening is done with the software ENVI in this research.

3.1.4. Image registration

Image registration is the process of determining the correspondence of images by overlaying them which are taken at different time and/or from different sensors and viewpoints (Goshtasby, 2005; Zitova & Flusser, 2003). Two images, the reference image and the sensed one, are aligned geometrically by image registration. Even though a lot of methods about image registration have been developed, there are still several problems for registering high-resolution images of hilly area, such as local geometric distortion caused by image perspective (tilt) and relief (terrain) effects, and also difficulty for locating control points precisely (Hong & Zhang, 2005). In this research, image registration is done with software ERDAS IMAGING 2014. The images for the mountainous study area are from different sensors with different characteristics and resolution, therefore, the first step for image registration is orthorectifying all images with the same DEM, and resampling all images to the same resolution. However, the author keeps using the original images which are orthorectified by different producer with different DEM because lacking of the DEM for this area. Point feature (control points) is selected manually and matched by image interpretation. Moreover, some images come from Google earth and the changes can be analyzed directly by comparing the images in Google earth instead of doing image registration.

3.2. Image interpretation

Image interpretation is applied to map the elements-at-risk instead of the automatic extraction. Even though methods can be used for automatic building extraction with object-oriented analysis, the resolution is required to be very high. With the Pleiades panchromatic image (0.5m) and the multi-spectral image (2m), Yang (2014) tried to map building automatically but the overall accuracy is 40% which is not sufficient for this research. Moreover, it will be more difficult and less accurate to extract buildings automatically with some other images whose quality are not as good as the Pleiades images.

Buildings, roads, bridges and mitigation works are required to be digitized in this research. Road, bridges and mitigation works are interpreted directly with their shapes and spectral characteristics. Buildings interpretation is first done with the big polygons instead of the individual building mapping, in terms of the individual village or similar buildings characterized from images (See Figure 14). During the fieldwork, these polygons for Figure 14 (a) can be grouped or separate, based on the occupancy type of buildings, the number of floors.

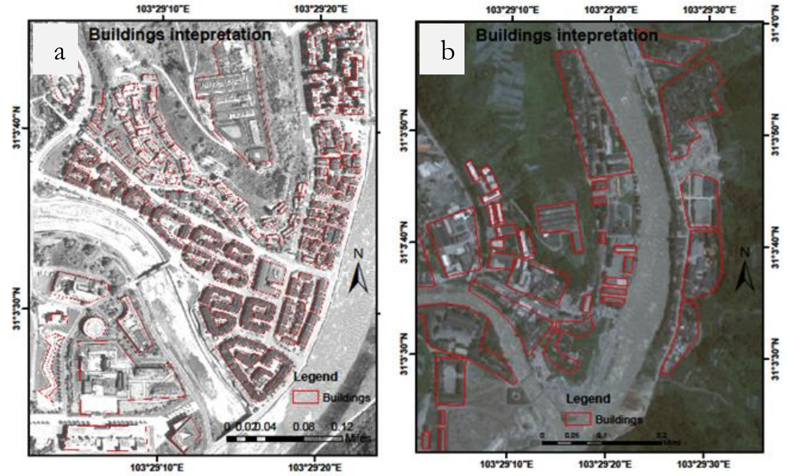


Figure 14. Buildings interpretation. (a) shows the image interpretation for 2013 with resolution of 0.5 m and (b) presents the interpretation result for the pre-earthquake with resolution of 2.5m.

3.3. Database generation

Elements-at-risk are all objects that can be affected by hazards, including the components of built environment, social system and natural system, such as buildings, facilities, population and economic activities (van Westen et al., 2011). Database about elements-at-risk plays a key role in risk assessment and analysis. Even though the digital information is available, there is still a problem about no link between non-spatial data and spatial data (van Westen et al., 2008). Therefore, a lot of work needs to be done about mapping the elements-at-risk, such as the types of buildings, the occupancy type of buildings and population information about the field. There are different levels of elements-at-risk inventories in terms of mapping scale and analysis scale for landslides (van Westen et al., 2008).

The mapping unit is polygonised in terms of the individual village or some homogenous area. The landuse types and the occupancy types of buildings were characterized during fieldwork for lacking of the landuse map. Even though the occupancy type of buildings is the same, for example, residential buildings, the density of buildings, the number of floors of buildings and the size of buildings are different. This means that these villages are inhomogeneous though they are with the same occupancy type. Therefore, the number of buildings, the number of households and the total number of people for each village are characterized during the fieldwork instead of sampling. For the Yingxiu town and Longchi town, the buildings were uniform after the reconstruction, the number of buildings are estimated by random sampling.

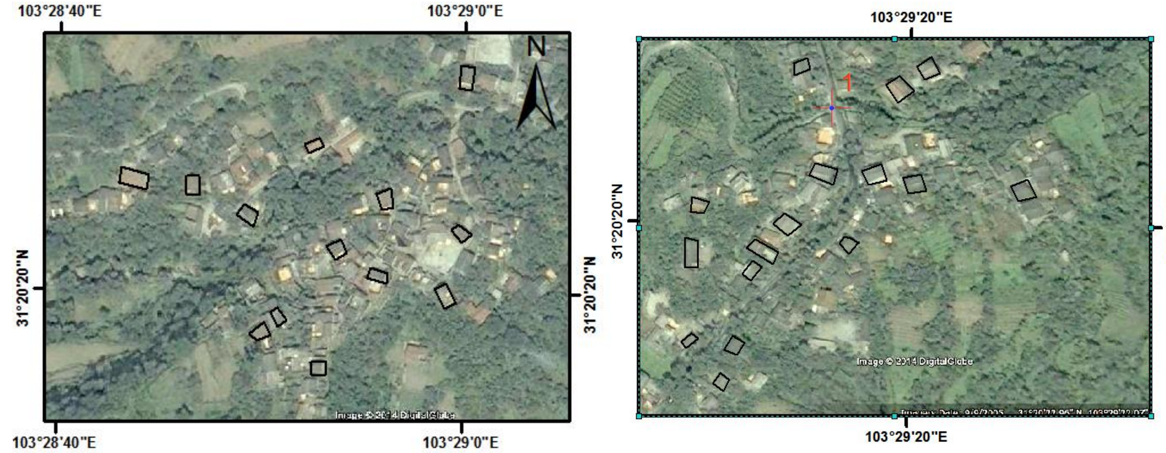


Figure 15. Buildings samples for pre-earthquake in Gaodiancun (V12) (See Figure 8) by using Dgital Globe image (1m).

Sampling is also applied to estimate the number of buildings for year 2005, which cannot be characterized during the fieldwork. Before the earthquake, most of the buildings were individual houses in the study area, and they are concentrated in some residential areas. In this case, random samples are selected from the image whose resolution is 1m (See Figure 15). The average size of buildings is calculated to estimate the total number of buildings (See Figure 16). For the other images whose resolution is 2.4m, only few individual buildings can be interpreted, in this case, the number of buildings is estimated by taking the samples that are easy to digitize (See Figure 17) and the average size is used to estimate the total number of buildings for the occupancy of "town_mixed".

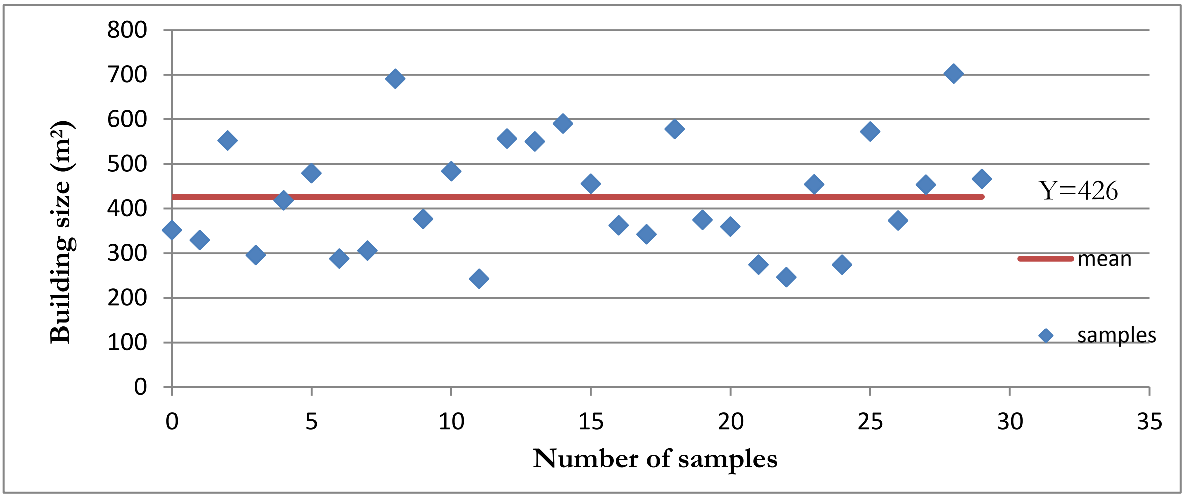


Figure 16. The average size of buildings calculated by samplings.

Figure 17. Building samples for town_mixed area in Yingxiu town by using Quichbird image (2.4m).

Figure 18. Residential area in Yingxiu town by using Quickbird image (2.4m).

The number of residential buildings in Yingxiu town is estimated in terms of the number of households obtained from fieldwork in Yuzixi, one village in Yinxiu town (See Figure 18). An assumption is made that the number of households are equal to the number of residential buildings. With the total residential area obtained from images and the number of households acquired from fieldwork in Yuzixi. The average size of buildings is calculated, which is 190 m. This is used to estimate the number of buildings in the other areas in Yingxiu town.

3.4. Change analysis and quantify some components of earthquake resilience

Earthquake resilience can be analyzed in terms of six dimensions and four properties. Many indicators are defined to quantify each dimension of resilience (See Figure 7). Two types of changes, which are quantitative changes and qualitative changes, are analyzed in this research (See Figure 13). And then these changes are linked directly or indicated indirectly to the indicators for each dimensions of resilience to simply quantify resilience.

Quantitative changes analysis is based on the indicators of buildings, transitional shelters, transportations and population. The indicators related to the four sections are: the number of buildings that damaged and reconstructed, including the number of transitional shelters; the occupancy types of buildings; the length of roads and their types that damaged and reconstructed; the number of population before earthquake, during earthquake and after earthquake. The multi-disaster graphs about social resilience and infrastructural resilience are generated in terms of the quantitative changes above. The analysis about these graphs with three properties of resilience can be done to show the level of robustness, rapidity and resourcefulness and illustrate simply how the study area "bouncing back". The reason for the level of robustness is analyzed based on the magnitude of earthquake and the earthquake mitigation works. The rapidity of reconstruction or recovery for the infrastructural resilience is analyzed in terms of the reconstruction mechanism and the investment for the reconstruction which also reflect the level of resourcefulness of infrastructural resilience.

Qualitative changes are analyzed in terms of the changes of occupancy types of buildings, the improvements of landuse types and buildings codes during the reconstruction, culture preservation and tourism development and livelihoods after the reconstruction. These changes have an effect on the reconstruction efforts and recovery quality (See Figure 13). The economic resilience, ecological resilience, institutional resilience and community competence resilience can be indicated by the indicators that are related to reconstruction efforts and recovery quality (See Figure 7).

4. RESULTS AND DISCUSSION

In this chapter, the changes of elements-at-risk are presented with the damage information collected from reports, fieldwork and published articles. Both quantitative changes and qualitative changes are shown an analyzed for buildings, roads and bridges, people and mitigation works.

4.1. Data from reports and articles

For lacking of damage information from fieldwork, the relevant geology investigation reports are collected, which include the records of debris flow occurrence for several main gullies and the damage information in the study area (See Table 6). Table 7 and Table 8 show the damage degree of tunnels during the Wenchuan earthquake and the damage to roads caused by debris flow in 2010. The damage degrees in Table 7 are from article (Li, 2008) directly but for the quantitative damage information in Table 8, the lengths of buried road were measured in terms of the 13 debris flows trigged by the heavy rainfall and their width of basin area in 2010 identified from satellite images.

Table 6. Damage caused by different debris flow gullies in 2013. Source: Investigation reports and field work identification.

Gully code	Gully name	Road		Building		Bridge length(m)
		name	length(m)	type	number	
DF30	Zhangjiaping gully	Village road	205	Residential	3	65
DF24	Gaojia gully	New G213	320	0	0	0
DF25	Taoguan gully	Taoguan tunnel	No information	Residential	18	78
				Industrial	8	
DF27	Huaxi gully	New G213	230	Residential	31	0
		Highway	200			
DF26	Mozi gully(in Caopo)	New G213	300	Residential	31	2136
		Highway	300			
DF28	Yangdian gully	New G213	184	0	0	0

Table 7. Damage information about tunnel for earthquake 2008.Source: (Li, 2008)

Name	Length(m)	Damage degree
Shaohuoping	450.5	Seriously damaged
Zaojiaowan	1926	Light damaged
Maojiawan	399	Light damaged
Chediguan	402.6	Medium damaged
Futang	2365.29	Medium damaged
Taoguan	625	Medium damaged
Caopo	759	Light damaged

Table 8. Damage caused by different debris flow gullies in 2010. Source: (Tang et al., 2011) with modification.

Gully code	Gully name	Road name	Buried length(m)
DF01	Hongchun	New G213	280
DF02	Shaofang	New G213	62
DF03	Xiaojia	New G213	65
DF05	Wangyimiao	New G213	38
Df06	Mozi	New G213	140
DF07	Laohuzui	New G213	60
DF11	Santaidi	New G213	59
DF12	Dagou	New G213	70
DF13	Dacaotou	New G213	82
DF17	Heicaotou	New G213	19
DF20	Supodian	New G213	158
DF22	Maojiawan	New G213	158
DF23	Yinxingping	New G213	165

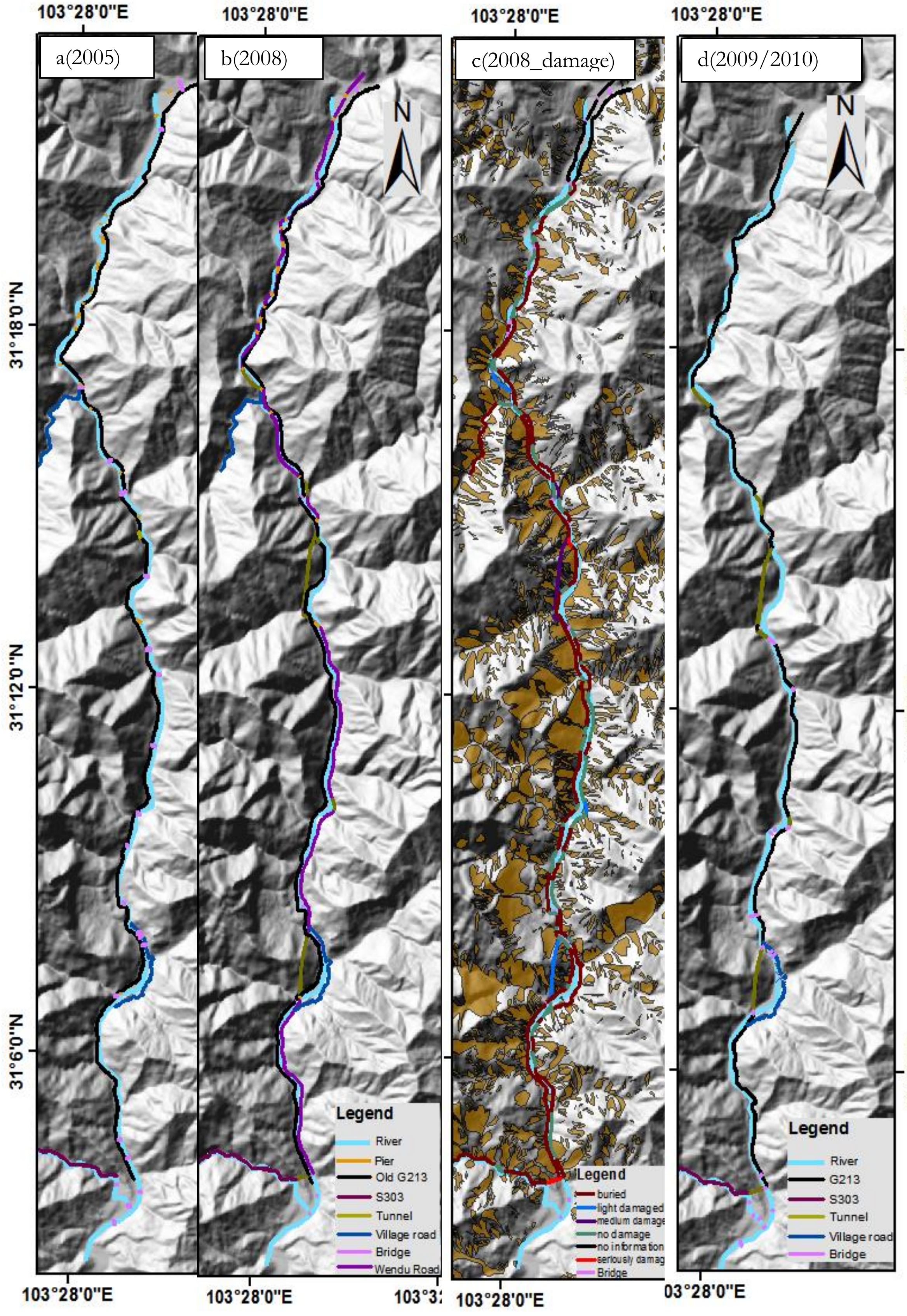
4.2. Change analysis

4.2.1. Roads and bridges changes

Road is the main transportation in this mountainous area. In 2005, the national road (Old G213) was the most important road from Wenchuan County to Yingxiu which was along the Min River (See Figure 19 (a)). With the complex geological structure, it was vulnerable to geological hazards, such as landslide, debris flow and flood. A development plan had been made to construct a new secondary national road and it was under construction in 2005 from the evidence of piers. In 2008 before earthquake, the new national road was completed and in use. This is shown in Figure 19 (b), named Wendu Road. To avoid the geological hazards, tunnels and bridges were the main elements for the Wendu Road and it contained seven tunnels and 2719m bridge. However, the devastating Wenchuan earthquake occurred in 2008 and all the old national road (G213) was damaged or buried by the earthquake and the co-seismic landslides during the earthquake. Figure 19 (c) shows the status of roads after the earthquake. The Wendu Road was more resistant to earthquake then the Old G213. Only one tunnel was severely damaged, and the others are light damaged or medium damaged. The bridges still existed even though there were different levels of damage. The road reconstruction starts from 2009. It took almost one year to complete the new G213 road, which started its function in the February, 2010. This new road combined small parts of Old G213 and large sections of Wendu road which was not damaged so severely during the earthquake (See Figure 19 (d)). Meanwhile, with the more geological hazards after the earthquake, such as landslides and debris flows, a new highway plan was made and the construction was started from 2010 and finished in 2012. Tunnels and bridges were the main components of Highway.

Damage of debris flows in 2010 and 2013 are shown in Figure 19 (e) and Figure 19 (h) in terms of the damage information obtained from filed work, reports and published articles. The new nation road G213 constructed after the earthquake suffered from debris flows in these two years, leading to the blocked road. Compared with the damage to Highway caused by debris flow, the Highway is less vulnerable and the damage is represented in Figure 19 (h). During the fieldwork in 2014, the national road G213 was blocked and the Highway was the only way that was available for transportation.

Table 9 shows the length of each type of roads and the corresponding damaged section measured in ArcGIS. Figure 20 is the thematic representation, where comprehensive quantitative changes are shown. Before the earthquake, the total length of functioning roads and bridges was 79222m and the percentages


a(2005)
b(2008)
c(2008_damage)
d(2009/2010)
103°28'0"E
31°18'0"N
31°12'0"N
31°6'0"N
N
Legend
River
Pier
Old G213
S303
Tunnel
Village road
Bridge
Wendu Road
Legend
buried
light damaged
medium damage
no damage
no information
seriously damag
Bridge
Legend
River
G213
S303
Tunnel
Village road
Bridge

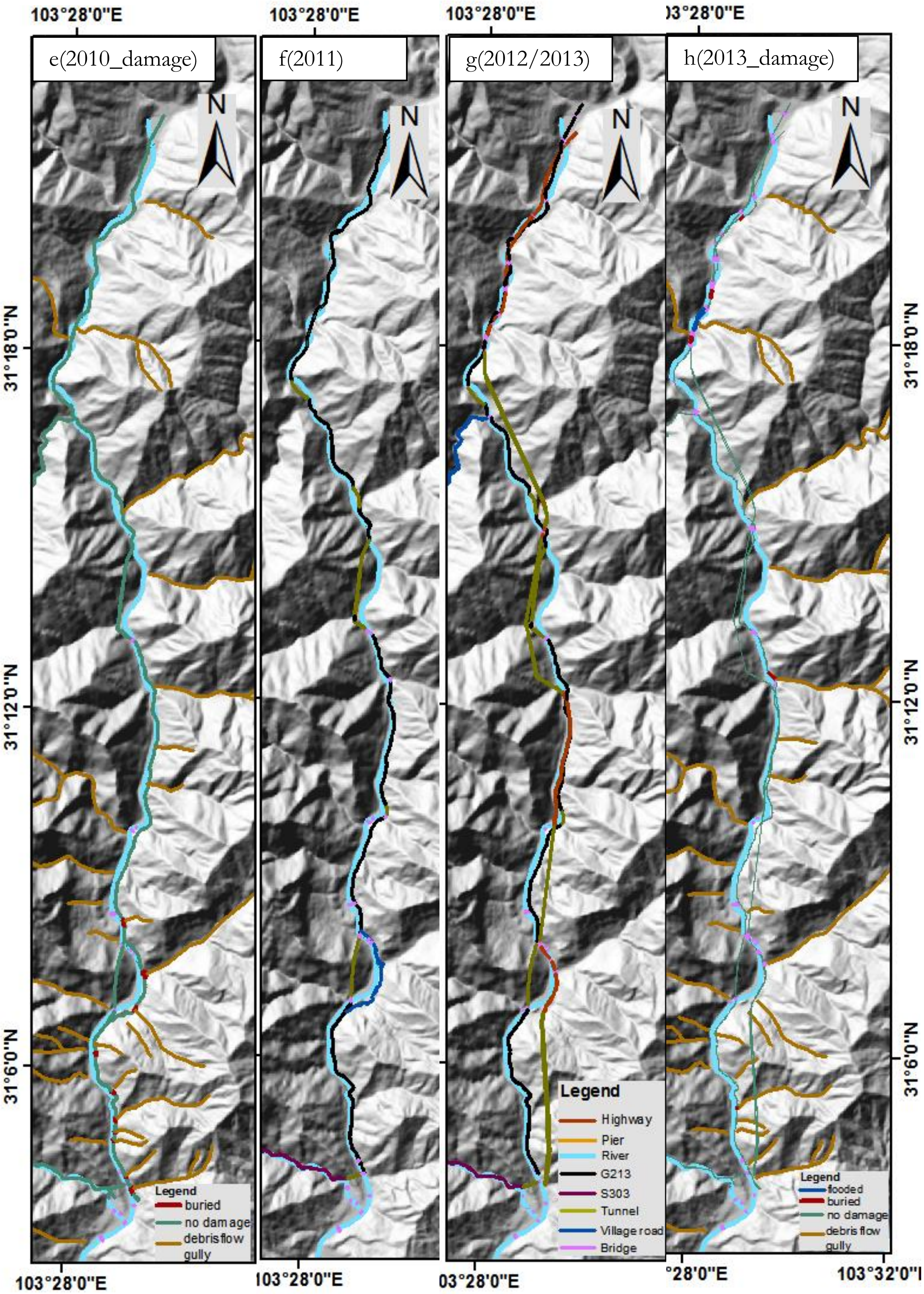


Figure 19. Changes about roads and bridges through time, including the development, earthquake damage, reconstruction and debris flow damage. Figure (a), (b), (d), (h), and (g) show the road status and their types in different years. Figure 19 (c) and Figure 19 (d) illustrate the damage caused by the debris flows in 2010 and 2013.

of bridges and tunnels are 6% and 9%, respectively. During the earthquake, the tunnels shows high resistance to earthquake and only 478m of tunnels was severely damaged. Considering the geological situation after the earthquake, more bridges and tunnels were constructed in this area. At the end of 2012 after the complement of highway, the percentage of bridges and tunnels were 8% and 40%, whereas, the total length of functioning roads was 81950.5m (See Figure 20 and Figure 21). Figure 22 shows the changes of bridges. Even though the line in Figure 22 is not continuous because the images for 2009 and 2010 cover the whole study area partially, the change for 2013 caused by debris flow can be seen clearly.

Table 9. The length of the roads and bridges in meters. The green one represents no information for that year and the red one represents the value comes from partial image of the study area for that year. The light orange one represents the un-function one.

	2005	**2006**	**2007**	**2008**	**2008**	**2009**	**2010**	**2010.8**	**2011**	**2012**	**2013**	**2013.7**	**2014**
Old G213	38537	38537	38537	38537	6297.5	6297.5	6297.5	6297.5	6297.5	6297.5	6297.5	6297.5	6297.5
Wendu road	0	0	0	28758	14018	14018	14018	14018	14018	14018	14018	14018	14018
G213	0	0	0	0	0	0	30283.5	29350	30283.5	30283.5	30283.5	28373.5	30283.5
S303	6127	6127	6127	6127	370	6127	6127	2674	🟩	🟩	🟩	🟩	🟩
tunnel	270.5	270.5	270.5	7420	6672	7149.5	7149.5	7149.5	7149.5	32396	32396	32396	32396
Highway	0	0	0	0	0	0	0	0	0	12729	12729	11810	12729
Bridge	1788.5	🟩	🟩	4507.5	4105	1640.5	1640.5	🟩	6542	6542	6542	4367	6542

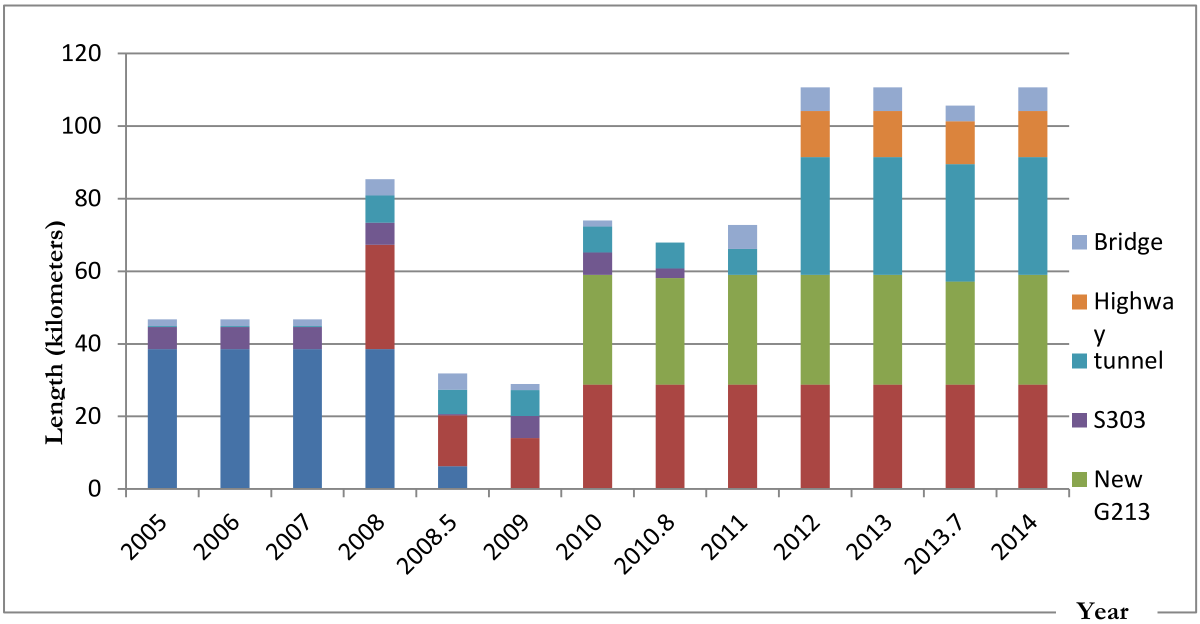


Figure 20. The changes of road types with length in meters.

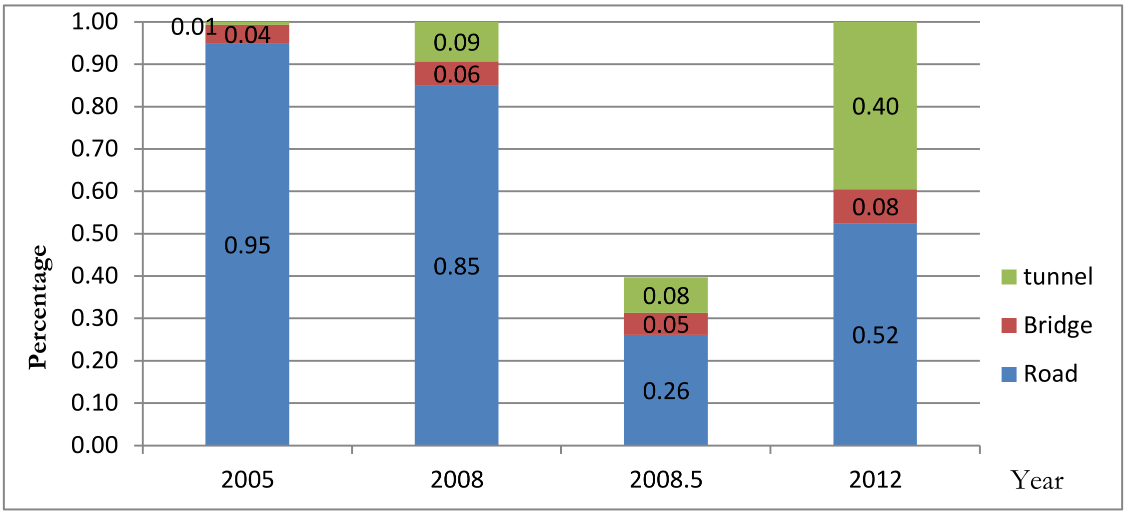


Figure 21. The changes of the proportion of road, tunnel and bridge for the whole functioning road.

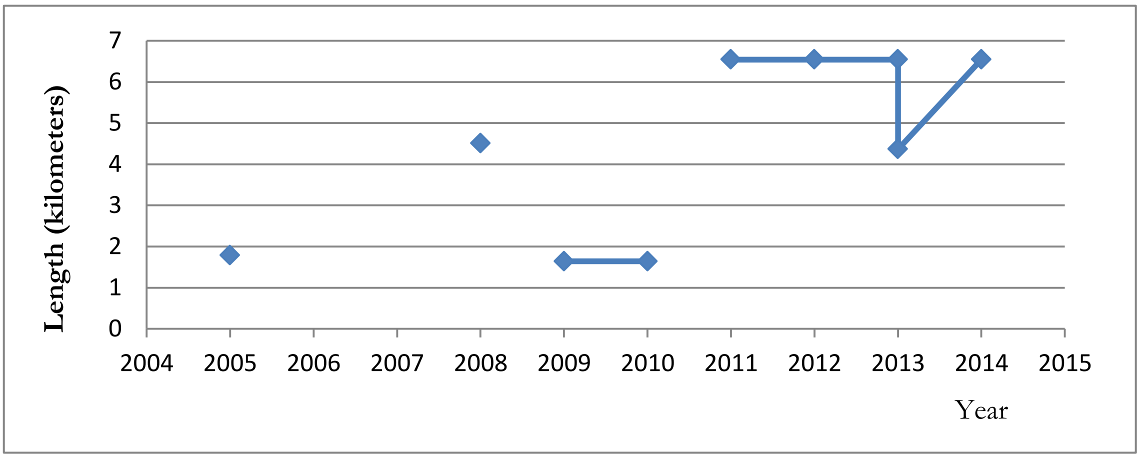


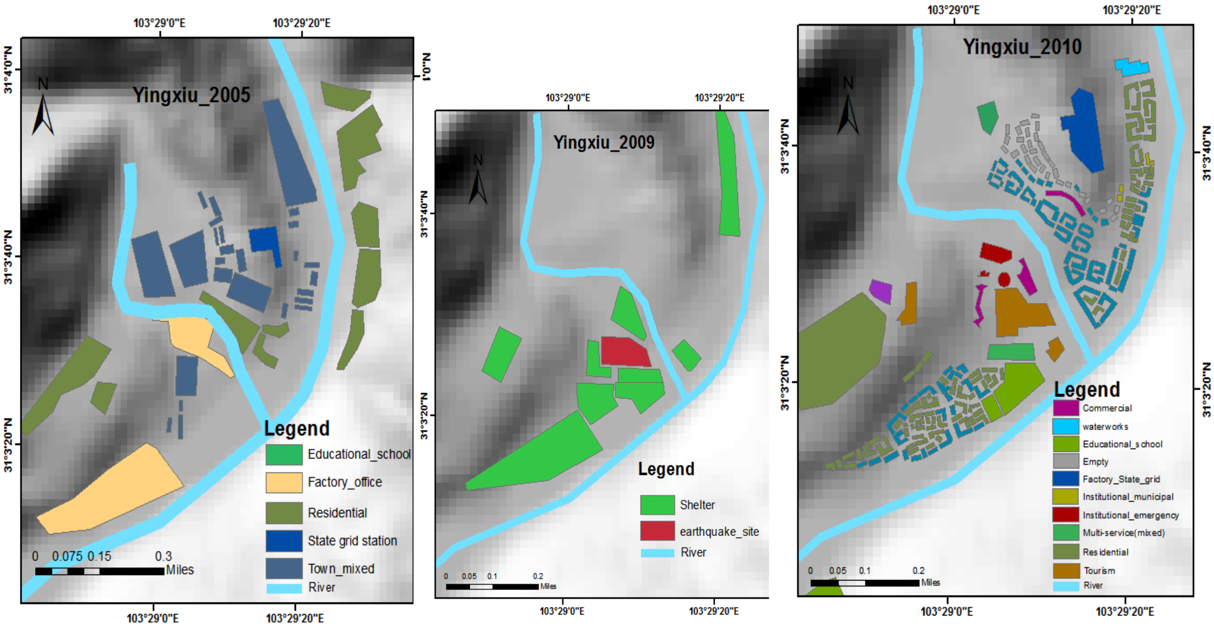
Figure 22. The total length of bridges changes in meters through time.

4.2.2. Changes of buildings

Building changes can be divided into three parts, the changes of number of buildings, the changes of occupancy types of buildings and the changes of location of buildings. Four typical areas, Yingxiu (epicenter of the earthquake), Longchi, Taoguancun (V5) and Yinjiaba (V8/V9) are selected to show these changes (See Figure 8). Yingxiu and Longchi have the biggest changes of occupancy types, and Taoguancun and Yinjiaba show the biggest changes caused by earthquake damage and debris flows.

4.2.2.1. Occupancy types changes

The occupancy types of buildings changes with the landuse type changes in Yingxiu town are shown in Figure 23. Yingxiu town was located in the epicenter of the Wenchuan earthquake and it was planned to be a tourism area after the earthquake. Before the earthquake, this town was known as “hydropower town” for its rich water resources and hydropower facilities. There were several factories and factory offices for the hydropower stations (See Figure 23 (a)). Most of people in this town are agriculture farmers and livestock farmers. However, the ecological environment was destroyed seriously by the earthquake and co-seismic landslides. It took two years to finish the reconstruction, from the transitional shelters (See Figure 23(b)) to a tourism area (See Figure 23 (c)). With the industry adjustments, the culture for minority group had been persevered and it was taken into the reconstruction planning, for example, the beauty of traditional buildings (See Figure 10). Moreover, the landuse types were various, which include emergency public service area, emergency municipal service area, earthquake site area, residential area and secondary hazard affect area (See Figure 23 (c)). However, just before complement of construction, the debris flow occurred in 2010, leading to more than 70 newly-built buildings flooded (See Figure 23 (d)).



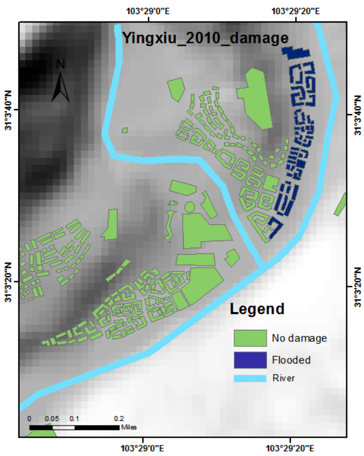


Figure 23. The changes of buildings in the center of Yingxiu through time.

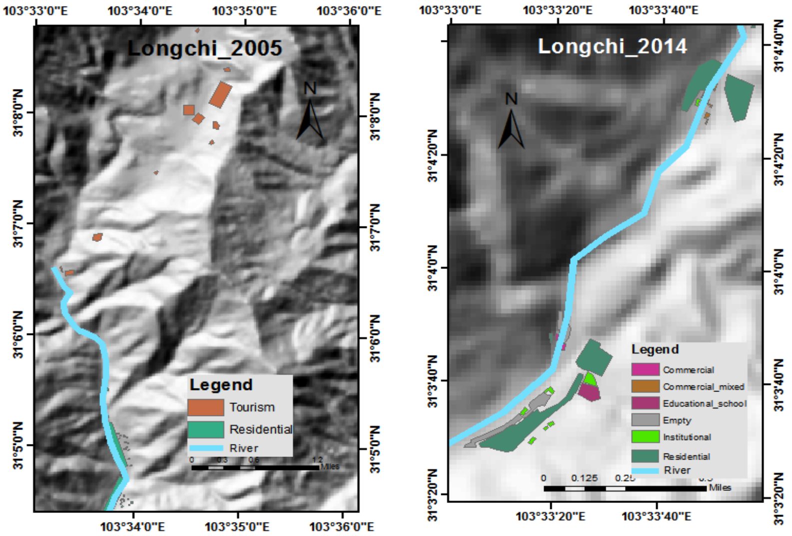


Figure 24. The changes of occupancy types of buildings in Longchi.

Figure 24 shows the main occupancy types in the high mountainous area in Longchi in 2005. Many of buildings were for tourists because they were located near the nature park (See Figure 24 (a)). And they were located in the high mountains. However, after the earthquake and debris flows, these buildings were severely damaged and people moved to the safer place (See Figure 24(b)).There are many empty buildings and only few houses which are labeled “commercial_mixed” are still for tourism, most of the others are residential (See Figure 24 (b)).

4.2.2.2. Two typical cases about location, mitigation works and number of buildings changes

Two villages, Taoguancun and Yinjiaba (See Figure 8 and Table 2), are the two typical cases to show the changes of buildings that were constructed, damaged by the earthquake, and then reconstructed in the same place or different place. However, both of the areas area suffered from debris flows during the reconstruction and recovery with no mitigation works or unsufficient mitigation works.

Taoguancun was a concentrated industrial area both before and after the earthquake. The factories were constructed in a mountain valley (See Figure 25 (a)). Even though they were damaged during the earthquake and the mountain valley can be a debris flow gully, the reconstruction work was made in the same area with some mitigation works (See Figure 25 (b) and Figure 25 (c)). However, the factories and mitigation works were totally destroyed by the debris flow in 2013 (See Figure 25 (d)). Meanwhile, the residential houses in Taoguancun were affected in different damage degree. After the debris flow, the mitigation works were constructed and completed in 2014, but all the factories were abandoned (See Figure 25 (e)). The quantitative changes about the number of buildings, factories, mitigation works and transformer stations are shown in Figure 26.

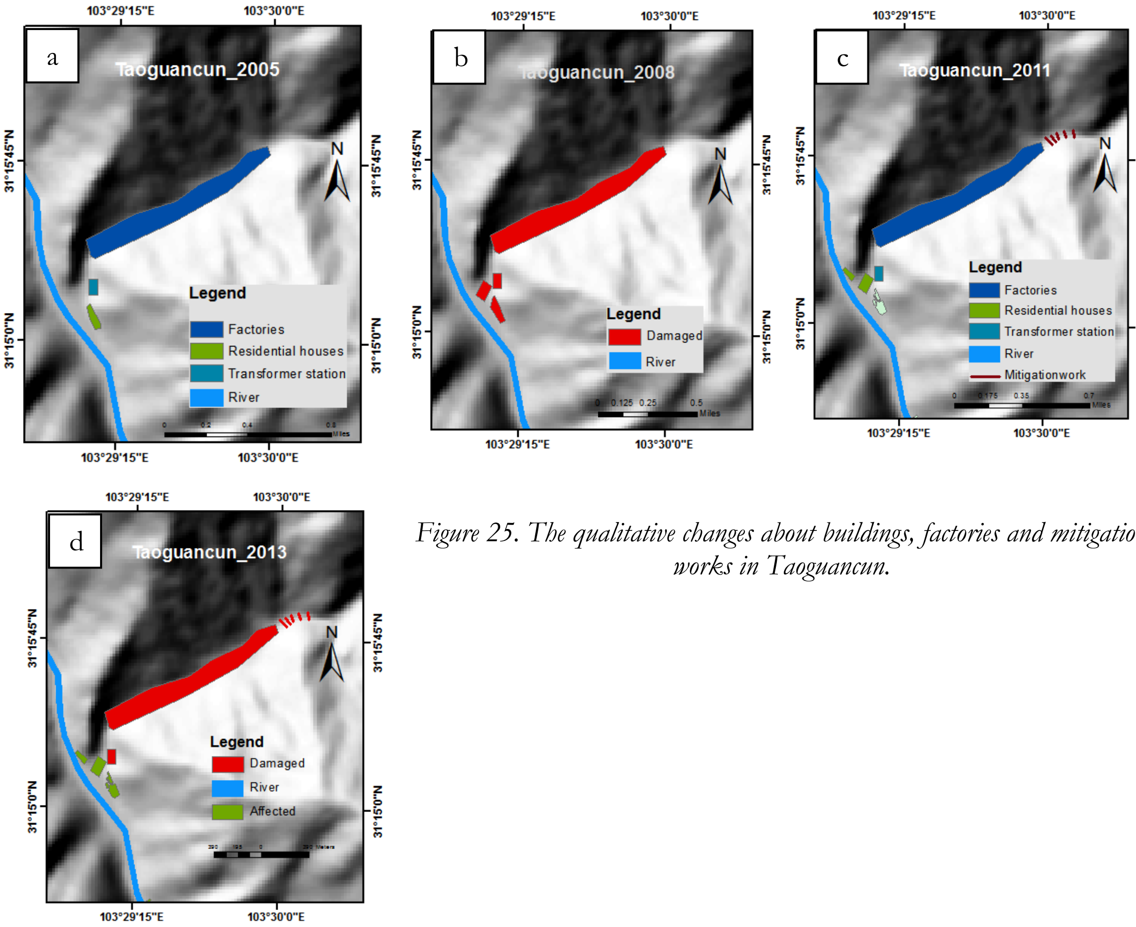


Figure 25. The qualitative changes about buildings, factories and mitigation works in Taoguancun.

Yinjiaba is another typical case to show the changes of damage for buildings through years. This area was open space and no one lived there before the earthquake (See Figure 27 (a)), however, around 200 people moved to this area event though there were two big debris flow gullies without mitigation works nearby after the earthquake (Figure 27 (b) and Figure 27 (c)). All the buildings are damaged or affected by the debris flow in 2013 and after that, people moved to some other places. In 2014, these two debris flow gullies were mitigated and the space were abandoned (See Figure 27 (e)). Figure 28 shows the quantitative changes about the number of buildings in this village.

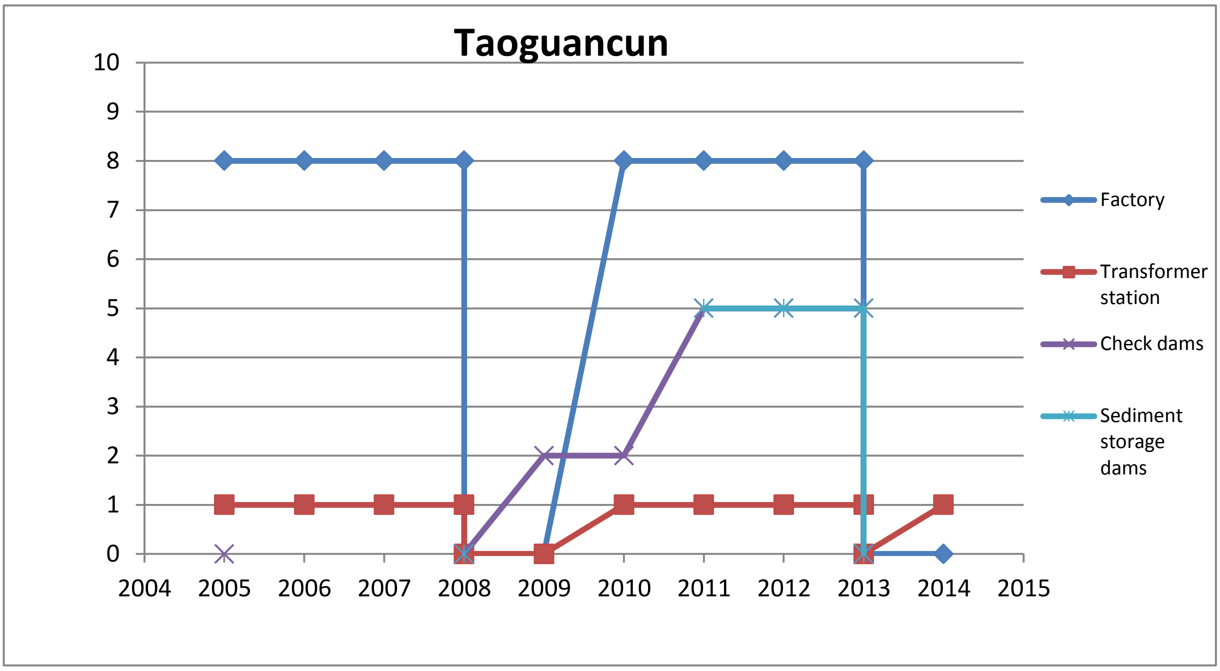


Figure 26. The quantitative changes in Taoguancun.

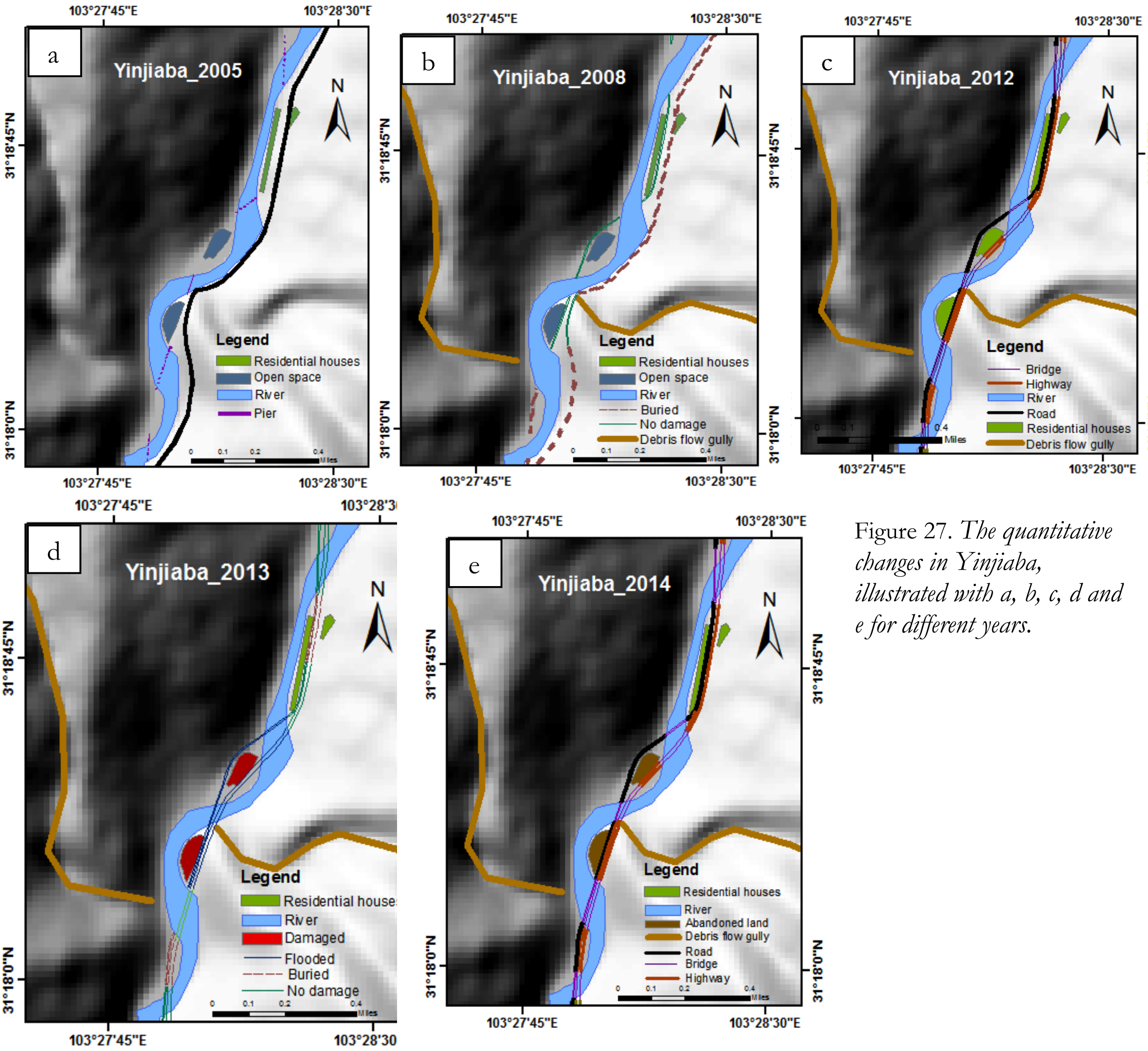


Figure 27. *The quantitative changes in Yinjiaba, illustrated with a, b, c, d and e for different years.*

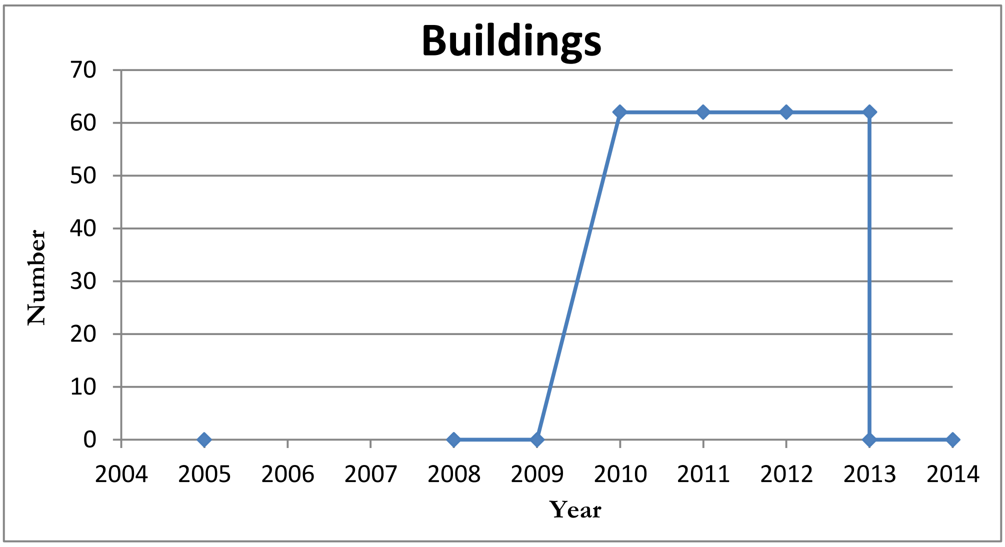


Figure 28. The quantitative changes of number of buildings in Yinjiaba.

4.2.3. Change of mitigation works

The changes of mitigation works and the debris flow occurrence are shown in Figure 29. There are 31 main debris flow gullies in the study area, and before the debris flows in 2010, there were only three gullied that were mitigated. However, debris flows occurred in 23 gullies and caused 1 mitigation works damaged. In 2011, the mitigation works had been done for three main gullies that threatened most to people, but the previous mitigation works were damaged by debris flow again. After the devastating debris flows in 2013, more and more gullies were mitigated.

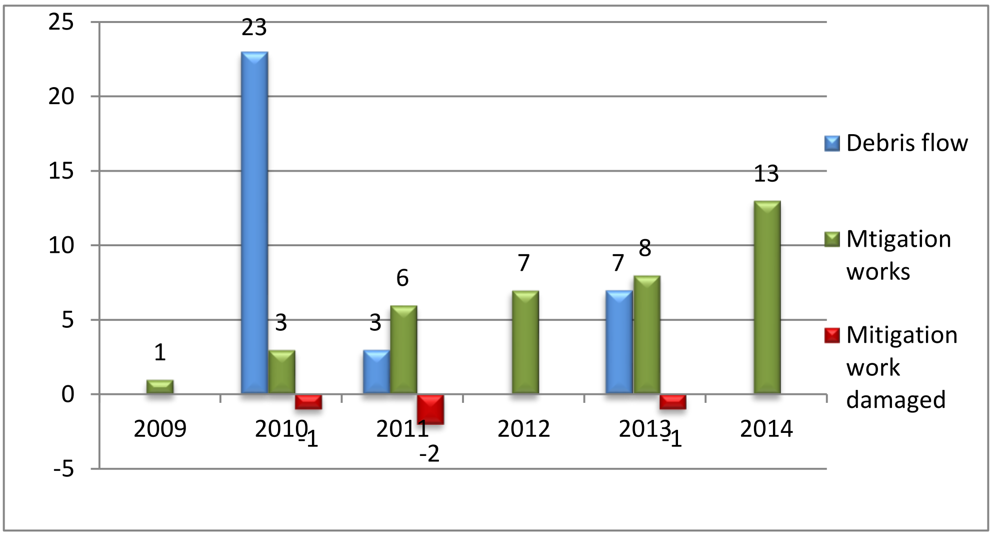


Figure 29. The changes of mitigation works, the occurrence of debris flows through years.

4.3. Resilience analysis

Combining the flowchart (Figure 13) and the framework (Figure 7), the six dimensions of earthquake resilience can be analysed in term of the changes analysis about the elements-at-risk.

The robustness of earthquake resilience can be shown with the damage and loss information. The study area was severely and almost totally damaged by the earthquake, which shows high robustness of built environment of this study area to earthquake. There are two reasons for it, the large magnitude of the earthquake or the low level of earthquake mitigation. However, the reconstruction and shot time recovery are rapid which shows the rapidity of resilience properties even with high robustness. The recovery of this earthquake affected mountainous area is not successful because of the influence and damage to built environment caused by post-earthquake landslides.

The resourcefulness of earthquake resilience can be analyzed with the rapidity of reconstruction which is illustrated from the changes in number of buildings, the length of functioning roads and the occupancy types of buildings. The changes show that China spent only two years to finish the reconstruction after the earthquake. One reason for this is that China is controlled by the centralized government, and the reconstruction planning was issued by the State Council, which were implemented by government bodies at lower levels. Furthermore, a new mechanism of post-earthquake reconstruction was applied, which was called "counterpart assistance". Counterpart assistance is a new mechanism for resource allocation and regional cooperation (Chen & Booth, 2011). Under this mechanism, the developed regions help the regions those were affected by the earthquake with financial support, martial support, advanced management support and the highly-qualified talents. Chen and Booth (2011) pointed that the government-administered mechanism was effective, efficient and powerful. From this view, Chinese society is high resilient with the "counterpart assistance" and the wealth in some part of China, compared to Haiti and Japan, who took longer time to make reconstruction.

The reconstruction efforts about culture preservation and industry adjustment are shown from the changes of landuse types and occupancy types of buildings in Yingxiu and Longchi (See Figure 23 and Figure 24). Most of people who live in the study area are minority with different minority groups. Chinese government and local government took the culture acceptance and preservation into account during the reconstruction planning. Moreover, Yingxiu town was reconstructed as a tourism area with better landuse planning, which contains the emergency service area, tourism area emergency municipal area and the secondary hazard control area. The economic recovery is not so well even with the sufficient facilities and designing. This is shown from the livehood in this area. Comparing to the diverse industries before the earthquake, such as agriculture and animal husbandry, there was only one way of income source, tourism, for the local people now. However, the development of local tourism is depressed which can be seen from the number of population after the earthquake and the abandoned commercial buildings from fieldwork. In another town, Longchi town, it shows the opposite way. Before the earthquake, it was famous of the nature park in the mountain and it attracted many tourists every year. But now, after the earthquake and the debris flows, many young people had moved to another city to work, leaving a lot of empty houses and buildings. Some buildings were reconstructed for tourists, however, they are not in use even newly constructed. The resilience between these two communities is different, one reason for this is the funding for reconstruction, and another one is related to the local government.

The measures taken for disaster risk reduction are shown in terms of the mitigation works, the changes of road types and the improvement of building codes and landuse planning (See Figure 20, Figure 23 and Figure 29). The tunnels and bridges that had been recently constructed show high resistance to the earthquake in terms of the damage analysis in this research, which was also presented by Chen and Booth (2011). Four years after the earthquake, the total percentage of bridges and tunnels are 48% for the whole functioning roads. This displays the adjustments of roads types for reducing the damage of future earthquake and the secondary hazards. The lessons about the Wenchuan earthquake were given by Chen and Booth (2011), one of which is to increase the fortification intensity of mainland China and improve the building standards. For the Yingxiu town, the fortification intensity has been improved to VIII and the basic seismic acceleration is 0.20g. Moreover, Chen and Booth (2011) analysed the different damage performance for different use types of buildings and the result showed the schools and industrial buildings were damaged more severely than government offices and residential houses. After the earthquake, the building codes for the new schools and rebuilt schools were improved in terms of one degree of intensity higher by the Chinese government. This was applied in Yingxiu town to improve the resilience of built environment. The strong buildings that were constructed after the earthquake make this study area more resilient to earthquake. Mitigation works for the secondary hazards, for example, the post-earthquake landslides and debris flows, received attention after the debris flow in 2010, which caused damage to roads and buildings. Even though some debris flow gullies were mitigated, the mitigation works were damaged or destroyed by the debris flows again. The continuous damage to mitigation works, buildings and roads shows the low community resilience to the secondary hazards caused by the major earthquake. This is related to the low capacity of local risk management, for example, the hazard assessment, relative mitigation works and the landuse planning.

4.4. Limitation discussion

Satellite images are an important source for extracting elements-at-risk and monitoring their changes. Based on the image interpretation and field work characterization, the database of elements-at-risk can be generated and used for changes analysis. However, there are several limitations about using satellite images to monitor changes of elements-at-risk and quantifying the components of resilience with these changes.

First, the qualities of satellite images and Arial photos have an important influence on image interpretation. The quality of these images/photos refers to the resolution, cloud cover, area cover and geometric correction.

1) Resolution. Even though the all the images are high resolution images, the required resolution for digitizing the buildings is at least 1m (Brown et al., 2010). In this research, the resolution changes from 0.5m to 5m. For the pre-earthquake image in 2005 whose resolution is 2.4m (See Figure 17), sampling is applied to get the average size of the individual building to estimate the total number of buildings. However, in some area, only few samples can be selected for most of the buildings are connected tightly and difficult to separate. This leads to relative bigger errors in the number of buildings. Moreover, because of the 5m resolution for the Arial photo in 2008, it is difficult to separate the un-collapsed buildings and the collapsed buildings. Here an assumption is made that all the buildings were damaged during the earthquake.

2) Cloud cover. The image interpretation is affected for 2012 because of the cloud cover. All the Yingxiu town is covered by clouds, leading to the elements-at-risk are difficult to be extracted. With the reconstruction information and disaster report collection, there is no change in buildings, and then the buildings were kept the same with the year 2011.

3) Area cover. Area coverage is a big limitation for this research. Only images 2005, 2008 and 2011 cover the full area. With some images covering partial study area, the changes of bridges and the total number of buildings are not continuous. However, the road construction was inferred for the whole study area with the reconstruction information and disaster report collection. It is obtained that the reconstruction for the G213 was completed in February 2010 and the construction for the Highway between Yingxiu to Wenchuan was finished in 2012. Then the roads in 2009 and 2012 are known even with partial images for these two years.

4) Geometric correction. Geometric correction refers to the image orthorectification here. Satellite images for mountainous area are always with big distortion caused by the relief displacement. For the changes analysis, image registration should be done and the accuracy is accepted if the RMSE is less than 3 pixels. However, the multi-temporal images are acquired from different sources and the orthorectification has been done with different DEM. This makes the RMSE of images registration in this research is around 5

pixels. The effect of the result is that the location is not accurate in case there are big changes in location about elements-at-risk.

Second, the changes play a key role in the resilience analysis. For the quantitative changes, for example, the lengths of functioning road changes and bridges changes, the results depend on image interpretation and damage data collection. With few data collection about the earthquake, most of the damage information comes from image interpretation. The influences of image interpretation and the limited data collection are explained below:

5) Damage interpretation. The damage caused by the earthquake is interpreted from the Arial photos that acquired after the earthquake. However, with not very high resolution (5m), the length of buried road is measured for the parts where the co-seismic landslides are clearly to be seen. If the line features can be seen, then it assumed that this part of roads is functioning. This means that damage degree is not taken into account, for example, the road is damaged but still can be seen on images.

6) Changes monitor. Some changes caused by the post-earthquake landslides, for example, the debris flows in 2010 and 2013, can be obtained from images because the images are not acquired immediately after these two debris flows and the clearance had been done quickly. Therefore, these changes are got from published articles and disaster reports. However, with the limited reports, only 31 main gullies are selected and the changes caused by debris flows in these gullies are analyzed. In fact, there are more than 31 debris flow gullies in this study area.

7) Database generation. Database generation is based on the fieldwork data collection. For the current situation, the database can be easy generated. However, there are two types of difficulties in the database generation. One is about the occupancy types of buildings for pre-earthquake. For Yingxiu, the landuse map is acquired and then the occupancy types are characterized based on the landuse types and information from local people during the fieldwork. But for some other areas, the occupancy types are defined in terms of the evidence from the images and general information from local people, but this is general occupancy types, for example, the town-mixed in Yingxiu and the tourism area in Longchi. Another one is about the disappearance of small villages. After the debris flow, two small villages in Yinjiaba (See Figure 27) were damaged and then it becomes to abandoned land. The attributes of the buildings in this area can't be obtained anymore. So the estimation should be made about the number of floors and number of units.

Third, the earthquake resilience can be shown and described based on some quantitative components of resilience. However, Resilience is a general and complicated concept which is related to the many aspects of society and more data are needed to have a comprehensive analysis of resilience.

8) Resilience analysis. Starting from satellite images and limited fieldwork data collection, only small part of resilience can be analyzed in terms of the qualitative and quantitative changes of elements-at-risk in built environment and population. Moreover, the resilience graphs are also simplified with the direct individual indicators or several indirect indicators. This research is only focus on how the study area "bouncing back" to show the six dimensions of earthquake resilience in community level. However, a lot of indicators are required to quantify and analyze resilience which is related the actual complete recovery and functions services (See Figure 7). Furthermore, to estimate the resilience, for example, the institutional resilience, the level of functions of the municipal services, the capability of local governance and the level of disaster preparedness and disaster risk reduction measures should be taken into account. For each sectors of institutional resilience, for instance, the level of disaster preparedness, there are several factors that have an influence on it. For instance, the quality of early warning system, the level and quality of communication risk and the degree of the education schools that provide the courses and training about

disaster reaction. In this case, more and more indicators are required to quantify resilience, and sometimes it is difficult to have an independent variable to measure each of these sectors, hence to quantify institutional resilience.

5. CONCLUSIONS AND RECOMMENDATIONS

By monitoring the changes in the built environment, caused by the impact of the magnitude 7.9 Wenchuan earthquake and the reconstruction and recovery efforts after the earthquake, this research monitors how the study area, the Wenchuan county in the earthquake's epicentral area "bounces back". In doing this we have adopted for this research the six dimensions of resilience represented by the multi-disaster graph with three properties of resilience (See Figure 7). As indicated in the objectives of the research and the research framework, this research has only analyzed some components of resilience. The monitoring of changes in the built environment provides direct indicators for some of the six dimensions, indirect ones for some others, but for a considerable number of dimensions it doesn't provide information at all.

The dimension of resilience where the research contributed most is the infrastructural resilience, which can be characterized with the quantitative changes of roads and buildings (See Figure 7). Figure 30 and Figure 31 show the infrastructural resilience in this study area. The impact of the 2008 was very severe, also due to the large magnitude of the earthquake. The robustness of the road network is low, as the impact was severe. With very low robustness to earthquake, the changes of buildings and roads are great. There are two main factors that contribute to low robustness to earthquake, the magnitude to the earthquake, the level of earthquake mitigation measures. The magnitude of the Wenchuan earthquake was large which can cause huge damage to infrastructures. However, the reconstruction and the recovery of infrastructures were very rapid which depends on the high level of resourcefulness. With the effective and powerful "counterpart assistance" mechanism implemented by Chinese government, in which each county was financially adopted by one of the main provinces and regions in the country, the earthquake affected area obtained the resources for reconstruction and recovery quickly from some other developed cities. Overall, the total length of functioning road after the recovery is longer than pre-earthquake situation. The trend of increase was already shown in 2008, before the earthquake, when an entirely new road alignment was taken into use a short time prior to the earthquake. As can be seen from Figure 31 the total number of buildings decreased after the earthquake. This is not only related to the fact that people moved out of the area, but also because of the larger average size of the buildings after the earthquake.

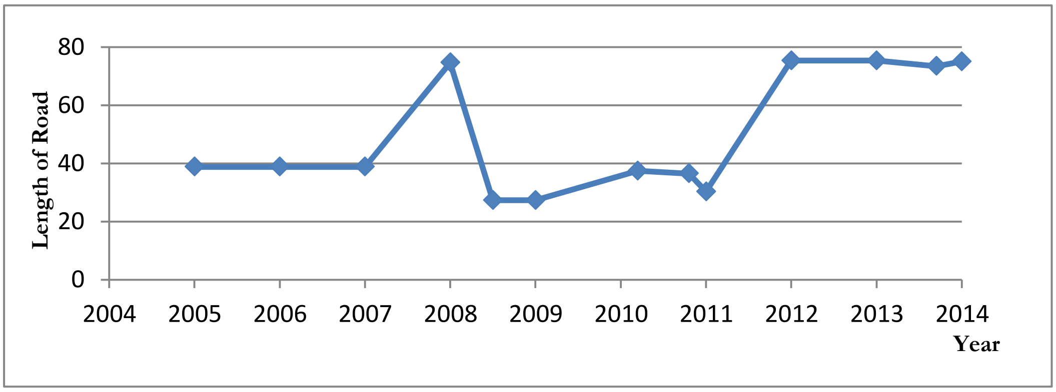


Figure 30. Infrastructural resilience in terms of functioning road length.

Social resilience is partly measured in terms of the number of people (See Figure 7), but also with a number of indicators that show the characteristics of the population. Social resilience is shown with Figure 32. There is a decreasing trend for the total number of people in this study area, comparing the pre-earthquake situation, during the earthquake situation and the after the earthquake situation. The major earthquake and the casualties it caused make the low robustness of social resilience. After the earthquake, the population keeps decreasing instead of "bouncing back". Several factors maybe contribute to this trend, such as the reduced job opportunities, the worsened ecological environment and the quality of life. With less and less tourists and less farming space, the main problem for the local comes from the livelihoods. Moreover, disruptive debris flows occurred in different years after the earthquake and the quality of life were affected severely by these secondary disasters.

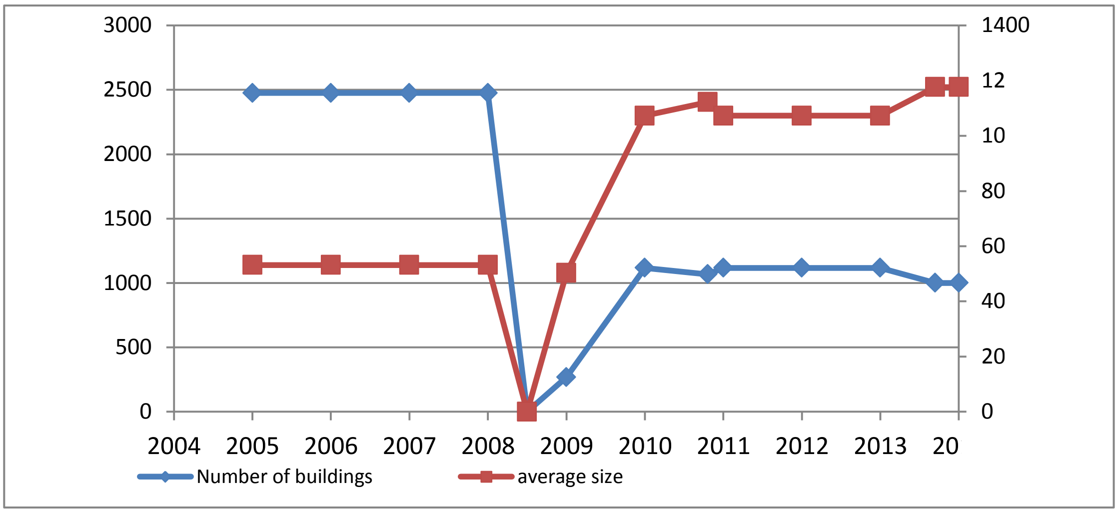


Figure 31.Infrastructural resilience in terms of number of buildings.

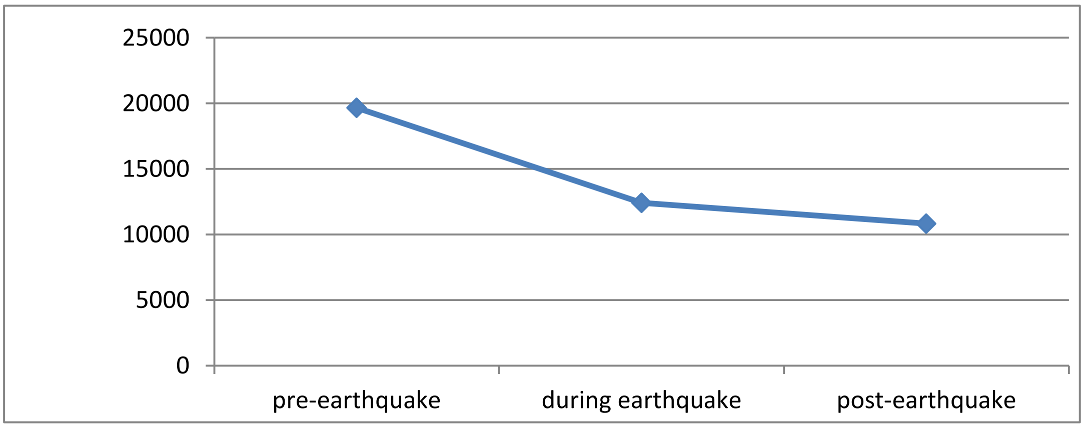


Figure 32. Social resilience in terms of population.

Ecological resilience is analyzed with a number of indicators, of which one is the forest land cover which is seriously damaged by the co-seismic landslides (See Figure 7). Figure 33 represents schematically the ecological resilience in this study area. With more than 56000 landslides triggered by the Wenchuan earthquake (Dai et al., 2011), the robustness of the ecological resilience shows to be low. It should be noticed here again that the robustness is in relation to the magnitude of the disturbing event. The recovery of the ecological system took a long time and the debris flows in 2010 and 2013 have a negative effect on the recovery even more. It is not sure how long it will take before the ecological system can recover to the level of the pre-earthquake situation. In Figure 33, the solid line shows the ecological system "bouncing back" to the original level after the earthquake. The loss functioning of ecological system between the solid line and the dashed line shows the long term impact of earthquake to ecological system.

Economic resilience is analyzed through a number of indicators, among which the employment/job opportunities and the investments of reconstruction activities (See Figure 7). Figure 34 presents a schematic representation of the economic resilience in this study area. The robustness and rapidity properties show similar with the infrastructural resilience above because of the large investments for the reconstruction and effective "counterpart assistance" mechanism. However, the level of recovery shows to be relatively lower, comparing to the infrastructural recovery. Even though the infrastructure was designed better during the reconstruction and the roads may have a positive influence on the economic recovery, the overall economic recovery is not high. This is caused by the strong decrease in tourists and limited industry after the earthquake and the post-earthquake landslides. Whereas the Longchi area was a national park with many visitors before the earthquake, and the Yingxiu area was a stopover for tourists to go to Wenchuan or the panda areas in the West, after the earthquake this type of tourisms ceased to exist. The Panda areas were also affected, and the connections are now faster along other roads. The new highway makes that tourist go straight to Wenchuan, and from there further into the Tibetan mountains, and do not stay in the Yingxiu area. The only other form of tourism that has come up is the "disaster tourism", where tourists come to visit the Wenchuan earthquake memorial sites, such as the Yingxiu Middle School or Earthquake Museum. Comparing to the diverse industries before the earthquake, such as agriculture and animal husbandry, there was only one way of income source, tourism, for the local people now. With less and less tourists and the effects of post-earthquake landslides, more and more people are confronted with stress about their livelihood.

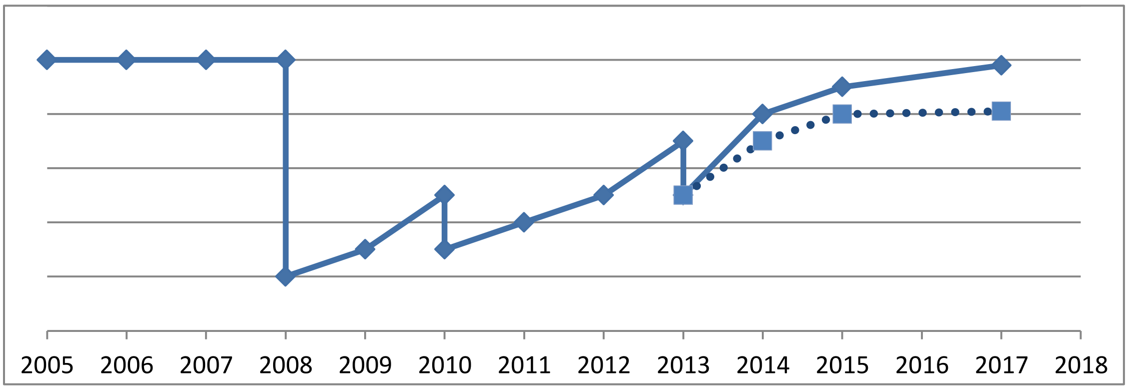


Figure 33. Ecological resilience in terms of forest land cover.

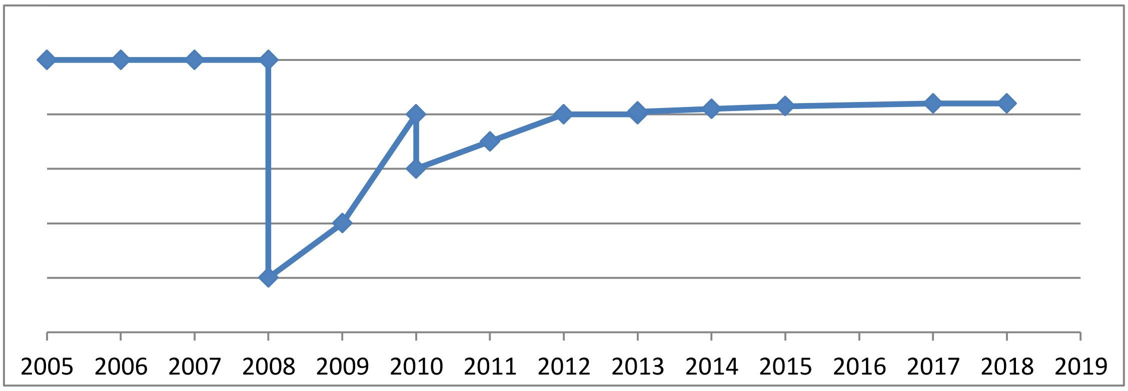


Figure 34. Economic resilience in terms of employment and funding.

Institutional resilience is analyzed with a number of indicators, such as the level of emergency response, the quality of early warning systems, the presence of proper building codes and disaster risk reduction plans (See Figure 7). Figure 35 shows the simplified institutional resilience graph drawn based on the indicators in Figure 7. With effective emergency measures and the rescue and relief from all over the world (Chen & Booth, 2011), the robustness of institutional resilience shows relative higher comparing to the other dimensions of resilience. Moreover, the improvements of the buildings codes, landuse planning, early warning system and the mitigation works after the reconstruction have a positive effect on institutional resilience. The damage caused by the post-earthquake landslides show the relative low local capacity for secondary hazards because of the insufficient hazard and risk assessment. Overall, the institutional resilience bounced back better than pre-earthquake.

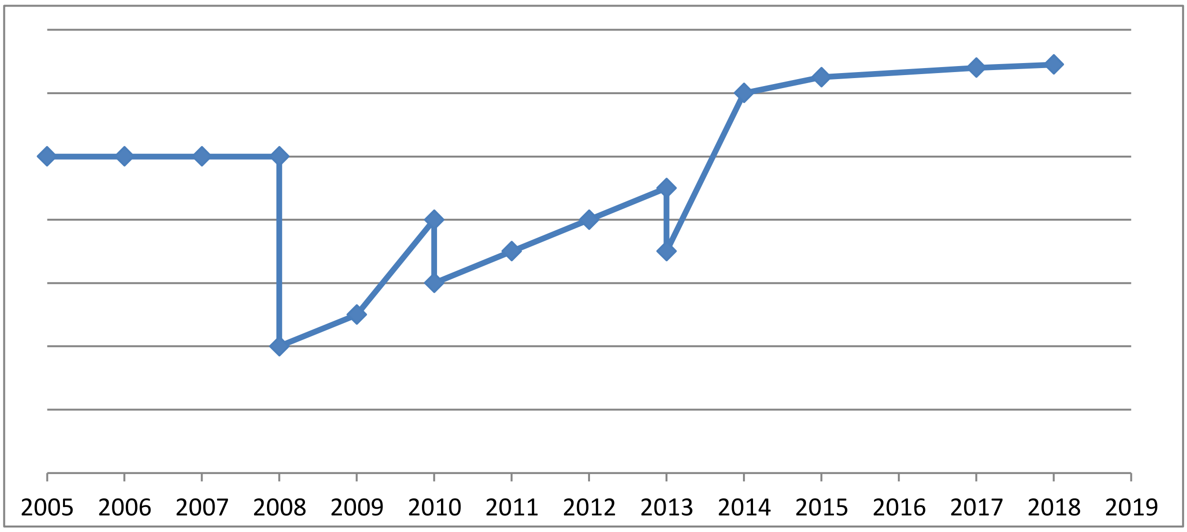


Figure 35. Institutional resilience in terms of the emergency response and the improvements on disaster risk reduction.

Community competence resilience is analyzed with indicators related to the quality of life and life satisfaction (See Figure 7). Simplified schematic graph of the community competence resilience is displayed in Figure 42. The community resilience shown in Figure 42 is similar with the economic resilience, for the quality of life is indicated by the job opportunity and the investments and the culture preservation during the reconstruction. With large investments and tourism development during the reconstruction, people were satisfied with their new life. During the interviews that were held during the fieldwork with local inhabitants, many indicated that the earthquake has led initially to a large shock, as many lost some of their close relatives. However, after some years they have noticed a large improved in their quality of life, given the improved housing conditions, access to basic services, etc. However, people get more and more worried about their life with the low recovery of economy and the secondary hazards.

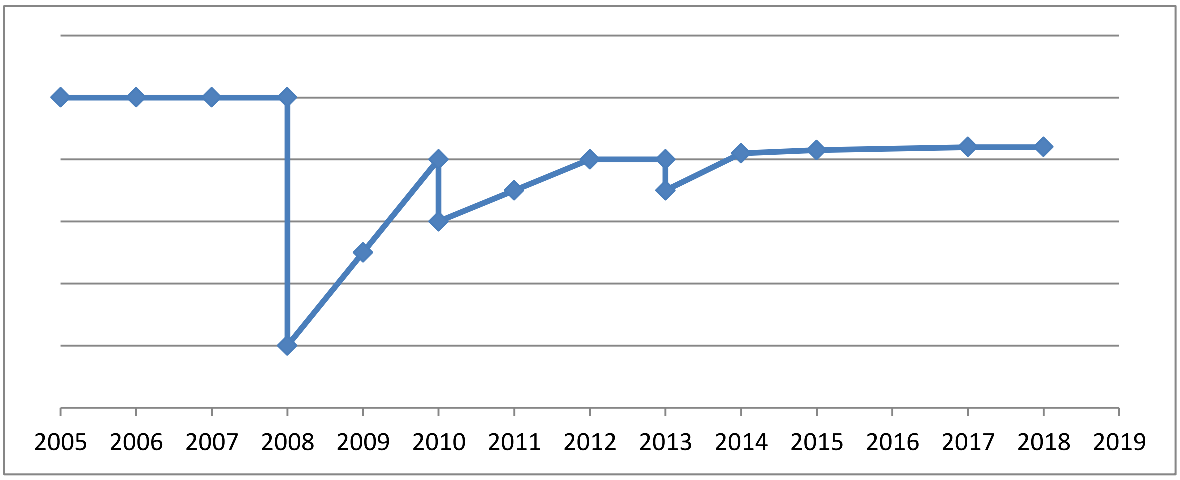


Figure 36. Community competence resilience in terms of the life satisfaction.

In general, with different levels of robustness to earthquake for the different dimensions of resilience, the "bouncing back" situations about the six dimensions of resilience show to be different for this earthquake epicentral area, and are in fact quite complicated.

The "bouncing back" of built-environment in this mountainous area was very rapid after this major earthquake. However, this happened with the fluctuations caused by post-earthquake landslides during the reconstruction and recovery. Disaster risk reduction had been taken into account in the reconstruction planning, but the secondary hazards caused by the earthquake, e.g. post-earthquake landslides, are now the main threat to people. Hazard assessment and the mitigation works should be improved in the earthquake affected area. Moreover, the social and economic recovery after the earthquake is another main issue for earthquake reconstruction and recovery. With limited livelihood opportunities, the economic situation of the communities could worsen quickly once the flow of outside funding comes to an end.

The complicated situation described above to show the earthquake resilience in the earthquake affected mountainous area can be explained with several reasons. The effective and powerful "counterpart assistance" mechanism plays a key role in the rapidity of reconstruction. Furthermore, the centralized government and its governance, and the relatively developed cities in China make this mechanism easy to be implemented. Some measures had been done to reduce the future earthquake loss and increase community earthquake resilience, for example, the improvement of building codes and the landuse planning, and the strengthening of the bridges and tunnels. However, this mountainous area show a high vulnerability to post-earthquake landslides in terms of the few mitigation works and high occurrence of debris flows and damage they caused. Even though more mitigation works had been constructed after the debris flows, hazard assessment and local risk management need to be improved to avoid the mitigation works destroyed again. Also the development of an early warning for debris flow is high on the agenda. A first version has been developed, and is now being implemented by the county officers. The adjustment of industry has been considered and implemented combining with minority culture preservation, which is beneficial for local people after reconstruction, however, the economic recovery shows to be low. This is not only because of less tourists and secondary disasters, but also because of the limited livelihood, for example, limited agriculture and animal husbandry, which caused by the destroyed ecological system.

Overall, the main lessons that learned from Wenchuan earthquake and the reconstruction and recovery are:
1) The "counterpart assistance" works well in China for reconstruction and recovery after earthquake, but the secondary hazard, especially the post-earthquake landslides in mountainous area, should be received more attention for risk reduction. Risk reduction should be taken into account into reconstruction planning instead of reconstruction rapidly without enough assessment and analysis on post-earthquake landslides.
2) Earthquake resilience can be quantified and represented with different indicators in terms of the six dimensions, by using the multi-disaster graph. Different dimensions of resilience show the different "bouncing back" situation. Even though with higher infrastructural resilience and institutional resilience, the social, economic and ecological resilience and community competence resilience show lower. This contributes to the lessons that the recovery of the lower aspects should be received more attention except for the improved infrastructural construction. It is important to establish job opportunities in different sectors, as a strong dependency on some sectors might have a negative impact on the long term.

In this research, the six dimensions of resilience are quantified or illustrated with direct or indirect indicators by using the simplified multi-disaster graph. This graph shows how this earthquake affected area "bouncing back" after several events occurred. And then the lessons are obtained from the resilience analysis. However, only few indicators and components of earthquake resilience are analyzed in this research and more quantitative indicators are required for analyzing the comprehensive earthquake resilience (See Figure 7). Another aspect of resilience analysis is to predict earthquake resilience with different indicators for each dimension of resilience. The quantitative information about the indicators in Figure 7 can be used predict earthquake resilience with the RIM model presented by Li et al. (2015)or some multi-criteria analysis with different weight.

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