Comments

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Thirdly, if referees kindly ask you to add information to Figures, such as the mentioned measured grid and the north arrow, why did you not follow this request throughout the entire manuscript? Your figure captions and table headers are exceptionally short and need to be made such that your figures and tables are self-standing. In other words, if a reader were to read the figure caption and the table header, look at the figure and the table, but not have the rest of the text from the paper, would they be able to understand what is written?

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Fourthly, as indicated by referee #1, the manuscript would gain in a discussion section where most of the findings are mirrored against the material from other studies published (the international literature requested by the referees) – here it is also highly recommended not only to follow those works exemplified by the referees but also to search own ones (and to my knowledge there are many available even with one of the co-authors as contributor), please carefully re-check available literature.

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requested to carefully consider the author guidelines when preparing your manuscript, this also includes the reference list which is NOT yet formatted according to the NHESS style.

Reply: Many sentences are now rephrased. NHESS style is now applied in the references.

Once again, please take these concerns serious. I am looking forward to receiving your revised piece of work as soon as possible. Should there any questions arise please feel free to contact me at any time, and please assure that all the co-authors have seen and approved the new manuscript version before re-submission.

Kind regards,

Sven Fuchs (Editor NHESS)

Comments of referee 1

Your comment: Line 68: “The increased debris flow activity lasted for five years”. Do you have an explanation for that (maybe I missed it)?

The sentence means: earthquakes create large amount of mass wasting and loss of vegetation, which amplified the subsequent mass movement activities. The amplification decays as environment recovers.

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Your comment: Figure 4: The color of the dormant landslides is not very well visible (it is better in the following figures). What is the dashed line in the image? There is only information later in the text, but not in the legend or the caption.

In Figure 4 and 6, there were no dormant landslides because all of them were freshly triggered by the earthquake.

I removed dormant landslides from the legend in these two figures and added the thick dashed line.

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This sentence is rewritten:

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construction types was observed, as the survive rate of the RCM, WB, W types were 23%, 17%, and 9%.

The damage ratios of the three major types (RCM, WB and W), are shown in Figure 5 A. There were only 4 RCF buildings and 2 survived.

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manuscript. Examples include but are not limited to: Section 1.1., lines 30-36 and 40, then further lines 270-284, and the events descriptions (e.g., in section 3.4) and also the final section 5.

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A major revision of the introduction section was carried out. Sub-section 1.1 describes a general background. the descriptions about the Wenchuan earthquake went to a separate sub-section (1.2). The study area is now in the sub-section 1.3. The gap was described in the last paragraph of section 1.1.

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Reply:

I added grid, location in Asia and north arrow in Figure 1.

Most of the figures are designed to be printed in full or nearly full page size to make elements visible and the font size was designed to fit for that. Larger fonts would result in the legend overlaying on the elements in the maps. To solve this, we added a figure of legends in the supplementary to assist map reading. Fonts in legend were enlarged and all figures now have north arrow and grid. An inlet was added in figure 1.

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Reply: Many of the result part was rewritten. We removed many unimportant text from the study area and reconstruction monitoring section. A discussion section was added to address the proposed gap and aim in the revised manuscript. I added research questions in the introduction section, and they were answered in the last two section.

the proposed research question “when and where to rebuild” (at the end of 1.1) was answered in the newly added recommendation section. The question of “how effective of the reconstruction and how much exposure created by the careless planning” (at end of 1.2) was answered in the conclusion section.

In my opinion, a complete story would be useful to a manuscript that aims to provide knowledge and experience for future rebuilding. If the referees insist, shortening of the manuscript will be done in the next revision.
Monitoring of the reconstruction process in a high mountainous area affected by a major earthquake and subsequent hazards a large earthquake and subsequent debris-flows

Chenxiao Tang¹², Xinlei Liu¹, Yinhua Cai³, Cees Van Westen², Yu Yang³⁵, Hai Tang³, Chengzhang Yang³, Chuan Tang³

¹ Institute of Mountain Hazard and Environment, Chinese Academy of Sciences, China

² Faculty of Geo-Information Sciences and Earth Observation (ITC), University of Twente, the Netherlands

³ State Key Laboratory of Geo-hazard Hazard Prevention and Geo-environment Protection (SKLGP), Chengdu University of Technology, China

⁴ Sichuan Institute of Land and Space Ecological Restoration and Geological Hazard Prevention, China

⁵ Station of Geo-environment Environment Monitoring of Chengdu, China

Corresponding to: Chenxiao Tang (c.tang@imde.ac.cn)

Abstract. Recovering from major earthquakes is a challenge, especially in mountainous environments where post-earthquake mass movements and floods hazards may cause substantial impacts for prolonged
periods of time. Although such phenomenon was reported in the 1923 Kanto earthquake and the 1999 Chi-chi earthquake, careless reconstruction in hazard-prone areas and consequently huge losses was witnessed following the 2008 Wenchuan earthquake in Sichuan province of China, as several reconstructed settlements were severely damaged by mass movements and floods. In order to summarize experiences and identify problems in the reconstruction planning, a monitoring of one of the settlements, Longchi town, was carried out by image interpretation and field investigation. We monitored the reconstruction of Longchi town in Sichuan, China, over a period of 11 years, following the 2008 Wenchuan earthquake. Seven inventories of containing buildings, land use, farmlands, roads and mitigation measures were made to study the dynamics in element-at-risk and exposure over a period of 11 years. It was found that by using remote sensing image interpretation and field surveys, most of the buildings were rebuilt by 2010 and reconstruction was completed by 2012. The total economic value of the new buildings in 2010 was much several times more than the pre-earthquake situation in 2007, because of enormous governmental investment. Unfortunately, post-seismic hazards were not sufficiently taken into consideration in the recovery planning before the catastrophic debris flow disaster in 2010. As a result, the direct economic loss from post-seismic disasters was slightly more than the loss caused by the Wenchuan earthquake itself. The society showed an impact - adapt pattern, taking losses from disasters and then gaining resistance by abandoning buildings in hazard-prone areas and installing mitigation measures. The areas potentially expose to post-earthquake hazards were summarized and a possible time table for reconstruction was proposed. Problems might be encountered in hazard assessment and possible solutions were discussed.

Keywords: Earthquake; Reconstruction; element-at-risk; exposure; Wenchuan earthquake; Multi-temporal mapping; reconstruction; element-at-risk; landslides; changing risk; Wenchuan earthquake.
1 Introduction

1.1 Background

Major disasters, such as earthquakes, have large impacts on societies, causing massive direct and indirect losses. Large earthquakes may also seriously affect the natural environment, in the form of secondary hazards. In mountainous regions one of the most severe secondary hazards is the triggering of co-seismic landslides. These may result in the loss of vegetation and the production of large volumes of landslide deposits, which drastically change the susceptibility to rainfall-induced mass movements and flooding after the earthquake (Fan et al., 2019a; Fan et al., 2019b; Tang et al., 2016; Yang et al., 2018; Guo et al., 2016). An amplification followed by a gradual decay in hazards were witnessed after the 1923 Kanto earthquake in Japan (Koi et al., 2008; Nakamura et al., 2000), the 1993 Finisterre earthquake in Papua New Guinea (Marc et al., 2015; Stevens et al., 1998), the 1999 Chi-Chi earthquake in Chinese Taipei (Lin et al., 2006; Shieh et al., 2009; Shou et al., 2011; Chen and Hawkins, 2009), and the 2008 Wenchuan earthquake in PR China (Fan et al., 2018; Fan et al., 2019a; Tang et al., 2019; Tang et al., 2016). The process could last from 6 (Hovius et al., 2011) to about 40 (Nakamura et al., 2000) years.

In addition to the prolonged effect, different post-seismic hazard types may interact with each other, forming hazard chains and further adding complexity to the situation. The most commonly witnessed cases includes landslides forming barrier lakes which later cause outburst floods (Fan et al., 2012; Dong et al., 2011) or debris flows (Hu and Huang, 2017). Moreover the debris flows could result in river damming (Ni et al., 2014; Forman et al., 2012; Xu et al., 2012) and river bed rise as well (Ni et al., 2014; Tang et al., 2012; Xu et al., 2012; Fan et al., 2019b), causing floods. A comprehensive summary of post-earthquake hazard chains was made by Fan et al. (2019b).

Rebuilding and recovering social functions in such circumstances are difficult tasks, as settlements face continuous threats of landslides, debris flows and flash floods. Based on how risk is calculated (van Westen et al., 2006; Fell, 1993; Varnes, 1984), the amplification in hazards and reconstruction would bring sharp changes in risk. Careless planning could result in a large increase in risk and consequently taking severe losses.
It has been reported that post-earthquake hazards caused severe damages in Chinese Taipei after the 1999 Chi-Chi earthquake (Lin et al., 2004; Cheng et al., 2005) and in Sichuan province of PR China after the 2008 Wenchuan earthquake (Tang et al., 2012; Xu et al., 2012; Zhang and Zhang, 2016), but there is a lack of studies summarizing the experiences and problems encountered during the relief and reconstruction periods. It is also not clearly stated when and where to rebuild in such mountainous regions. To fill this knowledge gap, we conducted a study concerning the recovery in an area hit by the 2008 Wenchuan due to data availability. Seven inventories of elements-at-risk from satellite images covering a period of 11 years (2007 - 2018) were generated to study the dynamics in exposure and recovery process. The aim is to show encountered problems during the recovering process and propose possible solutions, in order to provide knowledge for future reconstruction efforts in earthquake-susceptible regions.

1.2 The Wenchuan earthquake

The Mw 7.9 Wenchuan earthquake occurred on 12 May 2008 in Sichuan province, affecting an area of 110,000 km², most of which consisting of steep mountains with deeply incised valleys. The earthquake triggered a large number of landslides, and estimations varied between 48,000 and 200,000 (Tanyas et al., 2019; Xu et al., 2013; Dai et al., 2011). Around one third of the 87,537 casualties was estimated to have been caused by the landslides and not by ground shaking only (Wang et al., 2009a). The estimated losses from the earthquake were around 115 billion US dollar (Dai et al., 2011). After the relief stage the reconstruction began in 2009, and 19 of the Chinese provinces supported each one of the affected counties or cities in the recovery by using at least 1% of their annual provincial revenue for a period of 3 years (Huang et al., 2011; United Nations Office for Disaster Risk Reduction (UNISDR), 2010; Dunford and Li, 2011; Zuo et al., 2013). The provinces were requested to provide specialists in planning and design, as well as construction workers. A fast reconstruction progress was witnessed and the reconstruction was completed in 2012. However, extreme rainfall events in the years following the earthquake triggered numerous mass movements, mostly in the form of debris flows, destroying many of the reconstructed buildings. One of the most devastating events occurred in Qingping village (Mianzhu County) on 13 August 2010, when
two debris flows from the Wenjia watershed, destroyed the mitigation measures and buried most of the valley, including newly reconstructed villages and roads (Tang et al., 2012). Another example of a major post-earthquake disaster was the debris flow that dammed the Minjiang River which flooded the nearby Yingxiu town on 14 August 2010 (Xu et al., 2012). The increased debris flow activity lasted for five years, and a third major disaster occurred on 10 July 2013, when a debris flow formed by a breached landslide dam severely damaged the reconstructed buildings in Qipangou village, destroying most of the farmlands (Hu and Huang, 2017). The losses caused by these disasters have resulted from a lack of experience in post-earthquake reconstruction planning.

The catastrophic debris flows were caused by the amplified landslide activities as a result of the destabilized environment, the entrainment of co-seismic mass wasting by surface runoff. In the epicentral area of the 2008 Wenchuan earthquake, the total area of active landslide mass movement activities were highly active in the first three years, and has decreased then decayed largely rapidly in the first five to eight years (Tang et al., 2016; Yang et al., 2017; Yang et al., 2018; Zhang et al., 2016). Similar recovery patterns of co-seismic landslide surface were also observed in the Mianyang area in the other regions of the Wenchuan earthquake affected region (Li et al., 2016). The decay crisis is not a linear progress as it is largely affected by the precipitation (Tang et al., 2016; Fan et al., 2019b). On Aug 20 2019, several debris flows again severely damaged the reconstructed settlements and roads caused severe damages in the Wenchuan area, suggesting the mass movements were still enhanced.

The Wenchuan earthquake has initiated many studies related to assessing vulnerability and losses (Wang et al., 2009b; Wu et al., 2012), such as physical (Cui et al., 2013), social (Hu et al., 2010; Kun et al., 2009; Lo and Cheung, 2015; Wang et al., 2015; Yang et al., 2015), environmental (Yang et al., 2017), institutional (Hu et al., 2010), and economic vulnerability (Wu et al., 2012; Zhang et al., 2013). Household vulnerability was studied in particular by a number of studies (Sun et al., 2010a; Zhang, 2016; Sun et al., 2010b) which included subjective perceptions (Yang et al., 2015), factor analysis on household vulnerability (Wang et al., 2015) and on household income (Sun et al., 2010b), and household vulnerability to poverty (Sun et al., 2010a). Recovery was studied by (Dalen et al., 2012) and (Wang et al., 2015). But little has been investigated on how well effective was the reconstruction planned and how much property value was exposed to the post-earthquake hazards due to careless planning.
1.2.3 Study area description

The study was conducted in the Longxi watershed, located within 20 km from the epicenter of the 2008 Wenchuan earthquake in Sichuan province of China (Figure 1). The valley had 2306 permanent residents based on the national census in 2010 (Baidu Encyclopedia, 2016). The area of the watershed is about 89 km² and the elevation ranges from 810 to 3200 m. The main channel of the Longxi River, which is a tributary of the Minjiang River, has an average yearly discharge of 3.44 m³/s and the recorded maximum discharge was 300 m³/s. The river flows through the Zipingpu hydropower reservoir which is also one of the major water sources of the province, providing drinking water to the large city of Chengdu (with 16.3 million inhabitants). The climate is sub-tropical, with an average annual precipitation of 1135 mm, of which 80% occurs from May to September. The highest precipitation takes place in August with a maximum recorded intensity of 83.9 mm/h (Sichuan Geology Engineering Reconnaissance Institute, 2010).

One of the two major faults that ruptured during the earthquake passes through the area: the Yingxiu–Beichuan fault, which had a horizontal displacement of 4.5 m and a vertical displacement of 6.2 m (Gorum et al., 2011). The Guanxian–Jiangyou fault in the south was ruptured during the earthquake as well (Li et al., 2010). As shown in Figure 1 the surface ruptures splits into two branches in this region. At three kilometers the surface rupture continues in the eastern side of the watershed. Most of the area is underlain by granite, with some conglomerate distributed in the north, and carbonatite and sandstone in the south.

1.3 History of the study area

Longchi town was formerly called Longxichang and was located at the outlet of the Longxi watershed. It was founded in 251 B.C. as the first relay station in the mountains on the 320 km long Ranmang mountain path which connected the Chengdu Plain (Figure 1) with the counties in the mountainous region. It developed into a booming businesses area. The 1933 Diexi earthquake induced 11 landslide dams, which resulted in a catastrophic dam-breach flood, which killed at least 2500 people along the Minjiang River and damaged the irrigation system of Dujiangyan. Although not documented, the village
town of Longxi village was heavily damaged during this event, as it was located along the Minjiang River.

In 1940 the Republic of China assigned it township with nine villages under its jurisdiction and the name of Longchi town was formally used. It lost its function as a relay station in 1955 when an asphalt road connecting the mountainous region and the Chengdu Plain was constructed. Being a habitat of many wild animals including pandas and densely covered by forests, the northern part of the watershed was designated as a national forest park by the Chinese government in 1992, with the Longchi artificial Lake as its major attraction (Figure 1). In May 1998 the Zipingpu hydropower reservoir was built and the town residences were moved into the watershed. 400 meters west to the current location on the northern side of the river, with a newly built tunnel as the only road access (Figure 1, Access 1). Subsidies were distributed to the residents to build new houses. Forestry was an important economic activity in the heavily forested watershed of the Longchi River, with trees producing medicines, nuts and building materials. Agriculture and tourism were almost equally important, generating a gross output value of 6.9 million US dollar for the year of 1999. In 2006 to 2007 the government invested in building a new settlement at current location with apartment buildings. After the earthquake the location of the new settlement was used as the current town center location (Figure 1).

The 2008 earthquake resulted in only a few casualties in this valley, as it occurred at 14:28 when most of the inhabitants were working outdoors. The earthquake triggered a total of 1597 landslides in the watershed, which crashed four hostels, killing ten persons. The national park was closed due to high landslide threat. After the relief operations, the city of Shanghai was assigned responsibility to execute the recovery activities of the nearby Dujiangyan city, and the surrounding area, including the Longchi valley. In May 2009 the 7.3 km long Longxi tunnel (Figure 1) was completed for the Duwen Highway, which greatly helped disaster relief and reconstruction by reducing travel time greatly. A new tunnel was made to connect the Longxi watershed and the highway as an alternative access (Figure 1, access 2). Most of the reconstruction was finished by 2010, when in the same year a storm triggered debris flows from most of the sub-catchments, severely damaging the newly constructed buildings.
The location of the study area, Longxi watershed, which contains most of the buildings in the watershed. The roads and buildings reflect the situation in 2018. Buildings outside the study area polygon were not mapped.

The reconstruction was finished in 2012. In 2014, the government assigned two towns in neighboring watersheds under the jurisdiction of the Longchi township. In 2015 the tunnel connecting the Highway (Figure 1, access 2) was closed due to water leakage and there was no plan to repair it due to a low economic interest caused by the closing of the national park. In 2018, a new road was made to connect...
the neighboring watershed (Figure 1, access 3). Till the beginning of 2019, there was no official announcement about the time to reopen the national park and repair the access to the highway.

2 Data & methodology

In order to monitor the changes in the post-earthquake period, we acquired a series of ten high (5 -10 m) to very high (0.5 - 2.5 m) resolution satellite images covering the period between 2005 and 2018 (Table I).

<table>
<thead>
<tr>
<th>Data type</th>
<th>Data source</th>
<th>Collection date</th>
<th>Cell size Pan/Mul (m)</th>
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<td>2.4</td>
<td>Mul</td>
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<td>RGB</td>
</tr>
<tr>
<td></td>
<td>Spot 5</td>
<td>FEB 2009</td>
<td>2.5/10</td>
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<td>Worldview-2</td>
<td>MAR 2010</td>
<td>0.5/2</td>
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<td>Worldview-2</td>
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<td>0.5/2</td>
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<td>APR 2013</td>
<td>0.5/2</td>
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<td>0.5/2</td>
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<td>DTM</td>
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<td>1999</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>This study</td>
<td>2018</td>
<td>Polygon-based inventory based on image from June 2018</td>
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</tbody>
</table>

Table 1. Data used for interpretation (Pan= panchromatic image, Mul = multi-spectral image, RGB = Red/Green/Blue: color composite).

The images were georeferenced with Erdas IMAGINE Autosync Workstation and ARCMAP Geo-referencing Tool. A LiDAR DTM provided by the National Bureau of Surveying and Mapping of China was used to visualize images in a 3D environment in ArcScene software to assist interpretation. The multi-temporal landslide inventories reported in Tang et al. (2016) were used to identify the active landslides over time. An additional landslide inventory was made for 2018, to match with the mapping of the buildings, roads and landslide in this study using the Pleiades image from June 2018.
<table>
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<tr>
<th>Attributes</th>
<th>Varieties / descriptions</th>
<th>Source</th>
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</tr>
<tr>
<td></td>
<td>Reinforced masonry / Wood &amp; brick / Wooden</td>
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<tr>
<td></td>
<td>Temporary buildings: Pre-fabricated metal houses / Tents &amp; shacks</td>
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<tr>
<td>Builder</td>
<td>Self-constructed / government-build</td>
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</tr>
<tr>
<td>Unit price</td>
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<td>x</td>
</tr>
<tr>
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<td>Floors of a building. A maximum of 4 floors was allowed.</td>
<td>x</td>
</tr>
<tr>
<td>Floor space</td>
<td>Building area * building floors</td>
<td></td>
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<tr>
<td>Value</td>
<td>Floor space * unit price</td>
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<td>Type</td>
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<td>Mitigation works</td>
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<td>x</td>
</tr>
<tr>
<td>Type</td>
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<td>x</td>
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<td>all elements-at-risk</td>
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<td>No damage / Moderately damaged / severely damaged / Destroyed</td>
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</tr>
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<td>Normal / Abandoned / Empty</td>
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<tr>
<td>Geometry</td>
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<td>x</td>
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</table>

Table 2. Attributes of the element-at-risk inventories, and the main methods of collection (Image = Image interpretation, Mapping = field mapping, Interview= Interviews with local people and authorities, Literature = various published and unpublished sources, Calculated = calculated from other attributes)
Before interpreting built-up areas, we also consulted OpenStreetMap, in order to evaluate if data from this platform could be used. Unfortunately, the information in OpenStreetMap was very general for the Wenchuan earthquake-affected area, and was limited to the main roads, and general polygons of settlements. Given the current difficulty to digitize and store data in OpenStreetMap from different time periods we decided to generate our database outside of the platform.

We used the above mentioned data to interpret and digitized manmade features, including buildings, farmlands, plantations, roads and mitigation works. Inventories were made for the following years: 2007, 2008, 2010, 2011, 2013, 2015 and 2018. The inventory of 2007 was made first, then the 2008 inventory was created based on modifying the earlier inventory using the aerial photograph of 2008. The inventory of 2010 was derived by modifying the inventory of 2008 using the Worldview-2 image from 2010, and the inventory of 2011 was derived from the 2010 inventory, and so on. Digitizing in such a manner allowed us to keep consistency among the multi-temporal inventories. A series of attributes listed in Table 2 were acquired for the digitized features through image interpretation, field mapping, and interviews.

With the help from the Station of Geo-environment Monitoring of Chengdu, we were able to interview the local authorities about historical events and access some of their documents regarding rural planning and population. Based on their descriptions and records with our field investigation, the buildings in this region were classified based on their functions, construction types, and builders.

- **Residences** are buildings to accommodate locals or workers attending the relief and the reconstruction.
- **Hostels** were to provide accommodation and recreation for tourists.
- **Institutional** buildings refer to public service buildings like schools, hospitals and water pumping stations.
- **Commercial** buildings accommodate shops and local companies. **Agricultural buildings** are used for storage of livestock, agricultural products and farming equipment. **Shelters** are temporary residences, including pre-fabricated houses, tents and shacks.

A total of seven building construction types were found in this region, including three types served as temporary shelters. **Reinforced concrete frame (RCF)** (Figure 2 A), **reinforced masonry (RCM)** (Figure 2 B), **wood and brick (WB)** (Figure 2 C), **wooden (W)** structures (Figure 2 D1 & D2) are permanent.
buildings, and pre-fabricated metal houses (PFM) (Figure 2 E), tents (Figure 2 F1), and shacks (Figure 2 F2) served as temporary shelters. Tents and shacks were categorized as one type in this study due to similar cost and size.

Farmlands were classified into crops for food or commercial crops. Commercial crops are several local plant species, including kiwifruit, tea, and *magnolia officinalis*, that were widely cultivated and exported to benefit the local economy. Crops for food are the vegetables grown for local consumption.

Roads were categorized into: major road, which were wide and built by the national government; secondary road, which is narrower than the major road and could be either local-build or constructed with help from the government; dirt roads are roads without asphalt or concrete layer. Several bridges and tunnels were mapped as well.

Mitigation works were mapped, and were classified into: check dams, which block debris flow runout and slow down erosion; drainage channels are used to redirect runout of debris flows and floods into river directly, avoiding flow through built up areas; embankments are built to shield of debris flow and flood runout; reinforced slopes are stabilized with reinforcement measures and sometimes combined with drainages.
Figure 2: Examples of building construction types in the study area. A: RC frame (RCF) structure residences built by the reconstruction teams from Shanghai city. B: reinforced masonry (RCM) building of a hostel. C: wood and brick residence (WB). D1: wooden structure (W) serving as restaurant. D2: wooden residence with walls made by wooden plates and bricks. E: pre-fabricated metal (PFM) temporary houses. F1: tents distributed by the government. F2: a shack made from wood, asbestos tiles and waterproof cloth.

The status of a building is determined by the attributes of damage level, damage type and usage status. The *damage level* indicates the magnitude of damage a building receives and was assigned based on both image observation and interviewing local people and authorities. If a building is not damaged, *level 0* is assigned.

Moderately damaged (*level 1*) means a disaster-affected building was damaged and restored its function after repair.
If a building was damaged beyond repair and not collapsed, it was considered as severely damaged (level 2). If a building collapsed, it was classified as destroyed (Level 3). The damage type shows what type of hazard feature affected the building, such as ground shaking, landslide, debris flow and flooding. Under certain circumstances a building could be affected by more than one hazard type, for instance by ground shaking and landslide impact at the same time. The usage status indicates if a feature is functioning normally, is temporary not been used, or completely abandoned. It is assigned based on field mapping and interviews. The geometrical attributes (area or length) were calculated automatically in ArcMap, based on the polygon (buildings or land parcels) or line (road) features. Floor space was calculated by multiplying the number of building floors with the footprint area. The unit price is the cost to construct buildings per square meter and was obtained through interviews, and literature study. The replacement value of a building was estimated by multiplying the unit price with the floor space. All the economic values in this study were converted to US dollar (USD) with a 10-years-average exchange rate of 1 dollar = 6.51 Chinese Yuan.

We investigated economic recovery by interviewing the local inhabitants and village authorities. Unfortunately, most of them were not willing to share information regarding their income, thus we could only make a descriptive analysis. Each of the interviewees represents one family in the analysis. A total of 113 persons were interviewed in 2018.

3 Monitoring reconstruction

In this section we analyze monitor the changes of the built-up environment caused by human activities and disasters from 2007 to 2018. The overall statistics of each year are shown in Table 3.

3.1 Pre-earthquake (2007)

We created the 2007 inventory based on a Quickbird image from 2005 and an IKONOS image from 2007. The attributes of the inventory were based on the memories of our interviewees. 417 buildings were identified from the images (Figure 3). Many buildings were constructed along the river due to easy access to the main road. Most of the buildings were self-built residences (304), and more than half of them used WB structure (186). Buildings with a tourism function were the second class in terms of number (87).
and most of them consisted of RCM types (75). Only 16 buildings were constructed by the government, including 12 RCM apartment buildings and 4 RCF institutional buildings (Table 3).

Most of the buildings were not properly designed to withstand a major earthquake, because most construction was informal and no earthquake resistant building practices were applied by local people. The last major earthquake in this area dates back from 1933 (Deixi earthquake), and there were no eyewitnesses alive of that event anymore in 2007. Even though there were many RCM buildings, it appears that only the ones built by the government applied a certain standard against ground shaking, as none of them collapsed during the 2008 earthquake. A few old traces of small-size landslides triggered by road construction could be observed on the hill slopes to the south.

3.2.1 The impact of the earthquake (2007 – 2008)

A total of 417 buildings in 2007 were identified from visual interpretation (Figure 3 and Appendix) and most of them were self-build residences. Most buildings were not properly designed to withstand a major earthquake (Table 3). The last major earthquake in this area dates back from 1933 (Deixi earthquake), and there were no eyewitnesses alive of that event anymore in 2007. According to investigation reports, debris flows had not been witnessed in 50 years until the Wenchuan earthquake (Yi et al., 2009; Luo et al., 2010; Sichuan Geology Engineering Reconnaissance Institute, 2010, 2011; Sichuan Geological Survey institute, 2010).

The Wenchuan earthquake triggered 1597 landslides in the study area according to the landslide inventory of Tang et al., (2016). Only a few casualties were reported in this region, as the earthquake occurred at 14:28 when most of the inhabitants were working outdoors. Ten people were killed by a rockfall which crashed four hotels.

The earthquake affected 444 buildings including some newly built ones in 2008 (Figure 3). From 2007 to 2008, prior to the earthquake, 6 buildings were removed and 33 buildings were constructed by the local residents. A total of 144 buildings were affected by the earthquake, of which 142 buildings were being completed destroyed (Damage level 3), in which 29 were destroyed by co-seismic...
Based on the 2009 SPOT image and the 2010 Worldview-2 images a total of 221 buildings were severely damaged and subsequently removed.

The remaining 81 buildings were repaired and functioned normally in 2009 and 2010, thus were classified as moderately damaged (Figure 4). Tang et al. (2016) A total of 1597 landslides were induced by the earthquake in the study area, and 29 of the 142 destroyed buildings were hit by coseismic landslides. A summary of the building damage is shown in Table 4.
Overall the significance in damage ratio could only be observed in damage level 1. There were relatively more 1-floor buildings repairable (22%) than 2-floor buildings (11%) survived. A difference related with construction types was observed, as the survive rate of the RCM, WB, W types were 23%, 17%, and 9%. The damage ratios of the three major types (RCM, WB, and W) were shown in Figure 4 A. There were only 4 RCF buildings and 2 survived. The damage ratios of the three major types (RCM, WB and W) were shown in Figure 4 A.

<table>
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<th>Period</th>
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<th>RCM</th>
<th>WB</th>
<th>M</th>
<th>PM</th>
<th>Ps</th>
<th>Total</th>
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<td></td>
<td>Total</td>
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<td>36(32)</td>
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<td>0</td>
<td>76</td>
<td>0</td>
<td>72</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shelters</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>267(184)</td>
<td>77(1)</td>
<td>209</td>
<td>132</td>
<td>1</td>
<td>768(185)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013: reconstruction</td>
<td>Residences</td>
<td>142(132)</td>
<td>68</td>
<td>199</td>
<td>85</td>
<td>1</td>
<td>457(132)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 3: Number of functioning buildings per construction type and land use for the seven time periods considered.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hotels</strong></td>
<td>49</td>
<td>13</td>
<td>8</td>
<td>7</td>
<td>5</td>
<td>1</td>
<td>46</td>
<td>699(185)</td>
</tr>
<tr>
<td>Institutional building</td>
<td>19(19)</td>
<td>1(1)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20(20)</td>
<td></td>
</tr>
<tr>
<td>Agricultural</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>78</td>
<td>0</td>
<td>3</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>Commercial</td>
<td>36(32)</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>45(32)</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>272(183)</td>
<td>85(1)</td>
<td>208</td>
<td>127</td>
<td>3</td>
<td>0</td>
<td>693(184)</td>
<td></td>
</tr>
<tr>
<td><strong>Residences</strong></td>
<td>142(132)</td>
<td>68</td>
<td>199</td>
<td>49</td>
<td>3</td>
<td>0</td>
<td>461(132)</td>
<td></td>
</tr>
<tr>
<td>Hotels</td>
<td>71</td>
<td>13</td>
<td>1</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>Institutional building</td>
<td>19(19)</td>
<td>2(2)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>21(21)</td>
<td></td>
</tr>
<tr>
<td>Agricultural</td>
<td>2</td>
<td>1</td>
<td>8</td>
<td>77</td>
<td>0</td>
<td>0</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>Commercial</td>
<td>36(32)</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>43(32)</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>208(183)</td>
<td>86(2)</td>
<td>212</td>
<td>30</td>
<td>3</td>
<td>0</td>
<td>699(185)</td>
<td></td>
</tr>
</tbody>
</table>

*Sum of all buildings.*
带格式的：两端对齐

545
Figure 4: The damage map and the co-seismic landslide inventory. A map showing the damage level of buildings and the distribution of co-seismic landslides. Buildings on the foot wall (Southeast) and 1 km away from the north fault rupture (indicated by the thick dotted line) took significantly less damage.

Relatively more single floor buildings were destroyed by the earthquake than 2-floor buildings. Overall the significance in damage ratio could only be observed in damage level 1. There were relatively more 1-floor buildings repairable (22%) than 2-floor buildings (11%). A difference related with construction types was observed, as the survive rate of the RCM, WB, W types were 23%, 17%, and 9%. The damage ratios of the three major types (RCM, WB and W), are shown in Figure 5. A. There were only 4 RCF
The significance in building floors is very obvious for the RCM construction type, as 35% of the 1-floor buildings survived the earthquake while only 13% of the 2-floor buildings were repairable. No significant difference in damage levels related with different construction types was observed. The damage ratios of the three major types (RCM, WB and W) are shown in Figure 5.

<table>
<thead>
<tr>
<th>Construction type</th>
<th>Floors</th>
<th>Damage levels</th>
<th>Sum by floors and construction type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Level 1</td>
<td>Level 2</td>
</tr>
<tr>
<td>RCF</td>
<td>1 floor</td>
<td>2 (35%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td></td>
<td>2 floors</td>
<td>0 (0%)</td>
<td>2 (10%)</td>
</tr>
<tr>
<td>RCM</td>
<td>1 floor</td>
<td>22 (35%)</td>
<td>09 (30%)</td>
</tr>
<tr>
<td></td>
<td>2 floors</td>
<td>01 (10%)</td>
<td>51 (63%)</td>
</tr>
<tr>
<td>WB</td>
<td>1 floor</td>
<td>04 (21%)</td>
<td>70 (44%)</td>
</tr>
<tr>
<td></td>
<td>2 floors</td>
<td>03 (9%)</td>
<td>38 (55%)</td>
</tr>
<tr>
<td>W</td>
<td>1 floor</td>
<td>15 (10%)</td>
<td>58 (60%)</td>
</tr>
<tr>
<td></td>
<td>2 floors</td>
<td>01 (0%)</td>
<td>3 (0%)</td>
</tr>
<tr>
<td>Sum by building</td>
<td>1 floor</td>
<td>05 (22%)</td>
<td>127 (44%)</td>
</tr>
<tr>
<td></td>
<td>2 floors</td>
<td>02 (11%)</td>
<td>41 (60%)</td>
</tr>
<tr>
<td>Sum by damage level</td>
<td>01</td>
<td>211</td>
<td>142</td>
</tr>
</tbody>
</table>

Table 4: Statistics of building damages caused by the earthquake. The percentage in the brackets was calculated by the number in the cell divided by the total numbers of the row. *Sum of all affected buildings.

Figure 4: Damage ratio statistics of the three major structural types in 2008. The numbers in brackets under the x axis indicate the total numbers of buildings. A: damage ratio of all the earthquake-affected buildings. B: damage ratio on the northern side of the dotted line in Figure 5. C: damage ratio on the southern side of the dotted line in Figure 4.

A damage pattern controlled by fault rupture was found—building damage was more serious on the hanging wall or within one-kilometer distance of the Yingxiu – Beichuan fault rupture (indicated by a...
thick dotted line in Figure 4, and 6. The landslide area density was much higher in this zone as well. Both sides showed a clear difference in damage level, as the ratio of buildings being destroyed in the northwest was much higher (Figure 5A and C) than in the southeast, as only 17 of the 81 survived buildings are located in the northwest. The damage was not influenced by the construction types in the north, likely because probably indicating the shaking was so strong that it exceeded the resistance of all the three types (Figure 5B). The southern side showed a significance difference in damage for the construction types, as the loss of RCM buildings had the lowest collapse loss ratio and while wooden buildings had the highest (Figure 5C). The landslide area density in the northwest is much higher than the southeast, further suggesting the existence of a localized ground shaking difference (Figure 3).

Road stretches with a combined length of 3.7 km, which was 11% of the local road network of 33.5 km, were blocked by co-seismic landslides (Figure 4). The only access road, the tunnel in the southeast (Figure 1 Access 1), survived the earthquake. The earthquake reactivated human-induced landslides which were caused by road construction in the south. Fresh bare surfaces of the landslides could be observed from the 2005 image and they were almost fully covered by vegetation in the image of 2007.

None of the farmlands were directly affected by the co-seismic landslides, because most of them were located on gentle slopes or flat lands in the southern part.

3.2 The disaster relief (2009)

The aerial photos of 2008 and the SPOT image of 2009 were used to map shelters (Figure 5). Before the government could bring in pre-fabricated houses the survivors set up 229 shelters by building shacks and using tents provided by the government. Many The local residents mostly constructed the shelters next to their destroyed houses, even when this was very close to co-seismic landslides.

Before the winter of 2008 four temporary settlements were made with 82 pre-fabricated buildings, which housed multiple families (Figure 6 and table 3). A total of 81 buildings survived the earthquake, of which 64 were located more than one kilometer distance to the South of the Yingxiu–Beichuan fault (Figure 5). Most of the survived buildings were self-built residences and no significance in the construction types...
The government had problems in identifying suitable locations for the shelter settlements. The lack of awareness of the possible areas endangered by post-earthquake landslide and debris flow played an important role in this. Before the winter of 2008 four temporary settlements were made with 82 pre-fabricated buildings, which housed multiple families (Figure 5 and table 3). The local residents mostly constructed the shelters next to their destroyed houses, even when this was very close to co-seismic landslides. The largest planned temporary settlement with pre-fabricated buildings (PFM) along with some native shacks (TSs) was established on the lower part of the alluvial fan of one of the largest sub-watersheds, the Bayi catchment, which later posed a high debris flow threat, as 29% of its watershed area was covered by co-seismic landslides (Figure 4-5B).

It was difficult to estimate the accommodation status of the survivors since many of them went to relatives outside the area and many workers and soldiers stayed in the area to carry out the relief.
3.3 Early reconstruction stage (2009–2010)

The SPOT image of 2009 and the Worldview-2 image of 2010 were used to map the buildings, roads, and mitigation measures for 2010, which illustrates the changes brought by early reconstruction efforts. The city of Shanghai was assigned responsibility to execute the recovery activities of the nearby Duijiangyan...
city, and the surrounding area, including the Longchi valley. During this period all rubble was removed as well as most of the tents and shacks.

The new inventory contains 873 buildings, out of which 706 were newly constructed, including some new shelters. Among the 655 reconstructed permanent buildings, 481 were built by the residents themselves with the financial support from the government. There were 174 new buildings constructed by the government and most of them are concentrated in the center of Longchi town (Figure 6), which was proven to be a safe location in the later years and 174 by the government, mostly concentrated in the center of Longxi town, where a number of apartment buildings were made. An extra 34 pre-fabricated buildings, 17 TSs shelters and 6 mitigation works were constructed in this period (Table 3). Eighty-one buildings that survived the earthquake were still functioning in 2010. All the road damaged were repaired and a new highway entrance was made in May 2009, which contributed to the fast reconstruction (Figure 1, access 2 and Figure 8), which shortened the travel time to Longchi by nearly 340 minutes and bypassed many road sections threatened by landslides.

Unfortunately, the lack of knowledge about post-earthquake hazards had led to many careless decisions made by both the government and the local residents. Many buildings were rebuilt at outlets of sub-catchments because historical deposition fans provided relatively flat land. Most of the rebuilt and newly added hotels are located next to the Longxi River in order to attract tourists, ignoring the potential dangers caused by the river.

The Chinese government implemented a policy to avoid losses in future earthquakes and applied RCF framed structures for 99% of the reconstructed buildings. An example of such a government-built apartment building is shown in Figure 2 A. The construction types for self-built residences did not change significantly, as most of them (278) were built with locally available wood (WB and W construction types). Some of the residents chose to rebuild their houses on the original location of their old destroyed houses since the government-built apartments were far away from their farmlands.

A notable increase in using frame structures among the hostels was observed (Table 3), many of which were rebuild near the original locations along the Longxi River.
Unfortunately, the lack of knowledge about post-earthquake hazards had led to many careless decisions made by both the government and the local residents. Many buildings were rebuilt at outlets of sub-catchments because historical deposition fans provided relatively flat land. Most of the rebuilt and newly added hotels are located next to the Longxi River in order to attract tourists, ignoring the potential danger posed by the river.

The government chose to place most of the new apartment buildings together at the central location in Longchi town (Figure 3). An example of such a government-built apartment building is shown in Figure 2. A. No major disaster occurred in 2009, as the precipitation was not significant in this region. Only limited hazard mitigation projects were carried out. Three potentially dangerous slopes near the Longchi town were stabilized during the reconstruction process. Two check dams and a drainage were installed in the Bayi sub-watershed. After a small debris flow destroyed 9 PPM shelters during the monsoon of 2009, two check dams and a drainage were installed in the Bayi sub-watershed. (Figure 6) Some of the residents chose to rebuild their houses on the original location of their old houses since the government-built apartments were far away from their farmlands. The earthquake did not significantly change their preferences of construction types, and most of them (278) rebuild their house with locally available wood (WB and W construction types). A notable increase in using frame structures among the hostels was observed (Table 3), many of which were rebuild near the original locations along the Longxi River. During an extreme rainfall event in 2009, a total of 164 landslides were activated, and a debris flow destroyed nine pre-fabricated buildings and covered 619 meters of road at the outlet of the Bayi sub-watershed. After the debris flow, two relatively weak check dams were installed in the upper catchment and a drainage channel was made near the outlet (Figure 7 B & C).
Figure 7: Mitigation works that were under construction in 2010. A: stabilized slope near the newly built primary school in Longchi town. B: check dam being built in the Bayi sub-catchment after a debris flow in 2009. C: drainage channel being built at the outlet of the Bayi catchment after the debris flow in 2009.
Figure 86: The inventory of the situation in 2010 before the monsoon, showing the buildings, roads, and remedial measures for the period between 2008 and 2010. Overlain are the active landslides in 2009. A debris flow destroyed 9 PFM shelters, after which two check dams a drainage were installed.

3.4 The August 2010 debris flows: The late reconstruction stage and major debris flow disaster (2011-2013)

The Worldview-2 image from 2011 was used to map the changes caused by the large debris flow disaster that occurred during 13 - 14 August 2010 (Figure 97) (Xu et al., 2012; Tang et al., 2012). The most catastrophic debris flow event was triggered by a storm on 14 Aug 2010 with a maximum recorded rainfall intensity of 75 mm/h measured by rain gauges in the Longchi town (Xu et al., 2012). About 341 new landslides were triggered and 1151 of the co-seismic landslides were reactivated in this study area during this event, producing several massive debris flows which joined in the valley of the Longxi River (Yu et al., 2011), reaching the Zipingpu reservoir lake. Sedimentation was 5 – 7 m at about 300 meters upstream of the town (Xu et al., 2012; Sichuan Geology Engineering Reconnaissance Institute, 2011).

Nearly one-fourth of all buildings in the study area were impacted by debris flows and subsequent floods. The losses were largest for those buildings located either close to the river or near sub-catchment outlets (Figure 9). Among all the 213 affected buildings, 70 were destroyed, 41 were severely damaged and 102 were moderately damaged. The most severe loss occurred at the outlet of the Bayi sub-catchment, where 64 shelters were completely razed and 4 shelters were moderately damaged by a large debris flow severely damaged the temporary settlement (Figure 10-8 A & B). The drainage and the poorly constructed check dams in Bayi sub-catchment constructed in earlier years did not prove to be adequate and were destroyed (Figure 10-8 C). The total number of buildings in the area reduced to 712 (Table 3). Two government offices, a water treatment plant and a water pumping station were affected, with 9 RCF buildings moderately damaged. The debris flows and flood disasters also damaged 35,000 m² of farmlands and destroyed 7.5 km of road. The losses were largest for those buildings located either near sub-catchment outlets (Figure 10 A & D) or close to the river (Figure 8 E & F), were destroyed (Figure 9).
Figure 7: The building and landslide inventories mapped based on a Worldview-2 image captured in April 2011, showing the changes brought by the August 2010 debris flow disaster. A total of 213 buildings were affected. The losses were largest for those buildings located either near sub-catchment outlets or close to the river.
3.6 Post-reconstruction period (2013 – 2018)

Residences and hostels were the most affected building occupancy types (60% of all affected buildings). This was because the local people reconstructed many of their residences on historical debris flow deposits, which presented relatively flat lands at sub-catchment outlets (Figure 10 A & D), and most of...
The hostels were reconstructed beside the Longxi River in order to attract tourists (Figure 10 E). A few government-built apartment buildings were also being placed on similar locations (Figure 10 D and E).

3.5 The late reconstruction stage (2010-2013)

The WorldView image of 2011 and the Pleiades image collected in April 2013 were used to map the changes between 2011 and 2013. Another inventory was made based on the 2011 Worldview-2 and the 2013 Pleiades images, which represents the situation shortly after the post-debris flow debris flow and the official announcement of reconstruction completion (2012) (Figure 9) was completed in 2012. All the temporary buildings were removed by 2012. A total of 38 buildings, that were threatened by debris flows or floods, were abandoned. The government constructed another 25 buildings to replace these (Figure 11) and also local people constructed 67 new buildings.
Some self-built buildings were removed during the construction process. The total numbers of functioning buildings were reduced to 678 (Table 3).

Many mitigation measures, such as check dams, sediment retention basins, and debris flow early warning systems, were implemented and concrete embankments were installed along parts of the river (Figure 9). The debris flow warning is based on the accumulative rainfall and rainfall intensity recorded by rain gauges installed in the watershed. A camera was installed in the upper stream of the Longxi river to monitor debris flow and flood activities. Many mitigation measures, such as check dams, sediment...
retention basins, and debris flow early warning systems, were implemented in the three most dangerous sub-catchment and concrete embankments were installed along parts of the river (Figure 11).

Figure 10: Losses caused by the Aug 14, 2010 debris flows. The locations of the examples are shown in Figure 8. A: The temporary settlement at the Bayi sub-catchment outlet in 2009 (Luo et al., 2010); B: The shelters destroyed by a debris flow from the Bayi sub-catchment (Luo et al., 2010); C: One of the two under-designed check dams in Bayi sub-catchment which were destroyed (Lin, 2010); D: Residences reconstructed on old debris flow deposits were damaged; E: A hotel beside the Longxi River was struck; F: government-built apartment buildings beside the river were damaged.

The debris flow warning is based on the accumulative rainfall and rainfall intensity recorded by rain gauges installed in the watershed. A camera was installed in the upper stream, near the location of the
damaged hotel shown in Figure 10E to monitor debris flow and flood activities in the Longxi River. Due to the construction of the mitigation works, the total road length increased to 38.1 km.

From August 2010 to April 2013, the debris flow activities in most of the sub-catchments reduced decayed rapidly except for the Bayi sub-catchment. A flashflood took place in 2013, which damaged 20 buildings. A major cause of the floods was the dramatic raise of the riverbed (Yu et al., 2011) brought by debris flows. The authorities said because it was not possible to reopen the Longxi national park due to high landslide threat along the access road. The government decided to stop maintenance, maintenance for the major road in the north stopped due to being repeatedly damaged by floods, and the closure of the national park the damaged access road to the park in the north. A dirt road was made as a replacement. This did not affect the economy much directly as the tourism was low and most of the farmlands and forestry are in the south of the watershed.
Figure 11: The inventory of 2013 and active landslides in 2013 mapped based on the 2013 Pleiades image, showing the situation shortly after the official announcement of reconstruction completion. A new community was built to make up the loss caused by the 2010 debris flow and many mitigation measures were installed. The debris flows caused a rise of the riverbed and led to flooding.

From August 2010 to April 2013, the debris flow activity of most of the sub-catchments reduced except for the Bayi sub-catchment. A flash flood took place in 2013 which damaged 20 buildings. A major cause of the floods was the dramatic rise of the riverbed (Yu et al., 2011) brought by debris flows. Because it was not possible to reopen the Longxi national park due to high landslide threat along the access road, the government decided to stop maintaining the damaged access road to the park in the north. A dirt road was
made as a replacement. This did not affect the economy much directly as the tourism was low and most of
the farmlands and forestry are in the south of the watershed.


The last two change maps were made changes from 2013 to 2018 was identified by interpreting the 2015
SPOT 6 image and the 2018 Pleiades image. From 2013 to 2018 the Longchi society developed in a
stable manner without any major disruption, thus we only described the inventory of 2018 (Figure 12). In
this period 21 new buildings were constructed by local people. The total number of buildings in the area
grew to 699 (Table 3).

The road length increased to 46.2 km, as many dirt roads were made to access farmlands. The tunnel
connecting the highway was closed due to water leakage (Figure 1, access 2) and The government
decided to stop its maintenance was stopped, probably because of a low economic interest caused by the
loss of tourism. Only the old tunnel (Figure 1, access 1) could be used, which caused a delay in traveling
to Dujiangyan city by car of 40 minutes. A secondary road was made in 2018 connecting the neighboring
catchment and provided a second access road for the Longxi watershed (Figure 1 and Figure 10, access
3).

Landslides and floods did not cause any major loss since 2013 as due to the decaying hazard (Tang et al.,
2016) and the mitigation measures. A few debris flow watersheds were treated with mitigation structures
(Figure 12). Two elevated drainage channels were installed in 2015 in the southern part to redirect flash
floods from sub-catchments produced by two small sub-catchments into the river directly. The last
reported disaster was a flood cut the dirt road in the north on August 20, 2019. The Bayi catchment
produced floods that damaged dirt roads in almost every summer during this period.
Figure 10. The inventory made based on the 2018 Pleiades image, overlaying with landslide polygons made based on the standards of Tang et al. (2016). The society developed in a slow and stable manner, without major disruptions from 2013 to 2018. The last reported disaster was a flood cut the dirt road in the north on August 20, 2019.

4 Analysis of economic values

In this section the economic values of the built-up features were estimated in US dollar. The total value of the buildings was estimated by multiplying floor space with the unit price for construction. The values and the exposure in the seven investigated periods were evaluated.
4.1 Value estimation

The unit prices for different building types and roads were acquired through interviews with local builders and local government officers (Table 5). The unit prices of buildings increased after the earthquake due to several reasons: higher building standards, large consumption of building materials in
the earthquake-hit areas, and currency devaluation. The price of mitigation structures were estimated based on the mitigation design of a catchment in the neighboring watershed (Li et al., 2011). The mitigation structures of the three sub-catchments (Figure 11)—built after 2010—have a worth of approximately 30 million Yuan (Chengdu Bureau of Land and Resources, 2018). We were not able to acquire prices of farmlands, forests and other indirect factors. Therefore the analysis was limited to economic value, investment and direct loss caused by hazards. Severely damaged and destroyed buildings were counted as direct economic loss.

<table>
<thead>
<tr>
<th>Type</th>
<th>Value</th>
<th>Unit price before 2008 (USD / m²)</th>
<th>Unit price 2008 – 2012 (USD / m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction type</td>
<td>Code</td>
<td>RC frame structure</td>
<td>217</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reinforced masonry</td>
<td>144</td>
</tr>
<tr>
<td>Wood &amp; brick</td>
<td>WB</td>
<td>54</td>
<td>77</td>
</tr>
<tr>
<td>Wooden</td>
<td>W</td>
<td>27</td>
<td>46</td>
</tr>
<tr>
<td>Pre-fabricated metal houses</td>
<td>PFM</td>
<td>-</td>
<td>154</td>
</tr>
<tr>
<td>Tents &amp; shacks</td>
<td>TSs</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>Reinforced slopes</td>
<td></td>
<td>-</td>
<td>*205</td>
</tr>
<tr>
<td>Drainage channels</td>
<td></td>
<td>-</td>
<td>*103</td>
</tr>
<tr>
<td>Embankments</td>
<td></td>
<td>-</td>
<td>*362</td>
</tr>
<tr>
<td>Road (USD / m)</td>
<td></td>
<td>Major road (6 m wide)</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Secondary road (3 m wide)</td>
<td>23</td>
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<td></td>
<td></td>
<td>Bridge (5 m wide)</td>
<td>828</td>
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<tr>
<td></td>
<td></td>
<td>Tunnel (6 m wide road)</td>
<td>5069</td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td>Mitigation works of the three sub-catchments (Figure 11)</td>
<td>4.6 million USD in total</td>
</tr>
</tbody>
</table>

Table 5: Unit price of built-up features. All values were adjusted to the situation of 2012 by inflation rate of Chinese Yuan. *Calculated based on mitigation design of a nearby catchment.
The total value of all buildings was estimated to be about 19.5 million USD in 2007 (Figure 13 A). The earthquake caused 8.2 million USD direct loss in 2008, which was 42% of the value in the previous year. The temporary shelters in 2008 were worth 2.2 million USD, making the total building value in 2008 reaching 14.5 million USD. A 0.1 million USD loss was caused by the debris flow in 2009. The economic value estimation result is illustrated in Figure 11 A. As a result of the fast reconstruction, the total value increased rapidly to 96 million USD in 2010 and 133 million USD in 2013, which was nearly 5 and 7 times the value in 2007. This was caused by the increase in the number of buildings and the overall improvement in construction type, particularly the RCF buildings accounted for 75% of the total value.

The total direct loss during the monitored period was 16.5 million USD, out of which 8.4 Million was government losses and 8.1 million USD private losses. The disaster in August 2010 caused a loss of 8.3 million USD, which was slightly more than the loss caused by the Wenchuan earthquake. It is because many expensive RCF buildings were carelessly built in areas exposed to debris flows and were severely damaged beyond repair. The loss was further increased in 2013 in the form of buildings being abandoned by the local residents in fear of debris flow and flood threat.

As a result of the fast reconstruction, the total value increased rapidly to 96 million USD in 2010, which was nearly 5 times the value in 2007.
Figure 13: A: The total built-up values of the built-up features, investments and direct economic losses over the period between 2007 and 2018 in the Longxi area. B: The total building value that was at risk of element-at-risk exposed to debris flows and floods. The values were adjusted with the inflation rate. C: The total number of buildings that were at risk of debris flows and floods of being impacted by debris flows and floods.

As a result of the fast reconstruction, the total value increased rapidly to 96 million USD in 2010, which was nearly 5 times the value in 2007.
This was caused by the increase in the number of apartment buildings and the overall improvement in construction type, particularly the RCF buildings accounted for 75% of the total value. The disaster in August 2010 caused a loss of 8.3 million USD, making the building value dropped to 88.3 million USD in 2011. It is notable that the direct loss in 2010 was slightly more than the loss caused by the Wenchuan earthquake. New buildings and the mitigation structures raised the total value to 133.1 million USD in the 2013 inventory. A gradually small increase in the total values was observed from 2013 to 2018, which was caused by currency inflation and new buildings.

A total of 130.3 million USD was invested in the reconstruction and hazard mitigation. The government invested 104.9 million USD, which was almost four times the private investment (25.3 million USD), and a large portion of the private investment came from government subsidies. Over all investigated period the total direct loss was 16.5 million USD, out of which 8.4 Million was government losses and 8.1 million USD private losses.

4.2 Exposure

The risk could only be expressed analyzed by the value of potential exposed assets exposed to debris flows and floods, since we could not quantify the return period of the highly dynamic post-earthquake hazards as this was changing from year to year due to the changing landslide activity (Tang et al., 2016; Fan et al., 2019b). The area affected by the hazards were mapped based on the landslide inventories of Tang et al. (2016) and historical flood traces mapped found in field. The post-earthquake environment was highly dynamic due to the constantly changing amount of loose material and vegetation regrowth, making the triggering rainfall threshold and magnitude of disasters different in each of the years. The potential exposure described in this section includes buildings under threat of landslides and floods. The hazard extent was determined by the maximum extent of landslide and historical floods. Any building located in the hazard extent affected areas was considered to have a potential exposure (Figure 11 B & C) to the post-seismic hazards. A major increase in both of the value and number of the exposure in 2010 suggested a careless reconstruction plan. The decrease in 2011 was caused by the impact of the 2010 debris flow. After the debris flow the Longchi town adapted to the post-earthquake environment by initiating multiple mitigation projects and invested 5 million USD (Figure 11 B). By 2015 the majority of the exposure were protected by mitigation structures.
Luo et al. (2010); Tang et al. (2016)

The exposure in 2007 was 0.2 million USD (Liu et al., 2007), since the area did not present any major active landslide or debris flow areas, and was nearly completely forested before 2008. This changed dramatically after the earthquake. The landslide frequency and magnitude were high in the first three years in this area based on our previous work of monitoring post-earthquake landslide activities (Tang et al., 2016; Luo et al., 2010). In 2008 the total value of the exposed element-at-risk was only 2.6 million USD as many of the buildings were destroyed by the earthquake and reconstruction had not commenced (Figure 13 B). By 2010 the value of potential exposed buildings had increased enormously to 21.3 million USD as many buildings were reconstructed in the danger zone. A total of 1.3 million USD was invested in mitigation works (Yi et al., 2009; Luo et al., 2010). There were 2 million USD worth of buildings protected by the reinforced slopes shown in Figure 7 A and Figure 8. The check dam and the drainage at the catchment outlet did not count as protection due to their poor quality (Figure 7 B & C and Figure 8). After the 2010 debris flow disaster the landslide activity decayed significantly (Tang et al., 2016). In 2011 the total value of potential exposed buildings reduced to 15.4 million USD because of the loss caused by the 2010 disaster. The mitigation value reduced to 0.8 million USD because of the destroyed check dam and drainage. In 2013 the total value of the potentially exposed buildings was 13 million USD, and 8.7 million USD was under the protection of 5.8 million worth mitigation structures. The potentially exposed value remained stable at 12.4 to 12.7 million USD from 2015 to 2018, with 12 to 12.1 million USD protected. The total spending on mitigation works increased to 5.0 million USD. It is difficult to predict the future situation as the number of assets would increase if the Longchi National Park reopens, and hazard activity could further diminish as the environment recovers completely and reaches the pre-earthquake condition.

4.2. Economy

The economy is described based on the interviews with the local residents and authorities.

The economy prior to the earthquake relied mostly on farming, tourism, and working outside of the town. Forestry was an important economic activity in the heavily forested watershed of the Longchi River, with trees producing medicines, nuts and building materials. Agriculture and tourism were almost equally...
important, generating a gross output value of 6.9 million US dollar for the year of 1999 (Baidu Encyclopedia, 2016).

After the earthquake the government distributed subsidies to the residents based on the reported property damage and organized several companies to employ the local people. There were 29% of the families completely or partially relied on working out side of the area in 2018, which was 9% higher than the pre-earthquake situation.

The farmlands generated about half of the profit (Baidu Encyclopedia, 2016), occupying an area of 76 hectares and were used mainly for growing commercial crops (74%). The 87 hotel buildings in 2007 indicated that tourism played an important role in the local economy. Employment outside the study area (Mainly in the cities of Dujiangyan and Chengdu) had a significant contribution as well, as 70% of the interviewees stated it was one of the major income sources.

The earthquake lead to an unemployment of 19% of the population. The tourism activities came to a complete stop, but agriculture did not take much direct damage from the earthquake. The government distributed subsidies to the residents based on the reported property damage. They also organized several companies to employ the local people, causing an extra of 9% of the families that relied on working outside of the area.

Tourism was stopped completely due to the earthquake, and only started recovering since 2015. Severe losses were taken after the reconstruction of hotels, as many were damaged by debris flows and floods, and they were unable to attract tourists due to the valley was considered as a dangerous place to visit.

Although the business started flowing seven years after the earthquake, a fully recovery could only be expected upon the reopening of the national park.

The economy was more relied on agriculture than tourism after the earthquake. From 2007 to 2018, the farmlands have increased from 76 hectares to 98 hectares, and most of them are growing commercial crops. Sixty-five new agriculture buildings were built after the 2010 disaster, and many were used to house domestic animals such as chicken, ducks and goats.
Employment outside the study area (Mainly in the cities of Dujiangyan and Chengdu) had a significant contribution as well, as 20% of the interviewees stated it was one of the major income sources. After the relief efforts in 2008 and 2009 both the government and the local population were expecting the recovery of the tourism sector brought by the national park. Judged from the reconstructed hostels, there was a plan to restore economy by tourism. This was indicated by not only reconstructed destroyed hotels but also built many new ones, almost doubling the floor space. In May 2009, entrepreneurial local people built more hostels than there were in 2007 and the floor space was almost doubled. The government connected the town with the major highway to Wenchuan, which was already planned before the earthquake but which was executed at record rushing speed after the disaster, and which was completed in May 2009.

Agriculture was strongly encouraged by the government. The area of farmlands increased during 2008 to 2010 (+6 hectares) and commercial crops had a higher ratio (+9%) than in 2007. Sixty-five new agriculture buildings were built in 2010, as the local farmers started to raise domestic animals such as chicken, ducks, and goats. The unemployment rate was reduced to 3%.

The debris flows that occurred on August 14, 2010 had a large impact on the local economy since the Longxi National Park had to be kept closed for an indefinite period due to the increased landslide threat. The government realized the debris flow threat and the destruction of the access road and most of the tourist infrastructure. As a result, in 2011 the government stopped the road maintenance in the northern part which connects the settlements with the national park. A total of 12 hotels were closed and waited for the reopening of the national park. The economy could only rely on agriculture and working outside.

A fast increase in farmland area was observed during 2010 to 2013 (+9 hectares). Farmlands continued to expand from 2010 to 2018, reaching 98 hectares, which was 15 hectares more than in 2010. Since the temperature in the Longchi valley is always lower in summer than the nearby cities (Dujiangyan and Chengdu) and most of the landslides were stabilized, the tourism started to recover since 2015. The closure of the tunnel connecting Longchi town with the highway increased the fuel cost to transport goods and reduce potential tourism. Till the end of 2018, the government did not announce any plan to repair the tunnel or reopen the national park. The economy of the Longchi watershed is not likely to be fully recovered before the reopening of the national park.
5.1 Hazard and Risk Assessment

Challenges faced in post-earthquake reconstruction

Some existing examples such as Haiti (Jesselyn, 2017) and Nepal (Adhikari, 2017) are known for slow recovery process due to limitations in politics and limitations in economy. The Longchi town showed a contrary case that rebuilding in a very rapid manner led to high exposure and severe losses. The problems are majorly constructing many valuable assets in hazard-prone areas (spatial) and rebuilding too early before the environment could reach a relatively salable situation (time). The cause might be a lack of communication between the government and scientists because of the top-down political system. The necessity of hazard and risk assessment was not realized even though sharp increases in mass movement in hazards after major earthquakes were reported several times before 2008 (Lin et al., 2004; Lin et al., 2006; Nakamura et al., 2000; Liu et al., 2013).

Ideally hazard maps should be updated shortly after earthquakes, considering the enhanced hazards and hazard chains (Fan et al., 2019a; Tang et al., 2016; Hovius et al., 2011; Marc et al., 2015), as well as the long-term dynamics. Upon acquiring hazard maps, multi-criteria analysis could be carried out for reconstruction suitability assessment and land use models could be used to assess the possible consequences and potential risk generated by planning. For example, Barić et al. (2006), Cammerer et al. (2012), Promper et al. (2014), and Store and Kangas (2001). Barić et al. (2006); (Cammerer et al., 2012; Promper et al., 2014).

The major difficulties of reconstruction planning may lie in hazard assessment due to the spatial and temporal dynamics of hazards, as well as their chain-effect interactions (Fuchs et al., 2013; Kappes et al., 2012). These difficulties are enlarged in a post-earthquake environment as many factors change much faster than they normally do. For example, sediment discharge would be several times higher (Koi et al., 2008; Hovius et al., 2011) and vegetation regrowth at a rapid speed (Yang et al., 2018; Liu et al., 2010). (Fuchs et al., 2013; Kappes et al., 2012) The commonly used evidence-based
statistical assessment methods might be not valid shortly after earthquakes due to the changes in environment and triggering mechanism of hazards (Huang and Fan, 2013; Tang et al., 2011a; Tang et al., 2011b; Xu et al., 2012; Fan et al., 2019b). The application of deterministic methods would be more useful but is largely depending on the efficiency of data collection.

To our knowledge there are two models (van Asch et al., 2013; Bout et al., 2018) could simulate the both initiation and runout as well as incorporating temporal changes in environment, therefore have the potential to simulate such dynamics given sufficient data. Domenech et al. (2019). The model of van Asch et al. (2013) simulates initiation and runout of entrainment-based debris flows and was tested in one of the sub-watershed in our study area. Bout et al. (2018) incorporated the functions proposed by van Asch et al. (2013) and their model allows the simulation of multi-hazard interactions of hazards (earthquakes, mass movements and floods), further expanding its potential for post-earthquake hazard assessment. An example is given by Domenech et al. (2019) as they showed a case study to simulate the temporal changes in debris flow hazard affected by material depletion, revegetation and grain coarsening.

5.2 Exposure and mitigation

A sharp increase in exposure was demonstrated in this study, due to rises in both numbers and cost of buildings. Although many element-at-risk were protected by mitigation measures against debris flows and floods or not affected, many self-built buildings are still vulnerable to earthquakes. It is hard to judge whether building more expensive RCF buildings than enough is beneficial, for example buildings for commercial purposes. On one hand they do improve the earthquake resistance and life quality of the potentially improved life quality for the community if the national park could be reopened in future. On the other hand the increase in risk of earthquakes might result an increase in risk of earthquakes. It is advised to keep a close track of the changes in elements-at-risk and hazard in order to understand the up-to-date risk situation. Automatic extractions could help this task if image data could be systematically collected and well geo-referenced.
Mitigation measures are widely used to reduce mass movement hazard (Fuchs et al., 2004; Keiler et al., 2006; Hübl et al., 2005; Chen et al., 2015), however only when they are properly designed. A failed example was shown in this study (Figure 8 C), as the magnitude of the 2010 debris flow exceeded the mitigation capacity. Such mitigation might create a false sense of security and possibly leading to more losses (Olugunorisa, 2009; Cigler, 2009). It might be not beneficial to start installing mitigation measures right after an earthquake, as the magnitude and frequency of mass movement hazards might be too costly to mitigate. Several Researches have shown that after 3-5 years mass movement hazard activities decreased rapidly after 3-5 years (Fan et al., 2019a; Tang et al., 2016; Marc et al., 2015; Hovius et al., 2011), and therefore a delay in mitigation and reconstruction could give more beneficial results than taking measures immediately after large earthquakes. In case of avoiding building in risky areas is not possible (Fan et al., 2019a; Tang et al., 2016; van Asch et al., 2013; Bout et al., 2018); Yi et al. (2009); Sichuan Geological Survey institute (2010); Sichuan Geology Engineering Reconnaissance Institute (2010); Sichuan geo-engineering group corporation, 2010; Yang, 2010; Hao et al., 2011; State Council of China, 2003; United Nations Office for Outer Space Affairs (2014)

6 Conclusions

We monitored the changes in the Longxi valley during a 11-year period after the Wenchuan earthquake and the subsequent recovery process, with seven inventories from different years containing buildings, roads, land use and mitigation measures. Most of the stronger building construction types were only implemented after the earthquake, and mitigation structures were only installed after being impacted by debris flows and floods. A greater awareness to avoid living in hazard prone areas was observed after the 2010 debris flows. Despite the extensive and repeated damage, the earthquake, and subsequent landslides, debris flows, and floods gave Longchi town a chance to increase its resistance to these hazards in future, and to improve economically. Such is called development recovery (Davis and Alexander, 2016), which not only restoring all the recovery sectors but also to improve on what used to exist.

Due to the direct involvement of the Government and the city of Shanghai, who supported Longxi town financially and with expertise, the recovery was fast, considering the large loss and the mountainous...
terrain in the area impacted by the Wenchuan earthquake. The lack of experience of dealing with post-earthquake landslides was the largest flaw in the recovery planning. The damage caused by post-seismic landslides was not only restricted to Longxi, but was reported across the entire earthquake affected region. The post-earthquake disasters did not significantly slow down the reconstruction process because of the strong economy of China, and the large amount of funding that was invested in reconstruction and protection using mitigation structures.

However, recovering the economy through tourism was a failure in Longchi town, because post-seismic debris flow activity was underestimated. Many resources were wasted, for example the destroyed and abandoned hostels, the destroyed main road, and the revoked highway entrance. Similarly, despite of a handful of success examples, many unused and often destroyed tourism facilities can be seen all over the earthquake affected area. Among all the towns that had planned tourism, Longchi town had one of the worst failures, because its biggest attraction was the national park which could not be reopened. The recovery would have been much more efficient if it included the awareness of dealing with post-seismic hazard reactivations. However, the question remains if these hazard reactivations could have been predicted and mitigated properly.

In such a mountainous region it is recommended not to re-build near the outlet of catchments containing many co-seismic landslides. Limiting reconstruction too close to rivers is also recommended to avoid floods caused by riverbed raising and landslide dams. Avoiding build critical structures and residential buildings near major faults, like the Yinexiu – Beichuan fault in Figure 3, could lower the risk posed by earthquakes. The exact areas susceptible to hazards should be acquired by conducting hazard assessments.

A possible time table for recovery actions is presented in Table 6. Four post-seismic phases are identified based on landslide activity from Tang et al. (2016) and Fan et al. (2018). Period I (very high) means the period when the majority of co-seismic material in streams is not depleted and loosened slope materials have not failed. Period II (High and fast decay) means the time after the first major mass movement event which removes the majority of the stream blockages. Landslides occur frequently but not likely with a catastrophic magnitude in this phase. Period III (Low and slow decay) is when vegetation has mostly
recovered and landslide activity is no longer frequently observed. Landslide activity is much lower compared with the previous two phases, and slowly decays towards the pre-earthquake level, but still pose a significant threat. Period IV (Fully recovered) is when landslide activity is at the same level as the pre-earthquake rate.

<table>
<thead>
<tr>
<th>Post-seismic landslide threat</th>
<th>Very high</th>
<th>High and fast decay</th>
<th>Low and slow decay</th>
<th>Fully recovered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period number</td>
<td>I</td>
<td>II</td>
<td>III</td>
<td>IV</td>
</tr>
<tr>
<td>In the Longxi watershed</td>
<td>2008 - 2010</td>
<td>2010 - 2015</td>
<td>2015 - 2016</td>
<td>Unknown</td>
</tr>
<tr>
<td>Rebuilding in risky zones</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>with mitigation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rebuilding in safe zones</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Installing mitigation works</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Reopen tourism</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Hazard surveys frequency</td>
<td>Very High</td>
<td>High</td>
<td>Moderate</td>
<td>Same as pre-earthquake</td>
</tr>
</tbody>
</table>

Table 6: Suitability of actions after earthquakes, using the Longxi watershed as the example. 0 = not suitable, 1 = somewhat suitable, 2 = suitable

In period I rebuilding should be strictly limited to areas with low disaster threat. Even then risk still exists since rivers could be dammed by mass movement and cause flooding in areas outside of landslide-prone zone. It might not be appropriate to install mitigation works unless it is absolutely necessary because of expensive cost and high magnitude of hazards. Hazards, particularly mass movements, should be closely monitored in order to respond to emergencies in a timely manner. In period II extreme disasters are less likely to occur but building in landslide-prone area is still too risky. Mitigation works could be installed in key locations to keep critical infrastructures. In non-critical locations it is not beneficial to install mitigation works yet due to large amount of co-seismic debris that could still be easily activated by rainfall. It is still necessary to closely monitor hazards. Period III is the optimal time to install mitigation measures since the mass movement threat would be relatively low, therefore easier to be controlled.

Buildings are allowed to be constructed in risky areas under the protection of mitigations in order to
It could be concluded that hazard and risk assessment are necessary for a properly conducted post-earthquake recovery. The assessments should consider not only spatial but also temporal dynamics of hazards, as well as the possible interaction among different hazard types, so that proper locations and time for reconstruction could be acquired.


Author contributions. This work was carried out by Chenxiao Tang as part of his PHD thesis under the supervision of CVW. The field investigation and mapping were carried out by Chenxiao Tang, XL, YC, YY, HT, and CY. Chuan Tang provided resources and data.

Competing interests. The authors declare that they have no conflict of interest.

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7 Years After Haiti’s Earthquake, Millions Still Need Aid, 2017.


A figure showing the situation in 2007, before the Wenchuan earthquake. Most buildings were self-built by local residents and many adopted WB and W construction types. Most of the region were densely covered by vegetation and no active landslide was observed.