



## Monitoring of the reconstruction process in a high mountainous area affected by a large earthquake and subsequent debris flows

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### Abstract

15 Recovering from major earthquakes is a challenge, especially in mountainous environments where post-earthquake mass movements and floods may cause substantial impacts. We monitored the reconstruction of Longchi town in Sichuan, China, over a period of 11 years, following the 2008 Wenchuan earthquake. Seven inventories of buildings, land use, roads and mitigation measures were made by using remote sensing image interpretation and field surveys. Most of the buildings were  
20 rebuild by 2010 and reconstruction was completed by 2012. The total economic value of the new buildings in 2010 was much more than the pre-earthquake situation in 2007. 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 more than the loss caused by the earthquake itself. The society showed an impact - adapt  
25 pattern, taking losses from disasters and then gaining resistance.



Keywords: Multi-temporal mapping; post-disaster reconstruction; element-at-risk; landslides; risk assessment; Wenchuan earthquake

## 1 Introduction

### 30 1.1 Background

Large-scale disasters (e.g. earthquakes, cyclones, floods, volcanic eruptions and forest fires) cause wide-spread losses to society, leading to direct and indirect social and economic losses. Catastrophic earthquakes have caused severe damage to human societies in the past 20 years (e.g. 1999 Izmit Turkey, 1999 Chi-Chi Chinese Taipei, 2003 Bam Iran, 2004 Indian ocean, 2005 Pakistan, 2008 Wenchuan  
35 China, 2010 Haiti, 2011 Tōhoku Japan, 2015 Gorkha Nepal, and 2018 Palu Indonesia). The earthquakes caused heavy losses by damaging buildings due to ground shaking and several triggered secondary disasters like landslides and tsunamis. These events also have a large impact on the natural environment, and critically change the conditions related to vegetation, active processes and hydrology leading to new hazards or increased intensity and frequency of existing hazards. This aspect is often not  
40 fully considered in post-disaster reconstruction planning, leading to unfortunate new impacts and losses.

Earlier studies on post-earthquake recovery were carried out using field visits and statistics based on interviews (Sakamoto and Yamori, 2009; Bolin and Stanford, 1998; Wang et al., 2012; Wu and Lindell, 2004). Several studies on recovery monitoring used remote sensing methods (Yang et al., 2015b; Platt  
45 et al., 2016; Burton, 2015), however, few studies focused on multi-temporal monitoring of post-earthquake recovery in an environment affected by several multi-hazards. The aim of this study is to monitor the changing built-up environment in a mountainous region during the recovery process from the 2008 Wenchuan earthquake.

The  $M_w$  7.9 Wenchuan earthquake occurred on 12 May 2008 in Sichuan province, affecting an area of  
50 110,000 km<sup>2</sup>, 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  
55 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  
60 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  
65 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  
70 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.

Vegetation changes (mainly from vegetated to bare) which can be detected from high resolution remote sensing images are important indicators for landslide monitoring (Mondini et al., 2011; Saba et al.,  
75 2010; Stumpf and Kerle, 2011), and vegetation regrowth on landslide surfaces has been widely used to analyze the recovery of landslide surfaces (Khan et al., 2013; Yang et al., 2017; Li et al., 2016). In the epicentral area of the 2008 Wenchuan earthquake, the total area of active landslides has decreased linearly 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 Mianyuanhe  
80 area of the Wenchuan earthquake affected region (Li et al., 2016).

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., 2015a), environmental (Yang et al.,  
2017), institutional (Hu et al., 2010), and economic vulnerability (Wu et al., 2012;Zhang et al., 2013).  
85 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., 2015a), 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).

90 In this study we generated seven inventories of elements-at-risk from satellite images covering a period  
of 13 years (2005 - 2018) and conducted several field surveys to study the recovery of Longchi valley,  
located close to the epicenter of the Wenchuan earthquake. Image interpretation was carried out based  
on a series of satellite images collected between 2005 and 2018. The study aims to demonstrate and  
analyze the process of post-disaster recovery in an unstable geo-environment disrupted by a major  
95 earthquake.

### 1.2 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  
100 is about 89 km<sup>2</sup> 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 m<sup>3</sup>/s and the  
recorded maximum discharge was 300 m<sup>3</sup>/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  
105 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.

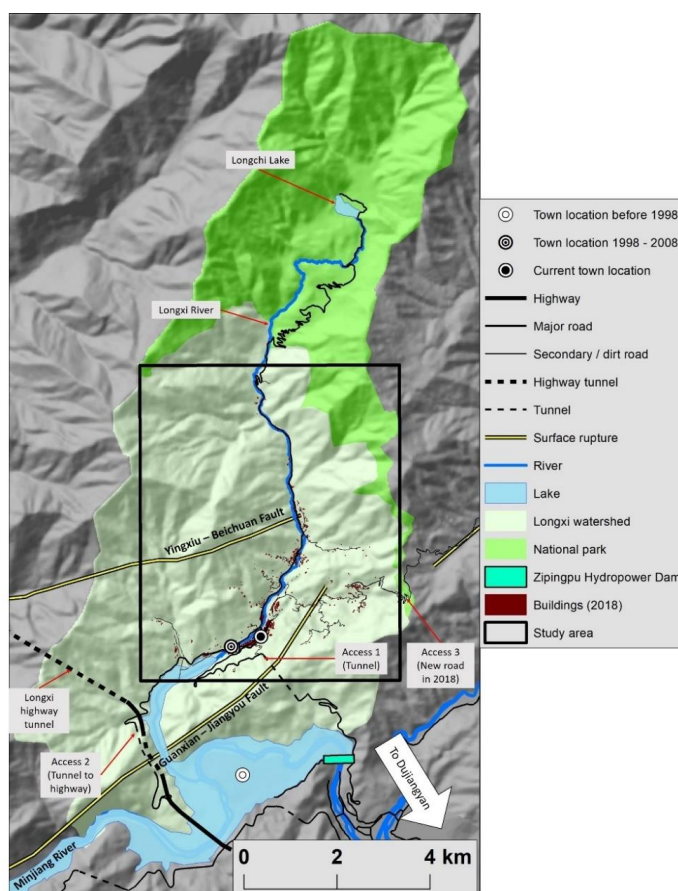
### 1.3 History of the study area

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 of Longxichang 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 was 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 residences 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, 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).  
145 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.



**Figure 1: The location of the study area. The roads and buildings reflect the situation in 2018. Buildings outside the study area polygon were not mapped.**

150 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 1).

Data type	Data source	Collection date	Cell size Pan/Mul (m)	Band
Satellite images	Quickbird	JUL 2005	2.4	Mul
	IKONOS	SEP 2007	1	RGB
	Aerial photographs	JUN 2008	1	RGB
	Spot 5	FEB 2009	2.5/10	Pan + Mul
	Worldview-2	MAR 2010	0.5/2	Pan + Mul
	Worldview-2	APR 2011	0.5/2	Pan + Mul
	Pleiades	APR 2013	0.5/2	Pan + Mul
	Pleiades	DEC 2014	0.5/2	Pan + Mul
	Spot 6	APR 2015	1.5	RGB
	Pleiades	JUN 2018	0.5/2	Pan + Mul
DTM	Aerial LiDAR	1999	5	-
Landslide inventory	Tang et al. (2016)	2016	Polygon-based vector data with landslide activity mapped for 5 periods (2008 - 2015)	
	This study	2018	Polygon-based inventory based on image from June 2018	

160 **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.

165 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 landside in this study using the Pleiades image from June 2018.

Attributes	Varieties / descriptions	Source				
		Image	Mapping	Interview	Literature	Calculated
<b>Buildings</b>						
<b>Construction types</b>	<i>Permanent buildings: RC frame structure / Reinforced masonry / Wood &amp; brick / Wooden</i> <i>Temporary buildings: Pre-fabricated metal houses / Tents &amp; shacks</i>	x	x	x		
<b>Function</b>	Residence / Hostel / Institutional/ Commercial / Agricultural building / Shelter		x	x		
<b>Builder</b>	Self-constructed / government-build		x	x		
<b>Unit price</b>	150 – 2700 Chinese yuan per m <sup>2</sup> , depending on Construction types			x	x	
<b>Building floors</b>	Floors of a building. A maximum of 4 floors was allowed.		x			
<b>Floor space</b>	Building area * building floors					x
<b>Value</b>	Floor space * unit price					x
<b>Roads</b>						
<b>Type</b>	Major road / Secondary road / Dirt road / tunnel	x	x			
<b>Farmlands</b>						
<b>Type</b>	Food crops / Commercial crops	x	x			
<b>Mitigation works</b>						
<b>Type</b>	Check dam / Drainage channel / Embankment / Reinforced slopes	x	x			
<b>all elements-at-risk</b>						
<b>Damage level</b>	No damage / Moderately damaged / severely damaged / Destroyed	x	x			
<b>Damage type</b>	Earthquake / Slides / Debris flows / Flood / No damage	x	x	x		
<b>Usage status</b>	Normal / Abandoned / Empty	x	x			
<b>Geometry</b>	Auto calculated in ArcMap					x

**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, 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  
175 time periods we decided to generate our database outside of the platform.

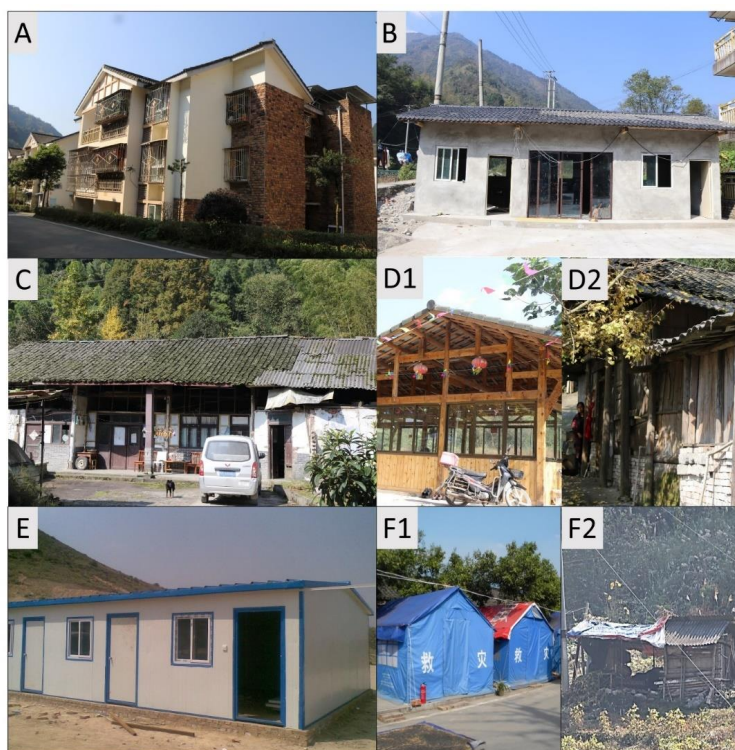
We used the above mentioned data to interpret and digitized manmade features, including buildings, farmlands, plantations, roads and mitigation works. Inventories were made for the following years: 2007, 2008, 2010, 2011, 2013, 2015 and 2018. The inventory of 2007 was made first, then the 2008 inventory was created based on modifying the earlier inventory using the aerial photograph of 2008.  
180 The inventory of 2010 was derived by modifying the inventory of 2008 using the Woldrview-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.

185 *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.

Farmlands were classified into *crops for food* or *commercial crops*. Commercial crops are several  
190 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*  
195 and *tunnels* were mapped as well.

Mitigation works were mapped, and were classified into: *check dams*, which block debris flow runoff and slow down erosion; *drainage channels* are used to redirect runoff of debris flows and floods into river directly, avoiding flow through built up areas; *embankments* are built to shield of debris flow and flood runoff; *reinforced slopes* are stabilized with reinforcement measures and sometimes combined  
200 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



215 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  
220 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  
225 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.

### 230 **3 Monitoring reconstruction**

In this section we analyze the changes of the built-up environment caused by human activities and  
disasters from 2007 to 2018. The 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  
235 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  
240 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 eye  
witnesses alive of that event anymore in 2007. Even though there were many RCM buildings, it  
245 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 slope to the south.

### 3.2 The impact of the earthquake (2008)

From 2007 to 2008, prior to the earthquake, 6 buildings were removed and 33 buildings were  
250 constructed by the local residents. A total of 444 buildings were affected by the earthquake, of which  
142 buildings were completely destroyed. Based on the 2009 SPOT image and the 2010 Worldview-2  
images a total of 221 buildings were severely damaged and subsequently removed.

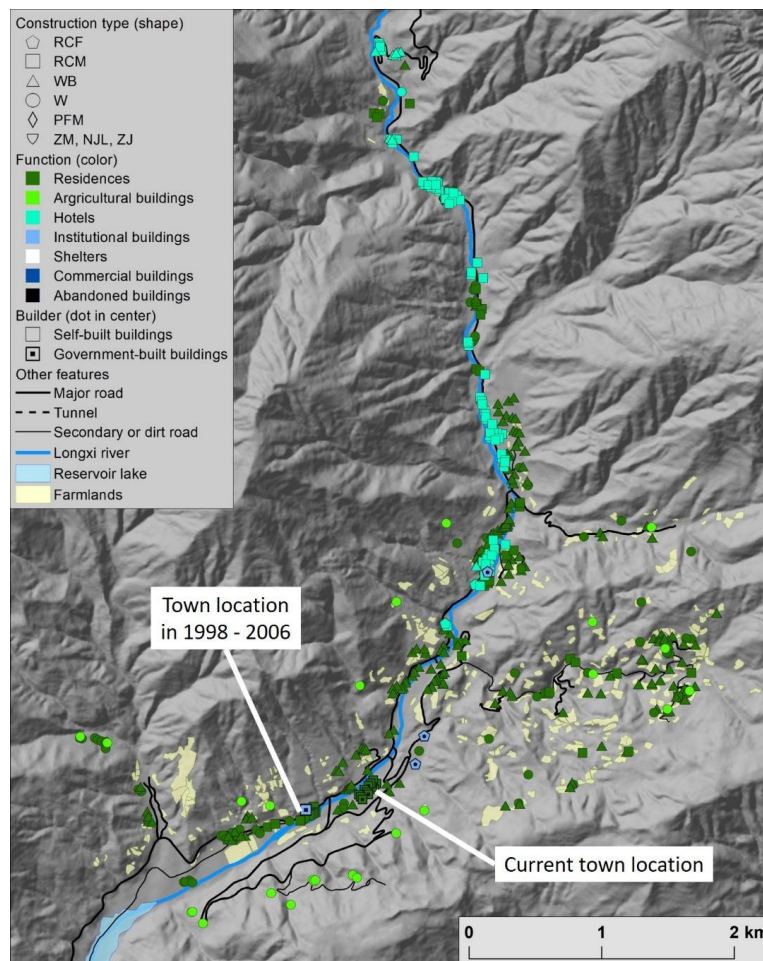


Figure 3: Map of the buildings, roads, land use and mitigation measures in 2007.



255 The remaining 81 buildings were repaired and functioned normally in 2009 and 2010, thus were classified as moderately damaged (Figure 4). A total of 1597 landslides were induced by the earthquake in the study area, and 29 of the 142 destroyed buildings were hit by co-seismic landslides. A summary of the building damage is shown in Table 4.

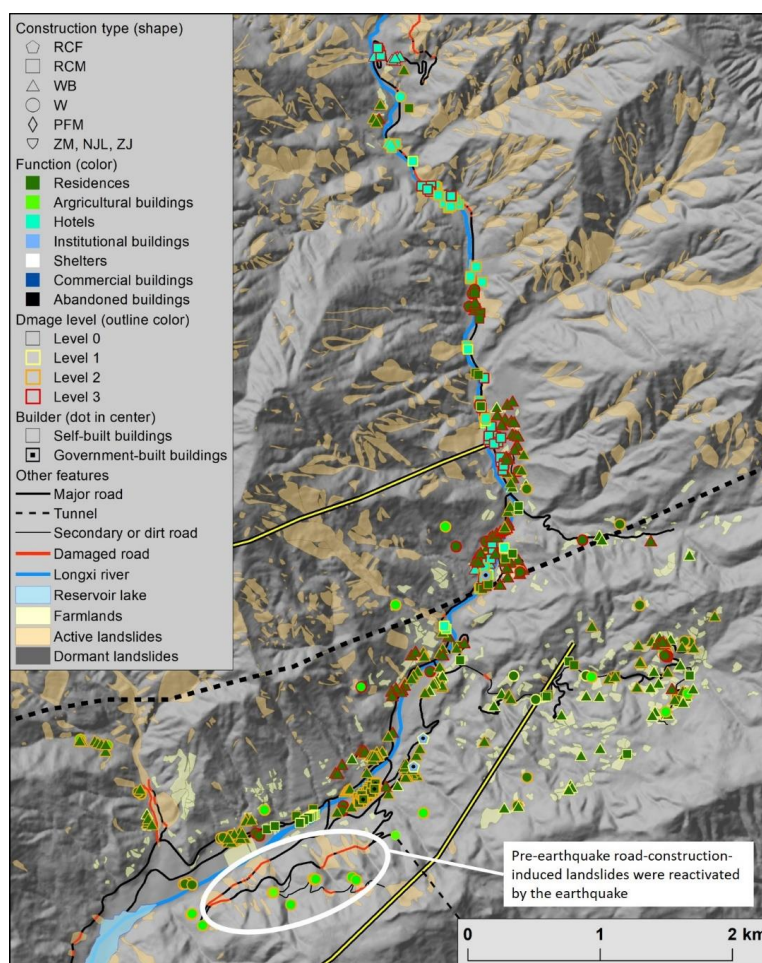
Period	Land use	Construction type						Total
		RCF	RCM	WB	W	PFM	TSs	
2007: pre-earthquake	Residences	0	66(12)	186	51	0	0	304(12)
	Hotels	1	75	10	0	1	0	87
	Institutional building	3(3)	1(1)	0	0	0	0	4(4)
	Agricultural	0	0	0	23	0	0	23
	total	4(3)	142(13)	196	74	1	0	417(16)
2008: shortly after the earthquake	Residences	0	24	40	5	0	0	69
	Hotels	0	9	0	0	0	0	9
	Institutional building	2(2)	0	0	0	0	0	2(2)
	Agricultural	0	0	0	1	0	0	1
	Shelters	0	0	0	0	82(82)	227	309(82)
Total	2(2)	33	40	6	82(82)	227	390(84)	
2010: earthquake reconstruction almost	Residences	126(118)	78	237	42	0	0	483(118)
	Hotels	77	18	2	3	0	0	100
	Institutional building	25(25)	1(1)	0	0	0	0	26(26)
	Agricultural	0	1	1	86	0	0	88
	Commercial	36(32)	2	0	1	0	0	39(32)
	Shelters	0	0	0	0	116(116)	21	137(116)
Total	266(175)	99(1)	239	132	116(116)	21	873(292)	
2011: after devastating debris	Residences	124(116)	65	236	40	2	0	467(116)
	Hotels	59	12	1	3	0	0	75
	Institutional building	25(25)	1(1)	0	0	0	0	26(26)
	Agricultural	0	1	7	86	0	0	94
	Commercial	36(32)	2	0	1	0	0	39(32)
	Shelters	0	0	0	0	50(50)	3	53(50)
Total	244(173)	76(1)	229	127	52(50)	3	712(224)	
2013 all reconstruction	Residences	143(132)	56	206	42	3	0	450(132)
	Hotels	68	17	1	3	0	0	89
	Institutional building	20(20)	1(1)	0	0	0	0	21(21)
	Agricultural	0	1	2	76	0	0	79
	Commercial	36(32)	2	0	1	0	0	39(32)
Total	267(184)	77(1)	209	122	3	0	678(185)	
2015	Residences	142(132)	68	199	45	3	0	457(132)
	Hotels	69	13	1	3	0	0	86
	Institutional building	19(19)	1(1)	0	0	0	0	20(20)
	Agricultural	0	1	6	78	0	0	85
	Commercial	36(32)	2	6	1	0	0	45(32)
Total	272(183)	85(1)	208	127	3	0	693(184)	
2018	Residences	142(132)	68	199	49	3	0	461(132)
	Hotels	71	13	1	3	0	0	88
	Institutional building	19(19)	2(2)	0	0	0	0	21(21)
	Agricultural	0	1	8	77	0	0	86





	Commercial	36(32)	2	4	1	0	0	43(32)
	Total	268(183)	86(2)	212	130	3	0	699(185)

**Table 3: Number of functioning buildings per construction type and land use for the seven time periods considered. The numbers before the brackets indicate the total number and the numbers in the brackets indicate the building numbers built by government. \*Sum of all buildings.**



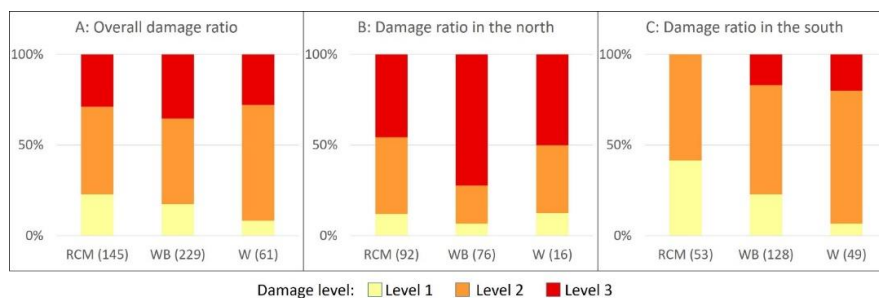
**Figure 4: The damage map and the co-seismic landslide inventory.**



265 Relatively more single floor buildings were destroyed by the earthquake than 2-floor buildings. 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.

Construction type	Floors	Damage levels			Sum by floors and construction type
		Level 1	Level 2	Level 3	
RCF	1 floor	2	0	0	2
	2 floors	0	2	0	2
RCM	1 floor	22(35%)	19(30%)	22(35%)	63
	2 floors	11(13%)	51(63%)	20(24%)	82
WB	1 floor	34(21%)	70(44%)	56(35%)	160
	2 floors	6(9%)	38(55%)	25(36%)	69
W	1 floor	6(10%)	38(60%)	19(30%)	61
	2 floors	0	3	0	3
Sum by building	1 floor	64 (22%)	127(44%)	97(34%)	288
	2 floors	17(11%)	94(60%)	45(29%)	156
Sum by damage level		81	221	142	*444

270 **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 5: Damage ratio statistics of the three major structural types. The numbers in brackets under the x axis indicate the total numbers of buildings. A: damage ratio of all the earthquake-affected buildings. B:**



275 **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, and 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.

280 Both sides showed a clear difference in damage level, as the ratio of buildings being destroyed in the north was much higher (Figure 5 B and C) than in the south. The damage was not influenced by the construction types in the north, because the shaking was so strong that it exceeded the resistance of all types (Figure 5 B). The southern side showed a significance difference in damage for the construction types, as the loss of RCM buildings had the lowest loss ratio and wooden buildings had the highest  
285 (Figure 5 C).

Road stretches with a combined length of 3.7 km, which was 11% of the road network of 33.5 km, were blocked by co-seismic landslides (Figure 4). 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  
290 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.

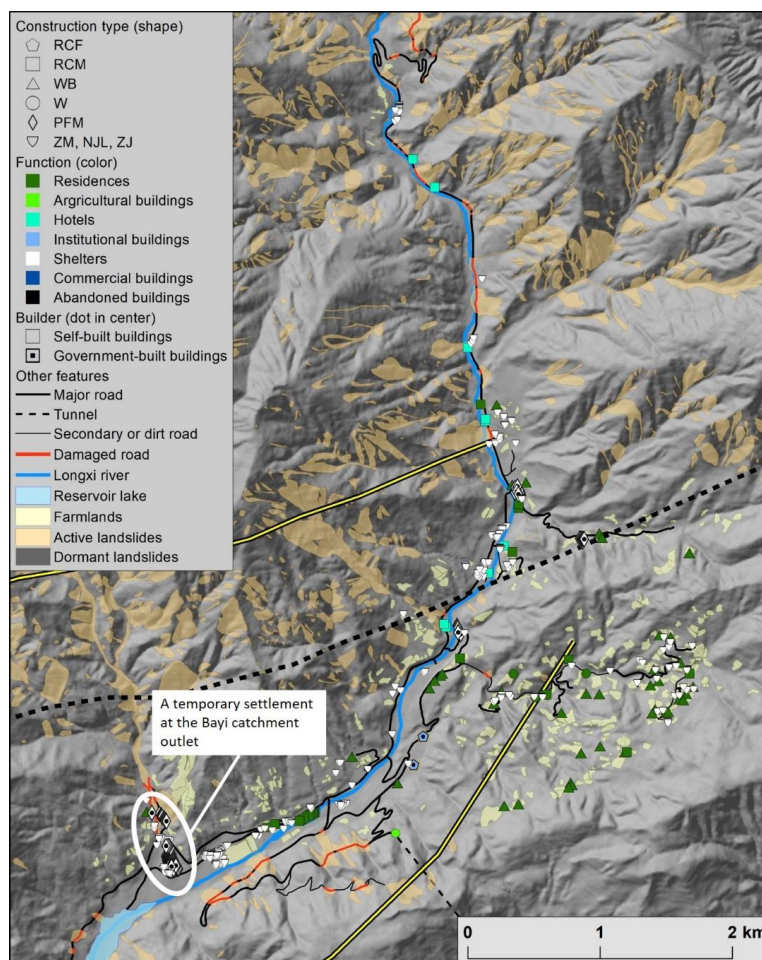
The aerial photos of 2008 and the SPOT image of 2009 were used to map shelters. Before the government could bring in pre-fabricated houses the survivors set up 229 shelters by building shacks  
295 and using tents provided by the government. Before the winter of 2008 four temporary settlements were made 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 was found. The government had  
300 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.





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 settlement with pre-fabricated buildings along with some native shacks was sited 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 B).

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.



310 **Figure 6: Map of the buildings that survived the earthquake and location of temporary shelters.**



### 3.3 Early reconstruction stage (2009 - 2010)

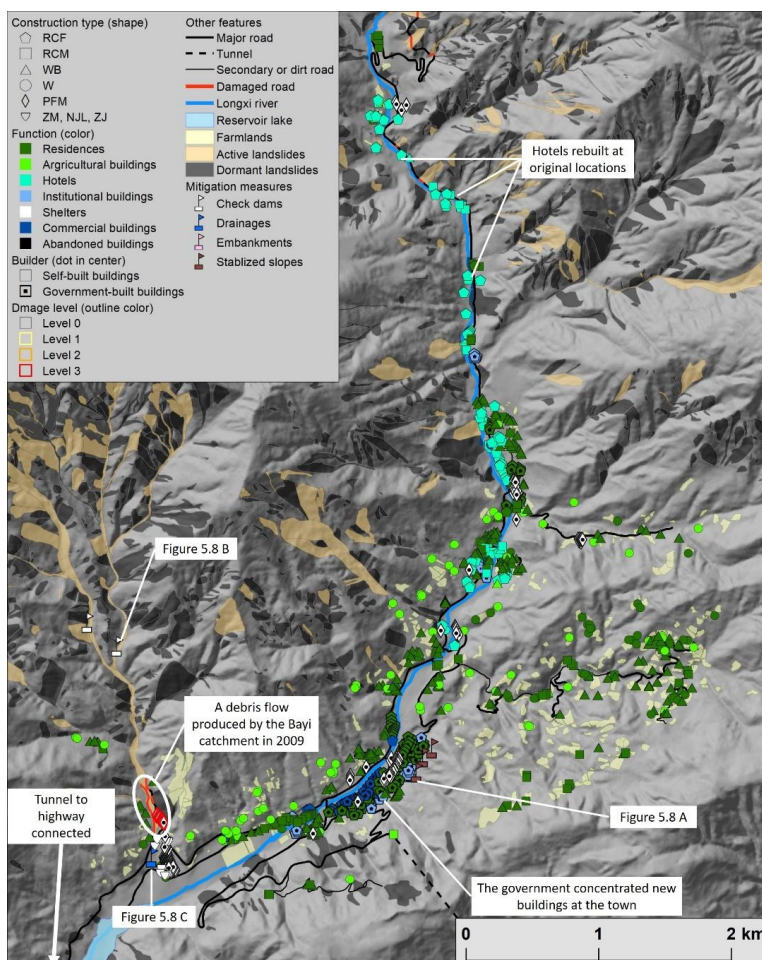
The SPOT image of 2009 and the Worldview-2 image of 2010 were used to map the buildings, roads, and mitigation measures for 2010, which illustrates the changes brought by reconstruction. During this period all rubble was removed as well as most of the tents and shacks.

315 The new inventory contains 873 buildings, out of which 706 were newly constructed, including new shelters. Among the 655 reconstructed permanent buildings, 481 were built by the residents themselves 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  
320 were still functioning in 2010. All the damaged roads 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).

The Chinese government implemented a policy to avoid losses in future earthquakes and applied framed structures for 99% of the reconstructed buildings. The government chose to place most of the new apartment buildings together at the central location in Longchi town (Figure 8). An example of  
325 such a government-built apartment building is shown in Figure 2 A. Three potentially dangerous slopes near Longchi town were stabilized during the reconstruction process (Figure 7 C). 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  
330 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 events 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  
335 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.**



340



**Figure 8: The inventory of the situation in 2010, showing the buildings, roads, and remedial measures for the period between 2008 and 2010. Overlain are the active landslides in 2009.**

### 3.4 The August 2010 debris flows

The Worldview-2 image from 2011 was used to map the changes caused by the large debris flow disaster that occurred in August 2010 (Figure 9). The most catastrophic debris flow event was triggered  
345 by a storm on 14 Aug 2010 with a maximum recorded rainfall intensity of 75 mm/h measured by rain gauges in the 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  
350 lake. Sedimentation was 5 – 7 m at about 300 meters upstream of the town (Figure 9) (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  
355 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 (Figure 10 A & B). The drainage and the poorly constructed check dams in Bayi sub-catchment constructed in earlier years by the government did not prove to be adequate and were destroyed (Figure 10 C). The total number of buildings in the area reduced to 712 (Table 3). Two government offices, a water treatment plant and a  
360 water pumping station were affected, with 9 RCF buildings moderately damaged. The debris flows and floods also damaged 35,000 m<sup>2</sup> of farmlands and 7.5 km of roads were destroyed (Figure 9).

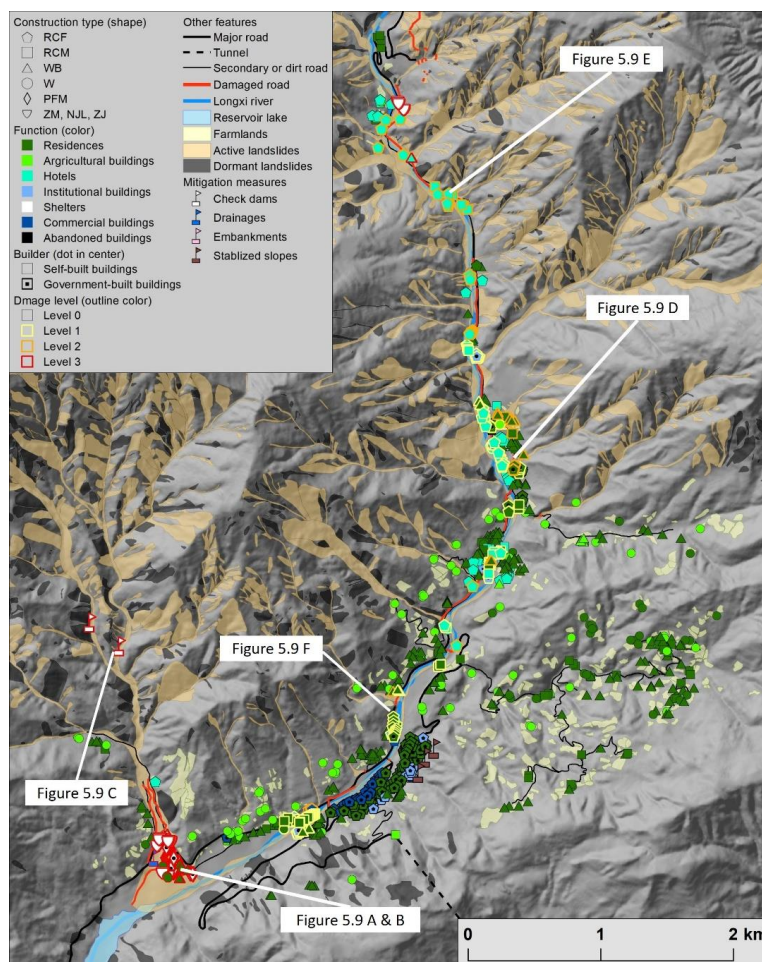
Residences and hostels were the most affected building occupancy types (60% of all affected buildings). This was because the local people reconstructed many of their residences on historical debris flow deposits, which presented relatively flat lands at sub-catchment outlets (Figure 10 A & D), and most of  
365 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 F).





### 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, which represents the situation shortly after the post-debris-flow reconstruction was completed in 2012. All the temporary buildings were removed by 2012. A total of 370 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.



375 **Figure 9: The 2011 inventory and the active landslides in 2010.**



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 in the three most dangerous sub-catchment and concrete embankments were installed along parts of the river (Figure 11).



380

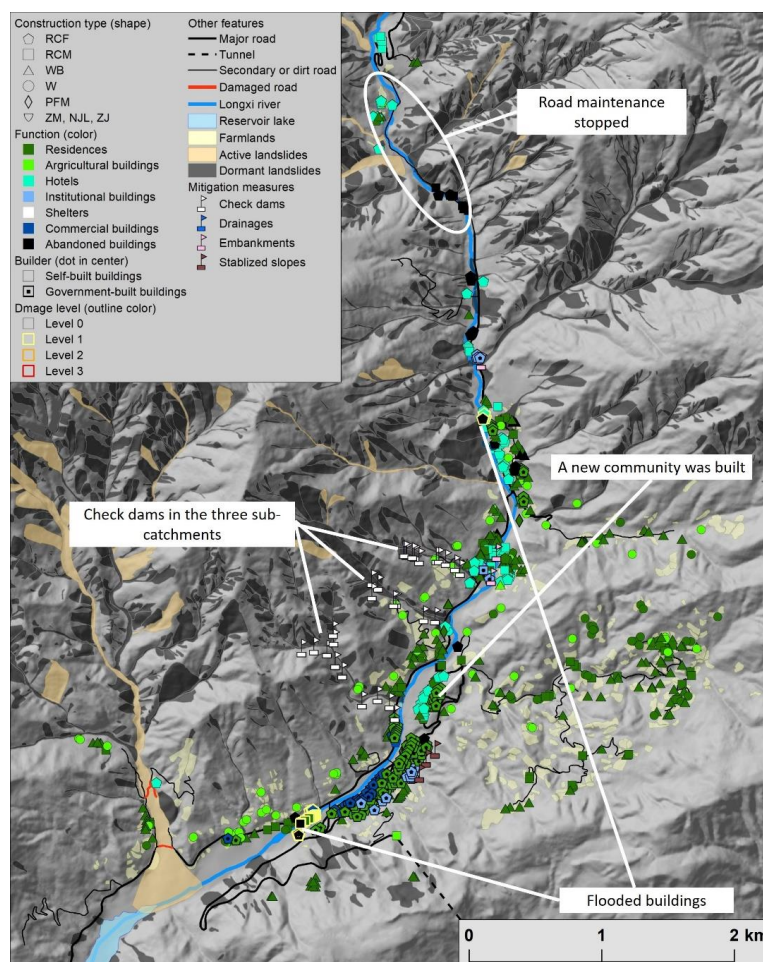
385

**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 (Liu, 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 10 E, to monitor debris flow and flood activities in the Longxi River.

390 Due to the construction of the mitigation works the total road length increased to 38.1 km.



**Figure 11: The inventory of 2013 and active landslides in 2013.**

From August 2010 to April 2013 the debrisflow activity of most of the sub-catchments reduced except for the Bayi sub-catchment. A flashflood took place in 2013 which damaged 20 buildings. A major  
 395 cause of the floods was the dramatic raise 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.

#### 400 **3.6 Post-reconstruction period (2013 - 2018)**

The last two change maps were made 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  
405 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). The government decided to stop its maintenance, 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  
410 and provided a second access road for the Longxi watershed (Figure 12).

Landslides and floods did not cause any major loss since 2013. 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 floods produced by two small catchments into the river directly. The Bayi catchment produced floods that damaged dirt roads in almost every summer during this period.

#### 415 **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.



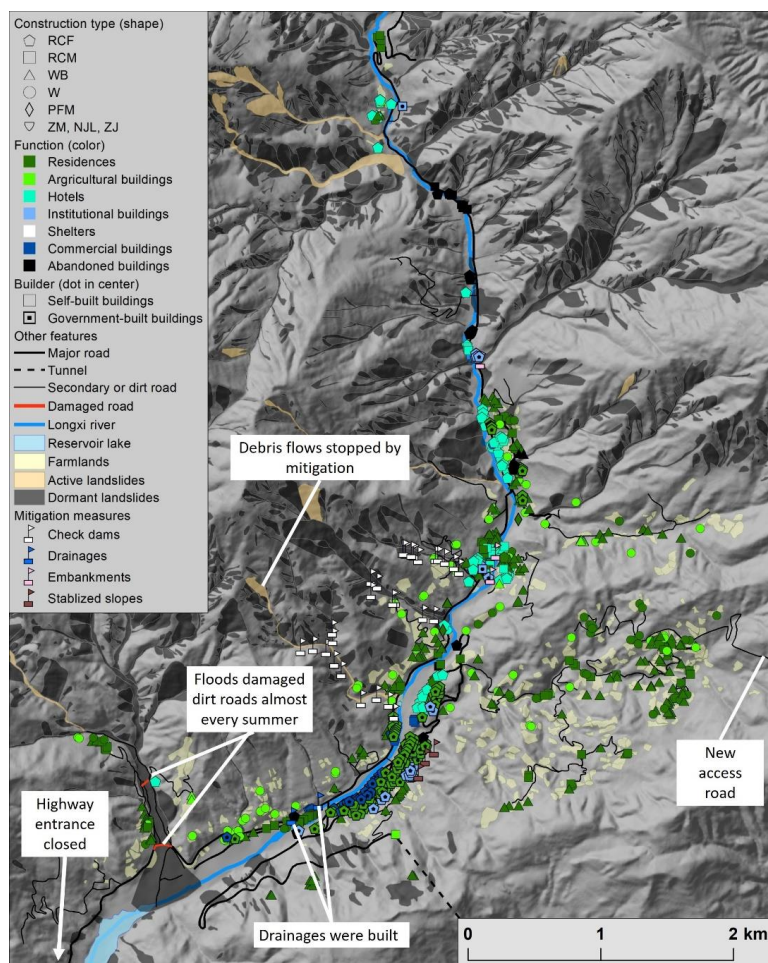


Figure 12: The inventory of 2018 and active landslides in 2018.

#### 4.1 Value estimation

The unit prices for different building types and roads were acquired through interviews with local  
425 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  
 430 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.

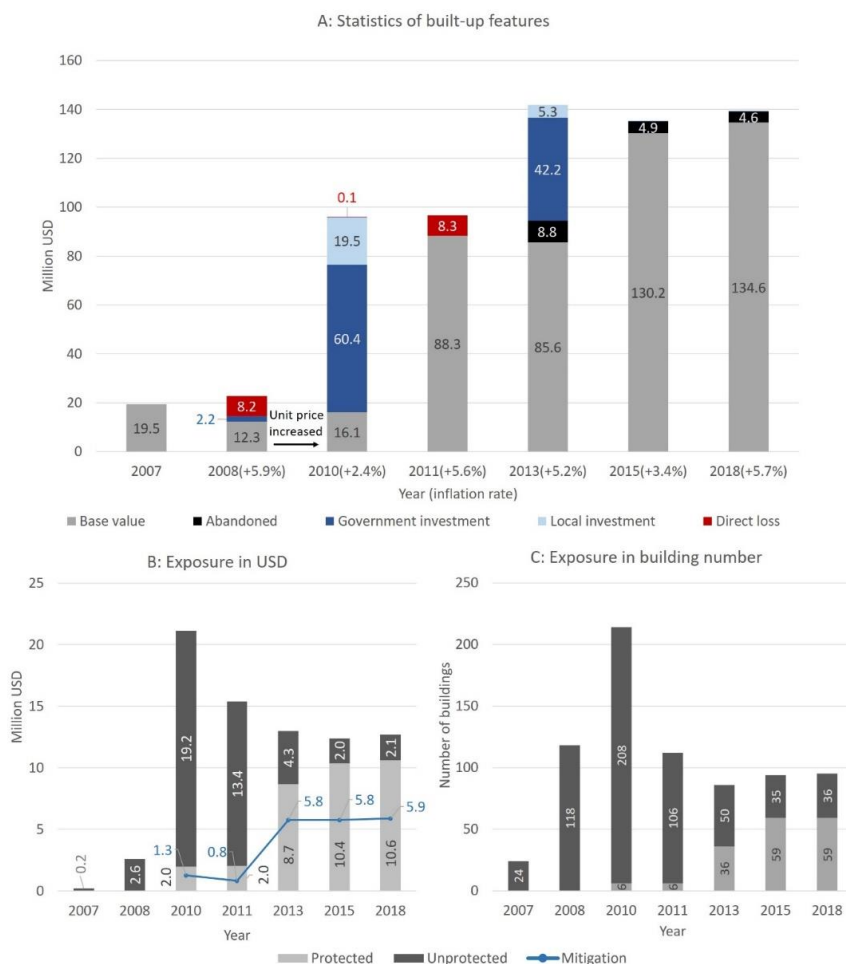
Type		Value	
Construction type	Code	Unit price before 2008 (USD / m <sup>2</sup> )	Unit price 2008 – 2012 (USD / m <sup>2</sup> )
RC frame structure	RCF	217	415
Reinforced masonry	RCM	144	200
Wood & brick	WB	54	77
Wooden	W	27	46
Pre-fabricated metal houses	PFM	-	154
Tents & shacks	TSs	-	6
Reinforced slopes		-	*205
Drainage channels		-	*103
Embankments		-	*362
<b>Road (USD / m)</b>			
Major road (6 m wide)		207	
Secondary road (3 m wide)		23	
Bridge (5 m wide)		828	
Tunnel (6 m wide road)		5069	
<b>Others</b>			
Mitigation works of the three sub-catchments (Figure 11)		4.6 million USD in total	

435 **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. As a  
 440 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.



445 **Figure 13: A: the total built-up values, 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 being impacted by debris flows and floods. The values were adjusted with the inflation rate. C: The total number of buildings that was at risk of being impacted by debris flows and floods.**



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  
450 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  
455 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. The risk was only analyzed by the value of potential exposed assets since we could not quantify the return period of the hazards, as this was  
460 changing from year to year due to the changing landslide activity. 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  
465 building located in the hazard extent was considered to have a potential exposure to the post-seismic hazards.

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  
470 years in this area based on our previous work of monitoring post-earthquake landslide activities (Tang et al., 2016). In 2008 the total value of the exposed elements-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 21.2 million USD as many buildings were reconstructed in the danger zone. A total of 1.3 million USD was invested in



475 mitigation works. There were 2 million USD worth of buildings protected by the reinforced slopes  
shown in Figure 7 A and Figure 8. The check dams 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  
480 disaster. The mitigation value reduced to 0.8 million USD because of the destroyed check dams 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 5.9 million USD. It is difficult to  
485 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 prior to the earthquake relied mostly on farming, tourism, and working outside of the  
490 town. 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  
20% of the interviewees stated it was one of the major income sources.

495 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.

500 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. Entrepreneurial local people built more hostels than there were 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  
505 executed at record speed after the disaster, and which was completed in May 2019. 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  
510 14, 2010 had a large impact on the local economy since the Longxi National Park had to be closed for indefinite period due to the increased landslide 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  
515 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 (Duijiangyan 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  
520 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. The economy of the Longchi watershed is not likely to be fully recovered before the reopening of the nation park.

## 5 Discussion & conclusions

We monitored the changes in the Longxi valley during a ten year period after the Wenchuan earthquake  
525 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  
530 landslides, debris flows and floods gave Longchi town a chance to increase its resistance to these  
hazards in future, and to improve economically.

Due to the direct involvement of the Government of 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  
535 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  
540 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 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 had one of the worst failures, because its biggest attraction was the national park which could  
545 not be reopened. The recovery would have been much more efficient if it included the awareness of  
dealing with post-seismic hazards. However, the question remains if these reactivations could have  
been predicted and mitigated properly.

The Longxi valley shows a typical example of the concept of dynamic risk, as both hazard and element  
at risk were constantly changing. Post-seismic landslides were controlled by the available amount of  
550 co-seismic loose materials and vegetation growth (Fan et al., 2018; Tang et al., 2019; Tang et al.,  
2016; Yang et al., 2018), which were different from time to time. Floods were closely related to  
landslide activities as they could dam rivers in the short term and caused raising of the riverbeds in the  
long term. The reconstruction made the total value of the built-up features nearly 4 times higher than it  
was in 2007, and many of them were reconstructed in the hazard prone zones. The risk was very high  
555 in 2010 as the reconstruction created many potentially exposes buildings and there had not been a  
major event to deplete the co-seismic landslide materials. The direct economic loss caused by the



debris flows alone was more than that caused by the earthquake. It is recommended to update hazard and risk map in an earthquake-hit region frequently, depending on the occurrence of hazards, human activities and environment recovery.

560 It is important to take multi-hazard effects into consideration in planning recovery. The Longxi watershed experienced an earthquake, slope failures, debris flows, and floods. The four disasters showed directly or indirectly interactions, which caused a high difficulty for hazard assessment. In such a mountainous region it is recommended not to re-build near the outlet of catchments containing many co-seismic landslides. Avoiding reconstruction too close to rivers is also recommended to avoid the  
565 floods caused by riverbed raising and landslide dams. However, in a mountainous region the flat lands are most likely created by historical landslides and river terraces, leaving very limited options to planners. One possible solution could be to delay reconstruction and wait for environment to recover to an acceptable point. Careful monitoring and analysis of post-earthquake hazards and risk is essential.

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#### **References**

Bolin, R., and Stanford, L.: The Northridge Earthquake: Community-based Approaches to Unmet  
575 Recovery Needs, *Disasters*, 22, 21-38, doi:10.1111/1467-7717.00073, 1998.

Burton, C. G.: A Validation of Metrics for Community Resilience to Natural Hazards and Disasters Using the Recovery from Hurricane Katrina as a Case Study, *Annals of the Association of American Geographers*, 105, 67-86, 10.1080/00045608.2014.960039, 2015.

Cui, P., Xiang, L.-z., and Zou, Q.: Risk assessment of highways affected by debris flows in Wenchuan  
580 earthquake area, *Journal of Mountain Science*, 10, 173-189, 10.1007/s11629-013-2575-y, 2013.





- Dai, F. C., Xu, C., Yao, X., Xu, L., Tu, X. B., and Gong, Q. M.: Spatial distribution of landslides triggered by the 2008 Ms 8.0 Wenchuan earthquake, China, *Journal of Asian Earth Sciences*, 40, 883-895, 10.1016/j.jseaes.2010.04.010, 2011.
- Dalen, K., Flatø H., Liu, J., and Zhang, H.: Recovering from the Wenchuan earthquake: Living  
585 Conditions and Development in Disaster Areas 2008–2011. , Fafo, Oslo, 2012.
- Dunford, M., and Li, L.: Earthquake reconstruction in Wenchuan: Assessing the state overall plan and addressing the ‘forgotten phase’, 998-1009 pp., 2011.
- Fan, X., Domènech, G., Scaringi, G., Huang, R., Xu, Q., Hales, T. C., Dai, L., Yang, Q., and Francis, O.: Spatio-temporal evolution of mass wasting after the 2008 Mw 7.9 Wenchuan earthquake revealed  
590 by a detailed multi-temporal inventory, *Landslides*, 15, 2325-2341, 10.1007/s10346-018-1054-5, 2018.
- Gorum, T., Fan, X., van Westen, C. J., Huang, R. Q., Xu, Q., Tang, C., and Wang, G.: Distribution pattern of earthquake-induced landslides triggered by the 12 May 2008 Wenchuan earthquake, *Geomorphology*, 133, 152-167, 10.1016/j.geomorph.2010.12.030, 2011.
- Hu, T., and Huang, R.-q.: A catastrophic debris flow in the Wenchuan Earthquake area, July 2013:  
595 characteristics, formation, and risk reduction, *Journal of Mountain Science*, 14, 15-30, 10.1007/s11629-016-3965-8, 2017.
- Hu, X., Salazar, M., Zhang, Q., Lu, Q., and Zhang, X.: Social Protection during Disasters: Evidence from the Wenchuan Earthquake, 107-115 pp., 2010.
- Huang, Y., Zhou, L., and Wei, K.: 5.12 Wenchuan earthquake recovery government policies and  
600 non-governmental organizations' participation, *Asia Pacific Journal of Social Work and Development*, 21, 77-91, 2011.
- Khan, S. F., Kamp, U., and Owen, L. A.: Documenting five years of landsliding after the 2005 Kashmir earthquake, using repeat photography, *Geomorphology*, 197, 45-55, <https://doi.org/10.1016/j.geomorph.2013.04.033>, 2013.



- 605 Kun, P., Han, S., Chen, X., and Yao, L.: Prevalence of post-traumatic stress disorder in Sichuan province China after the 2008 Wenchuan earthquake, 1134-1140 pp., 2009.
- Li, L., Yao, X., Zhang, Y., Iqbal, J., Chen, J., and Zhou, N.: Surface recovery of landslides triggered by 2008 Ms8.0 Wenchuan earthquake (China): a case study in a typical mountainous watershed, *Landslides*, 13, 787-794, 10.1007/s10346-015-0594-1, 2016.
- 610 Li, Y., Huang, R., Yan, L., L. Densmore, A., and Zhou, R.: Surface Rupture and Hazard of Wenchuan Ms 8.0 Earthquake, Sichuan, China, 21-31 pp., 2010.
- Lo, A. Y., and Cheung, L. T. O.: Seismic risk perception in the aftermath of Wenchuan earthquakes in southwestern China, *Natural Hazards*, 78, 1979-1996, 10.1007/s11069-015-1815-6, 2015.
- Mondini, A. C., Guzzetti, F., Reichenbach, P., Rossi, M., Cardinali, M., and Ardizzone, F.:  
615 Semi-automatic recognition and mapping of rainfall induced shallow landslides using optical satellite images, *Remote Sensing of Environment*, 115, 1743-1757, <https://doi.org/10.1016/j.rse.2011.03.006>, 2011.
- Platt, S., Brown, D., and Hughes, M.: Measuring resilience and recovery, *International Journal of Disaster Risk Reduction*, 19, 447-460, 10.1016/j.ijdr.2016.05.006, 2016.
- 620 Saba, S. B., van der Meijde, M., and van der Werff, H.: Spatiotemporal landslide detection for the 2005 Kashmir earthquake region, *Geomorphology*, 124, 17-25, <https://doi.org/10.1016/j.geomorph.2010.07.026>, 2010.
- Sakamoto, M., and Yamori, K.: A Study of Life Recovery and Social Capital regarding Disaster Victims &minus;A Case Study of Indian Ocean Tsunami and Central Java Earthquake  
625 Recovery&minus;, *Journal of Natural Disaster Science*, 31, 49-56, 10.2328/jnds.31.49, 2009.
- Stumpf, A., and Kerle, N.: Object-oriented mapping of landslides using Random Forests, *Remote Sensing of Environment*, 115, 2564-2577, <https://doi.org/10.1016/j.rse.2011.05.013>, 2011.



- Sun, M., Chen, B., Ren, J., and Chang, T.: Natural Disaster's Impact Evaluation of Rural Households' Vulnerability: The case of Wenchuan earthquake, *Agriculture and Agricultural Science Procedia*, 1, 630 52-61, <https://doi.org/10.1016/j.aaspro.2010.09.007>, 2010a.
- Sun, M., Chen, B., and Shi, G.: Comparative analysis of influence factors for household income before and after the natural disaster: a study of Wenchuan, *Technology Economics*, 2010, 2010b.
- Tang, C., van Asch, T. W. J., Chang, M., Chen, G. Q., Zhao, X. H., and Huang, X. C.: Catastrophic debris flows on 13 August 2010 in the Qingping area, southwestern China: The combined effects of a 635 strong earthquake and subsequent rainstorms, *Geomorphology*, 139-140, 559-576, <https://doi.org/10.1016/j.geomorph.2011.12.021>, 2012.
- Tang, C., Van Westen, C. J., Tanyas, H., and Jetten, V. G.: Analysing post-earthquake landslide activity using multi-temporal landslide inventories near the epicentral area of the 2008 Wenchuan earthquake, *Nat. Hazards Earth Syst. Sci.*, 16, 2641-2655, 10.5194/nhess-16-2641-2016, 2016.
- 640 Tang, C., Tanyas, H., van Westen, C. J., Tang, C., Fan, X., and Jetten, V. G.: Analysing post-earthquake mass movement volume dynamics with multi-source DEMs, *Engineering Geology*, 248, 89-101, <https://doi.org/10.1016/j.enggeo.2018.11.010>, 2019.
- Tanyas, H., Westen, C. J., Persello, C., and Alvioli, M.: Rapid prediction of the magnitude scale of landslide events triggered by an earthquake, 2019.
- 645 United Nations Office for Disaster Risk Reduction (UNISDR): Wenchuan earthquake 2008: recovery and reconstruction in Sichuan province, 2010.
- Wang, F., Cheng, Q., Highland, L., Miyajima, M., Wang, H., and Yan, C.: Preliminary investigation of some large landslides triggered by the 2008 Wenchuan earthquake, Sichuan Province, China, *Landslides*, 6, 47-54, 10.1007/s10346-009-0141-z, 2009a.
- 650 Wang, X., Ding, X., Wang, L., and Wang, Y.: Fast assessment of earthquake loss and its application to the 2008 MS8.0 Wenchuan earthquake, *Earthquake Science*, 22, 129-133, 10.1007/s11589-009-0129-8, 2009b.



- Wang, Y., Chen, H., and Li, J.: Factors affecting earthquake recovery: the Yao'an earthquake of China, *Natural Hazards*, 64, 37-53, 10.1007/s11069-012-0224-3, 2012.
- 655 Wang, Y., Zou, Z., and Li, J.: Influencing factors of households disadvantaged in post-earthquake life recovery: a case study of the Wenchuan earthquake in China, *Natural Hazards*, 75, 1853-1869, 10.1007/s11069-014-1400-4, 2015.
- Wu, J., Li, N., Hallegatte, S., Shi, P., Hu, A., and Liu, X.: Regional indirect economic impact evaluation of the 2008 Wenchuan Earthquake, *Environmental Earth Sciences*, 65, 161-172, 660 10.1007/s12665-011-1078-9, 2012.
- Wu, J. Y., and Lindell, M. K.: Housing Reconstruction After Two Major Earthquakes: The 1994 Northridge Earthquake in the United States and the 1999 Chi-Chi Earthquake in Taiwan, *Disasters*, 28, 63-81, doi:10.1111/j.0361-3666.2004.00243.x, 2004.
- Xu, C., Xu, X., Yao, X., and Dai, F.: Three (nearly) complete inventories of landslides triggered by the 665 May 12, 2008 Wenchuan Mw 7.9 earthquake of China and their spatial distribution statistical analysis, *Landslides*, 11, 441-461, 10.1007/s10346-013-0404-6, 2013.
- Xu, Q., Zhang, S., Li, W. L., and van Asch, T. W. J.: The 13 August 2010 catastrophic debris flows after the 2008 Wenchuan earthquake, China, *Natural Hazards and Earth System Science*, 12, 201-216, 10.5194/nhess-12-201-2012, 2012.
- 670 Yang, S., Du, J., He, S., Shi, M., and Sun, X.: The emerging vulnerable population of the urbanisation resulting from post-disaster recovery of the Wenchuan earthquake, *Natural Hazards*, 75, 2103-2118, 10.1007/s11069-014-1413-z, 2015a.
- Yang, W., Qi, W., Wang, M., Zhang, J., and Zhang, Y.: Spatial and temporal analyses of post-seismic landslide changes near the epicentre of the Wenchuan earthquake, *Geomorphology*, 276, 8-15, 675 <https://doi.org/10.1016/j.geomorph.2016.10.010>, 2017.
- Yang, W., Qi, W., and Zhou, J.: Decreased post-seismic landslides linked to vegetation recovery after the 2008 Wenchuan earthquake, *Ecological Indicators*, 89, 438-444, <https://doi.org/10.1016/j.ecolind.2017.12.006>, 2018.



680 Yang, W. T., Wang, M., Kerle, N., Van Westen, C. J., Liu, L. Y., and Shi, P. J.: Analysis of changes in  
post-seismic landslide distribution and its effect on building reconstruction, *Natural Hazards and Earth  
System Sciences*, 15, 817-825, 10.5194/nhess-15-817-2015, 2015b.

Yu, B., Ma, Y., Zhang, J., Wu, Y., Zhang, H., Li, L., and Chu, S.: Debris flow hazard in Longchi after  
the Wenchuan earthquake (in Chinese), *Journal of Mountain Science*, 6, 738 - 746, 2011.

685 Zhang, H.: Household vulnerability and economic status during disaster recovery and its determinants:  
a case study after the Wenchuan earthquake, *Natural Hazards*, 83, 1505-1526,  
10.1007/s11069-016-2373-2, 2016.

Zhang, S., Zhang, L., Lacasse, S., and Nadim, F.: Evolution of Mass Movements near Epicentre of  
Wenchuan Earthquake, the First Eight Years, *Sci Rep*, 6, 36154, 10.1038/srep36154, 2016.

690 Zhang, W., Jiang, L., Li, X., and Yang, T.: Exploration of mortality and economy vulnerability of  
wenchuan earthquake, 197-204 pp., 2013.

Zuo, K., Ping, X., Huan, Z., and Lu, X.: Post-Wenchuan Earthquake Reconstruction and Development  
in China, in, 2013.