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ORIGINAL RESEARCH PAPER

The use of remotely sensed data and ground survey tools to assess damage and monitor early recovery following the 12.5.2008 Wenchuan earthquake in China

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Abstract The M7.9 Wenchuan earthquake on May 12th, 2008 was the most destructive in China since 1976. The event caused huge damage and loss of life and exposed weaknesses both in the formulation and implementation of the regulations governing building in the affected provinces. Following the earthquake a massive relief and recovery operation was mounted by the Chinese government. The authors took part in field studies in the affected area which took place 5 and 11 months after the event, at which time recovery operations were well-advanced. The aims of the study were to assess the effects caused by the earthquake to the built environment and society, to collect information on the ongoing recovery efforts and future plans, and to demonstrate the use of tools that allow the collection of spatially referenced damage and recovery data. Based on available satellite imagery supplemented by ground observation, geodatabases were constructed containing information on damage and recovery in several parts of the affected area. The paper gives an overview of the recovery process, describes the methods used to construct these geodatabases, and offers some analysis of the data obtained. It is argued that such databases have great potential for the management of post-disaster recovery and for creating a permanent record of the recovery process.

Keywords Wenchuan · Earthquake · Damage · Recovery

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1 Overview of the May 12th, 2008 Wenchuan earthquake

The M7.9 Wenchuan earthquake in Sichuan Province in China was the most destructive and deadly earthquake to strike China for more than 30 years. The earthquake originated on the Longmenshan fault system which lies close to the north-western margin of the Sichuan basin, with a fault rupture length of about 240 km. At places a surface displacement on this fault of as much as 12 m was reported, more commonly 1–3 m (EEFIT 2008). Destructive levels of strong ground shaking were recorded over an extended area including many sizeable towns and villages; the CEA Intensity Map (CEA 2008) indicated an area of about 12,000 km^2 subjected to Intensity IX ("Severe Destruction") or above, with an estimated population exposure at that level of nearly 1.3 million people, and 120,000 km^2 subject to Intensity VII ("damaging") or above, with a total population of 18 million. A large number of ground shaking records were obtained, the largest of which had a peak horizontal ground acceleration of 0.96 g (EEFIT 2008).

Damage to building structures in the area of Intensity VII and above was enormous, and many collapsed due to ground shaking. A total of 216,000 buildings in Sichuan province were reported to have been destroyed, including 6,900 schools. Damage to infrastructure—roads, railways, power lines and water storage—was also very severe. Damage was further compounded by a very large number of landslides, the result of the unstable mountainous terrain. These landslides not only blocked and destroyed roads, severely hampering relief efforts, but also buried whole communities. According to official sources, as of 10th July 2008, there were 69,197 casualties, 374,176 injured and 18,377 reported missing (UN China 2008). About 1.8 million people lost their homes and needed at least temporary relocation. A particularly distressing aspect of the casualty toll was that so many of the victims were schoolchildren killed when their schools collapsed, the earthquake having occurred at 12:28 local time.

China has a long history of earthquakes: a neighboring region was affected by M7.3 event in 1933. Earthquake regulations for buildings have been in force since 1974, and these were upgraded in 1979, 1989, and again in 2001 (Paz 1994). At the time of the earthquake, the regulations in force in the affected area were designed to provide protection for an earthquake of intensity VII; however, the ground motions actually experienced exceeded the design level over a very wide area, and this certainly contributed very significantly to the extent of damage and loss of life, including the collapse of school buildings. Nevertheless, it was observed by reconnaissance teams that a form of construction (masonry walls supporting precast concrete floor slabs) which lacks basic features required for earthquake resistance is quite commonly used for low-rise buildings in the area.

The emergency response to the earthquake was immediate, massive, and very effective, but that is not discussed here. The next section summarizes the recovery process based on official documents, acquired in Chinese, from the State Council and relevant Government Ministries.

2 The recovery process

A few weeks after the earthquake, on June 8th, the State Council adopted and released its *Regulations on Post-Wenchuan-Earthquake Restoration and Reconstruction* (State Council 2008a) which divides the restoration and reconstruction into four periods: (1) the period of transitional resettlement, (2) the period of investigation and assessment, (3) the period of reconstruction planning and (4) the period of implementation of restoration and reconstruction. The main activities of each of these periods are described below.

2.1 The period of transitional resettlement

As early as May 18 the State Council identified a need to build a million temporary dwellings in the worst-hit area in Sichuan to provide for more than 3 million victims. The Ministry of Housing issued instructions to 23 provinces and cities to support the disaster-hit areas by building transitional temporary dwellings. Ten provinces were each required to build 60,000 sets of houses; while a further 10 provinces were each to build 40,000 sets of houses. All of these were expected to be in place by September 2008. To support this massive programme, the central and local government very rapidly issued technological guidelines and policy documents to support the construction of portable dwellings, makeshift shelters and tents (Ministry of Housing 2008).

2.2 The period of investigation and assessment

As defined by the *Regulations* (State Council 2008a) the damage investigation and assessment was to include determining the number of casualty and wounded in the earthquake, the number and the degree of houses damaged, the houses and facilities in need of reconstruction, the damage to natural environment and the cultural heritage, the geological aspects of the disaster and secondary geological effects. It was also expected that the engineering quality and the earthquake-resistance capability of the infrastructure and public service facilities worst-hit in the disaster should be identified. The Regulations prescribe the methods of investigation and assessment and require the earthquake-related departments and the earthquake monitoring stations to compile a database of all data collected pre and post-disaster. The evaluation of individual buildings was to include: the name of the building and its owner; the degree of damage, and a preliminary evaluation of its structural safety; problems identified, usability, and suggested rehabilitation work. The investigation and assessment of the losses caused by the earthquake were to be finished by September 2008.

2.3 The period of restoration and reconstruction planning

In September 2008 the State Council issued a planning document titled *State Overall Planning for the Post-Wenchuan Earthquake Restoration and Reconstruction* (State Council 2008b). The document's 15 chapters included sections on the reconstruction of foundations, the overall requirements, the space layout, urban and rural dwellings, town construction, village construction, public services, infrastructure construction, industrial reconstruction, reducing disaster risks, ecological environment, reconstruction financing and planning implementation. It established a plan to spend 1 trillion yuan (approximately US$150 million) to finish the main restoration and reconstruction in Sichuan, Gansu and Shaanxi within 3 years. The reconstruction was planned to improve the basic living conditions and economic development in the affected area up to or above their levels before the disaster. The reconstruction plan aimed to build "new homes, characterized by safety and harmony, where people can live in peace and work happily". The overall plan included 51 worst-hit counties in Sichuan, Gansu and Shaanxi provinces with the total area of 132,596 km^2, and including 1,271 towns and 14,565 villages, which had between them a population of 19.9 million at the end of 2007.

Multiple methods of resettlement were offered to households so that they could choose the option most suitable to their situation, including centralised, decentralised, ex situ or in situ resettlement. People affected by the disaster were mainly to be resettled on the spot in the planning area. A rural revitalisation program promoted the centralisation of scattered households to improve accessibility and to reduce construction costs (IFRC 2008). The living habits of minority groups were to be respected and they were to be resettled "in the compact communities of nationalities".

The Central Government undertook to set up a central reconstruction fund amounting to 30% of the total required investment demand in the reconstruction. Other channels, such as investment of local government, full support from other provinces, local loans, capital investment, overseas preferential loans, urban residential self-finance, cooperation self-finance and other creative investments, would provide the remainder.

2.4 The period of implementation of restoration and reconstruction

The government has issued periodic reports of the progress of reconstruction. At a press conference on May 7, 2009, the first anniversary, the secretary and spokesman of the Sichuan Provincial Government, Yu Wei, presented impressive figures suggesting that of 1.26 million rural houses needing repair, 80% had been completed, and of 314,000 urban houses needing repair 11% had been completed (Sichuan Provincial Government 2009). And on March 5th, 2010, Premier Wen Jiabao reported that by January 2010, 21,900 projects had been completed over the whole affected area, comprising 74% of the reconstruction projects, and 61% of the targeted investment of 1 trillion yuan (Wen 2010). This represents a colossal reconstruction achievement in a very short period of time, study of which is of great importance to all those involved in post-disaster recovery.

3 Motivation and scope of the study

The opportunity for the Wenchuan earthquake study described in this paper arose following a joint field trip with the Faculty of Urban Construction and Environmental Engineering at Chongqing University in the affected area. Given the infrequency of on-land earthquakes of this magnitude, it is essential for the experience of China to be recorded as much as possible for future generations. Although many national and international earthquake specialists visited the affected area in the months after the earthquake and have recorded their impressions of the event and its aftermath, systematic studies of the damage and relief have been relatively few. Moreover this event provided an opportunity to demonstrate the use of geospatial tools for the recording of post-earthquake damage and recovery using remote sensing (Brown et al. 2008; Brown et al. forthcoming).

In the past decade, the availability of various types of high-resolution remotely sensed data has motivated numerous studies of its application to all phases of the disaster cycle, particularly for earthquakes. An area that is growing rapidly is the use of these datasets for post-event damage assessment, particularly building damage assessment, although studies on methodologies to assess damage to other items such as roads and infrastructure are also being carried out using remotely sensed data.

For building damage assessment, optical and SAR data have been tested in the past, using both visual and semi-automated methods. The unit of analysis has been dependent on the spatial resolution (ground sampling distance) of the dataset used which has varied from the most detailed building-by-building level to a more aggregated neighborhood level. In general, with high-resolution optical images building-by-building assessments are made (e.g. Saito et al. 2004; Adams et al. 2004) whereas with SAR data neighborhood level assessments are carried out (e.g. Matsuoka and Nojima 2010; Dell'Acqua et al. 2011) due to the inherent data resolution. A detailed overview of the various methodologies for immediate post-earthquake building damage assessment that covers a wide range of datasets and case studies can be found in Saito (2009), Dell'Acqua et al. (2011) and Adams and Eguchi (2008). Regardless of the methodology and dataset used, one of the obstacles that have been preventing the remote damage assessments from being used as the primary source of building damage data is the lack of validation of the assessment results. The few studies in the literature that have carried out some form of validation suggest that these remote methodologies tend to underestimate the real damage level, making it essential for validation studies to be conducted at ground level. Following the Haiti earthquake in January 2010, a large scale crowd-sourced damage assessment was carried out in Port au Prince and adjacent populated areas and for the first time validation of the results was carried out extensively. The validation studies again suggested that even for the completely collapsed buildings, the success rate of identifying them was far lower than expected: around 50% (Booth et al. 2011).This goes to show the importance of validation for the remote damage assessment studies. For the Wenchuan earthquake, although some ground survey data obtained through other research groups were available, this was not detailed and comprehensive enough for a satisfactory comparison with remote-sensing based damage assessment.

There is a good reason to concentrate on remote building damage assessment methodologies, one of which is the fact that damage to buildings is the main cause of human fatalities. It also makes up a major part of the direct economic loss arising from earthquakes (Coburn and Spence 2002). However, after a major earthquake there are other types of damage that need to be looked at. For instance, road blocks would impede the rescue and relief process, damage to key infrastructure will affect the early recovery process. Availability of temporary shelters are key to the society's gradual and successful return to normal life. There is scope for remotely sensed data to be used to identify or assess the conditions of these various aspects other than damage to buildings. One of the objectives of this study is to demonstrate the use of remotely sensed data from damage assessment through to early recovery. An example on the detection of roadblocks is seen in Samadzadegan and Zarrinpanjeh (2008) where object oriented classification of high-resolution optical satellite images, combined with texture analysis and fuzzy segmentation was employed. Insurance companies use high-resolution optical remotely sensed data to carry out spot checks on the key infrastructures that are insured, such as port facilities.

As mentioned, remotely sensed data can also be used for the planning, monitoring and evaluation of long term recovery. Not many studies have been carried out in this area. The authors are members of a working group called ReBuilDD that looks at the recovery process from planning through to monitoring and evaluation using indicators for the various recovery sectors (Brown et al. forthcoming). One of the aims of ReBuilDD is to monitor and evaluate the indicators using the various geospatial datasets taken both from above and on the ground.

The aims of this paper are:

- To demonstrate the use of tools that allow the collection of spatially referenced damage/recovery data in support of planning and monitoring of relief and recovery
- To show that satellite imagery can be used to make valuable estimates of damage in locations not easily accessible on the ground, to buildings, roads and the natural environment
- To show that satellite imagery can be used to observe, monitor and measure aspects of the recovery process
- To compare observations made using satellite imagery with the ground observations.

The paper will concentrate on damage studies conducted on the ground in two different locations, Yingxiu and Wenchuan, and their correlation with satellite imagery available.

Observations of recovery made in Yingxiu and a number of other parts of the worst-affected area are also recorded.

4 Study methods

4.1 Acquisition and pre-processing of satellite images

Prior to the field mission, pre-event and post-event high-resolution optical satellite images of the areas to be visited were obtained, where available, and were used to familiarize the team with the area. The remotely sensed datasets used for this study were mainly optical high-resolution satellite images. Although it would have been ideal to have access to other types of data, unfortunately they were not available to the authors at the time of writing. Post-earthquake optical Ikonos images of Wenchuan were obtained without charge whereas the Quickbird pre- and post-earthquake images of Yingxiu were jointly purchased with other research institutes involved in damage assessment activities using remotely sensed data. The quality of the available images was used as one of the criteria when choosing the sites to visit. The images were also used to identify 'regions of interest' and to select sample areas for the ground survey work. After assessing the quality of the images, Ikonos images with a spatial resolution of 1 m were used for the damage assessment of Wenchuan, and Quickbird images with a spatial resolution of 0.6 m were used for Yingxiu. The images were pansharpened and geographically registered to each other using a third order polynomial transformation in GIS.

Manual information extraction methods were used to extract information for this study using the optical satellite images, except for the Normalised Differential Vegetation Index (NDVI) which is a well established method of classifying vegetation against other land cover types. This was due to the fact that the authors were more confident in the manual interpretation results. It can also be attributed to the fact that for most of the objects that the authors intended to extract, reliable, well established semi-automated extraction methods were lacking. Moreover, the objective of our work was not to develop a new data extraction method, but rather to carry out a feasibility study of the types of objects and processes that we can be confident in identifying in a high-resolution satellite image, whose identification has the potential to be useful to the decision makers.

4.2 Field work

Two field visits took place, the first between 16–21 October 2008, and the second on 24–27 March 2009 to observe the progress made in terms of the overall relief, reconstruction and recovery. The locations visited are shown in Fig. 1. In terms of the timing of the field visits, the first visit was planned to coincide with the reopening of route 213 from Dujiangyan to Yingxiu and Wenchaun, where a lot of the heavy damage was concentrated and had been inaccessible to earlier reconnaissance teams. The team first travelled north on route 213 across the Longmenshang fault to Yingxiu and Wenchuan, before travelling along the fault to Shifang and Beichuan (Fig. 1). Damage to the buildings and the recovery efforts were observed in these areas. The tools used in the field include geocoded high-definition video footage, geocoded still photographs as well as high-resolution optical satellite images. Some details of the types of data obtained as well as the observations made in each location and their analysis will be described in the following sections.

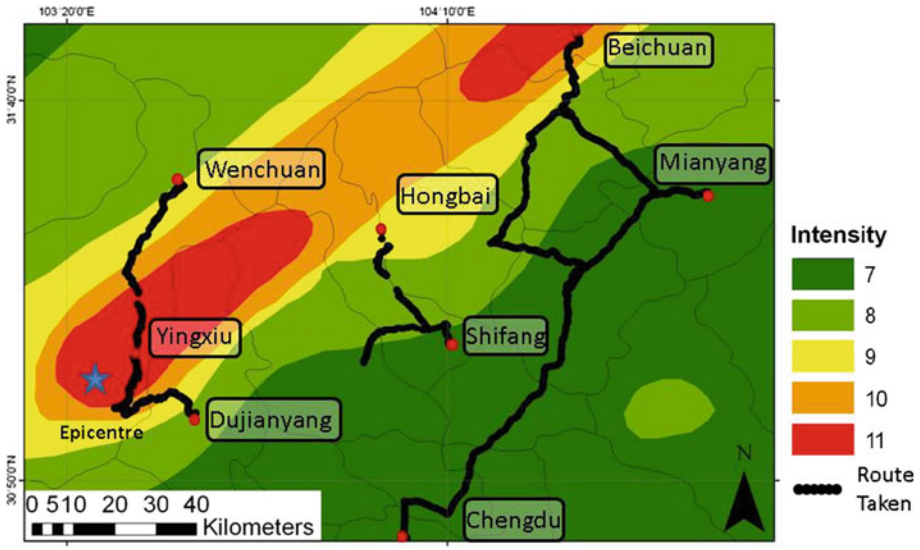

Fig. 1 The locations visited and routes taken during the field survey. The CEA intensity zones are overlaid on the route map. Intensity map taken from Chengdu Map Publishing (2009)

5 Damage and recovery study in Yingxiu

5.1 Overview

Yingxiu is a small town in Wenchuan county, on route 213, with a pre-earthquake population of around 10,000. It was located close to the fault, within 20 km of the epicentre, and damage was extreme. The CEA intensity map indicates that the intensity was XI on the Chinese intensity scale (CEA 2008). Destruction was almost total with few buildings left standing. Figure 2 shows the centre of Yingxiu before and after the Wenchuan earthquake. The town had a high collapse rate and was completely evacuated after the earthquake. At the time of the team's visit, the main part of the town was cordoned off and not accessible to the team, though photographs of the damage could be made from locations outside the town. A detailed assessment of damage is given by Sun and Yan (2008), which shows that 80% of the reinforce concrete buildings, and 90% of the masonry buildings either collapsed or suffered complete damage.

Using the pre- and post-earthquake Quickbird images for YingXiu, information on the extent of the damage and the subsequent relief and recovery work in Yingxiu was extracted. The pre-earthquake image was acquired on 26 June 2005 (3 years before the earthquake) and the post-earthquake image was acquired on 3 June 2008 (22 days after the earthquake). A 5.5 km^2 subset was extracted from the image to include the town of Yingxiu and the surrounding countryside so that both the built and natural environment could be analyzed. A detailed building damage assessment of Yingxiu was conducted using Quickbird imagery by identifying collapsed and non-collapsed structures. The impact on the transport network and the natural environment was assessed and signs of recovery, such as road clearance and the presence of transitional shelters, were also delineated and analyzed. This section discusses assessments of building damage, accessibility, environmental impact, and the condition of internally displaced populations, using these images. The results from each assessment were added as separate data layers in a spatial database of Yingxiu. Spatial analysis was then

Fig. 2 Two Quickbird satellite images (with a spatial resolution of 60 cm) showing the town of Yingxiu before and after the Wenchuan earthquake

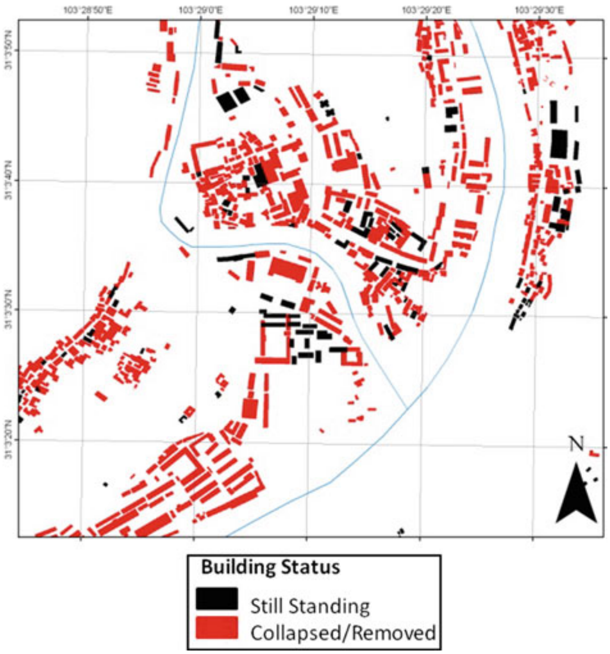

Fig. 3 Damage and recovery Geodatabase (Layer 1). The building damage assessment shows collapsed and non-collapsed buildings in Yingxiu, assessed using the Quickbird image

conducted in a GIS. Image processing was conducted with ENVI. The four layers of the damage and recovery database are shown in Figs. 3, 4, 5, and 6.

5.2 Building damage assessment

The extent of the damage in Yingxiu was so severe that most of the buildings were reduced to rubble, and many of the building footprints were not identifiable in the post-earthquake satellite image (Fig. 2). The building footprints were therefore delineated using the pre-earthquake

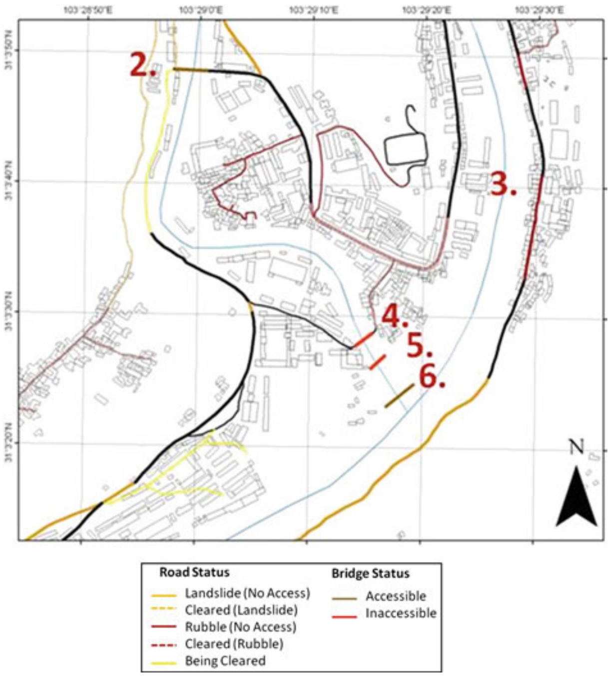

Fig. 4 Damage and recovery Geodatabase (Layer 2). The accessibility assessment shows the status of roads and bridges in Yingxiu. *Numbers* refer to bridge ID numbers in text

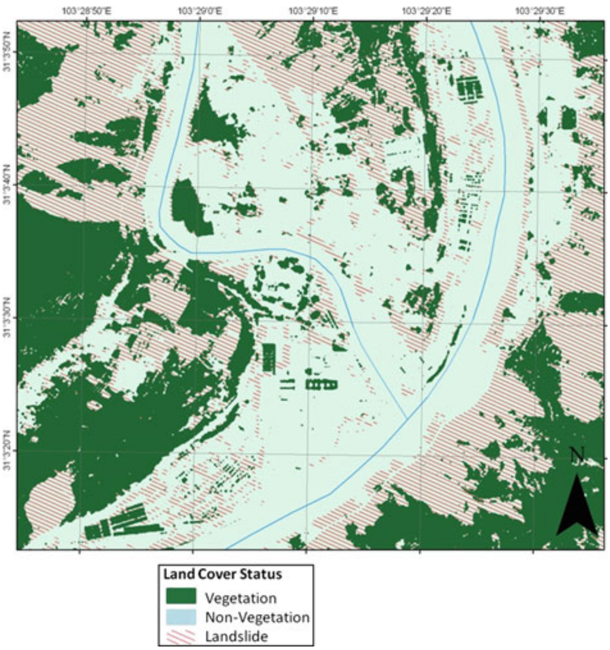

Fig. 5 Damage and recovery Geodatabase (Layer 3). The natural environment assessment shows vegetative and non-vegetative land covers and areas of likely landslides

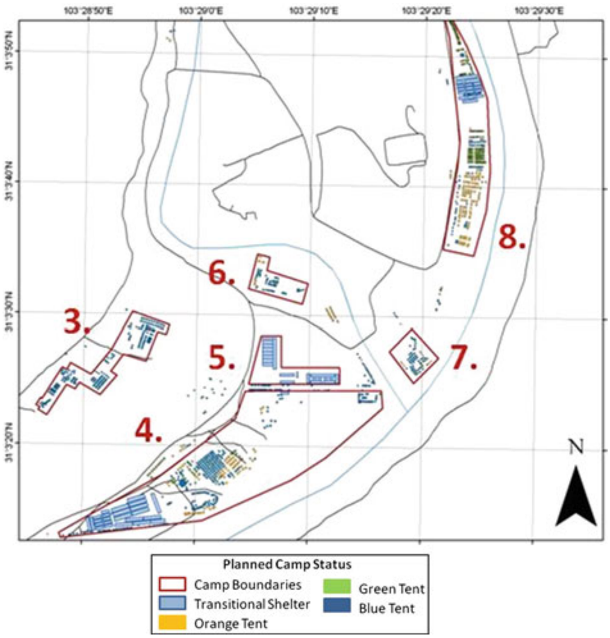

Fig. 6 Damage and recovery Geodatabase (Layer 4). The internally displaced persons (IDP) assessment shows the distribution of tents and transitional shelters around Yingxiu. *Numbers* refer to camps or clusters of tents or transitional shelters

image. Polygons were drawn manually around the base of the buildings by placing a node at each corner of the building.The post-disaster imagery was then registered to this dataset and the status of each building was manually classified as present or absent. The *absent* category included those buildings that had been demolished, collapsed or partially collapsed. Change detection analysis on this dataset was carried out in the following way: information on whether a building was present or absent in each image was assigned to each footprint manually. In each image, the status for each building (e.g. new build, existing or removed) was assigned, thus creating a building database. Using this database buildings that were "still standing", "new builds" (e.g. constructed between the acquisitions of the two satellite images) or "collapsed/removed" were identified. The results of the building damage assessment are summarized in Table 1.

The analysis delineated 1,073 buildings in 2005 before the disaster. After the earthquake, approximately 86% of these buildings (925 buildings) had collapsed or been removed. Of these, approximately 165 are believed to have been removed before the earthquake or immediately after the earthquake to make way for transitional shelters. In which case, the estimated number of collapses is around 760 (70%). This compares well to the percentage of collapsed buildings in Yingxiu (70%) published by Chengdu Map Publishing (2009). The analysis additionally observed that there were 21 new buildings constructed after the acquisition of the pre-disaster image (June 2005), 13 of which were part of the Yingxiu Xuankou Middle School, which—despite being built only 3 years before the earthquake—suffered serious structural damage and collapse. The other new builds were predominantly large multi-storey reinforced concrete apartments that were still standing after the earthquake but with serious structural damage. A map of the collapsed and non-collapsed buildings is shown in Fig. 3.

Table 1 Yingxiu building damage results obtained using Quickbird satellite imagery

Stage	Number of buildings	Area (m^2)
Pre-earthquake (June 2005)	1,073	239,459
Collapsed or otherwise removed between June 2005 and June 2008	925	203,723
Post-earthquake (June 2008)	169	42,795
New construction between June 2005 and June 2008	21	7, 058

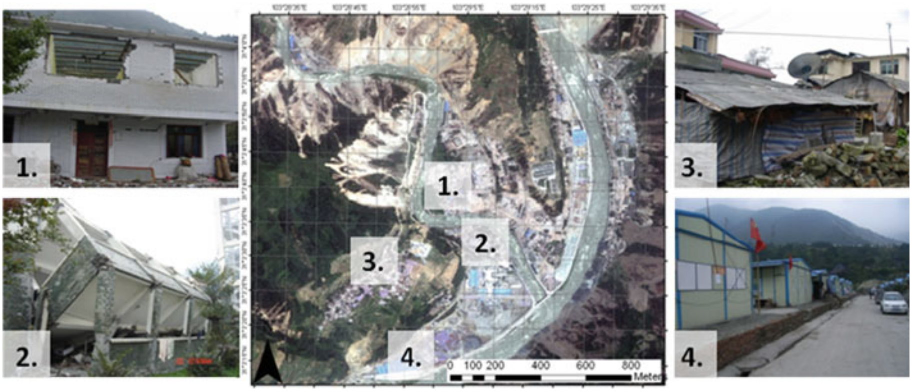

Fig. 7 Photographs taken by the team on 19 October 2008 showing damage and early recovery in Yingxiu. *Photograph 1* shows a residential building in Yingxiu with a roof collapse and broken windows. The *photograph 2* shows structural damage to Yingxiu Xuankou Middle School. *Photograph 3* shows a transitional shelter built by homeowners on the site of their original dwelling and *photograph 4* shows the transitional shelters used in Yingxiu

Field data collected by the team on 19 October 2008 shows examples of the damage and early recovery in Yingxiu (Fig. 7).

5.3 Accessibility assessment

5.3.1 Roads

Accessibility is a critical category that can determine the success of many other different aspects of relief and recovery. During the relief phase, key transport routes must be cleared and restored to allow relief vehicles and personnel access to severely affected areas. Throughout recovery, consistent access routes are also required to ensure the reliable import and export of food and other resources. Inaccessibility to an area may in turn affect people's health, the overall speed of reconstruction and the maintenance of reliable market prices. A geospatial

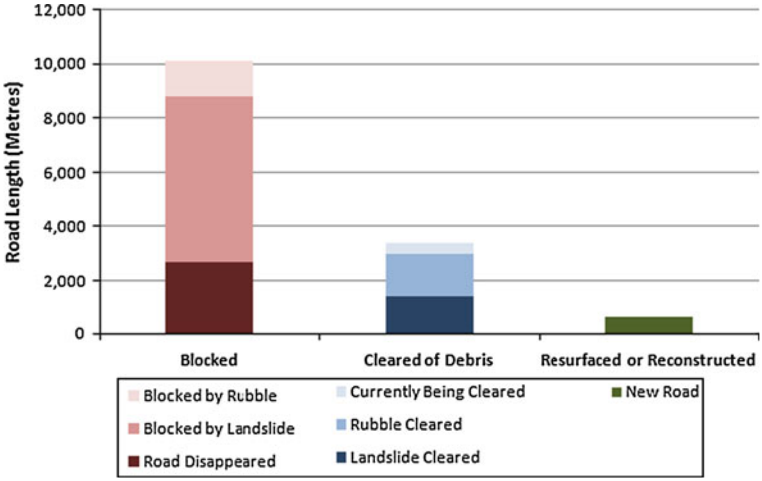

Fig. 8 The state of roads in the town of Yingxiu, approximately 20 km away from the epicenter, captured using Quickbird imagery acquired in June 2008, 1 month after the earthquake

representation of the transport network was created and used to produce statistics on the state of the main infrastructure and access routes (Fig. 8). Maps showing accessible and inaccessible areas are important for rescue teams and service providers in the aftermath of a disaster. Such data might also be used to quantify the impact to the transport network and to inform donor pledges as part of a Post-Disaster Needs Assessment. The roads were manually classified and delineated according to the road type as main roads (more than 2 lanes), minor roads (single lanes) and dirt tracks. The post-disaster segments were then further divided into 4 categories according to their accessibility: (1) Unaffected (no change), (2) Blocked (presence of debris, landslide), (3) Cleared (presence of diggers on the road, or surfaces with a thin layer of sediments) and (4) Re-surfaced or Reconstructed (presence of new roads that did not exist before, or upgraded dirt roads with a new surface). This taxonomy was devised so that the length and location of *affected* roads and inaccessible regions could be identified. A map showing the status of the transport infrastructure is presented in Fig. 4 and a summary of the results are presented in Fig. 8.

5.3.2 Bridges

It is important to rapidly identify bridge loss after an earthquake in order to highlight inaccessible areas. As part of the accessibility assessment, the location and status of bridges was also updated. It was assumed that if a bridge had disappeared between the acquisitions of the two images it had collapsed. There were 7 bridges: 2 footbridges and 5 road bridges. Three bridges collapsed, two were potentially affected by nearby landslips and another two received no visible damage. In total, 253 m of bridges in the scene collapsed as a result of the earthquake. Figure 4 shows a map of the bridges in Yingxiu coded according to whether they appear accessible or inaccessible. The loss of bridge #1, to the north of Yingxiu, resulted in no road access to the east bank of the Minjiang River. The reconstruction of this bridge would have been a high priority to reach the affected population there. Yingxiu town itself was still accessible despite the loss of bridges #4 and #5 due to the recent construction of bridge #6.

5.4 Environmental impact and landslide assessment

The earthquake caused extensive landslides in the area which led to severe environmental degradation and disruption to transport routes. A semi-automatic method was devised to locate the landslides in the June 2008 image. First, normalised NDVI maps were created from both the June 2005 and June 2008 images using the Normalised Difference Vegetation Index (NDVI) (Rouse et al. 1974). NDVI algorithm detects vegetation by identifying pixels that have significantly higher reflectance in the near infrared band compared to the red band, a pattern that is unique to green vegetation.

A threshold was then applied to these images to produce binary maps that showed the location of both vegetative and non-vegetative land cover. Raster Calculator in ArcGIS was then used to conduct a change detection analysis. This process identified areas that had changed from vegetative land cover to non-vegetative land cover between these dates. Due to the low level of construction in the scene at the time these areas corresponded to land that had been scarred due to landslides. In this 5.5 km^2 subset alone, approximately 26% of the scene was scarred due to landslides. Figure 5 shows the vegetation map of the area with landslide locations.

5.5 Internally displaced persons (IDP) assessment

One of the most prominent signs of relief and recovery in a post-disaster landscape is the presence of makeshift shelters, tents and transitional shelters. Makeshift shelters are commonly fragile structures built by households in the immediate aftermath of a disaster to provide temporary shelter until further assistance arrives. Transitional shelters are more permanent structures designed to house occupants for several years until their homes have been reconstructed. The transitional shelters in Sichuan Province were built with colour-coated steel sandwich panels and thermal insulation and positioned in rows within traditional camp boundaries.

In Yingxiu in October 2008, internally displaced persons (IDPs) were still residing in government-supplied tents while transitional shelters were in the process of being constructed. Tents and transitional shelters were all manually delineated in the imagery and mapped, and the tents were categorized according to their color: blue, green, orange or white. The structures were found to be located in 8 clusters across the scene. Figure 6 shows a map of these shelters and Fig. 9 shows the number of structures visible in each cluster.

In June 2008, two planned camps, containing transitional shelters, were in the process of being constructed; one to the south of Yingxiu (site #4) and the other to the north (site #8). Forty-one transitional shelters had been constructed at these sites in the month following the earthquake, with space remaining for many more. Site #8 was located nearest to the worse-affected area and contained a large number of orange and green tents which were hosting workers and SAR teams; while site #4 contained a higher proportion of blue tents which were housing IDPs. All of the camps were constructed in close proximity to the affected area and were easily accessible by its inhabitants. In addition, twenty transitional shelters were built in the grounds of Yingxiu Xuankou Middle School (site #5) to house the Yingxiu Administration and Emergency Services. The remaining clusters contained blue and orange tents and were located close to collapsed buildings. It can be presumed that the residents or owners of these tents were temporarily residing in them until appropriate shelters had been constructed.

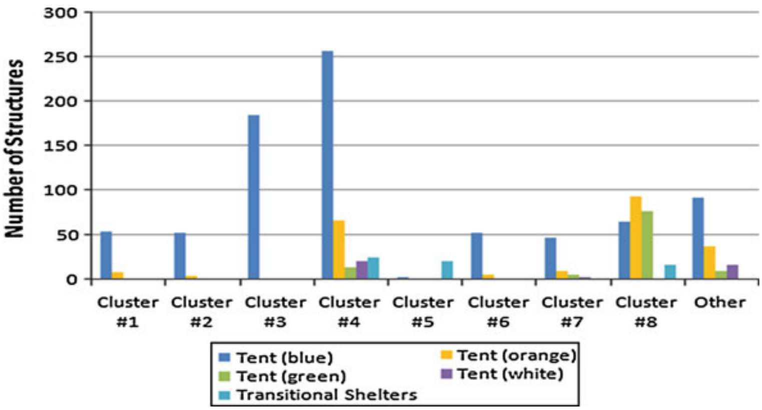

Fig. 9 Histogram showing the distribution of tents and transitional shelters in clusters (see Fig. 6) located across Yingxiu

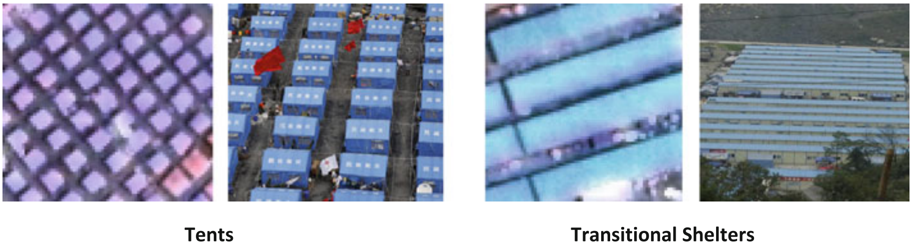

Fig. 10 Tents and transitional shelters in Yingxiu shown in ground photographs and Quickbird imagery

Structural attributes were also measured in the imagery to describe the structures' size and capacity and the density of buildings within the camps. The Chinese Technical Guidelines, published by the Ministry of Housing, focus on the size of the structures (*building* specifications) and the arrangement of the camps (*building* layout) (Ministry of Housing 2008). The document states that each dwelling must be at least 22 m^2. Independent satellite image analysis showed that the dwellings in Yingxiu were approximately 28 m^2, 6 m^2 (27%) larger than the guidance set by the authorities. The image analysis also confirmed that all residential shelters were facing south, as recommended, to optimize the amount of solar radiation received, and that most buildings were approximately 3 m apart from each other, thus ensuring adequate space, privacy and natural light. Infrastructure placement in the camps was also validated with the satellite imagery showing that residential structures were at least 15 m from sanitation facilities and that schools, clinics, food and retail points were all located no more than 600 m away from the furthest dwelling. Figure 10 shows some examples of the structures used in Yingxiu, as they appear in both ground photographs and satellite imagery. Table 2 summarizes the structural attributes of tents and transitional shelters located near to Yingxiu.

In summary, the supply of tents and transitional shelters to Yingxiu appeared rapid and well-organized. The camps were accessible whilst not impeding on-going construction work. Where possible, tents were kept close to people's damaged homes. The two largest camps were estimated to hold approximately 3,000 people, so more space may have been required depending on the number of survivors that required accommodating.

Table 2 Structural attributes of tents and transitional shelters in Yingxiu

Shelter type	Count	Size (m)	Total area (m^2)	Dwelling capacity	Distance between shelters (m)	Roof color	Notes
Tents	806	4 × 4.5	18	4 People	1.5	Blue (appear purple)	Orderly arrangement of tents in camps and near to affected homes
Transitional Shelter	61	40 × 7	280	6 People	2	Blue	Color coated steel sandwich panel with thermal insulation. Entrances open onto the back of adjacent shelters to ensure privacy of occupants

6 Damage study in Wenchuan

Since a building by building damage ground-based assessment was not possible in Yingxiu, the team took the opportunity to do such a study in Wenchuan. Wenchuan (Fig. 1) is a relatively small town on the confluence of the Min and Zagunao river, and the principal town of Wenchuan county, with a pre-earthquake population of about 30,000. It is located within 20 km of the fault, and according to the CEA intensity map it is within Intensity zone IX, implying that the earthquake was "severely destructive". However, overall the damage appeared to the team significantly lower than this, and at the time of the field survey the main commercial area appeared relatively lightly damaged, and shops and businesses seemed to be functioning normally.

An Ikonos 1 m resolution image was available, and this was used to make a building by building damage assessment for a small part of the town, which appeared relatively heavily damaged, comprising 40 buildings of mixed sizes, uses and forms of construction. Buildings were assessed as having observed damage level D5 (destruction), D4 (very heavy damage) D3 (substantial to heavy damage), according to the EMS98 damage scale, or D0 (no visible damage) (Grünthal 1998). However, even after pansharpening was applied, the level of detail visible in this image was poor. During the field visit, an on the ground damage assessment was made of the same 40 buildings with the results shown in Fig. 11. It can be seen from Fig. 12 that the damage assessment made using the satellite image was very poor. No buildings were identified as being at damage level D5, and of the 9 buildings identified by remote sensing as having damage level D3 and D4, only 4 of them were given the same damage grade in the ground survey. The remaining buildings were all classified as having no visible damage, although from the ground survey, many of them had

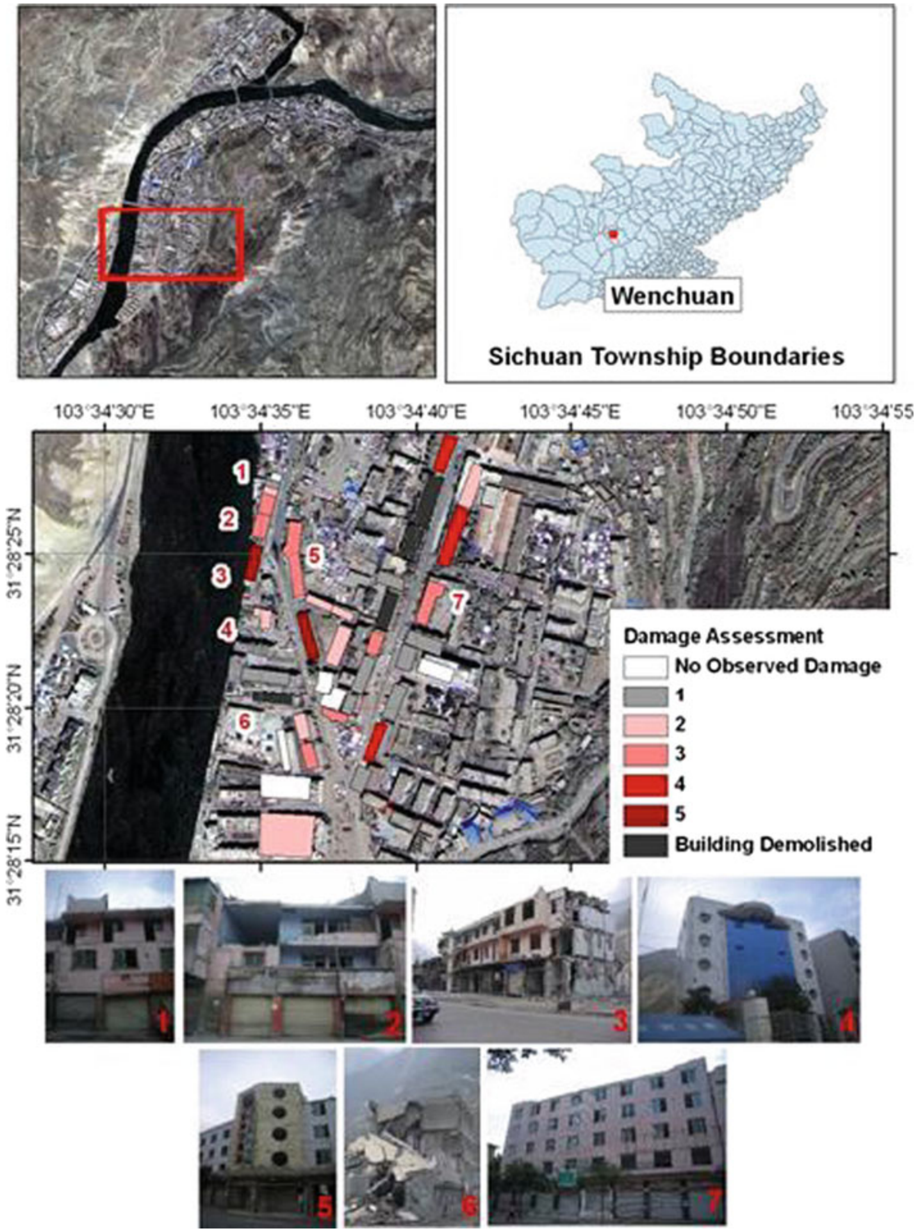

Fig. 11 The damage survey location in the southern part of Wenchuan. Building footprints are color coded according to the assigned damage level interpreted using the IKONOS satellite image. The *numbered buildings* are shown in the photos below. Most of the buildings were mid-rise reinforced concrete buildings

moderate to heavy damage (D2 or D3). From this pilot survey it is clear that the 1m resolution images available were not a suitable instrument for a reliable post-event damage survey.

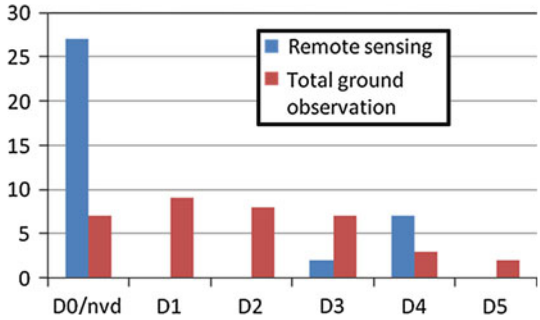

Fig. 12 Comparison of damage distribution of 40 buildings in Wenchuan town assessed using remote sensing and ground survey. D0 to D5 are damage levels defined in EMS98 (Grünthal 1998) and *nvd* no visible damage

7 Synoptic record of damage and recovery using ground survey techniques

7.1 Overview

Ground survey work was conducted across the whole affected region and signs of both damage and recovery were reported. Approximately 1,500 geocoded photographs and a series of geotagged video recordings were collected across a 17,000 km^2 area. Damage levels could be inferred from the photographs and signs of recovery were also reported. Some interviews were conducted with local people. There were numerous physical signs of recovery; the most prominent were in the form of tents, transitional shelters and makeshift shelters. The makeshift shelters were constructed by households using material that was freely available including plastic, tarpaulin and wood. The presence and absence of rubble was also noted as was the presence of construction materials. Bricks and concrete were commonly seen in piles outside damaged buildings and along road sides waiting to be used. Functioning sources of livelihoods, such as shops and factories, were also noted. Because the data was georeferenced it allowed the observations to be mapped and spatial disparity and patterns in the extent of damage and the progress of recovery to be analyzed. At the time of the visit in October 2008, there appeared to be some disparity in the speed of the reconstruction process with several mountain settlements still awaiting materials for permanent reconstruction. The data and geolocated photographs provide an objective record of recovery which can be archived and made available for future research. A summary of the key recovery observations is listed below:

Buildings: There was much evidence of reconstruction, but a significant variation in the progress of reconstruction across the region. Bricks and cement lined the roads in many areas and confined masonry was a commonly used construction technique.

Accessibility: Key access routes were cleared within several weeks with limited access. Temporary bridges had also been constructed on major routes to allow accessibility to resume quickly. The permanent repair and reconstruction of roads only occurred on major routes and not in rural areas.

Power: Power lines were brought down; particularly those located on steep slopes. The length of time taken to resume power to households varied from 2 weeks to several months. Temporary power was also provided to most transitional shelters within several months.

Water: Temporary water points were provided by China Water on the route to Hongbai village. Government workers were also seen repairing Duijiangyan's water system, which was said to take many months to restore.

Livelihoods: Re-opening commercial enterprises was seen to be a priority. For those living in camps temporary market stalls provided income. People also found money through craftwork and other cash-for-work schemes, such as rubble clearance.

Figure 13 shows some of the key observations that were made in Dujiangyan on 17 October 2008. In the downtown area (Point 1) and the nearby old district (Point 2) small businesses had re-opened whilst the residential quarters remained empty. Partial collapses and serious structural damage were observed to several 5-storey reinforced concrete residential buildings. The buildings in this area were predominantly vacant and waiting to be demolished. Members of the team interviewed several businesses that were struggling to function due to the relocation of people to the outskirts of the city. Outside the centre of Duijangyan the team visited a new district (Point 3), where there was evidence of shear cracking and damage to 5-storey reinforced concrete buildings. Unlike the old district, progress had been made to demolish damaged buildings and to clear rubble and debris. There were also signs that the businesses and markets were functioning well. On the outskirts of the city was one of the largest camps in Sichuan (Point 4), hosting a population of 20,000. The camp was located 4.2 km away from the centre of the city. Quickbird imagery acquired on 22 July 2005 shows that the land was previously agricultural fields with several small rural settlements. The rooms in the camp measured 25 m^2 and there was one kitchen and washroom for every 50 inhabitants. Located besides the camp was the construction site for a series of luxury apartments (Point 5).

7.2 Shifang transect

On 18 October 2008, geocoded photographs were acquired along a 34 km stretch of road running north-west from Shifang to Hongbai. The observations were later loaded into a geodatabase and mapped to assess disparity in the recovery process. The locations of the observations were then analyzed to see to what extent the progress in recovery could have been affected by the level of accessibility, the ground shaking intensity level of the earthquake or the proximity of the site to built-up areas.

Height information was added to the database by draping Landsat Satellite imagery over a Digital Elevation Model (DEM) created with 90 m Shuttle Radar Topography Mission (SRTM) data. The first half of the transect can be seen to cross the flat Sichuan basin which is well-populated, before entering the Sichuan mountain range where population density and accessibility drop dramatically. Earthquake Intensity was visualized using the CEA Intensity map which was manually georeferenced and digitized from the Wenchuan atlas (Chengdu Map Publishing 2009). The CEA Intensity varied from VII in Shifang to IX in Hongbai. Finally, the proximity to built-up area was represented by the Landscan global population dataset (Oakridge National Laboratory 2010). This is a worldwide population database compiled on a 30 arc-second grid. The population density of each grid cell is estimated based on proximity to roads, slope and land cover, and the integration of census information and administrative boundaries.

Observations from several locations are presented in map format in Fig. 14 and summarized in Table 3. The map displays both the Landscan layer and the CEA Intensity zones. The map to the right in Fig. 14 shows the change in land cover and topography.

The level of damage and progress of recovery are seen to vary along the transect. The extent of the damage was a lot less severe in the city of Shifang than in the rural parts. The progress of recovery in the mountainous regions appeared uneven with several communities already constructing building foundations, whilst other households remained in makeshift

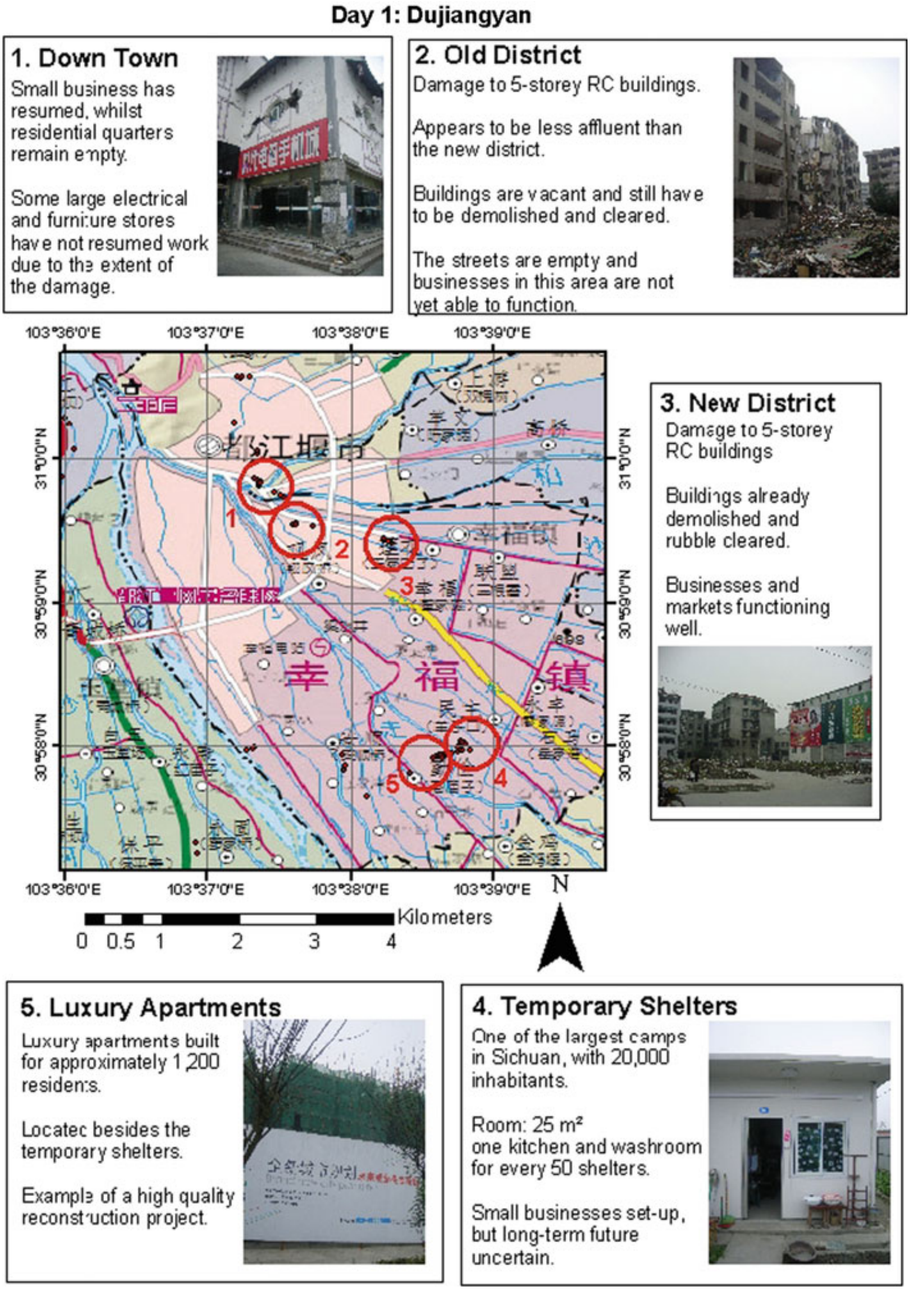

Fig. 13 A geocoded summary of the observations made in Duijangyan on 17 October 2008. Each *box* describes the characteristics and observations made in the locations visited, with the photos showing the typical building type seen in the district

shelters with no further plans. The reason for this disparity is unclear and appears to be unrelated to levels of accessibility or the proximity to other major built-up areas. The town of Hongbai (point 8, Fig. 14) was virtually destroyed by the earthquake. Although no permanent

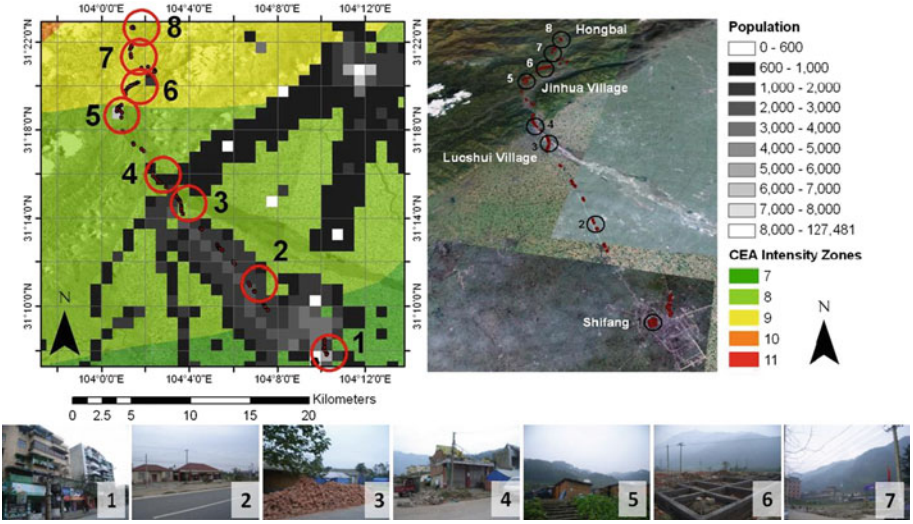

Fig. 14 Geocoded damage and recovery observations were made along a 34 km transect running from Shifang to Hongbai. The route crossed different terrain types, intensity zones and moved from a built-up area to a more rural setting. Recovery characteristics of each location are summarized in Table 3

reconstruction had begun there, substantial progress had been made to remove debris and rubble and provide transitional shelters to the residents and administration.

8 Discussion and conclusions

Following the magnitude 7.9 Wenchuan earthquake, China, on 12 May 2008, the authors carried out damage/recovery surveys 5 months after the earthquake. The survey was carried out in seven locations, namely Dujiangyan, Yingxiu, Wenchuan, Pengzhou, Shifang, Hongbai and Beichuan. The damage observed in the towns of Yingxiu and Beichuan were the most severe which could be described as total destruction. The towns are located on the two ends of the ruptured fault line that extends approximately 240 km. Beichuan, in addition to the damage caused by the ground shaking, was also hit by a devastating landslide 3 months after the earthquake, which almost completely buried the town.

Reconstruction efforts were continuing in most of the locations visited except for Beichuan, and the north half of Yingxiu where there are plans to preserve part of the town in its current devastated state as a memorial. The major cities in the earthquake affected area were already apparently functioning normally, with not much evidence of the damage still visible from the outside. Very large numbers of transitional shelters had been erected to house the people who had been displaced. The communities were being preserved by having people from the same community live close by. Businesses were flourishing.

As a result of this study, several geodatabases have been constructed providing geo-referenced observations of damage and recovery across the area providing a permanent archive of damage and recovery observations. These include:

- a geodatabase of Yingxiu containing buildings, roads and other large topographic features. The database contains four vector layers: (1) Building damage assessment, (2) Accessibility assessment, (3) Natural environment assessment and (4) Internally Displace Persons assessment

Table 3 A summary of observations made in seven locations on the Shifang to Hongbai route

ID	Location	Accessibility	CEA intensity	Distance to Shifang (km)	Notes
1	Shifang City	City centre with good accessibility	7	0	Fully functioning city
					No evidence of severe damage
					Some evidence of pounding damage (e.g. wall tiles removed)
2	Sichuan Basin	In the Sichuan Basin with good accessibility to Shifang by main road	8	8	Evidence of roof collapse and substantial damage
					1-storey residential buildings appeared undamaged from the outside
					Lots of building and road reconstruction in process
3	Rural housing	In the mountains, but still with good accessibility by road	8	20	Rural building stock: appeared more vulnerable
					Bricks and cement had been provided for reconstruction but little evidence of construction
4	Jinhua Village	8 km into the mountains	8	25	Severe building damage with upper-storey collapse
					Some buildings still looked vulnerable to collapse
					Bricks and cement had been provided for reconstruction
					People living in tents and makeshift shelters

Table 3 continued

ID	Location	Accessibility	CEA intensity	Distance to Shifang (km)	Notes
5	Small rural settlement	10 km into the mountains	8	27	7 small settlements, each with approximately 300 people—currently residing in makeshift shelters Water points and mobile phone mast provided Buildings and debris cleared No sign of materials or permanent reconstruction
6	Small rural settlement	Remote	9	31	Bricks and cement had been provided Foundations built using confined masonry techniques and slim reinforcement Buildings built by Sichuan administration
7	Hongbai	Remote	9	34	Town largely destroyed—now clear of debris Large open spaces where buildings once stood, including school where 100 students died Police and government operating in transitional shelters Remaining population living in makeshift shelters No evidence of permanent reconstruction

- a database of building damage in a part of Wenchuan
- databases of damage and recovery observations in Dujianyang, and along the route from Shifang to Hongbai.

The work demonstrates how remote sensing alone can be used to extract valuable information on the post-disaster landscape, particularly when pre-event images are available. Other features may also be monitored with satellite imagery, including school buildings, sources of livelihoods (e.g. commercial districts and sand extraction facilities) and features related to power generation (e.g. power stations). The acquisition of more satellite imagery would have allowed the process of recovery and reconstruction to be further monitored over time. Additionally, the geodatabase created with satellite imagery may be further populated with data from ground workers in the form of georeferenced field notes, electronic surveys, video footage and photographs. If each feature in the database is given a unique identifier the resulting recovery geodatabase may then be used to monitor the progress of recovery across the affected region at a per-feature scale.

Coupled with ground observations, remote sensing has been shown to enable the creation of a georeferenced archive of information about damage and the progress of recovery which can be of operational value to the administration responsible, and of lasting value to the research community.

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