Use of high-resolution FORMOSAT-2 satellite images for post-earthquake disaster assessment: a study following the 12 May 2008 Wenchuan Earthquake

Article *in* International Journal of Remote Sensing · July 2010

DOI: 10.1080/01431161003727655

Yuei-An Liou
National Central University

International Journal of Remote Sensing
Vol. 31, No. 13, 10 July 2010, 3355–3368

Use of high-resolution FORMOSAT-2 satellite images for post-earthquake disaster assessment: a study following the 12 May 2008 Wenchuan Earthquake

YUEI-AN LIOU*, SANJIB K. KAR and LIYU CHANG
Center for Space and Remote Sensing Research, National Central University, No. 300, Jhongda Road, Jhongli City, Taoyuan County 32001, Taiwan

A large earthquake struck Wenchuan County, China on 12 May 2008 and is one of the most severe natural disasters of recent decades that has changed the entire landscape of Wenchuan County. This paper presents a satellite image analysis of the landslide following the Wenchuan earthquake and its consequences, and demonstrates how remote sensing techniques can be used for civilian crisis-management purpose and disaster relief. Real-time high resolution 2-dimensional and 3-dimensional information on structural deformation of land areas, directional changes of rivers, creation of new lakes, and the water levels of rivers and lakes in the earthquake affected area have been provided using the FORMOSAT-2 and Satellite pour l'Observation de la Terre (SPOT)-5 satellite images. Satellite images taken before and after the 12 May 2008 Wenchuan Earthquake have been used for landslide investigation. Possible flooding and rupture of natural dams during the post-earthquake period have been indicated through the analysis of 3-dimensional images of FORMOSAT-2. Some rescue methods have been suggested for immediate recovery of the bereaved persons and to locate the corresponding area accurately using remote sensing techniques. Some precautionary measures have also been suggested to avoid further destruction. Comparisons of panchromatic and multispectral images of FORMOSAT-2 for a particular region have been made to quantify the location accuracy. Our results show that the real-time high-spatial resolution FORMOSAT-2 satellite images could be an efficient and useful resource for decision-makers to prepare rescue and post-event recovery operation plans, especially for some isolated earthquake areas where damage distribution is often very uneven and hard to reach in time.

1. Introduction

Within the geophysical system, natural disasters are considered to be unavoidable and are often characterized as rapid and extreme events that result in mortality and property damage, which exceeds the response and recovery capabilities of the affected area (Kerle and Oppenheimer 2002). Sometimes earthquakes are so widespread that the devastated areas are almost unreachable, making an overall *in situ* effective disaster mitigation and rescue investigation difficult or impossible. Present technology and knowledge are limited for preventing such natural disasters and such events continue to pose an increasing threat to human life and civilization. However, avoidance or mitigation of the impact of the disaster could be achieved with effective disaster management strategies along with proper utilization of remote sensing technology.

*Corresponding author. Email: yueian@csrsr.ncu.edu.tw

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2010 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/01431161003727655

Over the past several decades, satellites have extensively been used to acquire a wide variety of information about the Earth's surface, ranging from military applications to track environmental change, surface vegetations, water-pollution assessment, polar ice fluctuations, pollution, volcanoes and many other aspects (Piwowar *et al.* 1998, Yang *et al.* 1999, Chen 2003, Murthy *et al.* 2003). With the rapid development of space platform and digital imagery, remote sensing data have been broadly utilized for natural-hazard investigation and management as found in several studies (Gupta and Joshi 1990, Lin *et al.* 2000, 2002, Ganas *et al.* 2004, Lin *et al.* 2004, Yang *et al.* 2004). In the last decade, space geodetic techniques, especially the global positioning system (GPS), have successfully been used to measure the crustal movement across tectonic deformation zones (Wang *et al.* 2008). Such studies in the Tibetan Plateau and its vicinity provide us with a basic understanding of crustal deformation patterns in the region (Chen *et al.* 2000, Shen *et al.* 2005, Densmore *et al.* 2007, Li *et al.* 2008, Royden *et al.* 2008). Xu *et al.* (2008) indicated, critically reviewing the available investigations, that the 12 May 2008 Wenchuan Earthquake struck the Longmenshan foreland thrust zone. The event took place within the context of long-term uplift of the Longmenshan range as a result of the extensive eastward-extrusion of crustal materials from the Tibetan plateau against the rheologically strong crust of the Sichuan Basin. However, there is some discrepancy among various investigators about the locations, names, kinematics, and activity on the major margin-parallel faults in the Longmenshan region (Chen *et al.* 1994, Burchfiel *et al.* 1995, Xu and Kamp 2000). Thus remote sensing techniques have become an advanced tool to combat the natural disasters successfully due to the decreasing costs, increasing image resolutions, and greater availability of satellite images.

Agility in information collection, increased preparedness, advanced warning, real-time monitoring of the disaster, damage assessment and organization of relief strategies and operations are the main objectives of disaster management (Ayanz *et al.* 1997). Geo-spatial information at different scales is highly required for effective disaster management. However, in real-life situations, immediately after the occurrence of an earthquake, the response stage is the most crucial and challenging phase within the disaster management cycle. Especially due to the sudden breakdown of communication systems, blockage of roads and sometimes due to unfavourable weather, very little information is known about the exact location and amount of disaster, the number of people affected or what exactly happened. During such an emergency period, it is indeed a challenging task to obtain timely accurate and detailed information about the disaster situation due to the breakdown of communication systems and confusing information coming from different sources. Hence, following a disaster, potential high-speed acquisition and dissemination of air and space-borne data with synoptic coverage is highly desirable, in order to detect and monitor the natural disaster. Remote sensing technology provides a quantitative base for information about damage and aftermath monitoring to assist response operations (Van Westen 2002). To mobilize the response and relief operations, data capturing, assimilation and analysis results should be made available as early as possible so as to limit the death toll and further property loss. For post-earthquake damage assessment, remotely sensed data can provide valuable information for emergency activities.

Considerable research works are found in the literature on post-earthquake damage assessment utilizing the remotely sensed data (EDM 2000, Turker and San 2003, Yusuf *et al.* 2003). Remotely sensed data are very useful for damage assessment. Despite some limitations such as a short time gap between pre- and post-event imagery or changes in brightness values caused by external factors, a multitemporal approach using change detection is found to be the most commonly used methodology for post-earthquake damage assessment research. For damage detection, high resolution temporal and spatial data with oblique information are highly required. However, there are also some limitations due to the inherent characteristics of each sensor. Cloud coverage, the high cost of high spatial resolution data and vertical viewing are the main disadvantages of satellite images. Even high resolution spatial data may not be helpful for detecting the pancake collapse with intact roofs. High spatial resolution images for urban areas can be obtained from standard aerial photography, but the main obstacle is the cost of data acquisition and time required for processing the data. From the above discussion, it is clear that none of the sensors can fulfil all the requirements independently, but the requirements can be achieved by systematic integration of different data sources. On the other hand, the use of remote sensing technology has not been widely extended so far in emergency management activities despite its usefulness. A frequent lack of complete understanding of emergency activities and limited awareness among emergency managers of remote sensing technology and its potential use in disaster management are the main reasons for this situation (Bruzewicz and McKim 1995). Information is said to be valuable and useful only when it is easily accessible, understandable and manageable for the user (Ayanz *et al.* 1997).

High-spatial-resolution images can meet the demands of a complete disaster management to some extent. Nevertheless, for hazard response and recovery, 'real-time' information about a disaster area is highly desirable. Therefore, a better temporal resolution satellite image with a revisit capability is indeed worthy. In this paper we will present the high spatial resolution of 2-m panchromatic and 8-m multispectral as well as a high temporal resolution 1-day FORMOSAT-2 images to discuss and analyse the changes of the terrain features immediately after the recent earthquake of 12 May 2008 at Sichuan Province, southwest China. Efforts have also been made to show how FORMOSAT-2 images can provide the rich information necessary for hazard assessment and mitigation. Utilization of satellite images in disaster management and forecasting precautionary measures to avoid the possible dangers following the disaster have also been discussed at length. Three-dimensional simulation results of the FORMOSAT-2 imagery are critically examined for assessing the extension of flooding and widespread devastation to the coastal cities and surrounding areas. Instant response and rescue processes for hazard recovery are outlined through digital image processing of the FORMOSAT-2 imagery. Finally, an integration of GPS data with Satellite pour l'Observation de la Terre (SPOT)-5 images has been made to show how improved rescue operations can be achieved with remote sensing technology. These value-added satellite images can provide the information of square measure of the disaster area and also the barrier lakes. Such direct information after a natural disaster can increase the efficiency of disaster evaluation and land reconstruction.

2. FORMOSAT-2 and CSRSR in brief

The first remote sensing satellite developed by the National Space Organization (NSPO), FORMOSAT-2, was successfully launched on 21 May 2004 (http://www.nspo.org.tw ; http://www.csrsr.ncu.edu.tw). The main mission of FORMOSAT-2 is to conduct remote sensing imaging over Taiwan and also the entire Earth. The unique capability of daily revisiting and high spatial resolution of FORMOSAT-2 makes it superior to other commercial satellites. The orbit of FORMOSAT-2 is

Table 1. The sensor characteristics of FORMOSAT-2.

Mode	Band	Wavelength (μm)	Applications (Kramer 2002)
Panchromatic (Resolution: 2 m)	Mono	0.52 to 0.82	This band is usually used as the image source for cartography and cadastral mapping. It is also used to create a digital terrain model if a stereo pair is acquired.
Multispectral (Resolution: 8 m)	Blue	0.45 to 0.52	This band is used for mapping coastal water areas, differentiating between soil and vegetation, forest type mapping, and detecting cultural features.
	Green	0.52 to 0.60	This band corresponds to the green reflectance of healthy vegetation. Also used for mapping cultural features.
	Red	0.63 to 0.69	This band is useful for discriminating plant species. It is also useful for finding soil and geological boundaries.
	Near infrared	0.76 to 0.90	This band is used to find out the amount of vegetation biomass. It is also used to enhance the soil/crop or land/water contrasts.

Sun-synchronous at an altitude of 891 km, passing through Taiwan twice daily. It can acquire daily images for 14 strips of the worldwide area. The image swath of FORMOSAT-2 is 24 km with a limb view angle ±45°. It is capable of capturing 3-dimensional images. In addition, the spectral wavelength design for the multispectral mode of FORMOSAT-2 is similar to the Landsat system. Table 1 indicates the sensor characteristics of FORMOSAT-2.

Because it has a receiving station and over a decade of experience, the Center for Space and Remote Sensing Research (CSRSR), in conjunction with NSPO, has established an Ingest, Archive and Processing System (IAPS) in the receiving station to acquire and process FORMOSAT-2 remote sensing data. Figure 1 shows the reception zone of the CSRSR receiving station (http://www.csrsr.ncu.edu.tw), which covers an area of radius 3000 km; east of USA's Guam, west of China's Gang-Su, north of Japan's Hokkaido and south of the South China Sea. CSRSR acquires a regular real-time day pass of the first FORMOSA-2 orbit over Taiwan and also downloads the night pass simultaneously as NSPO does every day. In fact, CSRSR is not only the distribution centre of FORMOSAT-2 but also plays the role of full backup system and reference for cross validation process.

FORMOSAT-2 has been performing an image capturing mission since 4 June 2004. In summer 2004, several floods hit Taiwan. On 26 December 2004, Southern Asia was severely damaged by a tsunami caused by a strong earthquake. On 2 May 2008, Tropical Cyclone Nargis struck southwestern Myanmar. On 12 May 2008, an 8 magnitude earthquake hit Sichuan Province of southwest China. During these natural disasters, FORMOSAT-2 was able to immediately capture the images over the disaster areas. The images are very helpful for disaster evaluation and land reconstruction. Especially for the Sichuan earthquake event, CSRSR added an urgent mission to acquire simultaneously the FORMOSAT-2 data of the second orbit over the disaster area successfully in real time.

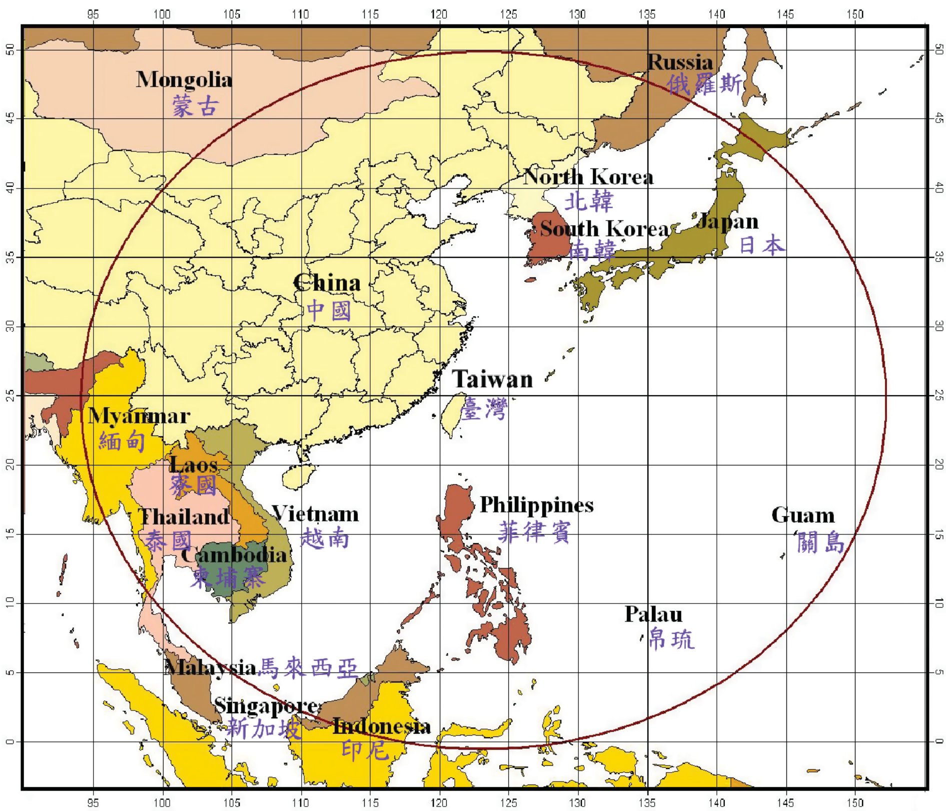


Figure 1. Reception zone of the Center for Space and Remote Sensing Research (CSRSR) receiving station (http://www.csrsr.ncu.edu.tw) covering an area of radius 3000 km; east of USA's Guam, west of China's Gang-Su, north of Japan's Hokkaido and south of the South China Sea.

Compared to the other commercial remote sensing satellites, FORMOSAT-2 has the advantages of daily revisit capability, vast image coverage area, and low cost. The FORMOSAT-2 satellite images have many useful applications, including land usage analysis, agriculture and farm forest prediction and planning, environment monitoring, disaster evaluation, and scientific research and education. FORMOSAT-2 images are very useful for natural-disaster evaluation particularly in assessing damage and performing the tasking orders possibly within a day if weather permits. The conditions of flooded areas, landslides, debris flows, and structural integrity of hillsides can also be assessed. Besides, FORMOSAT-2 is able to acquire images of both the North and South poles by taking advantage of its unique orbit design and agile capability. It is expected that FORMOSAT-2 polar images will be continuously collected and contribute to the research of the global environment change (Liou *et al.* 2007).

3. Data and methodology

The procedure for disaster mapping using a FORMOSAT-2 satellite image is followed as shown in figure 2. Once the location of the damaged area is confirmed, the image request for the corresponding area will be sent to NSPO and uplinked to the

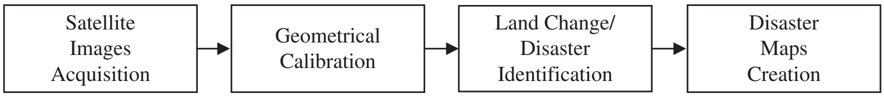


Figure 2. Flow chart of satellite image processing for disaster mapping.

satellite. While the satellite is acquiring the data, our ground station is receiving the acquired data simultaneously. When the raw images are collected, geometric calibration of raw images is followed. However, for the area without accurate ground control points and a digital terrain model, the geometric calibration is the only systematic calibration with on board orbital parameters. Especially for the emergency events in this study, precision ground control points and a digital terrain model are not available quickly. In general, the spatial error of systematic calibrated FORMOSAT-2 images is within 500 m. Consequently, further geometric processing is still needed to eliminate the geometric discrepancy between multitemporal images only through systematic calibration. In this paper, an image-to-image registration process has been used to relatively calibrate this discrepancy. In order to model and eliminate this discrepancy in limited time, only linear deformation has been considered and an affine transformation with manually digitized image control points has been used to solve this deformation.

Next, the land change identification is carried out according to the disaster type. In this case, the land change type is focused on the landslide or topographic change caused by a large scale earthquake. For regional scale assessment of the disaster, pre- and post-earthquake (14 May 2006 and 16 May 2008, respectively) FORMOSAT-2 panchromatic and multispectral images have been used. Finally the analysed results are used to create disaster maps with the assistance of Geographic Information System (GIS) tools.

4. Image analysis and interpretation

In this section the results of analysis of FORMOSAT-2 and SPOT-5 images are described. After geometric correction and post-processing, the FORMOSAT-2 image is used for constructing maps in true or false colour and is analysed for monitoring the disaster damage. However, the interpretation and analysis of images is limited to fundamental analysis and interpretation due to the lack of entire on-site information, such as a digital elevation model (DEM) and ground true reference. Despite the above mentioned limitations, several important findings and analysis results are presented in different subsections, which are useful for disaster region positioning, damage-level assessment, rescue planning, and environmental-impact evaluation. The result of analysis is organized in the following steps: (i) analysis of FORMOSAT-2 imagery, (ii) evaluation of results by comparison with SPOT-5 images and (iii) integration of GPS with SPOT-5 to provide improved rescue information.

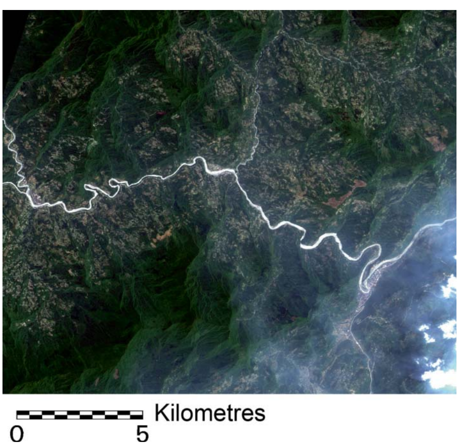
4.1 *Analysis of FORMOSAT-2 imagery*

The Wenchuan earthquake was so large (8 in magnitude), that almost half of Asia felt the earthquake. The earthquake not only caused damage to Wenchuan County, the epicentre, but also Beichuan County, which is 100 km away from Wenchuan County.

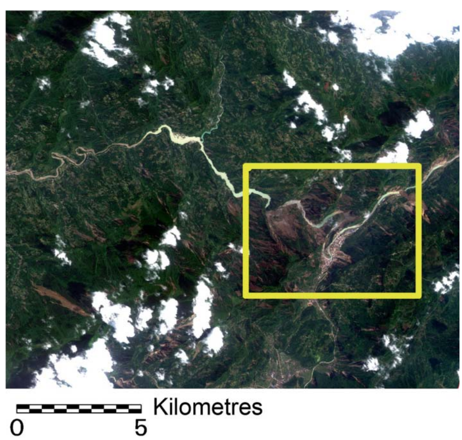
Three-dimensional simulation results of the FORMOSAT-2 imagery analysis have been evaluated at regional and local levels. A three-dimensional simulation satellite image is composed of topographical data and the primitive satellite. The image can be used to find out the topography, land stone collapse, and landslide. Thus, it helps people understand how bad the disaster was.

In figure 3, we have presented the pre- and post-earthquake images of the affected area. The pre-earthquake image was taken on 14 May 2006 (left one), while the post-earthquake image was taken on 14 May 2008 (right one). At the regional level, preliminary damage assessment analysis using FORMOSAT-2 imagery reveals that in Beichuan County the earthquake has caused landslides covering up to 1442 ha of land area, which has engulfed a substantial section of the mountain region of that county, turning its green slopes brown, blocking the river and forming new lakes, as is evident from figure 3. Both the roads and the river are entirely destroyed, buried under the rubble, which rises in a mound up the opposite slope. The landslide of Beichuan County is similar to that of the Taiwan 921 earthquake. Landslides have created earthen dams, and new lakes have been formed overnight. A large number of soil stones have collapsed and almost buried nearly one third of the villages, as is evident from the satellite images. In figure 4, we have shown the enlarged view of the devastated area, which has been shown in figure 3. The creation of new lakes, blocked rivers and landslides is prominently visible. It is also evident from the image that the bursting of newly formed lakes can happen if heavy rain events occur, which in turn can inundate the adjacent areas in the forms of floods.

FORMOSAT-2 satellite images illustrate landslides, flooding and buckled roads that have made travel within quake-affected regions difficult. It is important for the paratroops to select the location properly for rescuing operation. FORMOSAT-2 satellite images of Beichuan County have been released to help the paratroopers select the rescue location properly amid the devastated areas caused by the earthquake. These types of real-time high-resolution image are one of the fundamental needs of the paratroops for the accomplishment of their rescue operation.



(*a*)



(*b*)

Figure 3. Satellite images of the affected area taken on 14 May 2008 (*a*) well before the earthquake and (*b*) immediately after the earthquake.

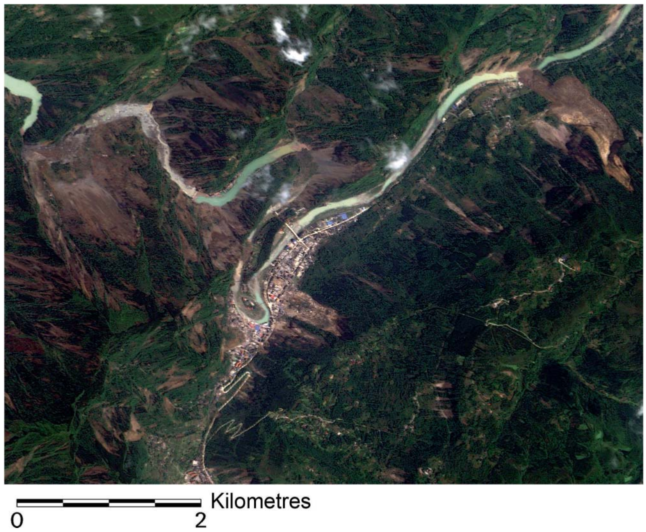


Figure 4. Enlarged view of figure 3(*b*) clearly showing the blocked rivers, creation of new lakes and landslides.

4.2 *An imminent danger: increased water level of newly formed lakes at Beichuan County*

We have presented successive FORMOSAT-2 satellite images of the post-earthquake situation to assess the increase of river width and compared it with the pre-earthquake images in figure 5. The three-dimensional simulation results of the FORMOSAT-2 imagery analysis have also been evaluated at regional and local levels to access the landslides and compared with the three-dimensional simulation result of the FORMOSAT-2 image taken well before the earthquake to measure the depth of the river (see figure 6). The images in figures 5(*a*) and 6(*a*) are the pre-earthquake images and were taken on 14 May 2006, while the rest of the images in figures 5 and 6 are post-earthquake images. It is clearly visible from the FORMOSAT-2 satellite image as shown in figure 5, that new lakes and dams have been formed due to Wenchuan Earthquake. Before the earthquake, the width of the river was 102 m as is evident from figure 5(*a*) and the water level was approximately 677 m as measured from the satellite images taken well before the earthquake. This FORMOSAT-2 pre-earthquake image was taken on 14 May 2006, which gives normal springtime conditions. Successive images, figures 5(*b*), (*c*) and (*d*), taken on 14, 18 and 22 May 2008, respectively, of the post-earthquake situation have been evaluated and compared with the pre-earthquake picture. The image in figure 5(*b*), taken just 2 days after the initial earthquake, shows the width of the river has been increased to 304 m inundating the nearby areas, while analysis of figure 5(*b*) indicates a land slide of approximately 5.6 km in the river basin and formation of new lakes. A quick increase of the water level of the river to nearly 10 m is also evident from figure 6(*b*). The picture in figure 5(*c*), taken after 6 days of the earthquake, clearly indicates that the increasing tendency of the river width has not been stopped and shows the width of the river at 520 m, which is almost five times wider than before. The depth of the river has also increased to almost 25 m, as measured from the three-dimensional simulation of the

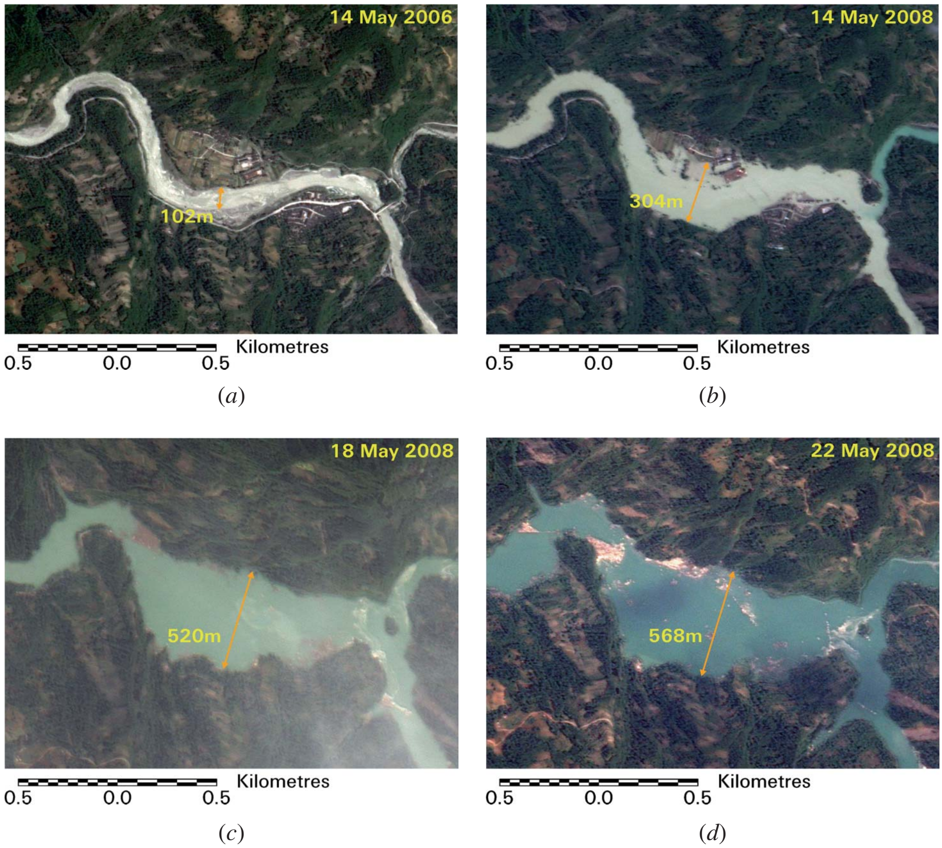


Figure 5. Successive FORMOSAT-2 satellite images of the pre- and post-earthquake situations of the river under study. (*a*) Pre-earthquake image taken on 14 May 2006, (*b*), (*c*), (*d*) successive post-earthquake images taken after 2 days, 6 days and 10 days, respectively, from the date of the earthquake.

FORMOSAT-2 image and shown in figure 6(*c*). However, the picture in figure 5(*d*), taken 10 days after the earthquake, reveals a further increase of the river width and shows the present width of the river at 568 m. A further increase of river depth is noticed from the three-dimensional simulation of the FORMOSAT-2 image even 10 days after the earthquake as displayed in figure 6(*d*). The measured new depth is found to be approximately 725 m. Dozens of lakes have been swelling behind walls of mud and rubble that have plugged narrow valleys in parts of the disaster zone, adding a new worry to millions of survivors. The villages remained above the waterline, as did portions of the roads leading to the villages.

It is worth mentioning that the earthquake-created dams create dual danger to the adjacent areas. Apart from the upstream floods that occur as a lake builds behind the natural dam, the piles of rubble that have formed the dam are expected to be highly unstable. Post-earthquake tremor or another quake or simply the pressure of water behind it could burst the dam resulting in a huge downstream flow of water. Downstream floods may also occur when water begins to cascade over the top of the dam. According to past information and experience, it is concluded that almost

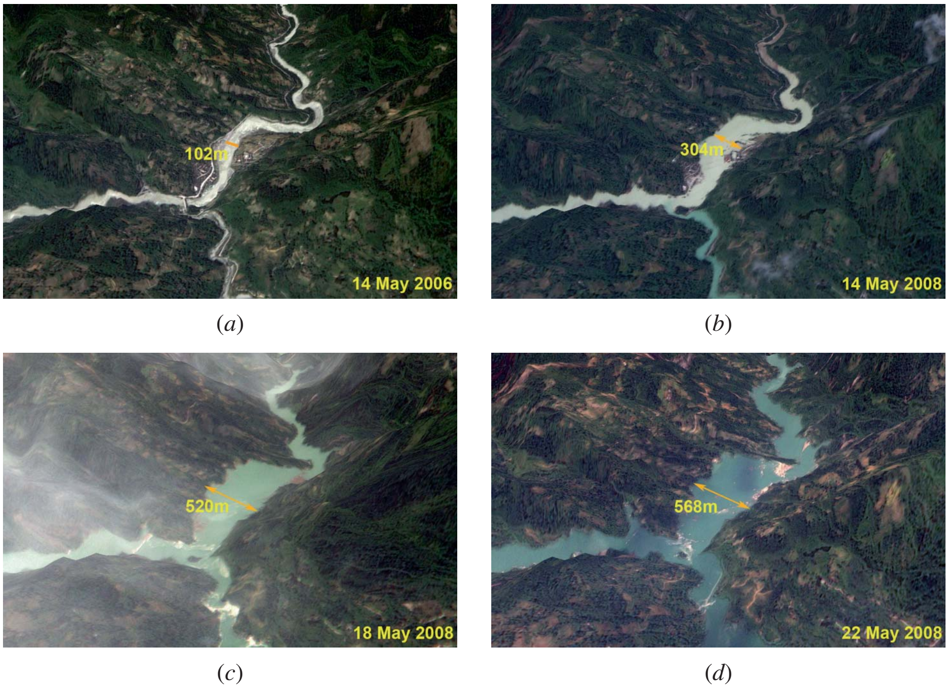


Figure 6. Successive 3-dimensional simulation with FORMOSAT-2 satellite images of the pre- and post-earthquake situation of the river under study. (*a*) Pre-earthquake image taken on 14 May 2006, (*b*), (*c*), (*d*) successive post-earthquake images taken after 2 days, 6 days and 10 days, respectively, from the date of the earthquake.

70% of the new lakes might burst within one month from their formation. Therefore, monitoring the height of the water level of the new lakes and assessing the stability of the dams is indeed an imminent and important job. Satellite images are one of the examining tools for the detection of such new lakes and can warn us of the danger.

4.3 *Integration of GPS with SPOT-5 for improved rescue information*

Xiang He, a travel agency in Taipei, had sent their tourist bus to visit Wenchuan County before the earthquake. Unfortunately, the bus was trapped due to the earthquake, while it was said the bus was on its way from Mao County to Wenchuan County. The sightseeing bus last made contact with the travel agency in Taipei at noon on 12 May. After that, it was lost and the 14 people onboard were missing. Nevertheless, according to GPS data sent out from the sightseeing bus, the missing point of the bus was located at a distance of around 4 km, southwest of Wenchuan County. Once the GPS data was known, the sightseeing bus could be located on the satellite image.

During the crucial moments, both SPOT-5 and FORMOSAT-2 satellites were scheduled to take images over the Sichuan earthquake affected areas. On 15 May 2008, FORMOSAT-2 passed Wenchuan County at 11:46:35 am. Because of the presence of thick cloud, it was unable to take a clear image of the earthquake-affected area. This image is displayed in figure 7. Obviously, most of the scene was covered by cloud. Since the weather of Wenchuan County was not good immediately after the

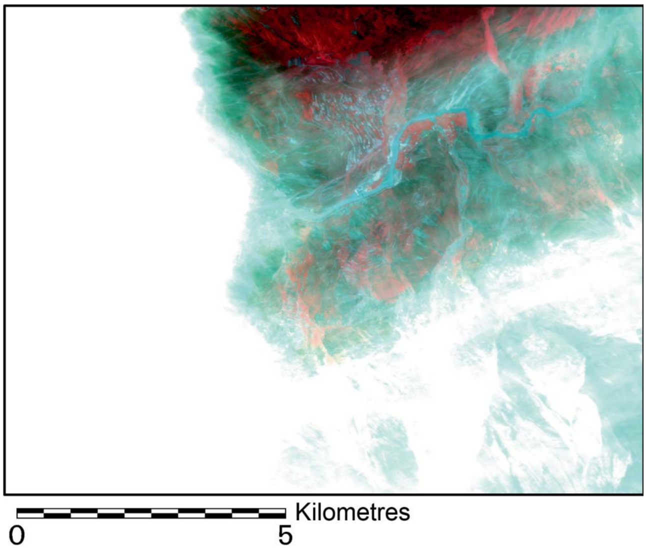


Figure 7. FORMOSAT-2 satellite image over-passing Wenchuan County at 11:46:35 am on 15 May 2008.

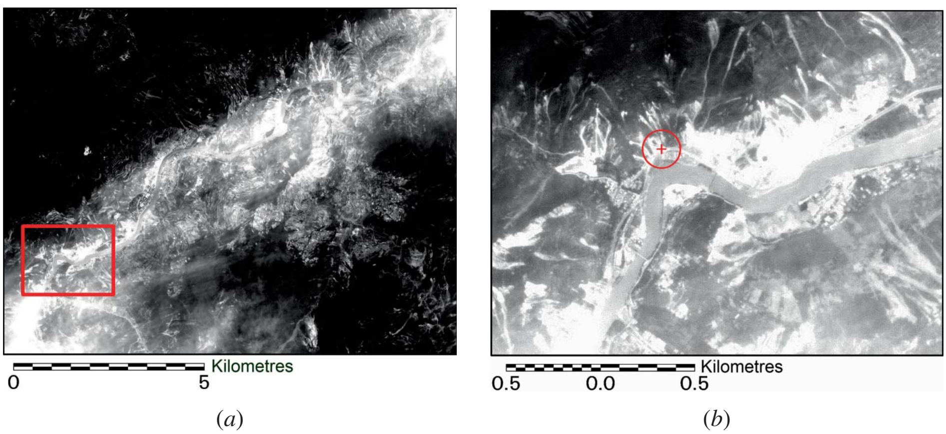


Figure 8. (*a*) SPOT-5 satellite image over-passing Wenchuan County at 11:47:52 am on 15 May 2008. (*b*) SPOT-5 satellite image after enhancement processing for identifying the possible location of the tourist bus as indicated by the cross in the red circle.

earthquake and the sky was full of clouds, significant blurring of the damaged area is observed. In contrast, the French SPOT-5 satellite passed Wenchuan County immediately after the visit of FORMOSAT-2 at 11:47:52 am. It captured a slightly blurred image of that region, presented in figure 8(*a*). There was a difference of only 1 minute and 17 seconds in the time of capturing images between FORMOSAT-2 and SPOT-5. In such a short time difference, the cloud over that region moved to another place, which enabled SPOT-5 to capture the image despite the presence of mist as shown in figure 8(*a*). With enhancement processing and a GPS coordinate, the location of the missing tourist bus is more prominently visible in figure 8(*b*) compared to figure 8(*a*).

This shows the importance of using a complementary resource satellite. The CSRSR then released an image from the SPOT-5 satellite, in order to help rescue operations. Even though this SPOT-5 satellite image is monochromatic and slightly blurred, it is still useful for giving direction to the rescue operation.

5. Conclusions and discussions

Despite some limitations such as external factors and technical limitations (vertical viewing characteristics, and spatial and temporal resolutions), FORMOSAT-2 imagery has shown considerable potentiality for post-earthquake damage assessment of the 12 May 2008 Wenchuan Earthquake. It has been found from the present study that in Beichuan County the earthquake has caused landslides covering up to 1442 ha of land areas, which have blocked the river and formed new lakes. A large number of soil stones have collapsed and almost buried nearly one-third of the villages, as is evident from the satellite images. Successive image analysis reveals the gradual increase of river width up to 10 days after the earthquake. An increase of 466 m in river width from 102 m is noticed within 10 days and the final width of the river is found to be 568 m. Successive three-dimensional simulation of FORMOSAT-2 imagery up to 10 days after the earthquake indicates a landslide of nearly 5.6 km in the river basin. Meanwhile, an increase of about 48 m in river depth is estimated. So far FORMOSAT-2 satellite imagery has not indicated any bursting of newly formed lakes. However, the natural burst depends on flooding or torrential rain. The earthquake-created new lakes are really a serious problem. Hence, as a precautionary measure, the Chinese government should take action as soon as possible either by evacuating the people of that region or by digging a canal to reduce the chances of a natural burst. Integration of GPS information with high-spatial satellite imagery has been found to be very effective for rescue operations, particularly for finding out the possible location of the missing tourist bus of concern in the study. For overall information about concentrated and highly damaged areas, FORMOSAT-2 images provide rich information necessary for hazard assessment and mitigation.

Utilizing the results of image analysis and interpretation, digital image processing could be useful for instant response and rescue of hazard recovery. Integration of vector data would certainly enhance the quality of visualization and interpretability of the results. It is highly necessary to integrate the base data with remote sensing data. FORMOSAT-2 imagery can play a crucial role in strategic decision-making and establishing a sound and comprehensive recovery plan and revamping the disaster areas. Aerial video imagery can also play an important role in coordinating emergency operations and guiding the ground teams. Moreover, for an effective and continuous flow of information between various rescue agencies, improvements in both technical infrastructure and organizational structure are strongly needed. Setting up of a spatial database, downloading and processing facilities for remote sensing data, and coordinated information flow between different users are the basic needs of disaster management and rescue research.

The CSRSR is equipped with a satellite receiving station to receive and process real-time satellite image data from a number of satellites such as SPOT-2,-4 and -5, European Remote Sensing Satellite (ERS)-2, Terra, Aqua and FORMOSAT-2. The reception zone of the receiving station covers an area of radius 3000 km; east of USA's Guam, west of China's Gang-Su, north of Japan's Hokkaido and south of the South China Sea as has already been shown in figure 1. FORMOSAT-2, the first Taiwanese satellite launched on 21 May 2004 onto the Sun-synchronous orbit and capable of capturing 3-dimensional images, is showing promise for rapid data gathering and future applications of remote sensing data for disaster management activities. Such systematic data acquisition can help us to overcome some of the limitations of video data for detailed videography (Ham 1998), such as mission planning and integration with GPS. Moreover, depending on the geometry and texture pattern of the damaged areas, further research can be planned for better understanding and proper implementation of remote sensing data.

Acknowledgments

The authors are extremely grateful to two anonymous reviewers for their valuable critical comments to improve the manuscript. The technical advice from the guest editor is sincerely acknowledged. We are also grateful to the CSRSR satellite receiving station and the NSPO for providing the real-time satellite image data from FORMOSAT-2 and SPOT-5. This research is supported by a grant from the National Science Council (NSC) of Taiwan via grant NSC 95-2811-M-008-033.

References

Ayanz, J., Verstratete, M., Pinty, B., Meyer-Roux, J. and Schmuck, G., 1997, The use of existing and future remote sensing systems in natural hazard management specifications and requirements. Available online at: http://naturalhazards.jrs.it/documents/fires/1997-presentations/enarmors.pdf (accessed 19 August 2003).

Burchfiel, B.C., Chen, Z., Liu, Y. and Royden, L.H., 1995, Tectonics of the Longmen Shan and adjacent regions, central China. *International Geological Review*, **37**, pp. 661–735.

Bruzewicz, A. and McKim, H., 1995, Remote sensing and Geographic Information Systems for emergency management: Effective implementation. Available online at: http://ltpwww.gsfc.nasa.gov/ISSSR-95/remotese.htm (accessed 11 August 2003).

Chen, C.M., Hepner, G.F. and Forster, R.R., 2003, Fusion of hyperspectral and radar data using the HIS transformation to enhance urban surface features. *ISPRS Journal of Photogrammetry and Remote Sensing*, **58**, pp. 19–30.

Chen, S., Wilson, C., Deng, Q., Zhao, X. and Luo, Z., 1994, Active faulting and block movement associated with large earthquakes in the Min Shan and Longmen mountains, northeastern Tibetan Plateau. *Journal of Geophysical Research*, **99**, pp. 24025–24038.

Chen, Z., Burchfiel, B.C., Liu, Y., King, R.W., Royden, L.H., Tang, W., Wang, E., Zhao, J. and Zhang, X., 2000, Global positioning system measurements from eastern Tibet and their implications for India/Eurasia intercontinental deformation. *Journal of Geophysical Research*, **105**, pp. 16215–16228.

Densmore, A.L., Ellis, M.A., Li, Y., Zhou, R., Hancock, G.S. and Richardson, N., 2007, Active tectonics of the Beichuan and Pengguan faults at the eastern margin of the Tibetan Plateau. *Tectonics*, **26**, TC4005, doi: 10.1029/2006TC001987.

EDM, 2000, *Report on the Kocaeli, Turkey Earthquake of August 17, 1999* (*6*). (Hirosawa, Japan: The Institute of Physical and Chemical Research).

Ganas, A., Aerts, J., Astaras, T., Vente, D., Frogoudakis, E., Lambrinos, N., Riskakis, C., Oikonomidis, D., Filippidis, A. and Kassoli-Fournaraki, A., 2004, The use of Earth observation and decision support systems in the restoration of opencast nickel mines in Evia, central Greece. *International Journal of Remote Sensing*, **25**, pp. 3261–3274.

Gupta, B.P. and Joshi, B.C., 1990, Landslide hazard zoning using the GIS approach – a case study from Ramganga Catchment, Himalayas. *Engineering Geology*, **28**, pp. 119–131.

Ham, D., 1998, Aerial photography and videography standards: Applications for stream inventory and assessment. Available online at: http://srmwww.gov.bc.ca/risc/pubs/aquatic/aerialvideo/aerialvid-04.htm (accessed 13 December 2003).

KERLE, N. and OPPENHEIMER, C., 2002, Satellite remote sensing as a tool in Lahar disaster management. *Disasters*, **26**, pp. 140–160.

KRAMER, H.J., 2002, *Observation of Earth and its Environment: Survey of missions and sensors*, 4th edn (Berlin: Springer).

LI, C., VAN DER HILST, R.D., MELTZER, A.S. and ENGDAHL, E.R., 2008, Subduction of the Indian lithosphere beneath the Tibetan Plateau and Burma. *Earth and Planetary Science Letters*, **274**, pp. 157–168.

LIN, C.Y., LO, H.M., CHOU, W.C. and LIN, W.T., 2004, Vegetation recovery assessment at the Jou-Jou Mountain landslide area caused by the 921 Earthquake in Central Taiwan. *Ecological Modelling*, **179**, pp. 75–81.

LIN, P.S., HUNG, J.C., LIN, J.Y. and YANG, M.D., 2000, Risk assessment of potential debris flows using GIS. In *Proceedings of the 2nd International Conference on Debris-Flow Hazards Mitigation: Mechanics, prediction, and assessment*, G. F. Wieczorek and N. D. Naeser (Eds.) pp. 608 (Rotterdam: Balkema).

LIN, P.S., LIN, J.Y., HUNG, J.C. and YANG, M.D., 2002, Assessing debris-flow hazard in a watershed in Taiwan. *Engineering Geology*, **66**, pp. 295–313.

LIOU, Y.-A., LIN, J., WU, A.M. and CHANG, G.S., 2007, Study of Arctic and Antarctic ice dynamics and wind field by using Formosat-2 satellite data. In *IGARSS*, 23–27 July 2007, Barcelona, Spain, pp. 1565–1568 (Piscataway, NJ: IEEE).

MURTHY, C.S., RAJU, P.V. and BADRINATH, K.V.S., 2003, Classification of wheat crop with multi-temporal images: performance of maximum likelihood and artificial neural networks. *International Journal of Remote Sensing*, **24**, pp. 4871–4890.

PIWOWAR, J.M., PDEELE, D.R. and LEDREW, E.F., 1998, Temporal mixture analysis of Arctic sea ice imagery: a new approach for monitoring environmental change. *Remote Sensing of Environment*, **63**, pp. 195–207.

ROYDEN, L.H., BURCHFIEL, B.C. and VAN DER HILST, R.D., 2008, The geological evolution of the Tibetan Plateau. *Science*, **321**, pp. 1054–1058.

SHEN, Z., LU, J., WANG, M. and BURGMANN, R., 2005, Contemporary crustal deformation around the southeast borderland of the Tibetan Plateau. *Journal of Geophysical Research*, **110**, pp. 1–17.

TURKER, M. and SAN, B., 2003, SPOT HVR data analysis for detecting earthquake induced changes in Izmit, Turkey. *International Journal of Remote Sensing*, **24**, pp. 2439–2450.

VAN WESTEN, C., 2002, Remote sensing and geographic information systems for natural disaster management. In *Environmental Modelling with GIS and Remote Sensing*, A. Skidmore (Ed.), pp. 200–226 (London: Taylor & Francis).

WANG, C.S., LIOU, Y.A. and YEH, T., 2008, Impact of surface meteorological measurements on GPS height determination. *Geophysical Research Letters*, **35**, L23809, doi: 10.1029/2008GL035929.

YANG, M.D., MERRY, C.J. and SYKES, R.M., 1999, Integration of water quality modeling, remote sensing, and GIS. *Journal of American Water Resources Association*, **35**, pp. 253–263.

YANG, M.D., YANG, Y.F. and HSU, S.C., 2004, Application of remotely sensed data to the assessment of terrain factors affecting Tsao-Ling landside. *Canadian Journal of Remote Sensing*, **30**, pp. 593–603.

YUSUF, Y., MATSUOKA, M. AND YAMAZAKI, F., 2003, Detection of building damages due to the Gujarat, India earthquake using satellite remote sensing. Available online at: http://www.edmbosai.go.jp/Landsat/paper_landsat.pdf (accessed 10 March 2003).

XU, G. and KAMP, P.J.J., 2000, Tectonics and denudation adjacent to the Xianshuihe fault, eastern Tibetan Plateau: constraints from fission track thermochronology. *Journal of Geophysical Research*, **105**, pp. 19231–19251.

XU, Z., JI, S., LI, H., HOU, L., FU, X. and CAI, Z., 2008, Uplift of the Longmen Shan range and the Wenchuan earthquake. *Episodes*, **31**, pp. 291–301.