DETECTION OF THE FLOODED AREA BY TSUNAMI USING SATELLITE THERMAL INFRARED IMAGES

Daiki HANADA[*1] and Fumio YAMAZAKI [2]

[1] Graduate student, Department of Urban Environment Systems, Chiba University,
1-33, Yayoi-cho, Inage-ku, Chiba, 263-8522, Japan; Tel: +81-43-290-3528
E-mail: d.hanada@chiba-u.jp

[2] Professor, Department of Urban Environment Systems, Chiba University,
1-33, Yayoi-cho, Inage-ku, Chiba, 263-8522, Japan; Tel: +81-43-290-3557
E-mail: fumio.yamazaki@faculty.chiba-u.jp

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ABSTRACT: Heavy casualties and severe property losses occurred by the tsunami in the Off Pacific Coast of Tohoku, Japan Earthquake on March 11, 2011. Satellite visible images are easy to grasp damages caused by disasters, but they cannot be obtained in nighttime. Hence a blank time of information may occur if a disaster happens in nighttime. On the other hand, a satellite thermal infrared image can be taken in nighttime while it has an inferior spatial resolution. It is also expected to grasp flooded areas by tsunami using the temperature distribution from thermal infrared band images. In this study, the extraction of flooded areas was carried out by superimposing ASTER thermal infrared band images captured before and after the Tohoku earthquake, obtaining the difference in temperature. This result was compared with the flooded area map that was created by the interpretation of aerial photos and site investigations. The comparison shows a reasonably good agreement although the times of acquiring the post-event images were not the same. A further improvement of flooded area extraction may be achieved by introducing land-cover information and DEM data.

1. INTRODUCTION

Heavy casualties and severe property losses occurred by the Tohoku, Japan Earthquake on March 11, 2011. In particular, the tsunami damage was significant causing transportation and information network to be suspended, by which it became difficult to grasp the overview of damage distributions. Early damage detection is very important to engage in the rapid response to disasters. Remote sensing is widely used especially for the sites where access from the ground is limited and damage distributes cover wide areas (Mitomi et al. 2000). However, it generally takes time to process the satellite images and aerial photos by visual interpretation to recognize the damage distribution by tsunami although it is relatively easy. Several researchers have studied an automatic extraction method of flooded areas from ASTER images with the use of NDVI, NDSI and NDWI indices (Kouchi and Yamazaki, 2007). However, many of satellite images such as visible and near infrared images cannot be used during nighttime, and thus "blank time" may occur. On the other hand, thermal infrared images can be used during daytime and nighttime without depending on sunlight (Hanada and Yamazaki, 2011). Yamazaki et al. (2009) confirmed that clear edges of buildings, roads, and greens can be extracted by aerial thermal infrared images of urban regions. Although spatial resolution of satellite thermal infrared images are inferior than aerial thermal infrared images, it is possible to grasp large scale disasters like massive inundation by tsunami. To grasp the flooded areas can be carried out easily and quickly, taking the temperature differences of pre- and post-event satellite thermal infrared images, and hence it is possible to eliminate the blank time in nighttime.

In this study, flooded areas are extracted by superimposing and taking the temperature difference of ASTER thermal infrared band images taken before and after the Tohoku earthquake. The accuracy of the extraction method by thermal infrared images is discussed compared to the inundated area map by Geospatial Information Authority of Japan (GSI). A further improvement of flooded area extraction is expected in a future by introducing land-cover information, which may lead to a rapid response by quickly recognizing tsunami effects' distribution.

2. THE 2011 OFF THE PACIFIC OF TOHOKU EARTHQUAKE

The 2011 off the Pacific of Tohoku Earthquake occurred on March 11 at 14:46 (JST). The epicenter was approximately 130 km offshore from the Oshika Peninsula in Miyagi Prefecture at the depth of 25 km. Earthquake magnitude was 9.0 which is the largest in Japanese historical events. Sever damages were caused by tsunami with its heights greater than 8.5 m in Miyako City (Iwate Prefecture), 8.0 m in Ofunato (Iwate Prefecture), 7.7 m in Soma City (Fukushima Prefecture), and 7.6 m in Ishinomaki City (Miyagi Prefecture). Tsunami ranged across the Pacific Ocean along the coast from Hokkaido to the Kanto region, caused extensive damages over a wide area (The Headquarters for Earthquake Research Promotion, 2011). A large number of aftershocks followed the main shock, and a high probability of new great earthquakes. Rapid countermeasure for earthquakes and the responses to disasters are strongly desired.

3. RESERCH METHODOLOGY

3.1 Analysis Data

In this study, the detection of flooded areas was carried out for the Tohoku earthquake/tsunami. As a study area, Ishinomaki City in Miyagi Prefecture was selected where serious damage was observed by tsunami (Figure 1a). To detect the flooded areas, thermal infrared images captured before and after the Tohoku earthquake were compared. To eliminate the seasonal variations in temperature as much as possible, pre- and post-event images taken in the same month in different years were used. Figure 1b and 1c are ASTER thermal infrared images taken on April 7, 2009 and April 6, 2011, covering the same area near the Ishinomaki region. Since the images immediately after tsunami was not available under a fine weather condition during nighttime, the daytime images one month after the earthquake was used. To visually understand the temperature changes, a different color was assigned for each image, to calculate the absolute difference by superimposing those.

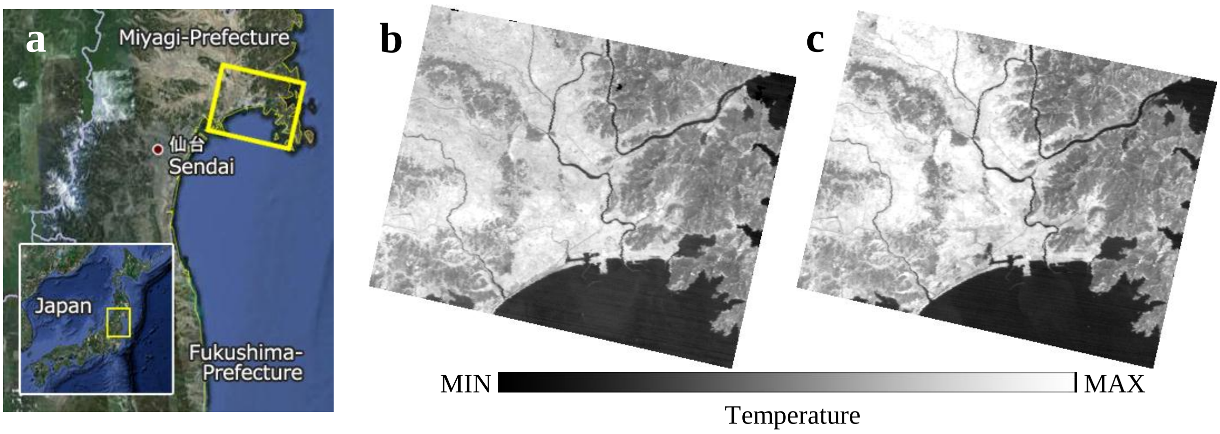

Figure 1. a: Study area, b: Thermal infrared image of April 7, 2009 at 10:33:38 (JST), b: Thermal infrared image of April 6, 2011 at 10:26:03 (JST). Clipped for Ishinomaki City, Miyagi Prefecture.

3.2 Estimation of Flooded Areas from Superimposed Thermal Infrared Images

ASTER thermal infrared sensor has 5 bands ranging from band10 to band14. Each band can observe wavelength from 8.125 to 8.475 μm, 8.475 to 8.825 μm, 8.925 to 9.275 μm, 10.25 to 10.95 μm, and 10.95 to 11.65 μm, respectively. The band10 images were used here since any difference could not be observed throughout 5 bands. The minimum size of the detected area is order of 100 m because spatial resolution of thermal infrared band is 90 m.

First, the thermal infrared images before and after the earthquake were superimposed using the image analysis software of ENVI. Panchromatic images represented by black to white colors were reassigned by other colors before superimposing those. The pre-event image is colored by red and the post-event image cyan. As a result, red was colored where the temperature is lower than the pre-event image and cyan was colored where the temperature is higher than the pre-event image after taking the difference between those images. By this process, temperature changes are illustrated visually. In the following section, the accuracy of the extracted areas is discussed, comparing to the false color image at same area.

3.3 Field Survey in Ishinomaki City

Site investigation in periphery of Ishinomaki City was carried out on July 10, 2011 at 10:00 to 20:00. As a purpose of investigation, the conditions of flooded areas were observed with the variation of temperatures between the daytime and nighttime depending on land covers. During the field survey, the estimated flooded areas from the thermal infrared images were compared with the inundated map created by GSI. Then the site investigation was performed especially at the sites where the large temperature difference was observed or the temperature change was observed over wide areas in the previous analysis. During the field survey, a small thermal infrared camera (NEC, TH9100MV) was used to record the temperature distribution of disaster areas including debris, buildings, and flooded areas. In addition, the outside the flooded area was also investigated where the large temperature differences were observed by the estimate flooded area map.

4. RESULTS

4.1 Superimposition of Thermal Infrared Images Acquired Before and After Tsunami

Figure 2a and 2b show a pre- and post-event image, respectively. Figure 2c shows the estimated flooded area by taking the difference of those images. Figure 2d shows extracted areas where the temperature is lowered in the post-image compared to the pre-image. Figure 3 shows the magnified images of two places surrounded by rectangles in Figure 2d. For a comparison, false color composites of the images taken before and after the earthquake are shown in Figure 4 for these locations.

Figure 3a and 3b shows the magnified images of region (1) in Figure 2d. There are many paddy fields in this region of Higashi-matsushima City. In this place, tsunami run up along Sada River and caused heavy damages in inland areas away from the coastline. From Figure 3a, large areas have still lowered temperature compared to that before tsunami although it was approximately a month after. This is because that flooded seawater was easily sustained due to many paddy fields. Figure 3c and 3d show the magnified images of region (2) in Figure 2d near the estuary of Kitakami River in Ishinomaki City. Similar to region (1), tsunami run up along the river and caused extensive damages. From Figure 4d, the land near the estuary was washed by tsunami, which left the flooded areas as seen from the image. In addition, paddy fields were still flooded by seawater with the lower temperature than before the earthquake.

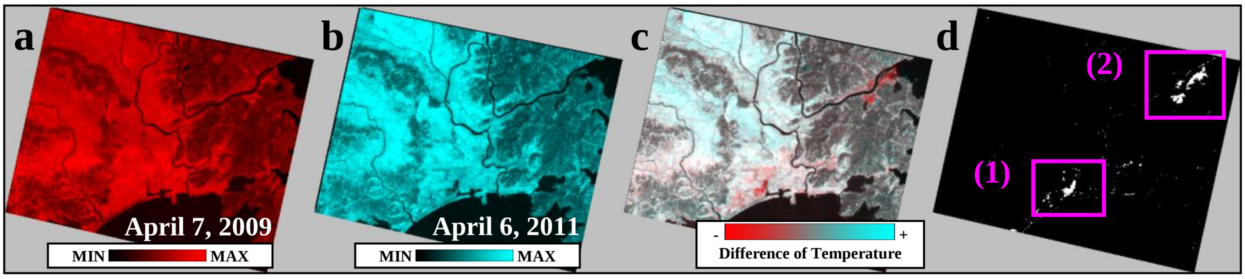

Figure 2. a,b: Colored images on 7 April 2009 and 6 April 2011, c: Temperature difference of the two images, d: The area whose temperature is lower than pre-event one (red area).

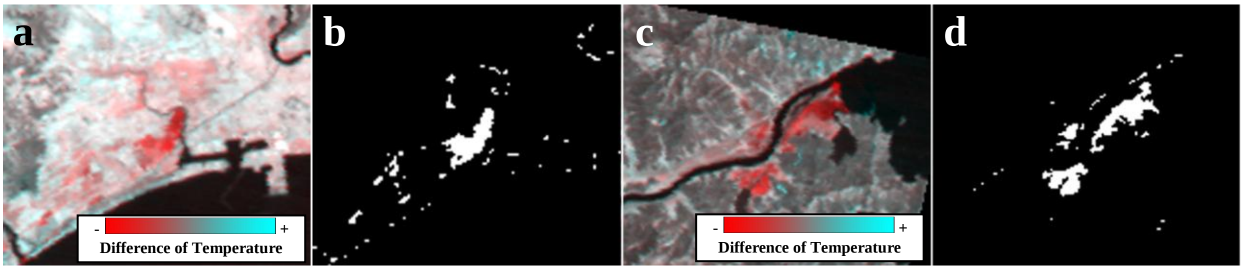

Figure 3. a,c: Enlargement of areas (1) and (2) in Figure 2d, b,d: The areas with lower temperature than the pre-event one (red areas).

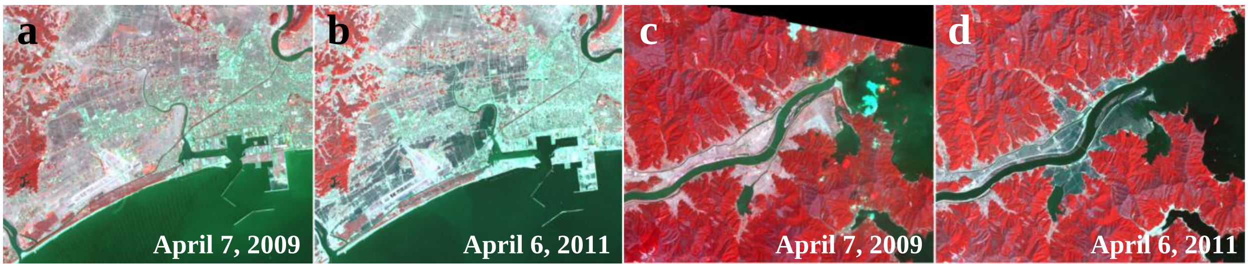

Figure 4. a,b: False color composite of the images before and after the earthquake in (1), c,d: that in (2).

Compare the extracted results from the superimposed images in Figure 3 with false color composites in Figure 4, the flooded areas were relatively in good agreement, which verifies the efficiency of the extraction method for flooded areas. However, thermal infrared images are affected by temperature, weather and season, which required the further discussion if this method is applied to the different situations. It is expected that this methodology may work better to understand the damages during nighttime since water temperature tends to be higher than the others because water has large heat capacity. However, a further discussion is still necessary.

4.2 Comparison with Inundated Area Map by GSI and Consideration from Site Investigation

Figure 5 shows the extracted areas where temperature increased or decreased after tsunami, superimposing on an inundated area map created by GSI. The inundated areas provided by GSI are displayed by blue color whereas the map is displayed in gray scale. Areas displayed by green colors were where temperature increased after the earthquake, whereas areas displayed by red were where temperature decreased after the earthquake. Areas where the temperature decreased after the earthquake match with the inundated areas by GSI, indicating the efficiency of the extraction method proposed in this study.

In site investigation, to grasp condition of the estimated flooded areas based on Figure 5. At region (1) in Figure 5 in Higashi-matsushima and Ishinomaki cities, it was confirmed that many areas with the lower temperatures than those before the earthquake were paddy fields, which can retain the water easily. In addition, many buildings were washed away by tsunami, which left vacant lots behind. In the region (2) in Figure 5 where Onagawa City locates, most of buildings were washed away by tsunami although the flooded area was small. It is noted that there are two places outside of the inundated area in region (2) where temperature was increased after the earthquake. By performing site investigation, it was confirmed that soils were exposed for these sites by deforestation, which increased the temperature easily. At the region (3) in Figure 5, where is the downstream of Kitakami River, it was confirmed that these areas still sustained the waters after four months from the earthquake. Paddy fields also exist along the river for

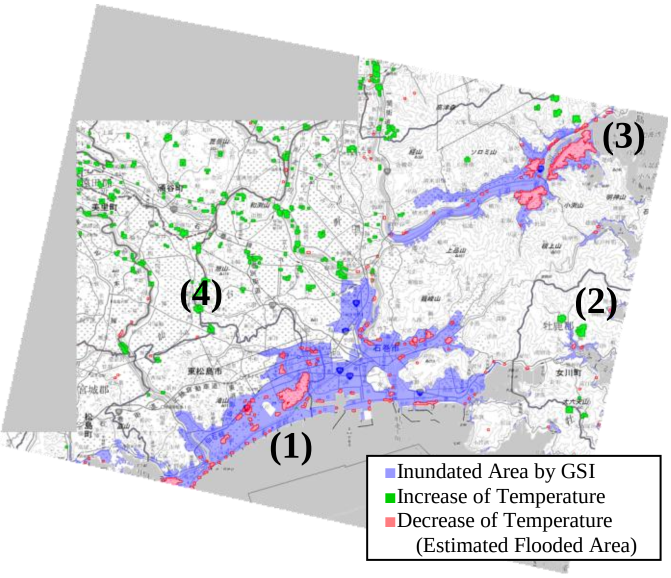

Figure 5. Superposition of large temperature difference areas on the inundated area map by GSI. The estimated flooded areas were confirmed by the flooded areas by GSI.

Table 1. The typical temperatures depending on the land covers

Land Cover	Temperature(^{o}C)	
	Daytime	Nighttime
Asphalt	60	30
Gravel	60	30
Debris	50~	20~30
Concrete	50	30
Paddy Field (dry)	50	25~30
Paddy Field (wet)	30~40	25
Grass	30~40	20~25
Flooded Area	20~30	25~30

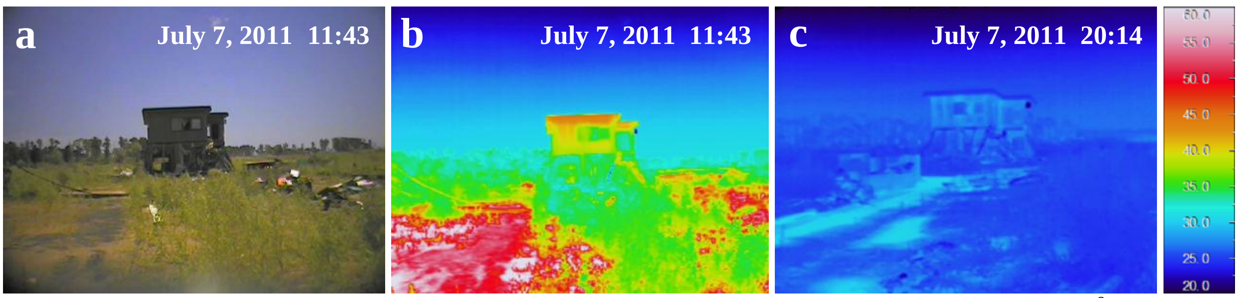

Figure 6. a: Optical image of daytime, b,c: Thermal infrared images of daytime and nighttime (Unit: ^{o}C). A house in a tsunami affected area is shown.

this region filled with seawater and debris after the earthquake. At region (4) in Figure 5, where is outside of the inundated area in Kitahara, Ishinomaki City, there are many places showing increased temperature areas after the earthquake. By the site investigation, it was confirmed that these areas were along the agricultural waterway. Since water has large heat capacity, temperature may be affected by the previous day's weather. However, it is not clear for the details.

During the site investigation, temperature distributions of each land-cover were studied in daytime and nighttime as well as the visual inspection of the estimated flooded areas. Table 1 shows the typical temperatures depending on the land-covers in disaster area. Figure 6 shows sample images taken by the thermal infrared camera, which shows a wooden house in inundated areas in Higashi-matsushima City. At this site, all the houses were washed away by tsunami except for the house in the image, by which the field of grasses and soils were created. In daytime, asphalt, concrete and the vacant lots created by tsunami had the temperature of about 70 ^{o}C. But the debris had the lower temperature of approximately 50 ^{o}C compared to the vacant lots. The flooded area had much lower values, approximately 20 ^{o}C, comparing with the surroundings. In nighttime, most of the materials showed the temperatures of around 30 ^{o}C. As it is expected, the temperature of water did not vary depending on daytime or nighttime since it has large heat capacity. Table 1 also shows that the temperature is small in nighttime compared to daytime. However, it is noted that the relatively clear contours of objects were obtained in nighttime by setting the range of display from 20 to 30 ^{o}C for the thermal infrared images. ASTER thermal infrared images cannot capture the temperature for the specific object since the resolution is 90 m. However, it can provide the category of land-covers such as green areas, building areas, and water areas by using the field investigation results as a reference. Since the temperature properties of each land-cover and the estimated flooded areas were relatively in good agreement, ASTER thermal infrared images will be used sufficiently at nighttime for the early detection of tsunami flooded areas.

4.3 Variation of Thermal Infrared Images after the Earthquake

Figure 7 shows thermal infrared images on April 6, June 9 and July 11, 2011 after the earthquake, superimposing with that on April 7, 2009. Table 2 shows properties of the three post-event images. In Figure 7c, deep red areas which were found at the left side of the image were caused by clouds. In the image of after June, sea areas and green areas became cyan, indicating the increase of temperature, which matches to the increase of the air temperature in Table 2.

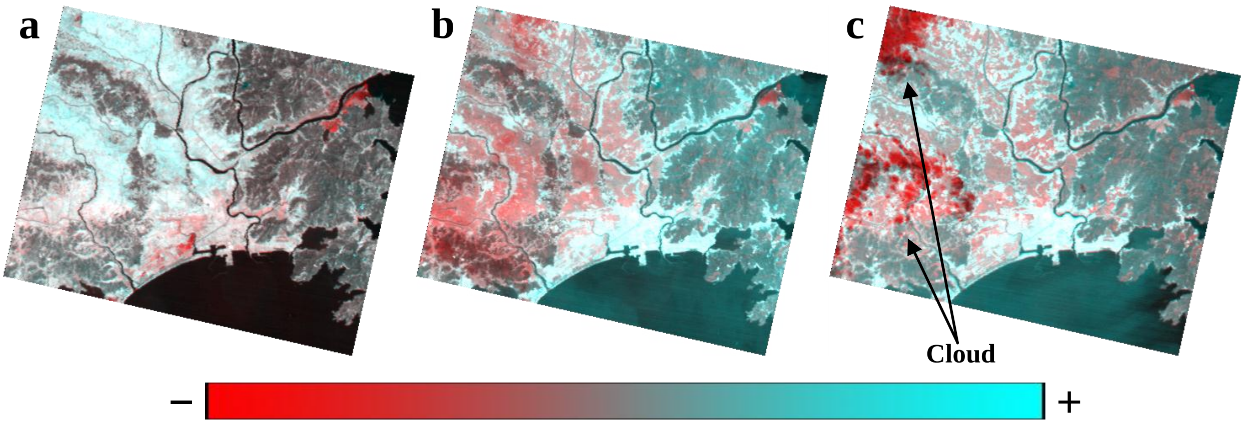

Figure 7. Land-use monitoring after the earthquake by thermal infrared images on April 6, June 9 and July 11, 2011 after the earthquake, superimposing with that on April 7, 2009.

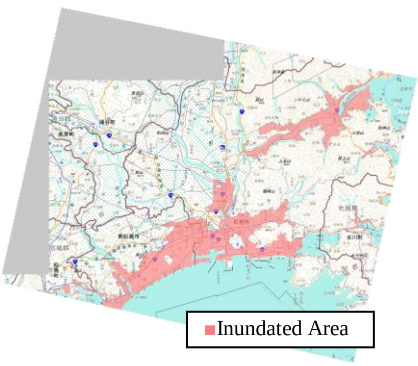

Figure 8. Inundation area map by GSI.

Table 2. Property of each thermal infrared image

Images	Date	Time (JST)	Max Air Temp (^{o}C)
-	April 7, 2009	10:33:38	19.6
Fig 7a	April 6, 2011	10:26:03	18.6
Fig 7b	June 9, 2011	10:26:03	23.4
Fig 7c	July 11, 2011	10:26:10	31.5

There are many areas showing red color at the center of the images indicating the decrease of temperature. This is because that the paddy fields at this area were filled with water for rice planting after the period of June, whereas many paddy fields in the flooded area in Higashi-matsushima and Ishinomaki cities showed the small increase of temperature after June as described in section 4.1.

These increased temperature areas are relatively in a good agreement with the inundated area map provided by GSI in Figure 8. This is because that the paddy field filled with sea water by tsunami cannot grow crops for a certain period, which kept the flooded condition after the earthquake. During the site investigation in Higashi-matsushima and Ishinomaki cities, the accumulate sea water had already gone, almost all the areas were dry condition. And this place has many vacant lots by tsunami. It is understood that these conditions created the increase of surface temperature of flooded areas, and it is concluded that ASTER thermal infrared images can be used effectively for the detection of flooded areas, and land-use monitoring after the earthquake.

5. CONCLUSION

In this study, ASTER thermal infrared images were used to grasp a tsunami disaster by the off the pacific of Tohoku earthquake occurred in March 11, 2011. Superimposed thermal infrared images before and after the earthquake were analyzed to estimate the flooded areas by taking the temperature difference between these images; the pre- and post-event image were assigned by red and cyan colors, respectively. Therefore decreased temperature areas were displayed in red, and increased temperature areas were displayed in cyan. The flooded areas were assumed to have lower temperatures after tsunami and extracted based on the superimposed images. These results are compared with an ASTER false color composite and they show the good agreement with the inundated area map created by GSI.

Site investigation was performed for the flooded areas. Variation of temperatures depending on the land-cover was studied to provide the relationships of those for more accurate detection of flooded areas. The difference of temperatures obtained from the superimposed images before and after the earthquake was explained physically based on the temperature properties of each land-cover observed during the site investigation. Therefore, ASTER thermal infrared images will be sufficient for early detection of the tsunami disasters.

By analyzing the variation of temperature differences against time with several post-event images reference to the same pre-image, it was confirmed that those data can be used for understanding the land-use condition after tsunami. Especially for paddy fields, temperatures increased if those were not used after flooded. Although a further study is required to discussing the accuracy of those observations, it may be concluded that thermal infrared images can be used to monitor the land-use conditions after tsunami disasters.

In future, nighttime thermal infrared images are necessary to be used to verify whether the same method is applicable. Thermal infrared images are affected by air temperatures, seasons, weathers and clouds, therefore may be difficult to provide those by the same condition. If thermal infrared images are not enough available, it needs to consider to create a methods that use GIS data as pre-event images. In addition, it must be discussed more on the temperature properties and their accuracy, to establish an early detection method of future tsunami disasters.

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