Assessment of Tsunami Flood Situation from the Great East Japan Earthquake

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Abstract

The massive tsunami from the 2011 off the Pacific Coast of Tohoku Earthquake (hereinafter referred to as the "Tohoku Pacific Coast Earthquake") that occurred on March 11, 2011, caused devastating damages along the Pacific Coast. The GSI immediately formed an emergency team and started investigating to uncover the situation of tsunami damage.

We emphasized on promptness in the beginning of the survey, created the "Tsunami flood area overview map" with a purpose of improving the accuracy in our best effort over time, and kept on distributing the maps to the municipalities of the affected areas, the national disaster response headquarters etc, while also releasing this information on the GSI website. In addition to calculating the areas of inundation by the municipalities and by land use, an attempt was made to analyze the distance and elevation reached by tsunami in coastal Miyagi Prefecture. Furthermore, elevation was measured precisely by aerial laser survey mainly on areas where ground subsidence occurred due to the earthquake, and high precision elevation data and the digital elevation topographic map have been prepared/provided.

1. Creating an inundation area overview map

1.1 Method of creation

Immediately after the tsunami disasters triggered by the Tohoku Pacific Coast Earthquake on March 11th, the GSI decided to create an "Tsunami flood area overview map" to find out the situation of tsunami damage, and created a damage overview map and also discussed about the methods/target regions for the Tsunami flood area overview map in the meantime until aerial photograph data was available.

The Tsunami flood area overview map was created by two teams: the "Interpretation Team" who records the results of aerial photointerpretation onto a 1:25,000 topographic map, and the "Digitization Team" who processes this information into digital data by Geographic Information System (GIS). Normally in aerial photointerpretation, the photographs are either printed onto photographic paper or printed out as hard copies to visually compare them in pairs and observe the landscapes and features in details. However, since it was required to promptly interpret a large number of aerial photographs this time, the Digitization Team prioritized the speed at first by interpreting with single (aerial) photograph data. Specifically, they displayed high resolution image data on the computer screen, checked for the presence of rubbles by zooming in where necessary, and then recorded the inundated areas on the topographic maps.

There are two types of error cause which are "interpretation error" and "error in transferring onto topographic map". Since single (aerial) photographs are used for the interpretation, difference in landform interpretation skills has little effect on the former, whereas landform interpretation skills would be required to minimize the latter. Thus it was decided to place those who are experienced in landform interpretation in charge for all interpretations this time as well.

1.2 Standard for interpretation

Interpreting the extent of tsunami is an act of recording spots where the water depth was 0 m from the ground level in areas inundated by tsunami. Generally, it is difficult to judge whether tsunami had reached such spots. Also, eight persons were assigned to the interpretation task, but it is not favorable to have different judgments by the interpreter. To avoid this, we set interpretation standards such as "flood", "destruction of buildings", "forest denudation/destruction", "tsunami flood trace on paddy fields and villages" and "scattering of rubbles/driftwood", and also performed crosschecks by multiple interpreters to improve the accuracy.

1.3 Interpretation and digitization

In early afternoon on March 13th, we received the aerial photograph data (southern Miyagi Prefecture/northern

Fukushima Prefecture) captured on the previous day, and started the interpretation work at 13:40. The results were constantly sent to the Digitization Team and digitized on GIS by six persons. Interpretation of the portion captured on the 12th was completed in less than 3 hours, and digitization was completed in 4.5 hours. Then the data was checked and mapped, and the GSI Tohoku Regional Survey Department started providing the data to public organizations such as on-site Disaster Response Headquarters from 14th the next day.

2. Announcement of tsunami flood area sizes (approximate numbers)

Interpretation/digitization of the aerial photographs (1,886 in total) captured on March 12/13th was completed by the evening of 15th, and the Tsunami flood area maps for Iwate and Aomori Prefectures were provided in the same night. On the other hand, we were unable to take additional aerial photographs from the 14th due to bad weather conditions in the Tohoku region.

As a tentative measure, we summed up the tsunami flood area sizes by the municipality from the inundation area maps that had already been created. At this point, the area covered from north to south was between Hachinohe City of Aomori Prefecture and Soma City of Fukushima Prefecture. It must be noted, however, that we were unable to grasp the overall picture of the tsunami flood area because only a few strips of aerial photographs were taken in the north area from Ishinomaki City. Upon calculating the area sizes, we clarified the areas that had already been photographed to avoid any misunderstanding, and also announced the areas scheduled to be photographed at the same time.

On March 18th which was one week after the earthquake, we held a press release on "Tsunami flood area sizes (approximate numbers)", and released the tsunami flood area sizes by the municipality as well as the "Inundation area overview map" on the GSI website.

As the photographing progressed, the Tsunami flood area overview map was additionally modified on March 24th and April 4th, and then the tsunami flood area sizes were updated.

3. Release of “Tsunami flood area overview map” of the entire area

On April 8th, interpretations were completed for the aerial photographs captured by GSI from Rokkasho Village (Aomori) to Minamisoma City (Fukushima) and for the satellite images of the region where flying restrictions were imposed due to the accident at the Fukushima Daiichi nuclear power plant. Then the Tsunami flood area overview map and tsunami flood area sizes were released on the GSI website. After that, we obtained aerial photographs of coastal Chiba/Ibaraki captured on March 12th and 27th by Chiba Prefectural Government and others, and conducted interpretation/digitization including the satellite images of southern Iwaki City, then released the "Tsunami flood area overview map" (Figure 1) from Aomori to Chiba Prefecture on April 18th.

This meant the completion of interpretation for the entire area along the Pacific Coast that supposedly experienced flood damages by this tsunami.

4. Land use in tsunami flood area

The land use map was created by combining the interpretation results of the tsunami flood area and the land use subdivision mesh data of digital national land information. Land use classification is a collection of several items from the digital national land information "Land use subdivision mesh data" (FY 2006) released by the National and Regional Planning Bureau of Ministry of Land, Infrastructure, Transport and Tourism, then reclassifying the data as shown in Table 1. From the land use map of the tsunami flood area, the section from Matsushima Bay to Sendai Plain (Matsushima Town, Matsushima District to Watari Town, Watari District of Miyagi Prefecture) is shown in Figure 2.

Figure 3 shows the area sizes by land use and by the municipality in the tsunami flood areas, calculated based on the land use map of tsunami flood area. Ishinomaki City recorded the largest Tsunami flood area size which exceeded 70 km^2, and its flood area size of building areas exceeds 20 km^2. In the order of tsunami flood area size, Minamisoma City, Higashimatsushima City and Watari Town exceeded 30 km^2 then followed by Iwanuma City, Soma City, Wakabayashi Ward (Sendai City), Natori City,

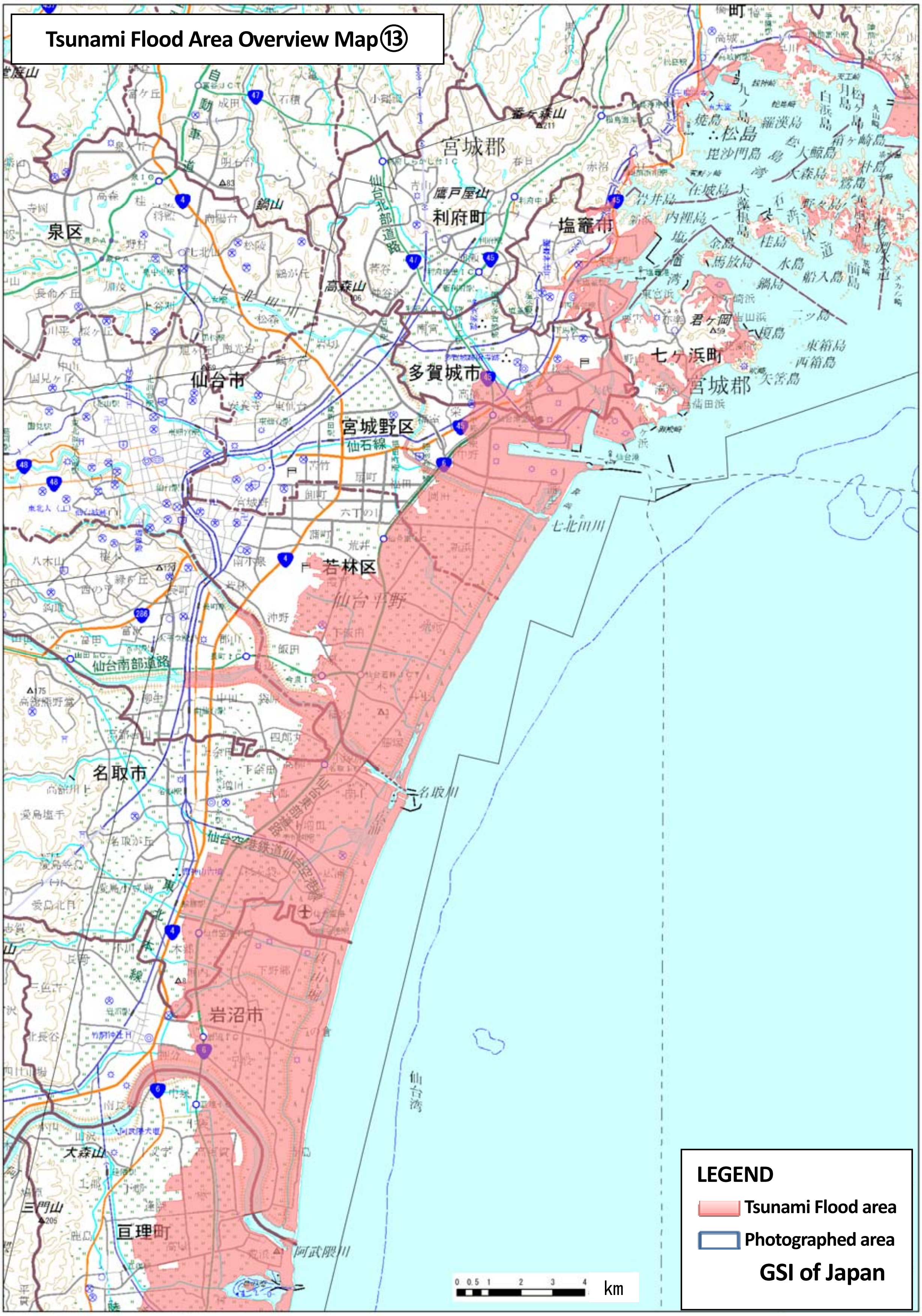


Fig.1 1:100,000 Tsunami flood area overview map (Sendai Area)

Land use classification in this survey		National Land Numerical Information Land use subdivision mesh data	
		Type of land use	Reference in definition
Building/arterial traffic site	Building	Building area	Residential/urban areas
	Arterial traffic	Arterial traffic area	Roads/railways/yards
Land for other use		Land for other use	Athletic complex, airport, race track/baseball field/ school port district/vacant artificial land, etc.
Paddy/other farmland/forest/wasteland/golf course		Paddy	
		Other farmland	
		Forest	
		Wasteland	
		Golf course	
Rivers and lakes/seashore/salt waters		Rivers and lakes	
		Seashore	
		Seawater	

Table 1 Land use classification

Yamamoto Town and Miyagino Ward (Sendai City) all exceeding 20 km^2, which indicates that the municipalities in Ishinomaki Plain and Sendai Plain occupy the top of the list.

When we looked at the tsunami flood area sizes of building areas by the municipality, high numbers were found in the area from the center of Iwate Prefecture to northern Fukushima Prefecture. In the order of tsunami flood area size by building areas, Ishinomaki City marked the highest number followed by Higashimatsushima City, Kesennuma City and Iwaki City all exceeding 5 km^2, respectively.

Also, Figure 4 shows the area size ratios of building areas inundated by tsunami in each municipality which are indicated with different colors. More than 50% in Otsuchi Town, Minamisanriku Town and Higashimatsushima City, and more than 40% in Rikuzentakata City, Ishinomaki City, Onagawa Town and Yamamoto Town were inundated.

Table 2 shows the land use component ratio of tsunami flood areas by the prefecture. Of the entire tsunami flood area, paddy field is the highest with 37%, followed by building area (20%), land of other use (10%), rivers and lakes (9%), and forest (7%). By the prefectures, Miyagi and Fukushima had high ratios of paddy field and Iwate had a high ratio of building areas, whereas Aomori, Ibaraki and Chiba marked high ratios of seashore and land for other use.

5. Analysis of tsunami travel distance and elevation

Using the data of the Tsunami flood area overview map released on April 18th, we targeted Miyagi Prefecture and analyzed the tsunami travel distance and elevation of the areas hit by the tsunami. Measurements were performed in the following method:

① Between the borders of Iwate and Fukushima in the Tsunami flood area overview map, count one mesh for longitude/latitude with a flood area boundary (sections of outer perimeter of the inundation extent polygon that are not shorelines such as coastlines) as 1 point, and randomly select 254 points reached by tsunami, then assign ID numbers clockwise from north along the coastline.

② On GIS, estimate the route from which the tsunami intruded into each spot in ①, then measure the distance (traveled by tsunami).

③ Measure the elevation of areas hit by the tsunami (points where boundaries are drawn on Tsunami flood area overview map) by overlaying the Tsunami flood area overview map and the high precision elevation data (DEM)

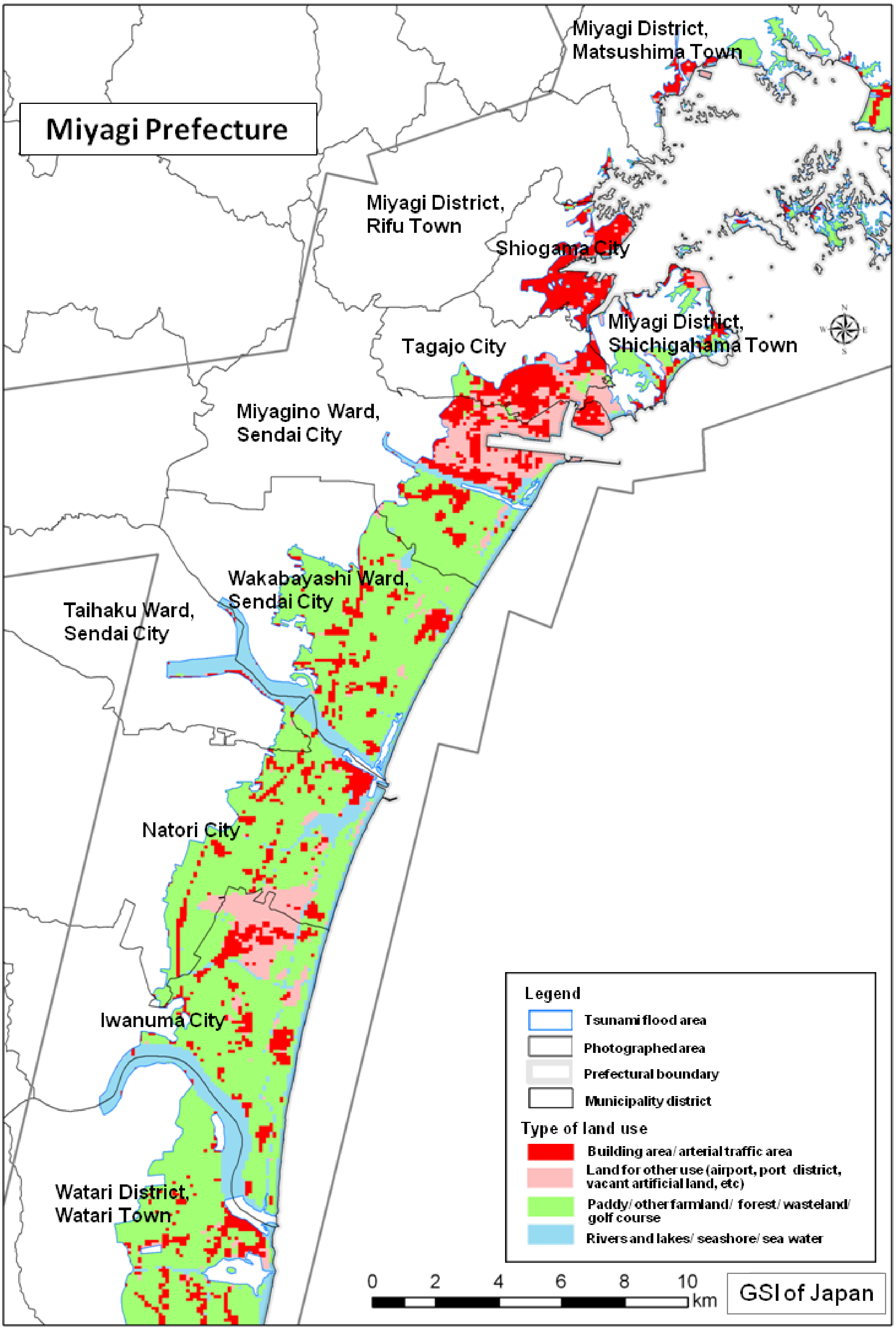


Fig.2 Land use map of tsunami flood areas (around Sendai Plain)

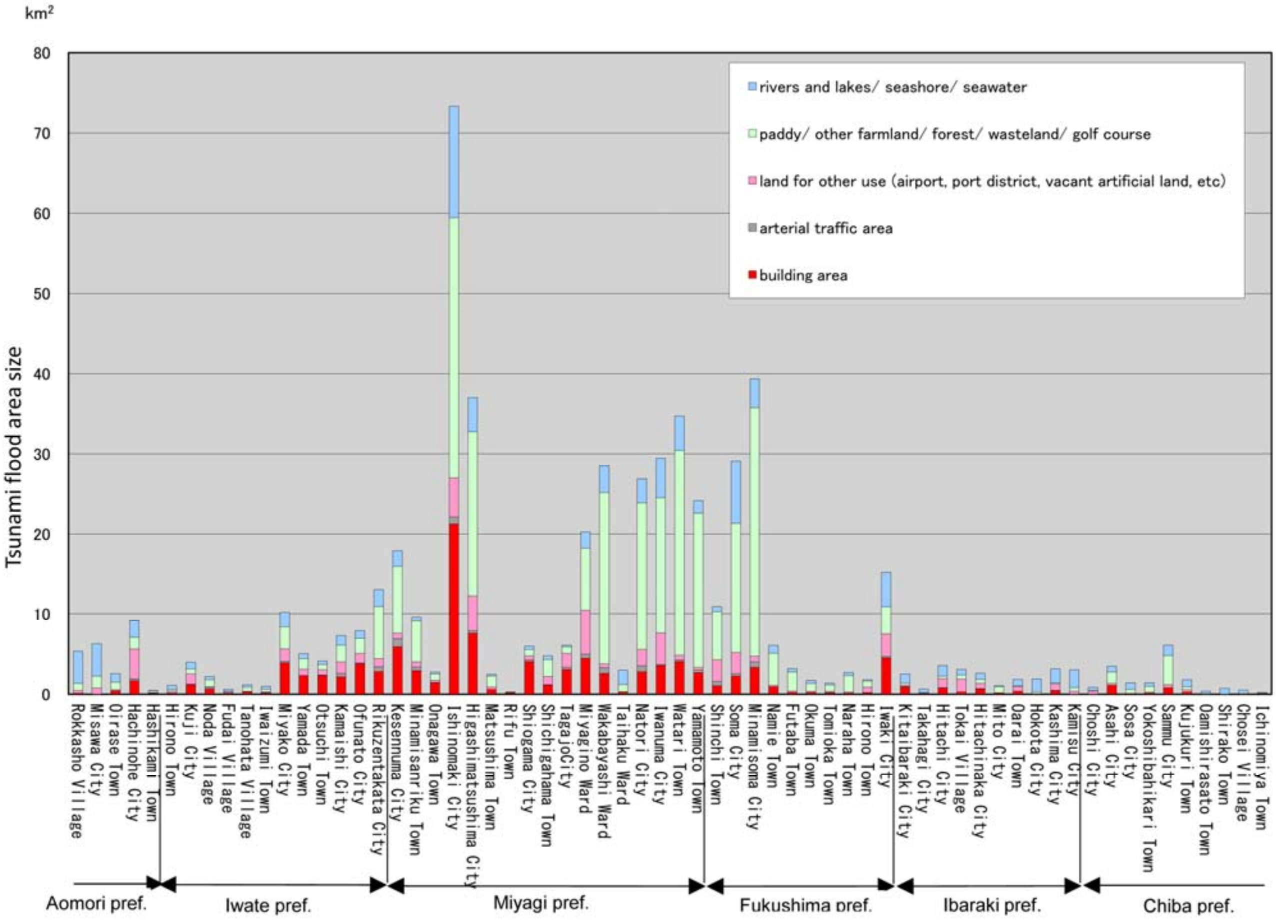


Fig. 3 Area sizes by land use in tsunami flood areas by the municipality

	Paddy	Other farmland	Forest	Wasteland	Building area	Arterial traffic area	Land for other use	Rivers and lakes	Seashore	Seawater	Golf course
Aomori	3%	2%	10%	6%	10%	1%	21%	9%	33%	6%	0%
Iwate	17%	4%	9%	1%	34%	3%	15%	10%	3%	4%	0%
Miyagi	41%	7%	7%	1%	21%	2%	8%	10%	2%	1%	0%
Fukushima	53%	3%	4%	1%	12%	2%	9%	7%	3%	7%	0%
Ibaraki	6%	2%	4%	1%	15%	1%	23%	6%	29%	12%	0%
Chiba	21%	6%	12%	2%	15%	0%	8%	2%	23%	12%	0%
Total	37%	5%	7%	1%	20%	2%	10%	9%	6%	4%	0%

Table 2 Land use component ratio of tsunami flood areas by the prefecture (%)

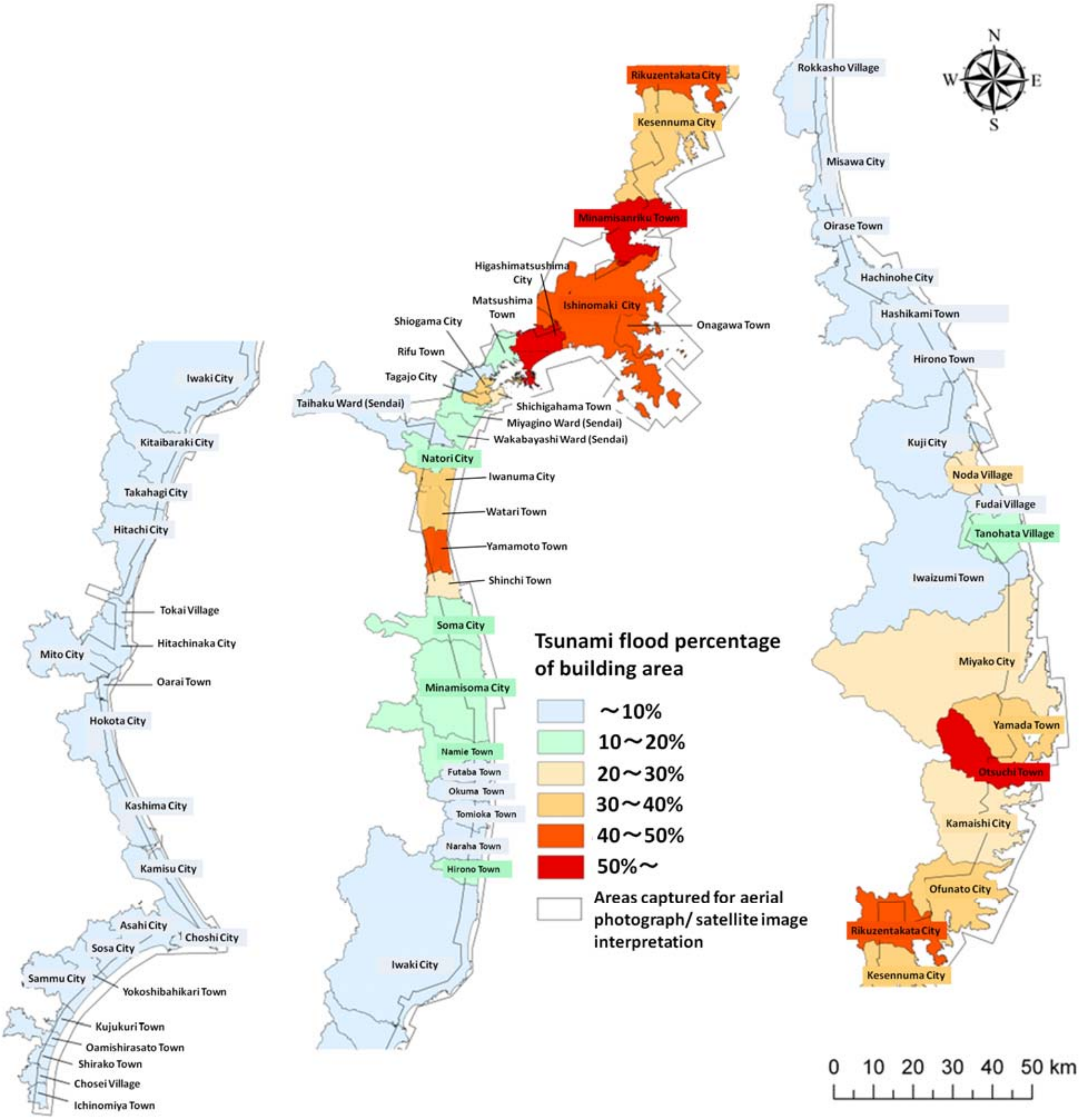
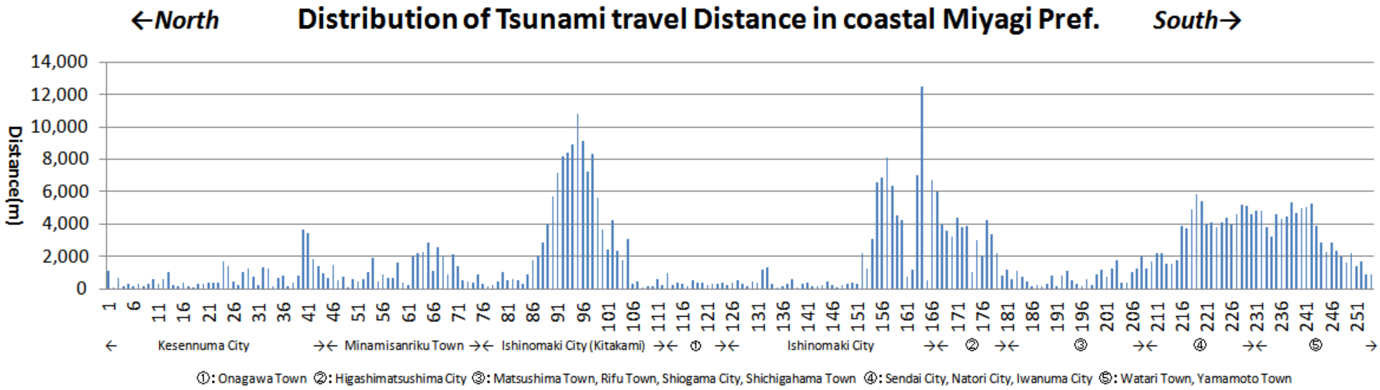


Fig. 4 Tsunami flood percentage of building area by the municipality

measured right after the disaster.

Figure 5 shows the distances and the heights reached by the tsunami from the Miyagi coastline with a graph (numbers on the horizontal axis indicate the ID numbers and municipalities). From this graph, it can be seen that the tsunami had reached 8 to 10 km or more off the coastline towards inland around Kitakami River and Old Kitakami River in Ishinomaki City. However, the elevation in this region was extremely low, ranging between 0 and 2 m. On the other hand, many spots with an elevation of 20 m or more can be found in ria coasts such as Kesennuma City and Minamisanriku Town.

Figure 6 is a graph showing an example of the relation between the distance and elevation reached by tsunami by the region. In low-lying regions such as the Sendai Plain, the height reached by tsunami decreases as the distance becomes greater off the coastline, which is something to consider when designing regional plans with a consideration of the elevation. In the northern part of Miyagi Prefecture which is a ria coast, the tendency varies with each gulf. For instance, the shore of Kesennuma Gulf (with the mouth of the bay facing south, the gulf is shaped narrow from north to south) does not seem to differ from the low-lying regions such as the Sendai Plain. On the contrary, at locations such as the shore of Shizugawa Gulf (with the mouth of the bay facing east, the gulf is horn-shaped) in Minamisanriku Town, there is a tendency for the elevation to increase as the distance becomes greater off the coastline.



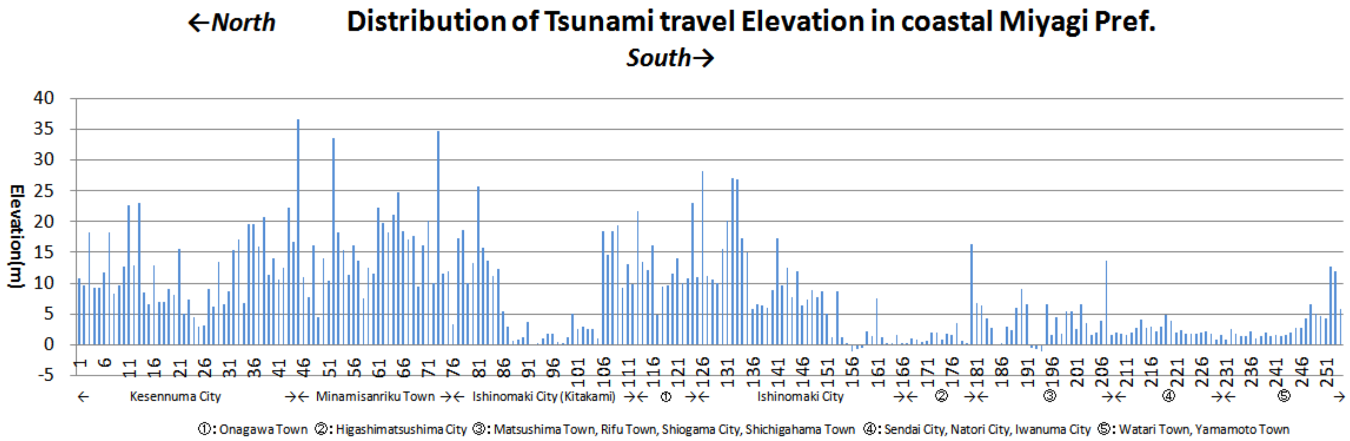
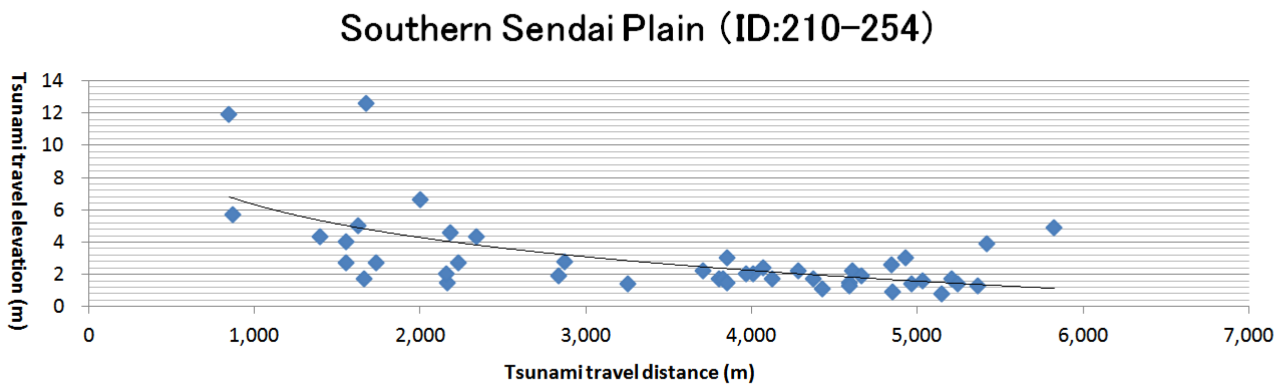


Fig. 5 Tsunami travel distance and elevation



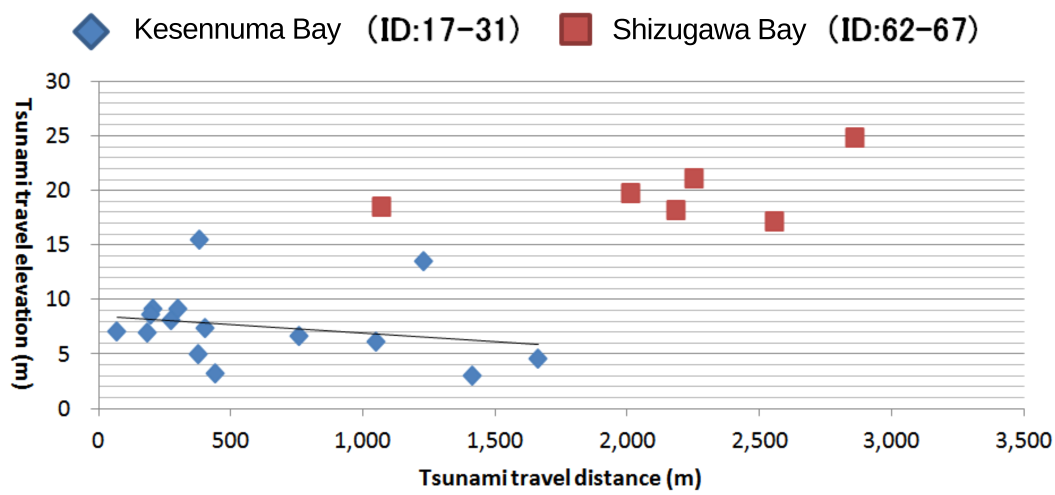


Fig. 6 Relation between tsunami travel distance and tsunami travel elevation

6. 1:25,000 Tsunami flood area map

Although a "1:25,000 manuscript map" was created since the interpretation results of the inundation area overview map had already been filled on a 1:25,000 topographic map and turned to GIS, this draft map does not satisfy the accuracy of 25,000 scale (for example, a topographic map includes building numbers which are not in the Tsunami flood area overview map) because speed was initially prioritized in the creation process. For this reason, the Tsunami flood area overview map was released as a 1:100,000 scale map in order to match its accuracy with the interpretation results.

However, since information with indications of the tsunami flood areas on a large scale map was necessary for the search of missing persons and recovery operations, we have been providing "manuscript maps" to public organizations such as the government and municipalities, on the condition that the accuracy of the information would be limited.

After releasing the overview map for the entire area on April 18th, the Interpretation Team performed interpretations once again to release the "1:25,000 Tsunami flood area overview map" at an early stage. In addition, the preparation of high precision elevation data by the post-quake aerial laser survey (see 8.) was almost complete by the end of April, which enabled us to perform checks base on this data. Hence it was assumed that the accuracy had improved by a certain level, and we also marked the inundated areas with the release of "1:25,000 digital elevation topographic map (PDF version)" created from the high precision elevation data mentioned earlier, and started releasing the information of Miyagi Prefecture from May 31st. Also, with the progress of the aerial laser survey, we started releasing a series of "1:25,000 Tsunami flood area overview maps" based on the Digital Japan Basic Map from June (Figure 7).

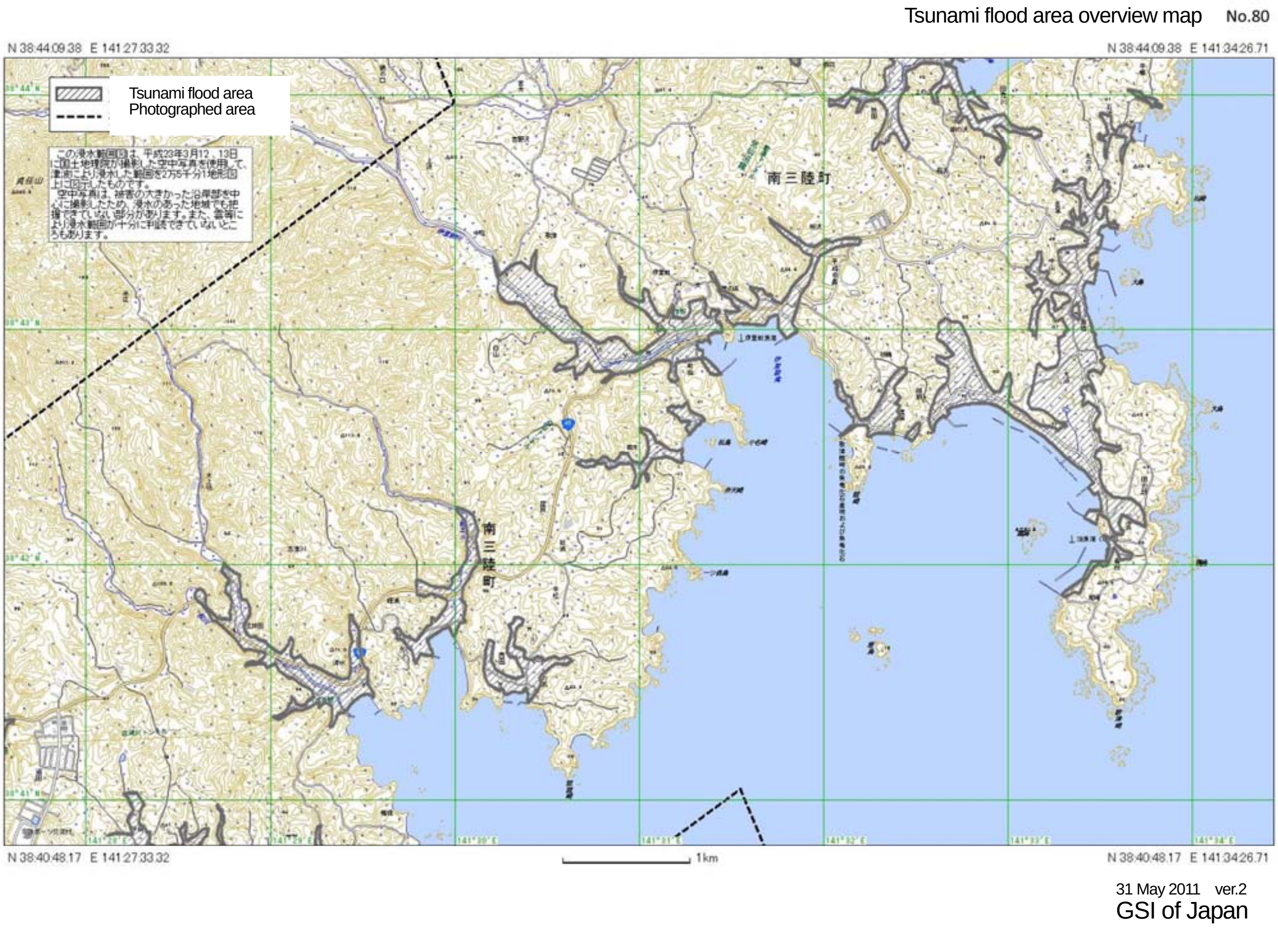


Fig. 7 1:25,000 Tsunami flood area overview map (Minamisanriku Area)
This tsunami flood area overview map was created by using the aerial photographs captured by GSI on 12/13 March, 2011 to map the tsunami flood areas on a 1:25,000 topographic map. Since aerial photography was conducted mainly in the coastal areas that suffered great damage, some tsunami flood areas may not be covered." Also note that some tsunami flood areas could not be completely interpreted due to the clouds, etc.

7. Survey of the damages and inundation extent in flood areas

7.1 Outline of survey

To investigate the building damages and inundation depths, field survey was conducted from Kuji City in Iwate to Iwanuma City in Miyagi using the Mobile Mapping System, while we also performed checks on the Tsunami flood area overview maps created from aerial photointerpretation.

Mobile Mapping System is a device capable of acquiring omnidirectional (360 degrees) image data, which can record the damages on individual buildings and roads by tsunami and the recovery situation such as the progress of debris removal as digital image information at eye level of citizens. By recording such data, we can share more detailed information of the affect areas with municipalities and the national organizations related to restoration work, which is essential for community-based restoration planning. This system allows for acquisition of accurate positional information by GPS and such, which enables 3D measurements (e.g. position, height) of the target on the image. In the survey, we acquired omnidirectional data around a highway with a total road length of approximately 700 km and measured the inundation traces left on the buildings to investigate the building damages and inundation depths.

7.2 Survey results on building damages and inundation depths

With an inundation depth around 1.5 to 2 m, many houses had retained their original shapes. When the depth was 3 to 4 m or above, many old wooden houses were completely destroyed. If the depth was 10 m or above, devastating damage was seen on most buildings except for a few robust, reinforced 4-5 storey buildings. It should also be noted that the inundation heights and the extent of damages on buildings vary depending the gulf shape or water depth.

7.3 Survey results on tsunami flood areas and extent

The tsunami flood areas and extent reached by tsunami were checked on site from the situation of rubble deposition and inundation traces on the buildings. When the traces were unclear, we conducted hearings from the local residents.

The results of on-site survey mostly matched with the Tsunami flood area overview map created from aerial photointerpretation.

8. Aerial laser survey and creation/provision of digital elevation topographic map

As mentioned earlier, the Tohoku Pacific Coast Earthquake caused ground subsidence in a wide area mainly around the Pacific Coast due to crustal movements, as well as landform changes by the tsunami. The GSI first coordinated with Miyagi Prefecture to immediately prepare high precision elevation data for coastal Miyagi area by using the data from the aerial laser survey that the prefecture conducted right after the disaster, and provided this data to associated organizations from late April.

Also, upon the passage of the first supplementary budget of FY 2011, we conducted aerial laser survey along the Pacific Coast between Iwate and Chiba Prefecture from May to obtain high precision elevation data of a large area to be used as basic documents for recovery/restoration plans, and then provided this data to associated organizations from late August. In addition, we prepared a 1:25,000 digital elevation topographic map which is the visualization of these results (Figure 8).

As of end of 2011, digital elevation topographic maps for which we conducted aerial laser survey in the area from Hirono Town in Iwate to Ichinomiyama City in Chiba along the Pacific Coast (except for some parts of Fukushima Prefecture), have been provided in 25,000 scale maps (40 sides in A0 format) to the affected municipalities and other associated organizations, and also released as PDF map images (205 sides in A3 format) on the GSI website. The A0 format maps are also scheduled to be provided in printed forms to the associated organizations. Note that all the high precision elevation data will soon be available to the public as the Fundamental Geospatial Data (5 m mesh elevation).

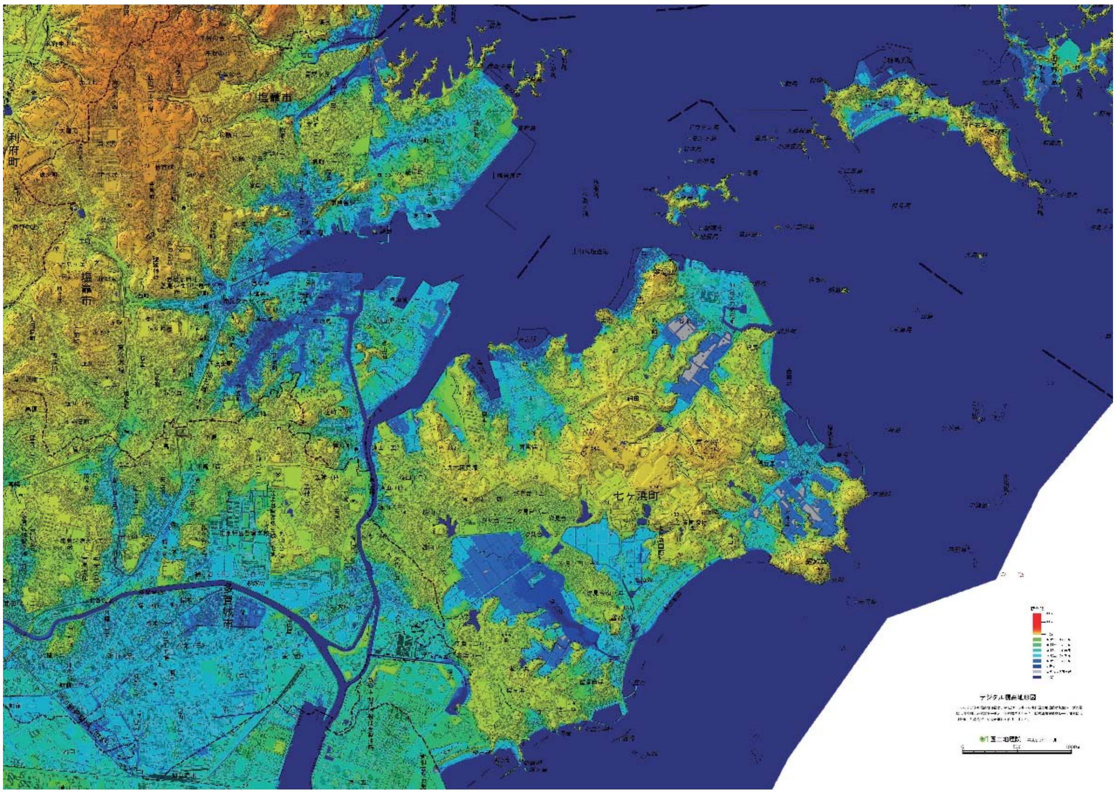


Fig. 8 1:25,000 digital elevation topographic map (Minamisanriku Area)

9. Conclusion

The Great East Japan Earthquake was a catastrophic disaster affecting an extremely large area, and an assessment of the situation was needed urgently. For the fact that we managed to grasp the damage situation by aerial photography and interpretation immediately from the day after the Tohoku Pacific Coast Earthquake and also provide Tsunami flood area overview maps from the fourth day with the cooperation of the GSI Tohoku Regional Survey Department in spite of very limited transport/communication infrastructures, we consider this result as an outcome of utilizing the experiences and technical strengths accumulated through our past disaster responses. For disaster responses in the future, it is necessary to summarize the experiences from this disaster while keeping up-to-date with new technologies. In particular, the high precision elevation data and the digital elevation topographic map which are products of aerial laser survey, turned out to be extremely useful for improving the interpretation accuracy and analyzing the tsunami flood areas. It indicates that these are also extremely effective for disaster prevention, that we need to expand the methods to utilize and notify the local authorities of such information.

As the Great East Japan Earthquake led to the reacknowledgment of the effectiveness of geospatial information in tsunami countermeasures, a budget to conduct aerial laser surveys in areas with possible disaster concerns such as "Chishima Trench earthquake" and "Tokai/Tonankai/Nankai earthquake" was approved at the third supplementary budget of FY 2011. Surveys have already been started in Tokushima/Kochi/Ehime/Miyazaki coastal regions where tsunami disasters by Nankai earthquake are concerned, and the results are expected to be available around April in 2012. For the other target regions, we also plan to start the surveys while taking into account the weather conditions.

In regard to the affected areas of the Great East Japan Earthquake, it is expected of the whole nation to deal with the recovery/restoration on a continuous basis. Also, earthquakes are something that cannot be avoided for us living in the seismically active Japanese Archipelago. However, we have also learnt from the lessons in the past that damages can be dramatically reduced by implementing prevention measures in advance. We would like to continue giving our best effort so that fundamental geospatial information such as aerial photographs, maps and high precision elevation data will be of any assistance in building disaster-resistant, vibrant regions, as well as for the purpose of disaster prevention/minimization.

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