Ishinomaki Tsunami Intensity Mapping ($ITIS_{2012}$) for the 9Mw Tohoku Event, March 11 2011, Japan

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Abstract

The study applies the Integrated Tsunami Intensity Scale[1] ($ITIS_{2012}$) criteria to map the tsunami intensities distribution in the broader Ishinomaki area, for the 9Mw March 11, 2011 event offshore Tohoku, Japan. Reports, satellite imagery and published point and zone data were taken into account to rank the impact of the tsunami in each of the six criteria categories of the ITI Scale. Impact of all categories was mapped on city blocks, point measurements, findings etc, so that thematic impact maps were first created. Then intensity values were assigned, depending on the impact for each category to produce thematic tsunami intensity maps (layers). Most of the criteria result in a mosaic of intensities, which is in many cases due to lack of data, depending on the land use zoning. The complementary function of the criteria is evident in the final map. Two different methodologies of criteria combination were used for the production of a final map. A land-use-based weighted overlay was applied integrating the layers of the criteria, resulting in a final map that rather shows damage assessment or total impact of the tsunami on Ishinomaki area. The second final map was produced using the cell statistics "max" function, so that the maximum grade throughout the layers was selected for each pixel. This map showed an excellent zoning filling in any gaps due to lack of information in some layers and areas with maximum intensity data from the others and it is the tsunami intensity map of the area. It was made very clear though, that field data, especially during the first hours or days after such an event, are extremely useful for the intensity assessment. Once restoration works begin, it is difficult to estimate impact for some categories, especially when the area has been hit by both earthquake and tsunami.

Introduction

On 11 March 2011, at 14:46 local time a M_w 9.0 earthquake occurred offshore from northeast Japan and generated an unexpected tsunami that caused substantial damage and more than 19300 fatalities[2] along the east-northeast coast of Honshu Island. On 2013, the Integrated Tsunami Intensity Scale ($ITIS_{2012}$) has been purposed[1], based on field work data, collected from the two mega-tsunamis that took place in the Indian Ocean in 2004 and Tohoku event in 2011. $ITIS_{2012}$ is 12-grade and based on the assessment of a large number of objective criteria, grouped in six categories (phenomenon quantities and impact on human, displaced objects, infrastructure, the environment and structures). Tohoku mega-tsunami provides a wide range of damages and a variety of damage quality and quantity characteristics. This study aims to use this large amount of available data, in order to conclude on both: the study area's tsunami vulnerability and the applicability and the perspective of the $ITIS_{2012}$.

Study Area

The study area is located about 100 km from the earthquake epicentre, and the tsunamigenic zone (Figure 1a). Inundation zone in Ishinomaki Bay combines a variety of land use zoning, including urban, industrial, residential and rural zones and allows the usage of almost all of the $ITIS_{2012}$ criteria. Matsushima military airport (RJST) and two ports (commercial and fishing) are located in the inundation zone (Figure 1c). Local economy is mainly based on fishing, fishing products' industry and rice production[3]. The inundation zone is politically divided on two municipalities: Higashimatsushima and Ishinomaki: (Figure 1d). Geomorphologic characteristics of the bay make the area notably vulnerable to tsunami events: it is a plain coast, surrounded by Ishinomaki and Matsushima Bay, both shallow and characterized by a relatively smooth seabed[4]. The area includes a wide hydrographic network, consisting from Kitakami, Jo and Naruse rivers, interconnected with canals. Hiyoriyama hill and locally coastal forests are the only natural barriers to tsunami waves in the inundation zone.

Before this event the Japanese government reported that a magnitude 7.4.earthquake along a 200 km fault off-shore of Sendai was expected to occur with 99% probability within 30 years[5] and the area were shield by prevention infrastructure and measures including:

- early warning system[6]
- tsunami hazard planning (predicted inundation zone, shelters, annual citizens' training etc) by municipality[5],
- seawalls, breakwaters and coastal forest along the shore[5],
- high-level prevention measures in lifelines, e.g. railway automation in case of earthquake[7], earthquake-resistance water supply tubes[8], backup telecommunications lines[9], underground telecommunication cabling[9], governmental data backup system[3] etc.
- periodic evacuation drills in workplaces[10] and
- a strict earthquake-resistance legislation.[11,121,13]

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Ishinomaki municipality had developed a plan predicting an inundation zone for a magnitude 7.7 earthquake, much narrower than the one eventually shaped in 2011[14] (Figure 1b).

Materials and Methods

1. Data and Methodology

Data have been collected from Google Web applications' imagery (Google Earth, Google Street View and Google Memories for the Future[15]), air photos by Geospatial Information Authority of Japan[16], digital libraries,[17,18] the literature, official reports, ESRI World Topo map[19], the press and the web. Data have been mapped, evaluated against the $ITIS_{2012}$ criteria and have been used to create a thematic impact map for each one of the $ITIS_{2012}$ criteria categories. The composition of these six impact maps produced the final intensity zoning map of the area. Methodology and data sources used for each one of the categories are described in more detail in the relevant sections.

ESRI ArcMap v. 9.3 has been used for maps creating and processing.

2. Uncertainties and Assumptions

As source of uncertainties could possibly be considered:

- the accuracy of NOAA[18] wave height measurements and the used DEM[19],
- the reliability of informal sources data (military airport data)

- the adequacy of sampling surveys data (industrial infrastructures' damages[10], ground polution points[20], NOAA wave height measurements[18])
- the lack of data (damages on networks and in the airport area)
- some mising data or possible evaluation divergence due to lack of in-time satellite imagery (displaced objects, debris distribution, uprooted trees)
- the applied spatial interpolation methods
- the indirect approach methods (impact on human and debris distribution)

Some assumptions have been made, as:

- earthquake impact, possibly affected coastal profile changes, structures and infrastructures, considered as zero
- recorded fires and absence of trees attributed to the tsunami
- masonry and RC structures homogenized on their vulnerability class[1]
-

Results and Discussion

1. Quantities

Inundation zone is delimited by Harvard University Geospatial Library[17]. Both, inundation area (114 km^2) and maximum inundation distance classify the study area as a XII-grade zone (Figure 3a).

Wave height point measurements by NOAA[18] have been used to create the zoning map. As some of them are located at the inundation line, they have been converted to runup point measurements, by adding the local attitude and subtracting the local ground subsidence, which ranges between 39 and 78 cm in the area. DEM of the inundation zone have been produced based on the 10-meters contour-lines by ESRI Topo Map[19] and subsidence produced by IDW spatial interpolating the point subsidence measurement of the area[21] (Figure 3b). Wave height and runup point measurements have been evaluated against the ITIS$_{2012}$ criteria and imported into an integrated map (Figure 2). Applying the IDW spatial interpolation method produced the quantities' thematic map (Figure 5c).

XII-grade zones are located at the shoreline, or in near shoreline steep-relief areas. Maximum water height is located at the commercial port, while maximum runup height at the foot of the Hiyoriyama hill (Figure 5b). Notable are:

- the data gap in the airport area (Figure 5a)
- the low intensity zones behind Hiyoriyama hill, in Ishinomaki city centre (Figure 5c).
- the min X intensity zones in areas, where the altitude is increasing in a relatively short distance from the shoreline.
- the influence of the river network to the expansion of the inundation zone.
- intensity grade is gradually decreased inland, except of steep-relief areas.

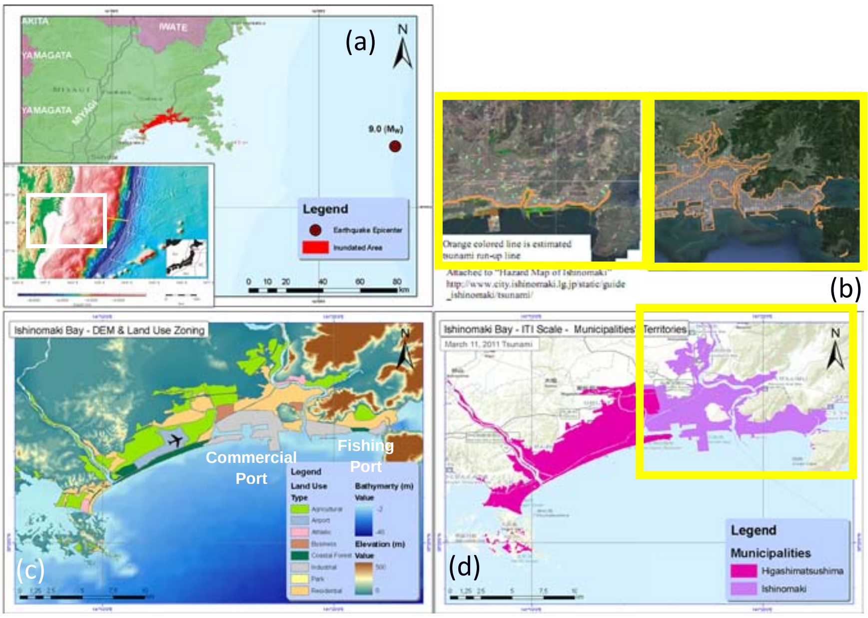

Figure 1: (a) Location of study area (b) Predicted (left) and reality 2011 (right) Inundation Zones (S. Fraser et al., 2012) (c) DEM and Land Use Zoning in Inundation Zone (d) Municipalities' territory in the Inundation Zone

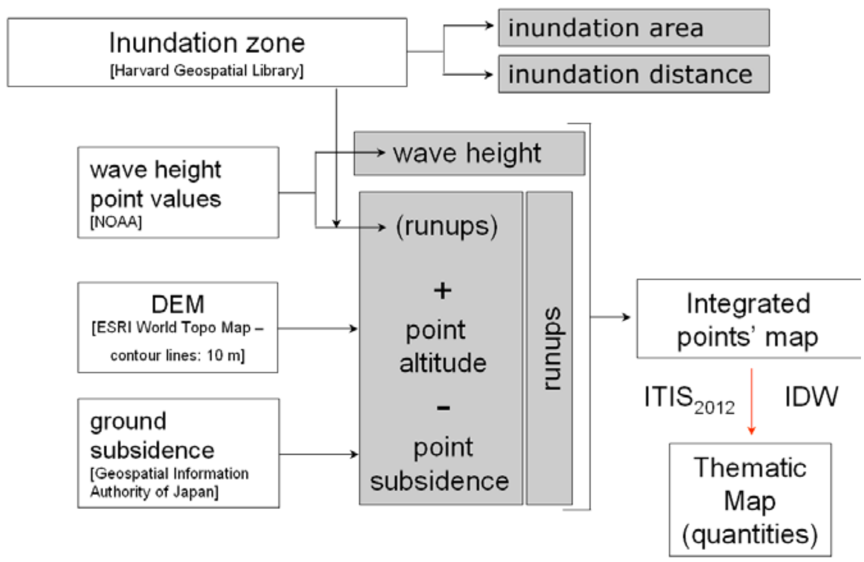

Figure 2: Data Sources and Methodology on Quantities Criteria's Category

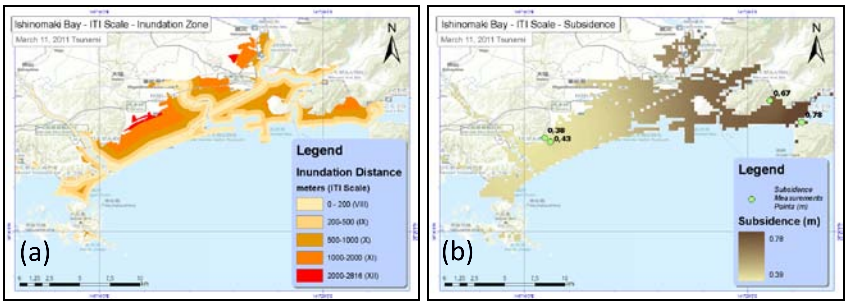

Figure 3: (a) Maximum Inundation Distance > 2 km. (b) Subsidence: point measurements and spatial interpolation result map.

2. Impact on Human

Perception of people in the inundation zone is presumed in mega-events. Ishinomaki recorded the highest number (5867) of fatalities among the affected municipalities, while Higashimatsushima recorded 1039 casualties.[22] Massive-death incidents are recorded in Omagari elementary school[23] and in Nippon Paper industry facilities.[10] However spatial locating all victims in mega-events is de facto difficult, due to the washed-away bodies, the limited witnesses and the missing people.

A questionnaire survey to survivors[24] has been taken into account in order to create the human related thematic map. The survey revealed the hazard underestimation by both, citizens and authorities (reaction) and the limited citizens' participation in tsunami drills and concluded that the victims 'majority were residents of Ishinomaki. Based on these facts, an indirect approach has been followed by a weighted factor composition of population density[25] based on 2005 Census, total destruction zones[26] and population gathering points maps, based on ESRI World Topo Map. (Figure 4).

The produced map agrees with the massive-death recorded data (Figure 6a) and with the victim's ratio per municipality (Figure 6b). Note the high population density in Ishinomaki centre, which shows that this part of the area has been probably protected by Hiyoriyama hill.

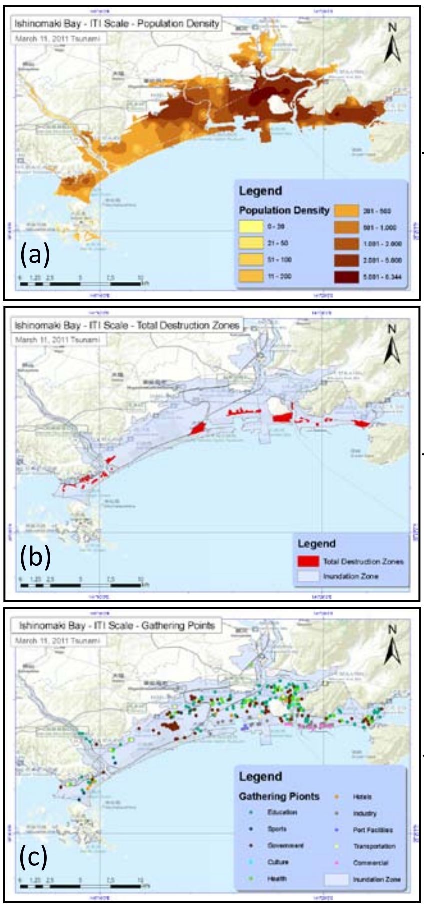

Figure 4 (a) Population Density (b) Total Destruction Zones (c) Gathering Points

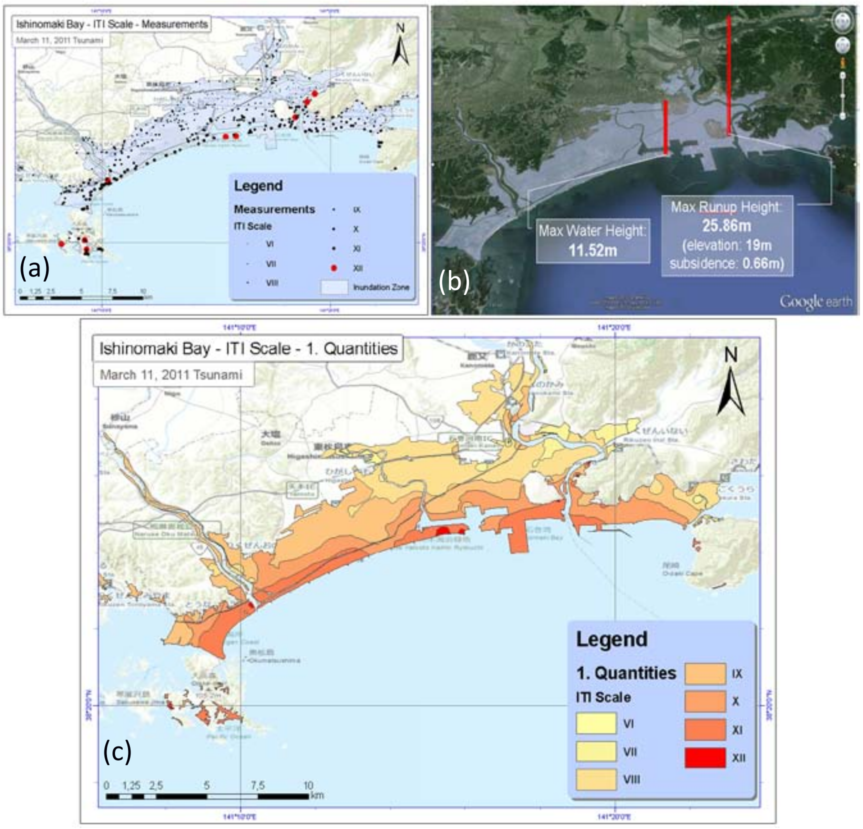

Figure 5: (a) NOAA point measurements [18] evaluated against the $ITIS_{2012}$ criteria. A data gap is visible in Matsushima Airport area (b) Maximum wave height and runup height in the study area (c) Intensity thematic map on Quantities Criteria's Category

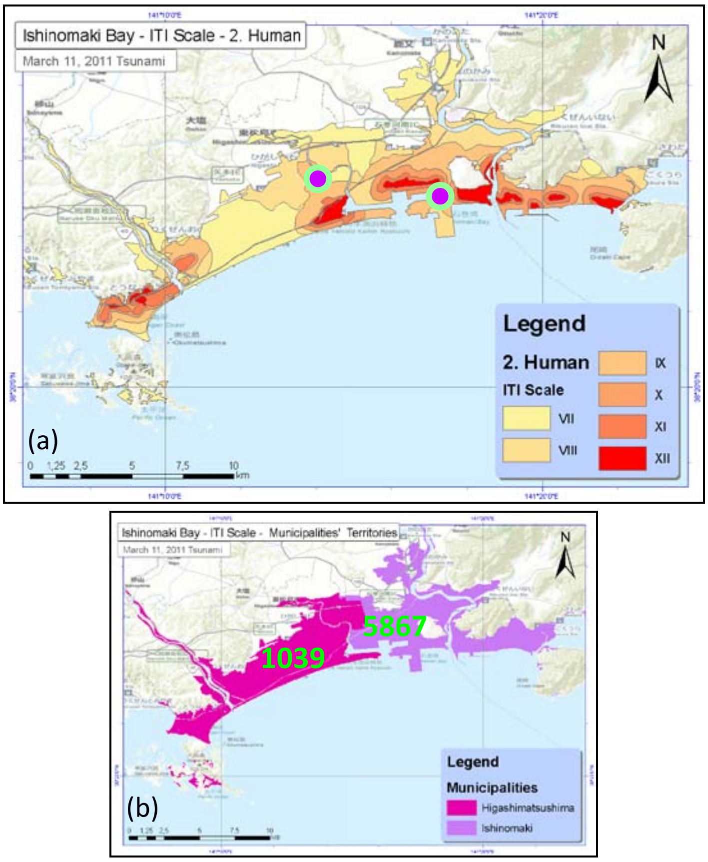

Figure 6: (a) Intensity thematic map on Impact on Human Criteria's Category and the two recorded massive-death incidents' location (purple points). Both belong to X-grade zones (b) Fatalities per Municipality. Their ratio agrees with the produced map.

3. Impact on Displaced Objects

Data have been collected by using Google Earth imagery and air photos of March 18th, 2011.[16] A weighted factor (Figure 7) has been given to displaced vehicles (Figure 9a), vessels (proportional to their size, Figure 9b), train wagons (Figure 9c), fight aircrafts and helicoptersXX (Figure 9d) and tanks (Figure 9e). Kriging interpolation method has been applied to the map including all the points and intensity has been set between V and XII, according to the grades of ITIS$_{2012}$.[1] Finally fire zones map[10,27] (Figure 9f) has been overlaid, as both fire incidents seems to be caused by objects' displacement.

In the produced map (Figure 10), noted:

- the data gap in the broader airport area, probably due to urgent restoration works took place in the meantime between the event and the date on which the images were recorded. For the same reason Kriging method has been proffered instead of the IDW one.
- the protection facilities lack in eastern Ishinomaki coast (Figure 11), between the coastal forest and the port facilities and
- the multilateral inundation in western Higashimatsushima, as tsunami hit the area from four different directions, both bays, Naruse river and Tona canal (Figure 10).

Additionally:

- limited number of displaced vehicles at the shoreline attributed to the tsunami water backwash.
- low intensity grades at the shoreline attributed to the land use or the protection facilities.

Objects	Weighted Factor
vehicles	2
vessels (big size)	3
vessels (middle size)	2
vessels (small size)	1
train wagons	2
fighter aircrafts	2
helicopters	2
tanks	2

Figure 7: Weighted-factor table on located displaced objects

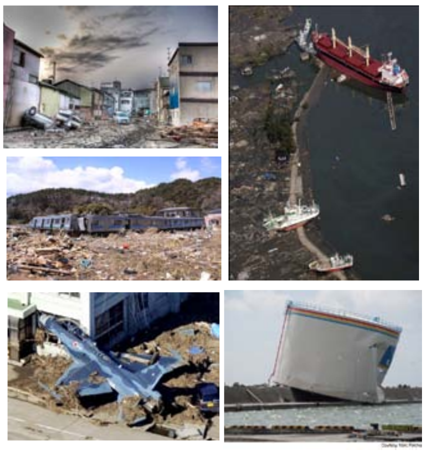

Figure 8: Indicative findings

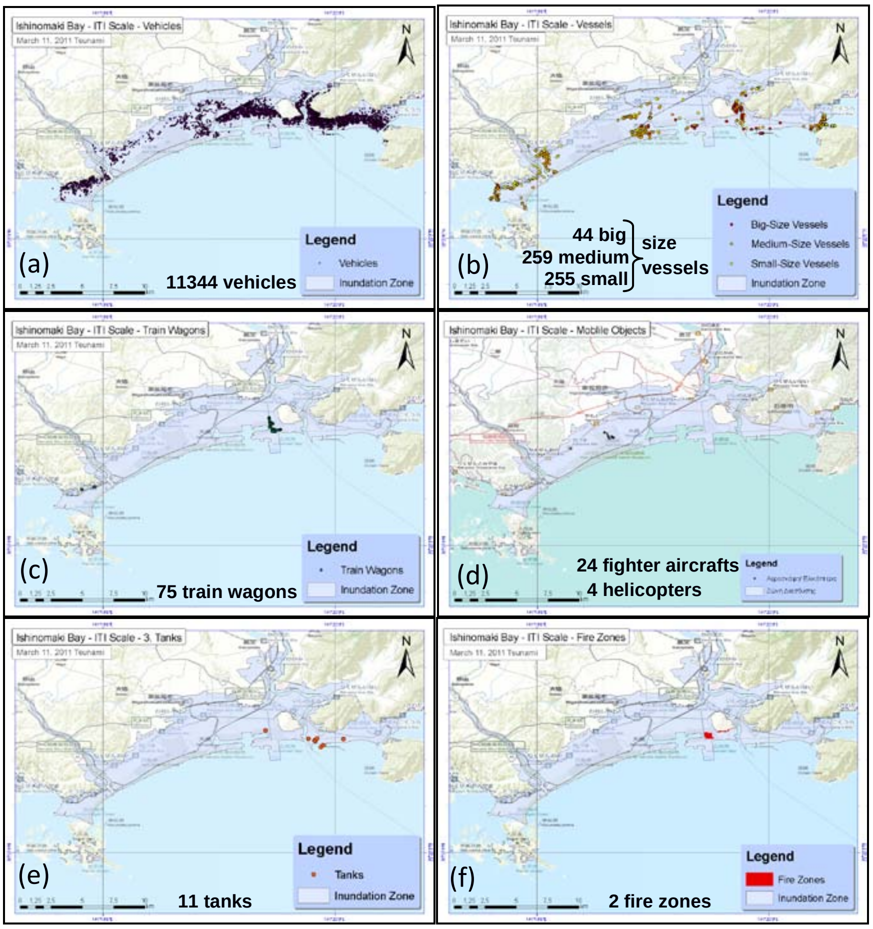

Figure 9: (a) Displaced vehicles (b) Displaced vessels (c) Displaced Train Wagons (d) Displaced Fight aircrafts & helicoptersXX (e) Displaced Tanks (f) Fire Zones[10,27]

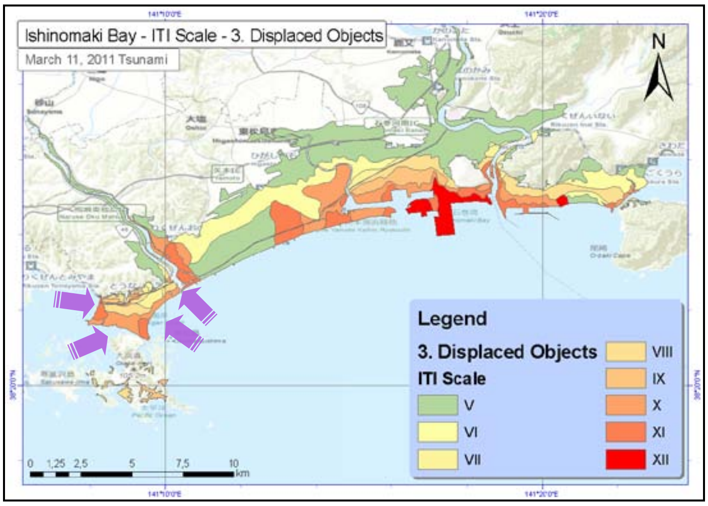

Figure 10: Intensity thematic map on Impact on Displaced Objects Criteria's Category

Figure 11: Protection lack in the area between the coastal forest and the port facilities in eastern Ishinomaki

4. Impact on Infrastructure

Damages have been mapped and evaluated against the ITIS$_{2012}$ criteria on bridges and road parts[28,29,30] (Figure 13a), a significant part of the railway line using the Google Earth imagery and the relative literature[31,32] (Figure 13b), several lifelines' nodes (telecommunications' systems,[3,9,28,33,34] drainage[10,35,36] and water supply systems[8,37], airport facilities[37] and LNG facilities[28] - Figure 13c), industry facilities[10] (Figure 13d) and port facilities[39,40] (Figure 13e). Protection facilities lack has been noticed at the Matsushima Bay.

The thematic impact map has been produced by applying the IDW spatial interpolation method. (Figure 14) and shows a gradual intensity degradation inland. Centralization of XI-grade intensity zones in both ports' areas attributed mainly to the infrastructure gathering in these areas and secondarily to high wave heights.

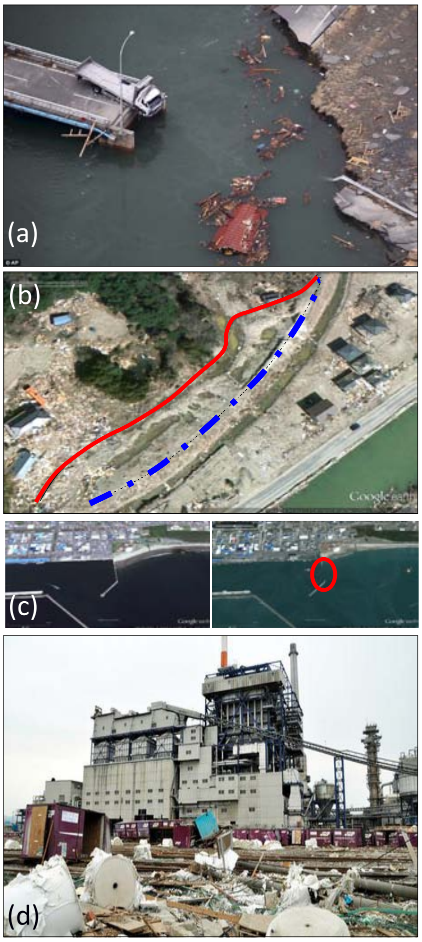

Figure 12: (a) Jo river bridge Sadakawa [Associated Press, Daily Mai]) (b) Displaced railway line part (c) Collapsed Breakwater (d) Nippon Paper Group Facility at Ishinomaki commercial Port [Hitoki Nakagawa –Asahi Shimbun archive photo]

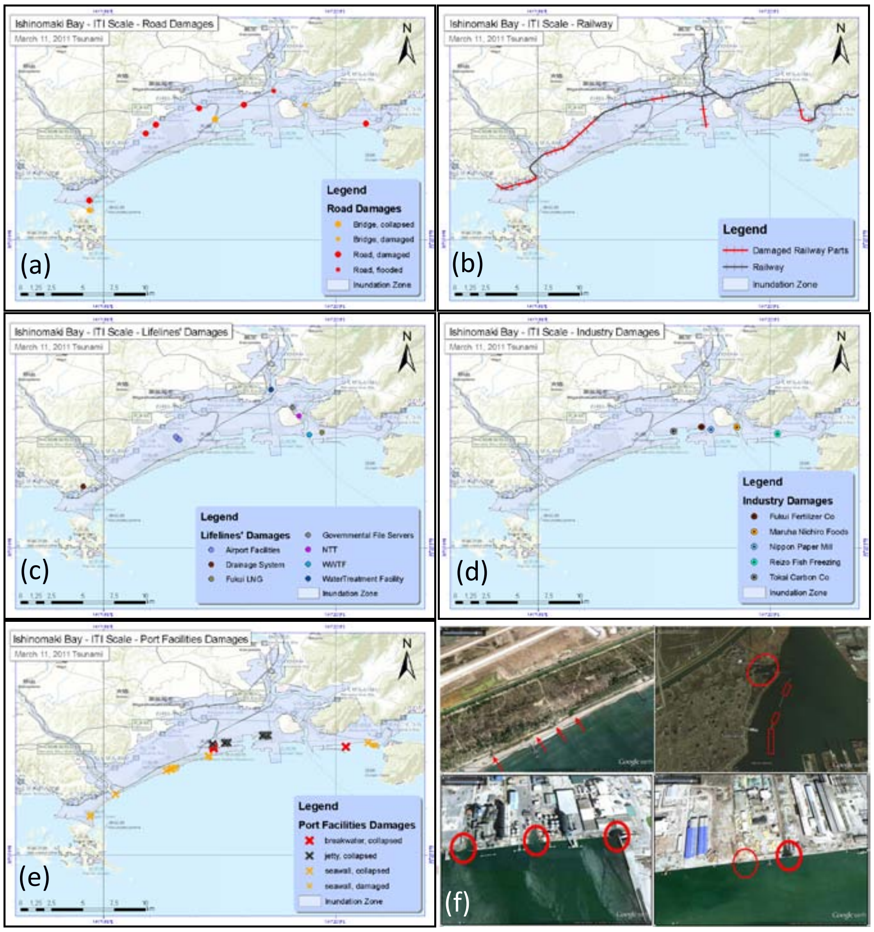

Figure 13: (a) Damages on bridges and road parts[28,29,30] (b) Damages on railway lines (c) Damages on several lifeline nodes (d) Damages on Industry facilities[10] (e) Damages on port facilities[39,40] (f) Indicative damages on port facilities (Google Earth)

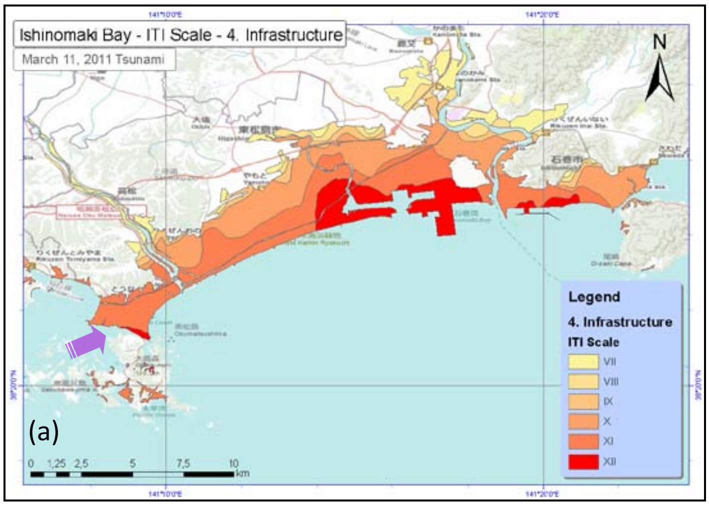

Figure 14: Intensity thematic map on Impact on Infrastructure Criteria's Category

5. *Impact on the Environment*

Shoreline changes have been mapped by using the Google Earth imagery and the relative literature[41] (Figure 18a) and along with the ground pollution points[20] (Figure 18b) have been directly evaluated against the $ITIS_{2012}$ criteria. Uprooted trees (Figure 18c) and deposits (Figure 18d), located in Google Earth imagery, have been evaluated based on their spatial density. Boulders displacement and in-situ fires have not been reported, however the displaced object triggered by fire-zones[10,27] have been took into account as ground pollution areas (Figure 18b). A first approach for the thematic map has been created by applying the IDW spatial interpolation method on these data (Figure 18e). Especially for the debris distribution and given the lack of in-time field data, an indirect approach has been followed by composing 5 maps: (a) total destruction zones[26], (b) displaced objects, (c) uprooted trees (d) areas near the bridges at the shoreline (Figure 17) and (e) steep-slope areas located behind residential zones. Based on the fact that in Ishinomaki area the biggest amount of debris has been recorded[20], debris distribution map (Figure 18f) classified between VII and XII. Finally a weighted factor has been given to the two produced raster maps.

The environmental impact map (Figure 19) shows an intensity discontinuity in the airport area due to lack of data and relatively low intensity grades at the shoreline mainly because of protection infrastructures or the land use.

The 9-meters-altitude coastal forest in eastern Ishinomaki greatly protected the rear area.

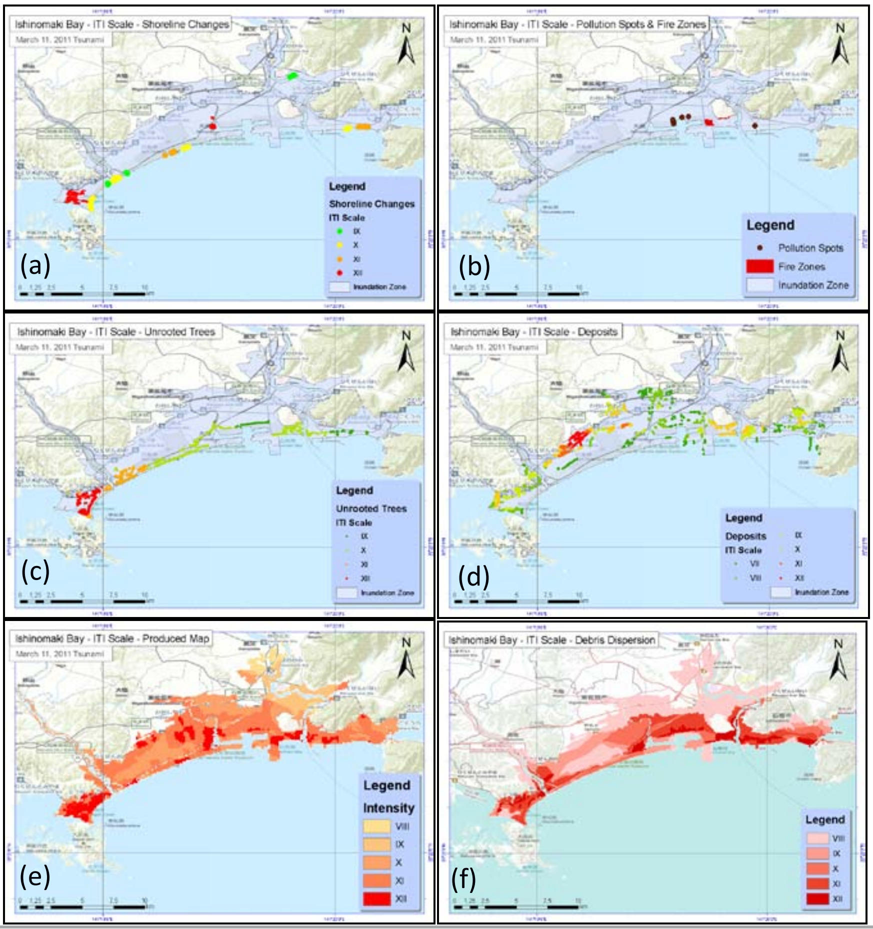

Figure 18: (a) Shoreline changes (b) Pollution points and areas (c) Uprooted trees (d) Deposits (e) Composition result of the above criteria (f) Debris Dispersion produced map

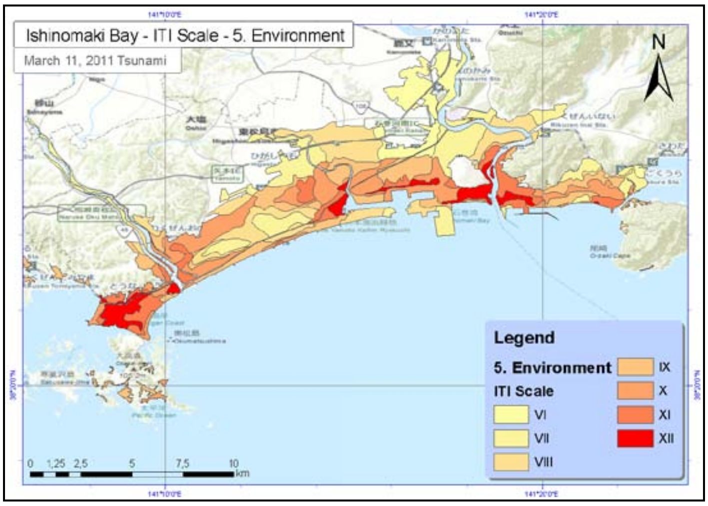

Figure 19: Intensity thematic map on Impact on Environment Criteria's Category

Figure 15: 27 km^2 area in western Higashimatsusima before (up) and after (down) the event.[15]

Figure 17: Debris on Kitakami River Bridge at 15-03-2011 (Kim Jae-Hwan, Toru Yamanaka/AFP/Getty Images)

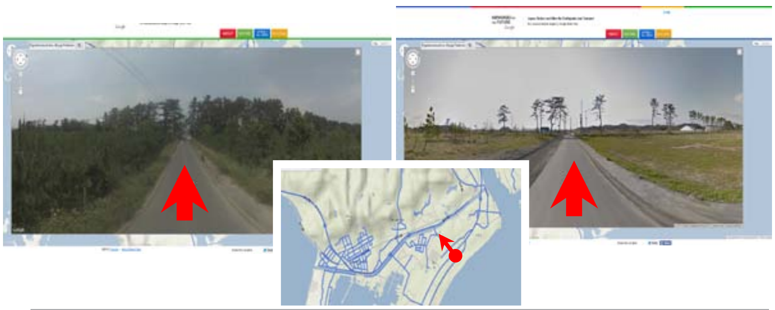

Figure 16: Western Hihashimatsushima coastal forest before (left) and after (righ) the event[15]

6. Impact on Structures

Several studies[42,43,44,45,46] have mapped the structures' damages using remote-sensing methods on high-resolution satellite images or air-photos. Especially part of the study area has been partly mapped by Harvard University[17] and an interactive web map has been published.

However results of these approaches are not detailed enough to be used on $ITIS_{2012}$ implementation study, as they do not cover the grade of damage and the structural material of each structure, as $ITIS_{2012}$ requires. Therefore data from Google Earth (25-06-2010 and 30-03-2011) in combination with the Google Memories for the Future web application[15], witch displays a Google Street View before and after the mega-event, have been extracted and used.

All structures in inundation zone have been mapped, the washed-away and demolished ones have been distinguished and the construction-free areas have been isolated (Figure 20) in order to produce a density map of the removed structures (Figure 21). Based on this map, as second step the majority (31885) of the structures -the ones located in destruction zones- have been evaluated against the $ITIS_{2012}$ criteria, based on their damage grade and their structural material and the impact thematic map has been produced (Figure 22). Masonry considered as vulnerability class B structures; all RC considered as vulnerability class E structures.

After data analysis on available data on Ishinomaki structures[47], the percentage of structure in the area has been extracted. The result shows the overwhelming majority of wooden structures in the area. (Figure 23).

Data analysis on evaluation results showed that wood and masonry structures are the most vulnerable to tsunami, fact that agrees with the relative field surveys [48,49,50,51,52,53] (Figure 24).

The produced map (Figure 22) shows a relatively low-grade intensity zone at the commercial port, due to the steady structure of the industry facilities in the area and an intensity grade discontinuity in the around area due to the destructed wooden houses near the industrial zone.

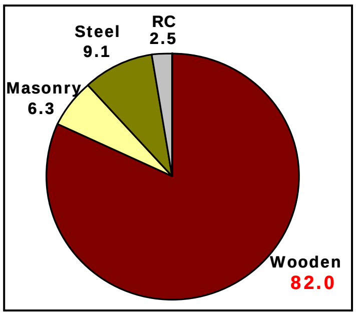

Figure 23: Percentage of structural material in Ishinomaki area[47]

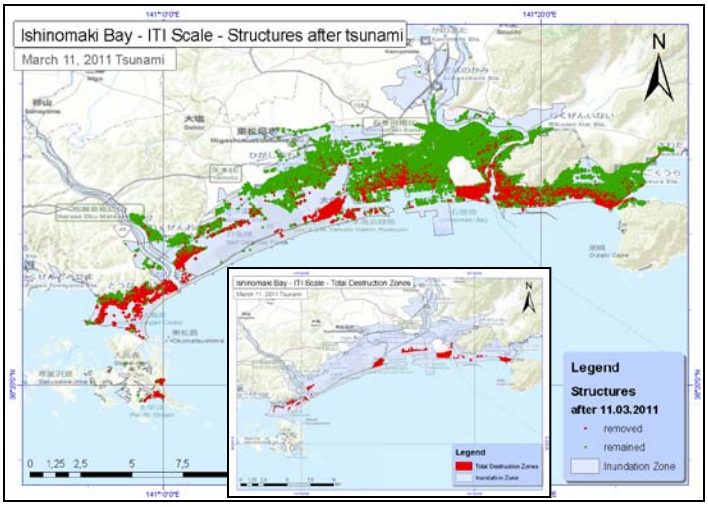

Figure 20: Removed (washed-away or demolished) and remained structures in study area. The map is similar with the one displaying the total destruction zones[26].

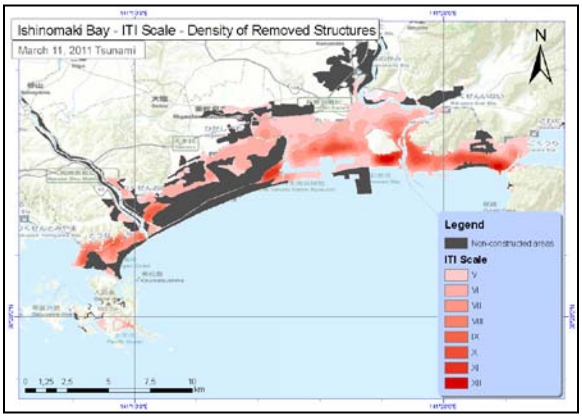

Figure 21: Density map of removed structures and construction free zones.

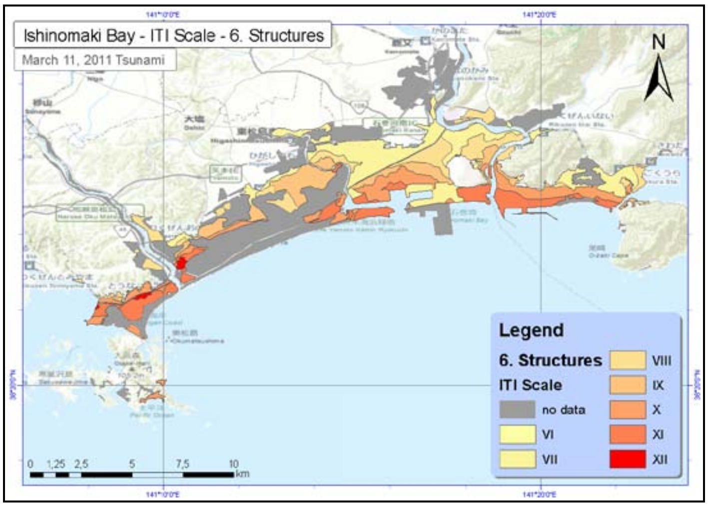

Figure 22: Intensity thematic map on Impact on Structure Criteria's Category

TYPE	CH	%	REMOVED	%
WOOD	28123	88.20%	13918	49.49%
STEEL	3227	10.12%	611	18.93%
RC	455	1.43%	65	14.29%
MASONRY	80	0.25%	32	40.00%
	31885	100%		

Figure 24: Qualitative evaluated structures and their quota of the removed ones, based on their structural material

7 Intensity Zoning Map

Two different integrating approaches have been followed to produce the final intensity zoning map.

For the first one, land use zoning of the area has been taken into account. A weighted factor has been given to each one of the land use zones per $ITIS_{2012}$ criteria category (Figure 25), so that criteria characterizing each land use to be highlighted in the result map. Especially for the first criteria category, the one relative to the quantities of the phenomenon, a mutual weighted-factor has been used to all types of land use zones. The integration of the land-use-based weighted overlay with the six thematic impact maps resulted in the final map, an equalized image of the event and its impact, covering intensity grades from VI to XII. This map rather could be considered as the damage assessment map of the specific event in Ishinomaki area. (Figure 26)

For the second approach the maximum intensity grade per pixel throughout the six thematic layers -using the cell statistics “max” function- has been taken into account, so that the evaluation of each pixel to be based on its objective vulnerability, regardless of its land use or the incident timing. This approach covers the worst case scenario and uses the complementarity of $ITIS_{2012}$, in order to cover possible lack of data. The produced map covered intensity grades from VII to XII and showed an excellent zoning filling in any gaps due to lack of data in some layers and areas – airport area in this case- with maximum intensity data from the others and it is the tsunami intensity map of the area (Figure 27). The image is very closer to the theoretical approach, whereby the degree of destructiveness is greatest in the coastal zone and depreciates inland. Any variations to this image associated with the recorded data and attributed either to protection infrastructure, or the peculiarities of the geomorphology locally. Notable is that total destruction zones[26] are located in XI or XII-grade zones in the first approach map, while they almost totally belong to XII-grade zones in the second approach one (Figure 28).

Second approach is a time and land use-independent and could therefore contribute to new tsunami prevention and response plans, new urban plan designs and insurance or reinsurance evaluations.

	1	2	3	4	5	6	
Industrial	16.7%	20.0%	20.0%	20.0%	3.3%	20.0%	100%
Residential	16.7%	20.0%	20.0%	20.0%	3.3%	20.0%	100%
Commercial	16.7%	20.0%	20.0%	20.0%	3.3%	20.0%	100%
Parks	16.7%	10.0%	20.0%	15.0%	35.0%	3.3%	100%
Athletic	16.7%	10.0%	20.0%	20.0%	18.3%	15.0%	100%
Airport	16.7%	5.0%	10.0%	60.0%	3.3%	5.0%	100%
Forest - Agriculture	16.7%	1.5%	1.5%	20.0%	60.3%	0.0%	100%

Figure 25: Weighted-factor table on land-use overlay.

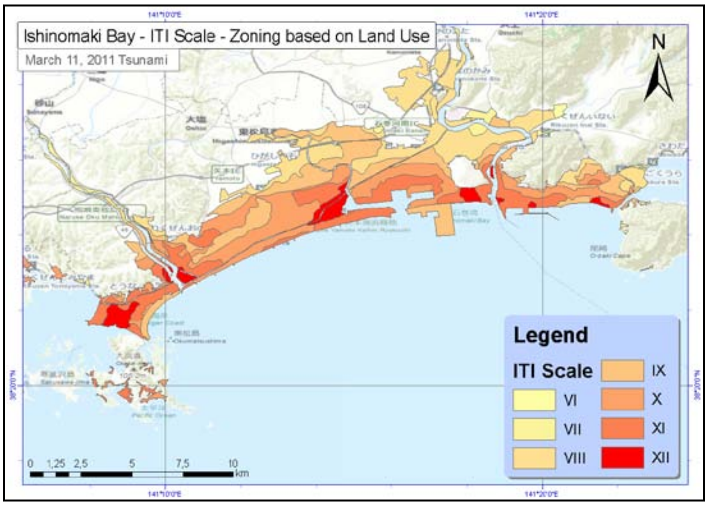

Figure 26: Damage Assessment Map

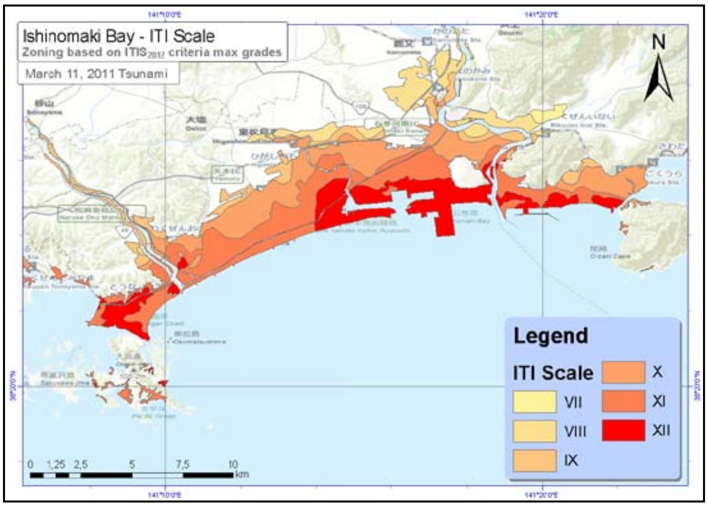

Figure 27: Tsunami Intensity Map ($ITIS_{2012}$) after the Tohoku event (Hazard Assessment Map)

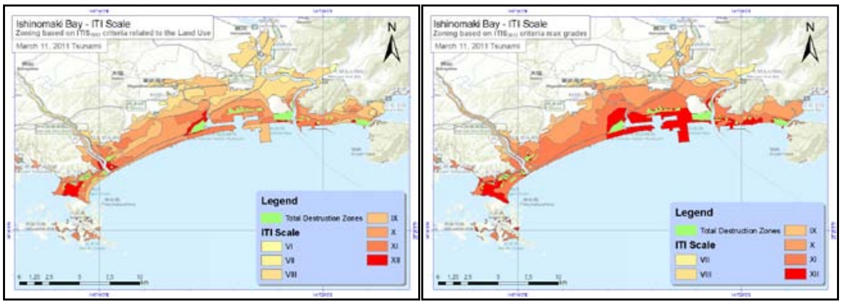

Figure 28: Total Destruction Zones[26] overlaid on the two maps

Conclusions

1 Study area

During the research pros and cons relative to the characteristics of the study area have been revealed per $ITIS_{2012}$ criteria categories:

- despite the positive coastal forest response, rivers and canals in the plain area broadened the inundation zone
- despite the positive port facilities response, a lack of protection facilities have been noticed at Matsushima Bay
- despite the protected city centre, the industrial zone is vulnerable and a potentially source of further disasters
- despite the high-level prevention measures and legislation, more than 80% of the structures are vulnerable
- despite the annual citizens' training program, a limited participation has been recorded
- despite the in-time working Early Warning System, the hazard had been underestimated

Fact is that despite the unpredictable magnitude of the event, prevention and management measures reduced damage and losses. However, Tohoku mega-tsunami revealed aspects of protection and prevention measures, highlighted by $ITIS_{2012}$ application, that require further study on both: their adequacy and their applicability.

Historical maps (Figures 29 and 30) of the study area reveal the human intervention on the terrain and the shoreline over the years. Along with urbanization and terrain modification, human presence expanded, setting itself in risk[29]. Despite the high-end protection and prevention measures, the area has been eventually vulnerable to the natural force of Tohoku mega-tsunami.

2 $ITIS_{2012}$

All of the $ITIS_{2012}$ categories have been easily applied and most of their individual criteria complemented each other. No saturation phenomena have been noticed. In two cases an indirect approach fully or partly, has been followed. However the limited available data confirmed partially the results.

All of the $ITIS_{2012}$ criteria are important factors of tsunami propagation and destructiveness. Especially criteria relative to the impact on displaced objects, on infrastructure, on the environment and on structures, are potentially destruction sources themselves. Displaced object and infrastructure categories are for the first time included in a tsunami intensity scale. Especially infrastructure criteria category covers possible NaTech events and is important to management and restoration processes. Categories relative to the tsunami quantities and the environmental impact are land-use independent and applicable on historical evens

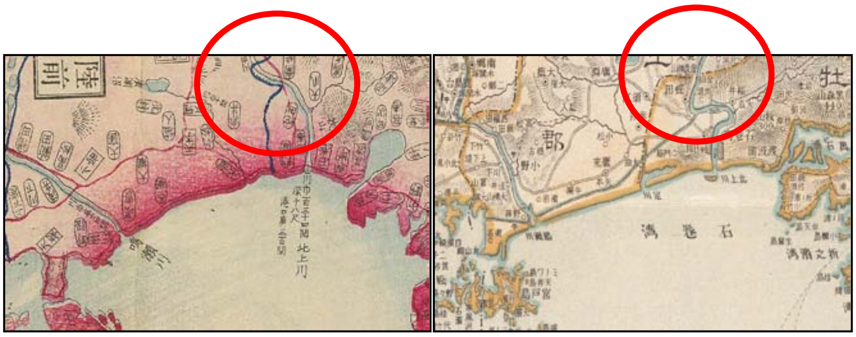

Figure 29: Study area's historical maps[54] of 1988 (left) and 1907 (right). Human intervention on the shoreline and the hydrographic network is visible

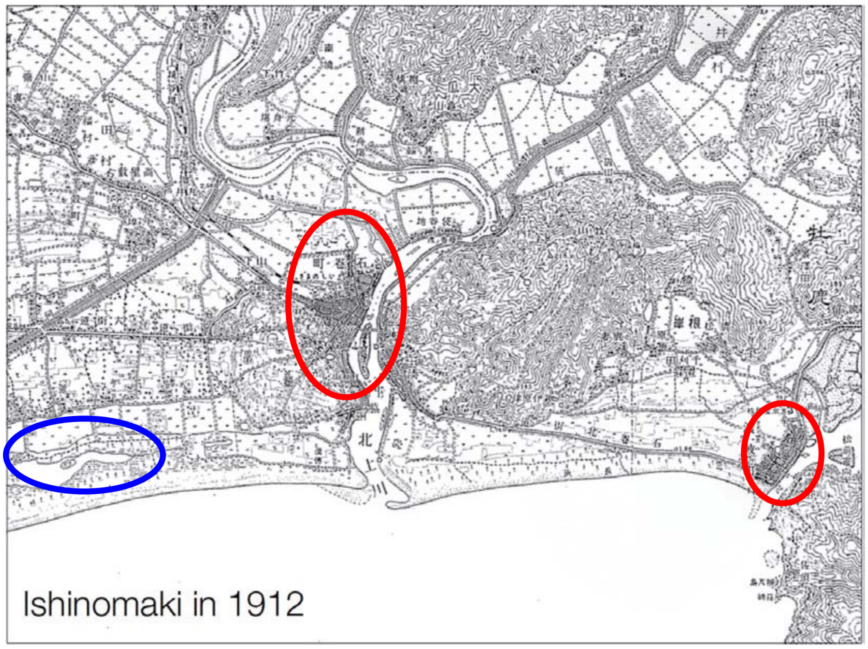

Figure 30: Map of the study area of 1912[28]. Residential zones (red cycles) were located in relatively protected from tidal waves, storms and tsunamis, while the area along the shore was wetland (blue cycle)

Accuracy issues could be caused by using earthquake as tsunami damages or by lack of data due to possible restoration works. However this study confirmed that lack of data in specific categories or areas could be greatly covered as categories and individual criteria complement each other.

As result of recently mega-tsunamis field surveys and consisting mostly of objective criteria, $ITIS_{2012}$ results are objective, integrated and detailed. Given the complementarity of its criteria, $ITIS_{2012}$ is applicable on historical events and capable to highlight the pros and cons of each area. Therefore $ITIS_{2012}$ could be considered as a modern planning and management tool.

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