

Tsunami intensity mapping: applying the integrated Tsunami Intensity Scale (ITIS₂₀₁₂) on Ishinomaki Bay Coast after the mega-tsunami of Tohoku, March 11, 2011

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Abstract

The study applies the Integrated Tsunami Intensity Scale (ITIS₂₀₁₂) criteria to map the tsunami intensities distribution in the broader Ishinomaki area, for the 9 Mw March 11, 2011 event offshore Tohoku, Japan. Based on reports, satellite imagery and published information, impact data was mapped, intensity values were assigned and thematic impact maps (layers) were created for each of the ITIS₂₀₁₂ six criteria categories. 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. Two methodologies were used to produce the final map. A land-use-based weighted overlay was applied integrating the six layers, resulting in a final map that rather shows damage tsunami assessment on Ishinomaki area. The second final map was produced using the maximum intensity grade throughout the six layers for each pixel. This map showed an excellent zoning filling in any gaps due to information lack in some layers and areas, with maximum intensity data from the others, highlighting the ITIS₂₀₁₂ criteria complementarity and is the tsunami intensity map of the study area.

Introduction

On 11 March 2011, at 14:46 local time a Mw 9.0 earthquake occurred offshore from north-east Japan and generated a large tsunami that caused substantial damage and more than 19,300 fatalities¹ along the east-northeast coast of Honshu Island. Until then several tsunami intensity scales had been purposed and used, most of them not capable to qualitatively and quantitatively cover the impact of a mega-tsunami, or the impact to developed societies and some of them confusing the significance of intensity and magnitude. The first 12-grade tsunami intensity scale based on sev-

eral criteria were introduced by Papadopoulos and Imamura (2001).² On 2013, the integrated tsunami intensity scale (ITIS₂₀₁₂) has been purposed, enriching the Papadopoulos and Imamura 2001 scale and based on field work data, collected from the two mega-tsunamis that took place in the Indian Ocean in 2004 and Tohoku event in 2011³. ITIS₂₀₁₂ 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 ITIS₂₀₁₂.

Study area

The study area is located about 100 km from the earthquake epicenter, and the tsunami-genic source (Figure 1A). Inundation zone in Ishinomaki Bay combines a variety of land use zoning, including urban, industrial, residential and rural zones⁴ and allows the usage of almost all of the ITIS₂₀₁₂ criteria. Matsushima military airport 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 agriculture.⁵ 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.⁶ 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 the Tohoku 2011 earthquake the Japanese government reported that a magnitude 7.4 Mw earthquake along a 200 km fault off-shore of Sendai was expected to occur with 99% probability within 30 years⁷ and the area were shield by prevention infrastructure and measures including: i) early warning system;⁸ ii) tsunami hazard planning (predicted inundation zone, shelters, annual citizens' training, etc.) by municipalities;⁷ iii) seawalls, breakwaters and coastal forest along the shore;⁷ iv) high-level prevention measures in lifelines, e.g. automatic train immobilization triggered by the SEWS,⁹ earthquake-resistance water supply tubes;¹⁰ v) backup power genera-

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Key words: Tohoku 2011 tsunami; integrated tsunami intensity scale application; Ishinomaki Bay tsunami impact; tsunami intensity mapping.

Contributions: the authors contributed equally.

Conflict of interests: the authors declare no potential conflict of interests.

Conference presentation: part of this work was presented at the *Mega Earthquakes and Tsunamis in Subduction Zones (METSZ) International Workshop*, 2014 October 6-8, Rhodes island, Greece.

This research has been co-funded by the European Union (European Regional Development Fund - ERDF) and Greek national funds through the Operational Program *Competitiveness and Entrepreneurship* of the National Strategic Reference Framework (NSRF) - Research Funding Program: *Research on Key Technologies of Geological Disaster Early-warning Geographic Information System (GIS) Platform and Pilot Project (Disaster Data Center development) in Greece*.

Received for publication: 8 February 2015.

Revision received: 7 December 2015.

Accepted for publication: 22 December 2015.

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Research in Geophysics 2016; 5:5857
doi:10.4081/rg.2016.5857

tors and telecommunications lines,¹¹ underground telecommunication cabling,¹¹ governmental data backup system,⁵ etc.; vi) periodic evacuation drills in workplaces;¹² and vii) a strict earthquake-resistance legislation.^{13,14}

Ishinomaki municipality had developed a plan predicting an inundation zone for a 7.7 Mw earthquake, much narrower than the one eventually shaped in 2011 (Figure 1B).¹⁵

Materials and Methods

Data and methodology

Data have been collected from Google Inc. (Mountain View, CA, USA) web applications' imagery (Google Earth™, Google Street View™ and Google Memories for the Future™),¹⁶ air-photos,¹⁷ digital data libraries,^{6,18,19} the litera-

ture, official reports, ESRI World Topo™ map (Environmental Systems Research Institute - Esri, Inc., Redlands, CA, USA),²⁰ the press and the web. Data have been mapped, evaluated against the ITIS₂₀₁₂ criteria and have been used to create a thematic impact map for each one of the ITIS₂₀₁₂ 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 (Environmental Systems Research Institute - Esri, Inc.) has been used for maps creations and processing.

Uncertainties and assumptions

As source of inevitable uncertainties could possibly be considered: i) the accuracy of wave height measurements¹⁹ - especially the ones being result of eye witnesses or model - provided by National Oceanic and Atmospheric Administration (NOAA); ii) the produced digital elevation model (DEM)²⁰ (contours resolution: 10 m); iii) the reliability of informal sources data in case of military airport data; iv) the adequacy of sampling surveys data relevant to: industrial infrastructures' damages,¹²

wave height measurements,¹⁹ ground pollution points²¹ and subsidence;²² v) the lack of data (minor and/or detailed damages on telecommunication, drainage, water and liquefied natural gas (LNG) supply networks and in the airport area); vi) possible missing data or possible evaluation divergence due to lack of in-time satellite imagery (displaced objects, debris distribution, uprooted trees); vii) the applied spatial interpolation methods in point data, depending by case on the data quality and quantity; viii) the indirect approach methods (impact on human and debris distribution).

Each one of these uncertainties is described and most of them analyzed in the respective sections.

Some inevitable assumptions have been made, as: i) earthquake impact, possibly affected coastal profile changes, structures and infrastructures, considered as zero; ii) recorded fires and absence of trees attributed to the tsunami; iii) masonry and reinforced concrete structures homogenized on their vulnerability class.³

In any case, both assumptions and uncertainties do not affect significantly the results of the study, given the complementarity of the individual criteria composing the ITIS₂₀₁₂.

Results and Discussion

Quantities

Inundation zone is delimited by Harvard University Geospatial Library.¹⁸ Both, inundation area (114 sq. km) and maximum inundation distance classify the study area as a XII-grade zone (Figure 2A). Wave height point measurements¹⁹ have been used to create the zoning map (Figure 2F). As some of them are located at the inundation line, they have been converted to run-up point measurements (Figure 2E), by adding the local attitude and subtracting the local ground subsidence, which ranges between 39 and 78 cm in the area.²² DEM of the inundation zone have been produced based on the 10-m contour-lines by ESRI Topo Map²⁰ and subsidence produced by inverse distance weighting (IDW) spatial interpolating the point subsidence measurement of the area (Figure 2B)²². Wave height and run-up point measurements have been evaluated against the ITIS₂₀₁₂ criteria and imported into an integrated map (Figure 2C). Applying the IDW spatial interpolation method produced the quantities' thematic map (Figure

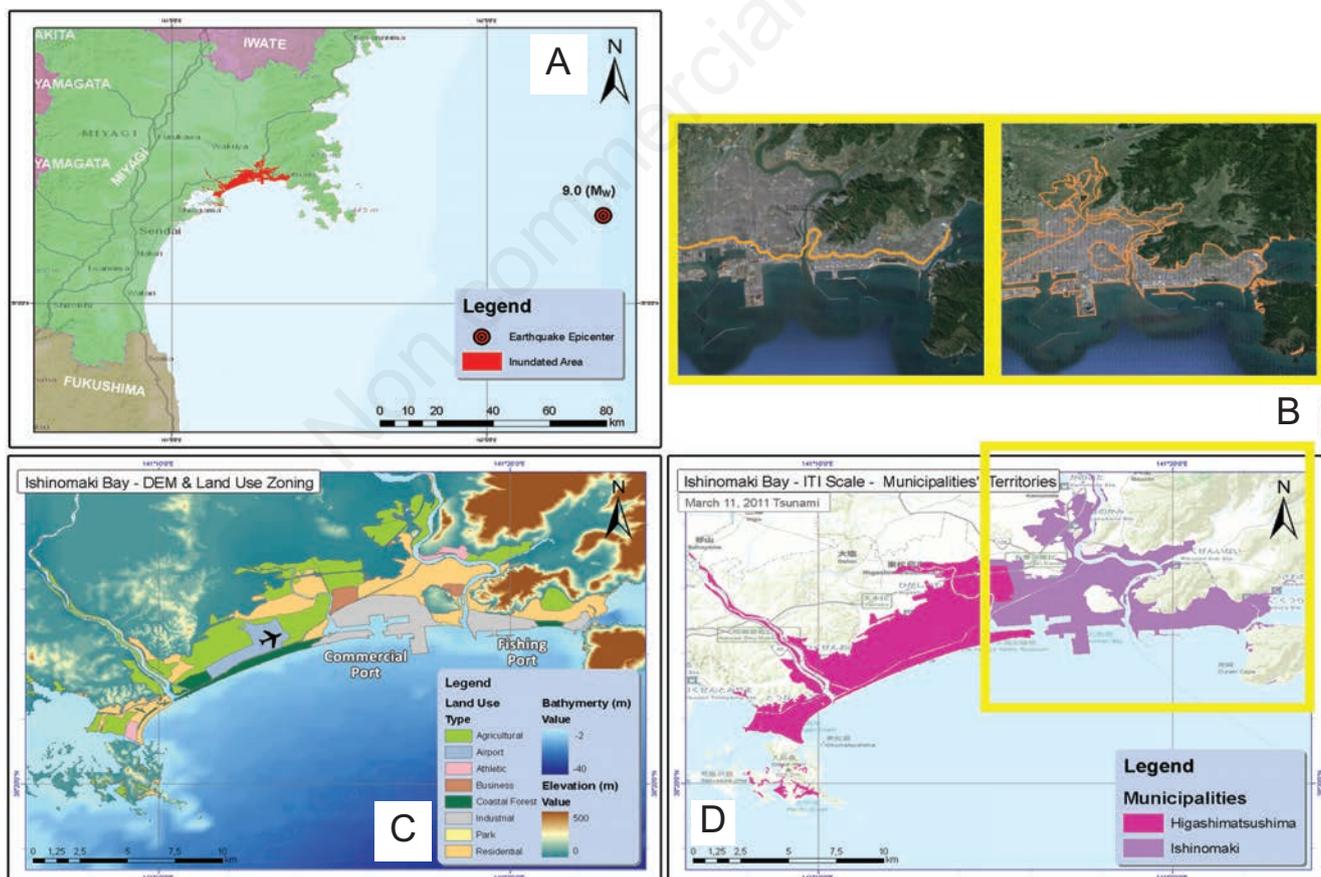


Figure 1. A) Location of the study area; B) Predicted (left) and reality 2011 (right) inundation zones;¹⁵ C) Digital elevation model and land use zoning in the inundation zone; D) Municipalities' territory in the inundation zone.

2F). XII-grade zones are located at the shoreline, or in near shoreline steep-relief areas. Maximum wave height is located at the commercial port, while maximum run-up height at the foot of the Hiyoriyama hill (Figure 2D).

Notable are: i) the data gap in the airport area (Figure 2C); ii) the low intensity zones

behind Hiyoriyama hill, in Ishinomaki city center (Figure 2F); iii) that narrow lowland zones at the shoreline were classified as of X grade minimum; iv) the influence of the river network to the expansion of the inundation zone; v) that intensity level is gradually decreasing inland, except of steep-relief areas.

Impact on human

Mega-tsunamis are totally perceptible by people located within the inundation zone. Ishinomaki recorded the highest number (5867) of fatalities among the affected municipalities, while Higashimatsushima recorded

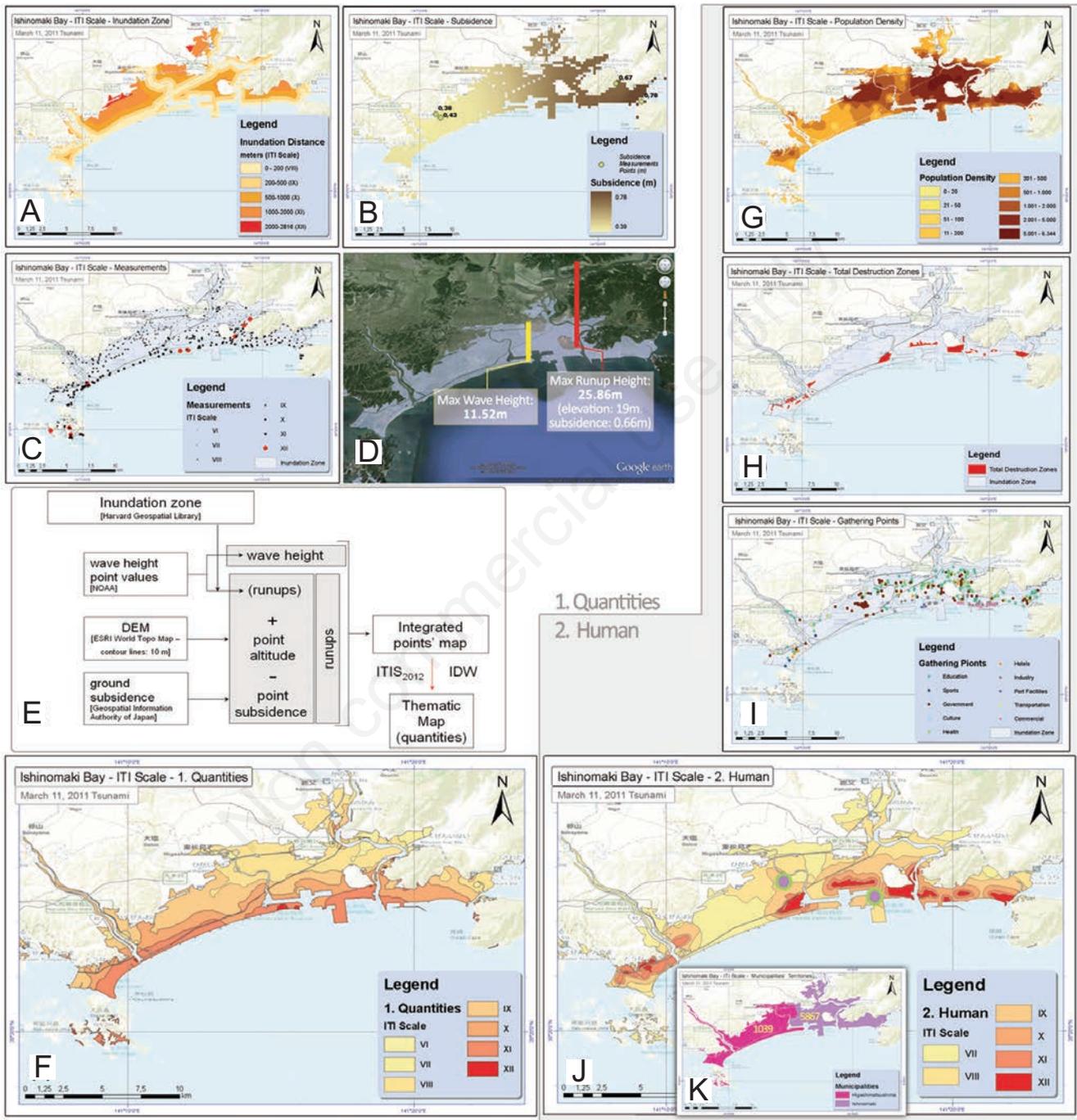


Figure 2. A) Maximum inundation distance >2 km; B) Subsidence: point measurements and spatial interpolation result map;²¹ C) Point measurements²⁰ evaluated against the ITIS₂₀₁₂ criteria. A data gap is visible in Matsushima airport area; D) Maximum wave height and run-up height in the study area; E) Data sources and methodology on quantities criteria category; F) Intensity thematic map of quantities criteria category; G) Population density;²⁵ H) Total destruction zones;²⁶ I) Gathering points; J) Intensity thematic map on impact on human criteria category and the two recorded massive-death incidents' location (purple points).^{12,24} Both belong to X-grade zones; K) Fatalities ratio per municipality²³ agrees with the produced map.

1039 casualties.²³ Massive-death incidents are recorded in Omagari elementary school²⁴ and in Nippon Paper industry facilities.¹² 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 survivors¹⁵ 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 density²⁵ based on 2005 Census, total destruction zones²⁶ and population gathering points maps, based on ESRI World Topo Map (Figure 2G, H and I).

The produced map agrees with the massive-death recorded data (Figure 2J) as well as with the victims' ratio per municipality (Figure 2K). Note the high population density in Ishinomaki center, which shows that this part of the area has been probably protected by Hiyoriyama hill.

Impact on displaced objects

Data have been collected by using Google EarthTM imagery and air-photos of March 18th, 2011.¹⁶ A weighted factor (Table 1) has been given to displaced vehicles (Figure 3A), vessels - proportional to their size - (Figure 3B), train wagons (Figure 3C), fight aircrafts and helicopters²⁷ (Figure 3D) and tanks (Figure 3E). Kriging interpolation method has been applied to the map including all these points and intensity has been set between V and XII, according to the grades of ITIS₂₀₁₂. Finally fire zones map^{12,28} (Figure 3F) has been overlaid, as both fire incidents seems to be caused by objects' displacement.

In the produced map (Figure 3H), one may note the following: i) the data gap in the broader airport area, probably due to urgent restoration works took place after the event and before the time the images were recorded. For this reason, Kriging method has been preferred instead of the IDW one; ii) the lack of protection facilities in the eastern Ishinomaki coast (Figure 3G), namely between the coastal forest and the port facilities; and iii) the multilateral inundation in western Higashimatsushima, as a result of that the tsunami hit the area from four different directions of both bays, the Naruse river and the Tona canal (Figure 3H).

In addition, one may note the: i) limited number of displaced vehicles at the shoreline attributed to the tsunami water backwash; ii) low intensity grades at the shoreline attributed to the land use or the protection facilities.

Impact on infrastructure

Damages have been mapped and evaluated against the ITIS₂₀₁₂ criteria on bridges and road parts (Figure 3O and 3I),^{29,30} a significant part of the railway line - using the Google EarthTM imagery (Figure 3P and 3J)^{31,32} and the relevant literature - several lifelines' nodes (telecommunications systems,^{5,11,29,33,34} drainage^{12,35,36} and water supply systems,^{10,37} airport facilities²⁷ and LNG facilities³⁸ - Figure 3K), industry facilities (Figure 3Q and 3L)¹² and port facilities (Figure 3N, 3R and 3M).^{39,40,41}

Port facilities alternating with coastal forests compose a kind of firewall in front of the coastline of the study area. However, a lack of protection facilities has been noticed at the Matsushima Bay.

The thematic impact map (Figure 3S) has been produced by applying the IDW spatial interpolation method and shows a gradual intensity decrease inland. Centralization of XII-grade intensity zones in the two ports areas is attributed to the infrastructure concentration and to the high wave heights observed in these areas.

Impact on the environment

Shoreline changes have been mapped by using the Google EarthTM imagery and the relative literature (Figure 4A and 4G)⁴¹ and along with the ground pollution points (Figure 4B)²¹ have been directly evaluated against the ITIS₂₀₁₂ criteria. Uprooted trees (Figure 4C and 4H) and deposits (Figure 4D), located in Google EarthTM imagery, have been evaluated based on their spatial density. Boulders displacement and *in situ* fires have not been reported, however the fire-zones triggered by

displaced objects^{12,28} have been taken into account as ground pollution spatial density. Boulders displacement and *in situ* fires have not been reported, however the fire-zones triggered by displaced objects^{12,28} have been taken into account as ground pollution areas (Figure 4B). A first approach for the thematic map has been created by applying the IDW spatial interpolation method on the above data (Figure 4E). Especially for the debris distribution and given the lack of in-time field data, an indirect approach has been followed by composing 5 maps: i) total destruction zones;²⁶ ii) displaced objects; iii) uprooted trees; iv) areas near the bridges at the shoreline; 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,²¹ the debris intensity distribution (Figure 4F) was classified as of VII and XII grades. Finally a weighted factor has been given to the two produced raster maps.

Table 1. Weighted-factor table on located displaced objects.

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

Table 2. Qualitative evaluated structures and their quota of the removed ones, based on their structural material.

Type	Evaluated	%	Removed	%
Wood	28,123	88.20%	13,918	49.49%
Steel	3227	10.12%	611	18.93%
Reinforced concrete	455	1.43%	65	14.29%
Masonry	80	0.25%	32	40.00%
	31,885	100%		

Table 3. Weighted-factor table on land-use overlay.

	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%

The environmental impact map (Figure 4I) 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-m-altitude coastal forest in eastern Ishinomaki greatly protected the rear area.

Impact on structures

Several studies⁴²⁻⁴⁶ have mapped the structures' damages using remote-sensing methods on high-resolution satellite images or air-photos. Damages on part of structures of the study area have been evaluated and mapped by Harvard University,¹⁸ which also published an interactive web map.

However results of these approaches do not cover the grade of damage and the structural material of each structure, as ITIS₂₀₁₂ requires and are not detailed enough to be used on ITIS₂₀₁₂ implementation study. Therefore data from Google Earth™ (25-06-2010 and 30-03-2011) in combination with the Google Memories for the Future™ web application,¹⁶

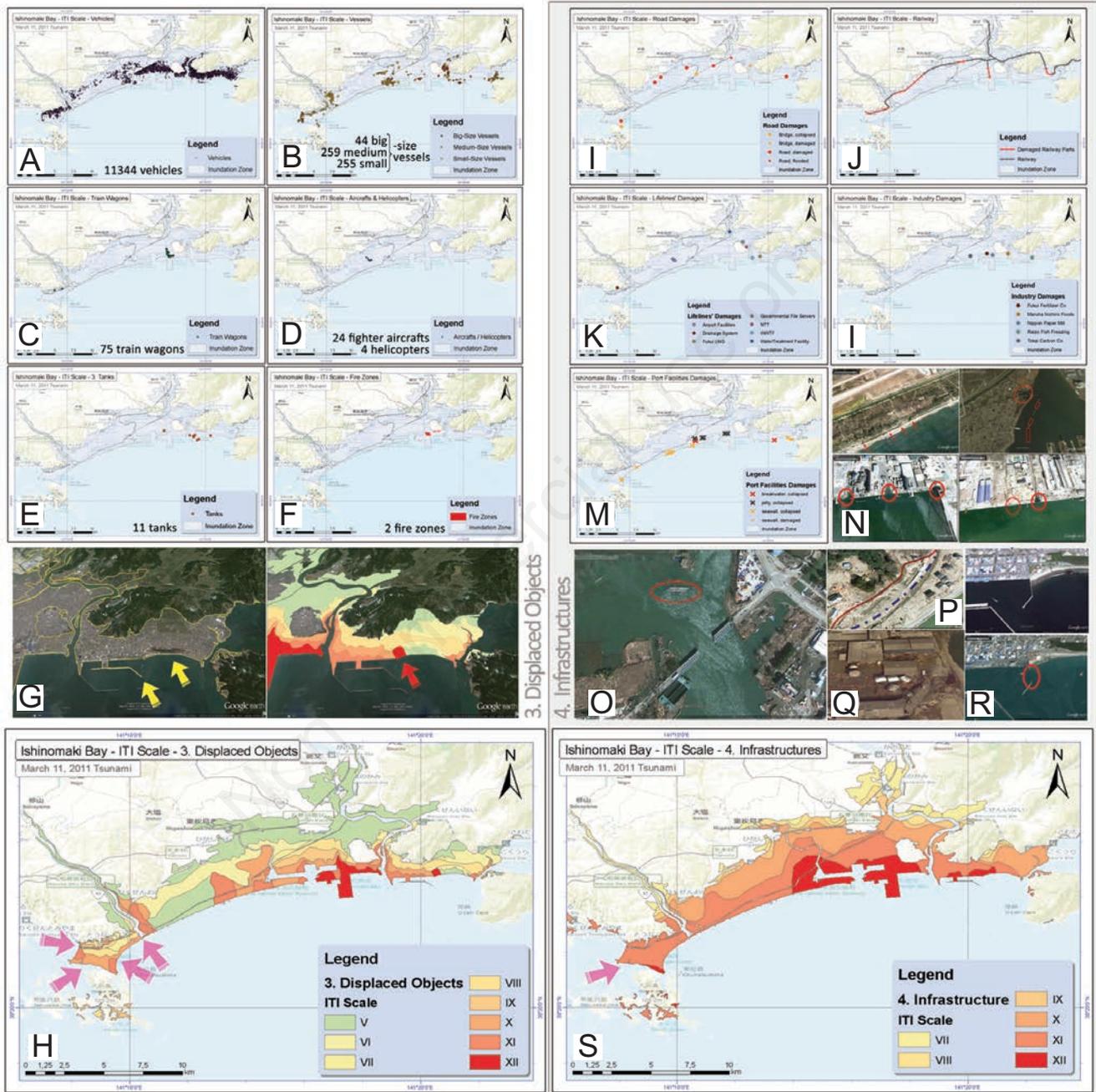


Figure 3. A) Displaced vehicles; B) Displaced vessel; C) Displaced train wagons; D) Displaced fighter aircrafts and helicopters; E) Displaced tanks; F) Fire zones;^{12,28} G) Protection lack in the area between the coastal forest and the port facilities in eastern Ishinomaki; H) Intensity thematic map of impact on displaced objects criteria category mapped damages: I) on bridges and road parts,^{29,30,31} J) on railway lines, K) on several lifeline nodes, L) on industry facilities,¹¹ M) on port facilities;^{39,40} N) Indicative damages on port facilities [©Google Inc./Google Earth]; O) Jo river bridge Sadakawa [©Google Inc./Google Earth, 19-03-2011]; P) Displaced railway line part [©Google Inc./Google Earth]; Q) Damage in industrial zone [©Google Inc./Google Earth, 30-03-2011]; R) Collapsed breakwater [©Google Inc./Google Earth, 19-03-2011]; S) Intensity thematic map of impact on infrastructure criteria category.

that 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 (Figure 4J) and the construction-free zones have been isolated in order to produce a density map of the removed structures (Figure 4K). Based on this

map, as second step the majority (31,885) of the structures - the ones located in destruction zones - have been evaluated against the ITIS₂₀₁₂ criteria, based on their damage grade and their structural material and the impact thematic map has been produced (Figure 4M). 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 4L).

Data analysis on evaluation results showed that wood and masonry structures are the most vulnerable to tsunami (Table 2), fact that agrees with the relative field surveys.⁴⁸⁻⁵³

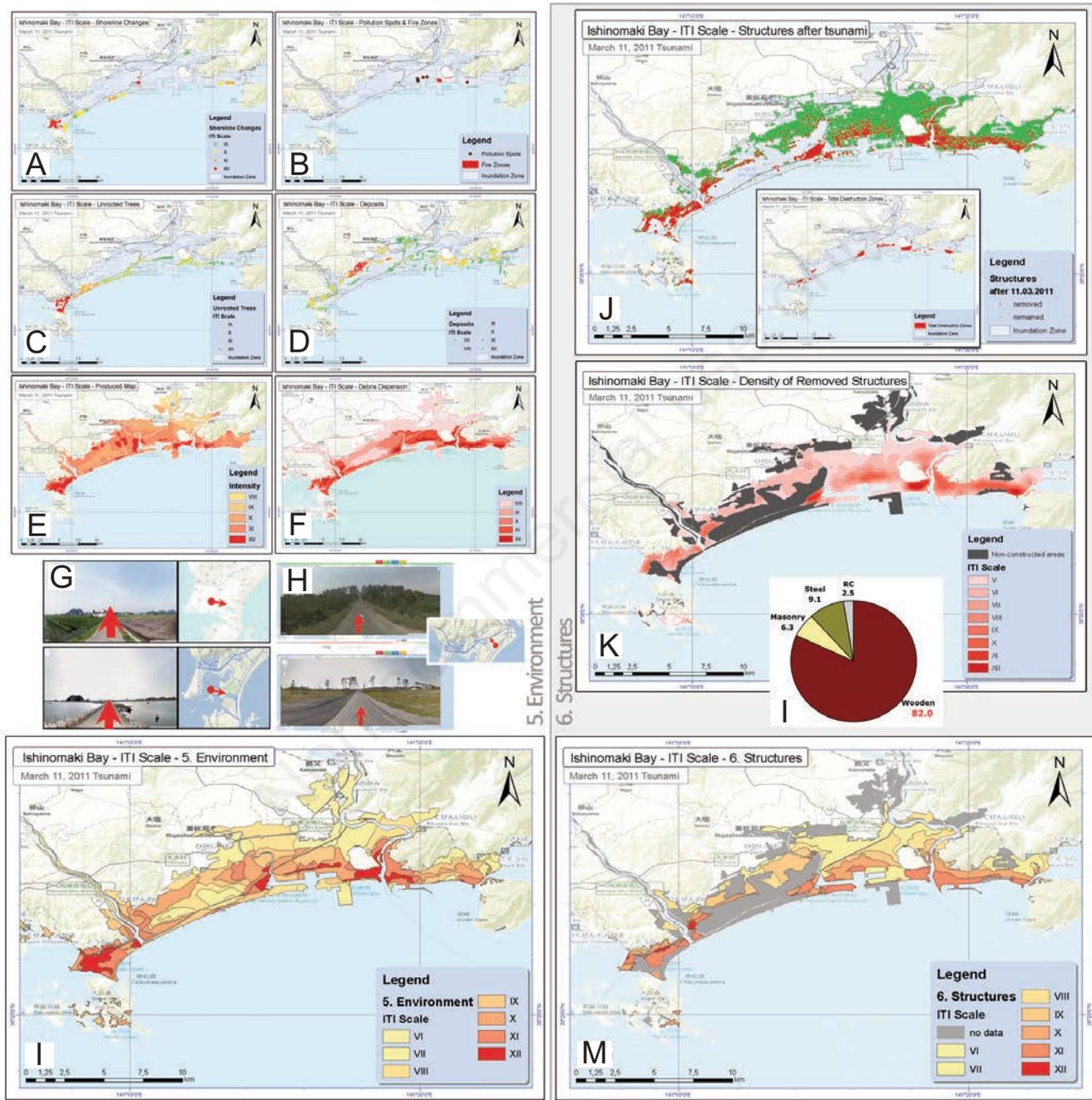


Figure 4. A) Shoreline changes; B) Pollution points and areas; C) Uprooted trees; D) Deposits E) Composition result of the above criteria; F) Debris dispersion produced map; G) 27 sq. km area in western Higashimatsushima before (up) and after (down) the event;¹⁶ H) Western Hihashimatsushima coastal forest before (up) and after (down) the event;¹⁶ I) Intensity thematic map of impact on environment criteria category; J) Removed (washed-away or demolished) and remained structures in study area. The map is similar with the one displaying the total destruction zones;²⁶ K) Density map of removed structures and construction-free zones; L) Percentage of structural material in Ishinomaki area;⁴⁷ M) Intensity thematic map of impact on structure criteria category.

The produced map (Figure 4M) 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.

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 ITIS₂₀₁₂ criteria category (Table 3), 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-

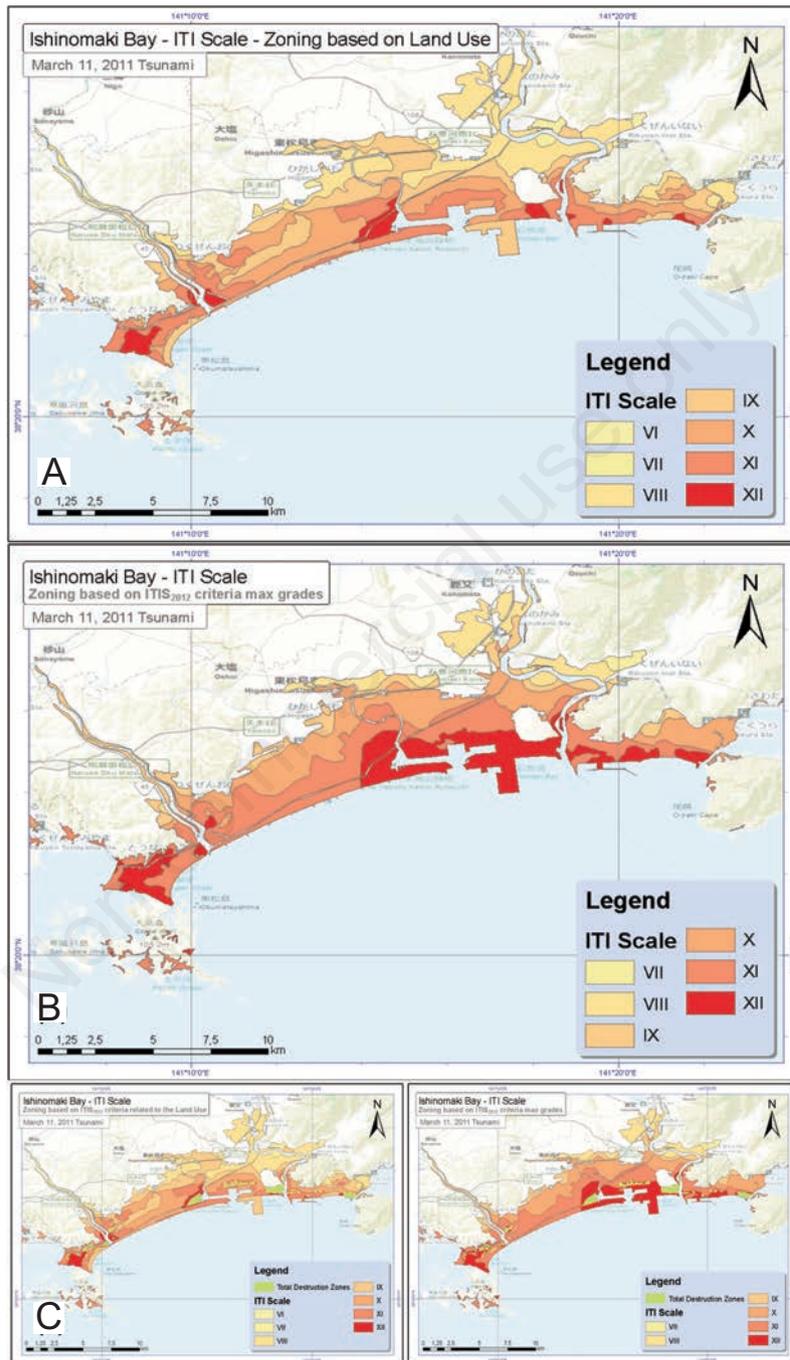


Figure 5. A) Damage assessment map; B) Tsunami intensity map (ITIS2012) after the Tohoku event (hazard assessment map); C) Total destruction zones²⁶ overlaid on the two maps.

use-based weighted overlay with the six thematic impact maps resulted in a 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 5A). 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 incidents timing. This approach covers the worst-case scenario and uses the complementarity of ITIS₂₀₁₂, 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 5B). The image is very closer to the theoretical approach, whereby the degree of destructiveness is the 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 zones²⁶ 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 5C). The complementary function of the ITIS₂₀₁₂ criteria is evident in the final map.

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

Conclusions

Study area

During the research pros and cons relative to the characteristics of the study area have been revealed per ITIS₂₀₁₂ criteria categories: i) despite the positive coastal forest response, rivers and canals in the plain area broadened the inundation zone; ii) despite the positive port facilities response, a lack of protection facilities have been noticed at Matsushima Bay; iii) despite the protected city center, the industrial zone is vulnerable and a potentially source of further disasters; iv) despite the high-level prevention measures and legislation, more than 80% of the structures are vulnerable; v) despite the annual citizens' training program, a limited participation has been recorded; vi) despite the in-time working early warning system, the hazard had been underes-

timated. 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 ITIS₂₀₁₂ application, that require further study on both: their adequacy and their applicability. Historical maps^{29,54} of the study area reveal the human intervention on the terrain and the shoreline over the years. Residential zones were located in relatively protected from tidal waves, storms and tsunamis areas, while the area along the shore was wetland.⁵⁴ 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.

ITIS₂₀₁₂

All of the ITIS₂₀₁₂ categories have been easily applied and most of their individual criteria complemented each other. Recorded destructiveness never exceeded the upper limits of the ITIS₂₀₁₂, indicating that the scale does not saturate. In two cases an indirect approach fully or partly, has been followed. However the limited available data confirmed partially the results.

All of the ITIS₂₀₁₂ 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. All kind of infrastructure impact - important to management and restoration processes - is for the first time included in a tsunami intensity scale, covering possible NaTech events. Categories relative to the tsunami quantities and the environmental impact are land-use independent and applicable on historical events.

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, causing accuracy issues. 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, ITIS₂₀₁₂ results are objective, integrated and detailed. Given the complementarity of its criteria, ITIS₂₀₁₂ is applicable on historical events and capable to highlight the pros and cons of each area. Therefore ITIS₂₀₁₂ could be considered as a modern planning and management tool.

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