Rapport / Report

GBV Sårbarhetsanalyser og risikohåndtering

Analysis of the 2011 Tohoku tsunami

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Summary

On March 11th 2011 the Tohoku earthquake and tsunami devastated the East coast of Japan claiming thousands of lives and destroying coastal settlements and infrastructure. The severity of the natural disaster was further increased by a cascading nuclear catastrophe at the Fukushima power plant. The Tohoku tsunami hit a coast well prepared for earthquakes and tsunamis. Nevertheless, coastal protection was underestimated or failed to a large extent and buildings were not able to withstand hydrodynamic forces. Since the Tohoku tsunami is well documented, it is a unique possibility for a retrospective analysis in order to learn from the event and to improve tsunami risk mitigation.

This report summarizes results from the modeling of the Tohoku tsunami including tsunami generation, propagation, and inundation as well as subsequent impact assessment based on the modeling results and a literature review. Earthquake source models with heterogeneous slip were developed. The best fit scenario shows an initial sea surface elevation with water levels up to 8 m. Tsunami propagation

was then modeled and simulations were compared to buoys in the Pacific, showing good agreement. Furthermore, inundation simulations were performed for ten different study areas and compared to run up measurements from field data and trim lines derived from satellite images. The modeling was supposed to be a rapid hazard assessment, based on medium-resolution, freely available data for topography, local bottom friction, and bathymetry. Taken the resolution of the underlying data into account, results provide a good agreement with the observed inundation, but with some overestimation of the modeled surface elevation in the fjords of the northern part of the Sanriku coast.

The literature-based analysis of the tsunami impacts includes an overview of fatalities and damages, their spatial distribution as well as a determination of factors influencing vulnerability and the degree of damage, e.g. coastal protection.

Results showed a correlation of water levels and fatalities, with the highest number of fatalities at the northern ria coasts where water piled up to very high levels. The damage to buildings was extraordinarily high. Especially wooden houses were not able to withstand the tsunami forces and even major breakwaters and seawalls failed. Coastal forests did not show an effect of wave dissipation since the water levels were too high. Nevertheless, tsunami damages are supposed to have been worse without coastal protection measures, which have shown to provide partial protection from the tsunami even when partly or totally destroyed.

Japan was well prepared and sophisticated early warning systems and evacuation plans were in place. These preparedness measures are considered to have saved many lives. However, the destruction of lifelines (e.g. telecommunication) turned out to be a major problem.

Based on the Tohoku 2011 findings some suggestions were made on how to improve the tsunami risk model used at NGI for further application. The most important suggested extensions are:

- A specification of people exposure according to different scenarios,
- an inclusion of economic values of private buildings and companies,
- accounting for environmental impacts and socio-ecological interrelations (e.g. loss of ecosystem services), and
- an inclusion of risk to lifelines, such as railway networks or social facilities in the overall risk assessment, and of risk mitigation measures.

Contents

1 Introduction

On March 11th 2011 a Mw 9.0 earthquake occurred 130 km east of the Sendai coast, Japan (Lay et al. 2011, Mori et al. 2011). Its epicenter was located offshore Minamisanriku, with an extension of about 400 km along its strike direction and a maximum slip exceeding 20 m (Lay et al. 2011, Ozawa et al. 2011). The earthquake triggered a tsunami that reached the coastline 20-40 minutes later with run-up heights of up to ~39 m. Both the earthquake and tsunami caused enormous destruction in the prefectures Iwate, Miyagi, and Fukushima (Mimura et al. 2011b, Mori et al. 2011). Approximately 20,000 people lost their lives, most of them in the tsunami, 76,000 houses were completely destroyed and damage costs added up to $300 Billion (EM-DAT 2011, Mimura et al. 2011a, Mori et al. 2011) making it to one of the costliest natural disasters ever. The Tohoku earthquake and tsunami were stronger than some of the world’s largest tsunami barriers were designed for (Cyranoski 2011), and although the tsunami hit an area that was well prepared, it caused enormous structural damage. In some areas only very few buildings were able to withstand the forces from the water masses. Major coastal protection structures, such as walls, revetments, or dikes, although showing some disaster reducing effects, failed to a large extent (Mori et al. 2011). Moreover, extensive damage occurred at the Fukushima power plant followed by a nuclear radiation leak (Brumfiel 2011, http://www.nature.com/news/specials/japanquake/index.html). According to EERI (2011) the recovery process is expected to last eight to ten years.

Through the recorded history, the Pacific coastline of northeastern Honshu has faced a number of destructive tsunamis (see e.g. NGDC 2011). Two of the most damaging events in recent history were the 1896 and 1933 Sanriku events. The former caused 27,000 fatalities (Tanioka and Satake 1996), while the 1933 event caused considerably less casualties (Kanamori 1971). Nevertheless, the Tohoku event came as a “surprise” to the scientific community, since there are reports suggesting that tsunamigenic earthquakes of magnitudes in excess of Mw 8.0 were not expected in the area (Geller 2011, Monastersky 2011).

A thorough analysis of the event is therefore important. The Tohoku tsunami can probably be considered the most extensively documented tsunami event in history. Within hours videos and pictures as well as satellite images were made available for the world providing information about the amount of destruction, the inundation dynamics, and the efficiency of measures (e.g. by http://www.zki.dlr.de). Within a few weeks field survey teams published their first results (Coastal Engineering Committee of the Japan Society of Civil Engineers 2011, Tsunami Damage Mapping Team, Association of Japanese Geographers 2011, Goto et al. 2011, TETJSG 2011), including measured run-up heights and observed damages. The extra-ordinary scale of the event, the cascading coincidence with a nuclear disaster, and the availability of data is an outstanding opportunity to learn from the event in order to improve tsunami risk assessment and management.

In this report an overview is provided on impacts of the Tohoku tsunami as well as on lessons learned from the event. Numerical modeling of the 2011 Tohoku tsunami is performed in order to gain a spatial distribution of run-up heights and flow depths. Model results together with information available from literature are then used to analyze interrelations between tsunami wave heights and their impacts. Finally, conclusions are drawn on how to improve NGIs tsunami risk assessment model.

2 Tsunami modeling

The immediate availability of tsunami heights and run-up measurements gave the opportunity to numerically hindcast tsunami propagation and inundation in order to gather information on inundation patterns. Tsunami modeling was based on medium resolution, freely available bathymetry and topography, as well as land cover information from Google earth, since there were no high resolution data available for this work. The data lack the accuracy required for detailed local risk and vulnerability studies, but they allow a fast and cost-efficient hazard mapping of past or possible future events, and are therefore important for risk assessment and mitigation.

To compute the tsunami propagation, we have applied the Boussinesq model labeled GloBouss (Pedersen and Løvholt 2008, Løvholt et al. 2008), allowing for wavelength dependent wave speed (frequency dispersion). To simulate tsunami inundation the nonlinear shallow-water wave (NLSW) equations are used together with the Community Model Interface for Tsunami (ComMIT) (Titov and Synolakis 1995, 1998, Synolakis et al. 2008, Titov et al. 2011). Inundation modeling in ComMIT is based on three nested rectangular computational grids (here called A-, B-, and C-grid) with bathymetry and topography as underlying data sets. For the inundation simulations the ComMIT model was used with varying resolution for the A-grid (700 m x 500 m), B-grid (178 m x 140 m) and C grid (90 m x 90 m). By using a one way nesting procedure, ComMIT was coupled with GloBouss interpolating the output from GloBouss over the A grid boundary at each time step, using the global propagation simulation to drive the local inundation model (Løvholt et al. 2010).

A total of 17 scenario simulations were conducted over a period of about one month. Out of these, four different scenarios (labeled A, B, C, and D) turned out to fit best and were analyzed in more detail. In the following a short summary of the numerical simulations is provided. A detailed description of the earthquake source modeling including rupture and seabed surface displacement, the computational approach for tsunami propagation and inundation, as well as validation and convergence tests for the four scenarios are described by Løvholt et al. (2012), see also Simons et al. (2011).

2.1 Tsunami generation and propagation modeling

Scenario slip distributions and initial surface elevations for the four scenarios (A, B, C, D) are displayed in Figures 1 and 2. Whereas scenario A represents one of the simplest cases with a uniform slip, the other scenarios are all heterogeneous. Moment magnitudes range from 8.85 to 8.95 and maximum initial elevation range from 4 to 13 m. In all cases, the scenarios are surface rupturing, and a shear stiffness of 40 GPa is assumed. Dip angles are 25° except for scenario A, which has a dip angle of 15°. The simulation that overall matched the field observations best is scenario D, which is described and used in the following analysis. It comprises 6 x 6 segments along the strike and dip direction, respectively. The source has a maximum slip of 15-20 m located between latitudes 38° and 40°, a dip angle of 25°, and a total width of 150 km. The total length of the modeled source rupture is approximately 400 km. Compared to the co-seismic slip distribution of Ozawa et al. (2011), the slip distribution of scenario D is extending slightly further north. Some of the segments display a slight overlap due to the bending of the source, resulting in small areas of locally increased slip. However, the overlapping areas are mostly displaying short wavelengths and therefore vanish due to the smoothing. The maximum initial sea surface response is slightly above 8 m.

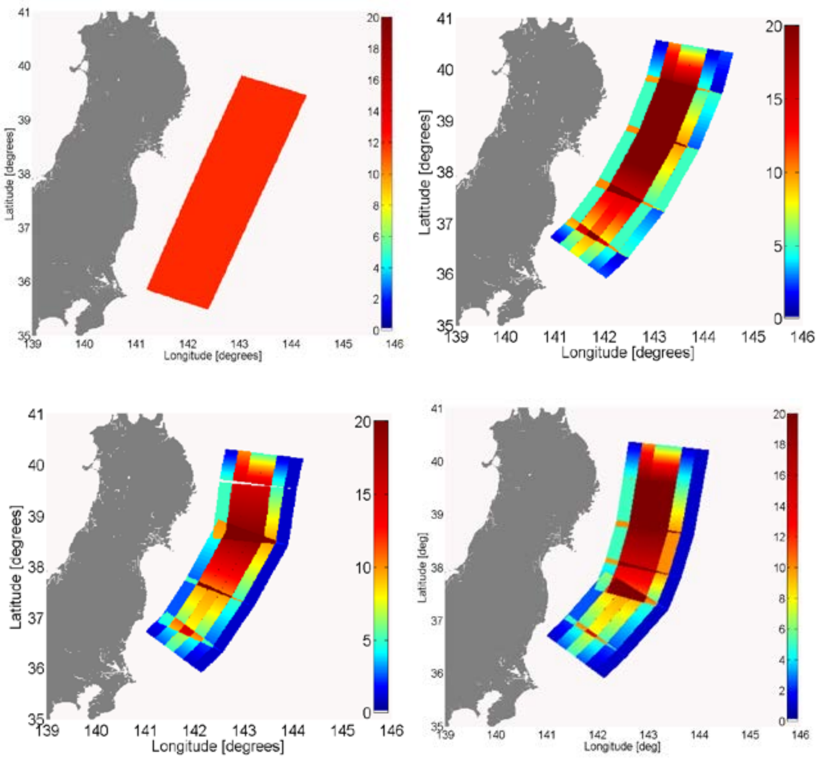

Figure 1: Slip distribution for the four different earthquake source scenarios A-D. Upper left, scenario A, Mw 8.89. Upper right, scenario B, Mw 8.85. Lower left, scenario C, Mw 8.95. Lower right, scenario D, Mw 8.87 (Løvholt et al. 2012).

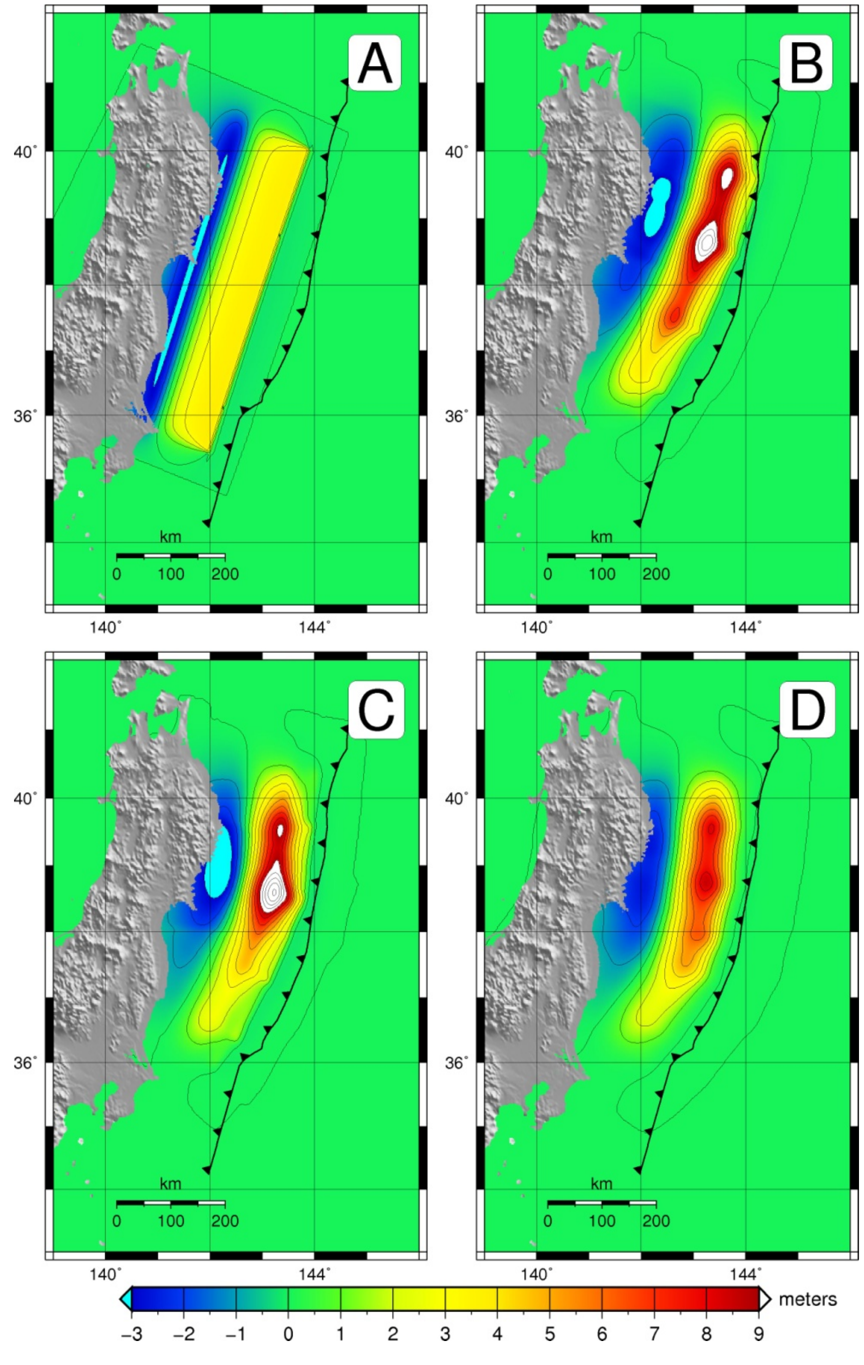

Figure 2: Initial surface elevations for the four different earthquake source scenarios A-D (Løvholt et al. 2012).

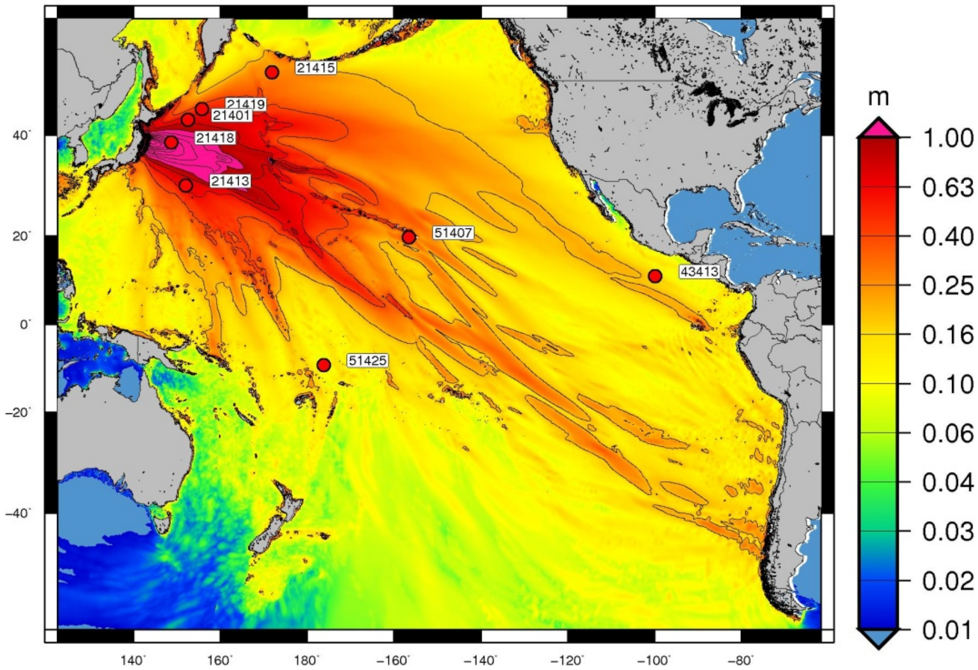

Figure 3: Maximum surface elevation for scenario D and DART locations for the entire Pacific Ocean, dispersive solution. Contour lines are drawn for every 20 cm (Løvholt et al. 2012).

In Figures 3 and 4 the maximum modeled surface elevations for the offshore tsunami simulations are depicted. Outside the eastern coast of Japan the maximum surface elevation is up to 10 m, while the directivity of the source is about ENE-WSW. Comparison between the surface elevations for the different scenario simulations A-D were evaluated at the DART buoys given in Figure 3. The comparisons are given in Figure 4. Generally, scenario D gives the best agreement both with respect to the elevation and arrival time, with errors seldom exceeding 10% for the maximum leading wave. In summary, the numerical results for the best fit scenario D compare very closely with the recorded data both in shape and height. Between the simulated data and the recorded data from the DART buoys there is a small time shift for a few locations. The reason for this shift may be an incorrect location of the buoys in the numerical model, inaccuracies in the bathymetric data, or minor errors in location of the source. Hence, for Figure 4 the DART data were given a small time shift for easier comparison between the leading waves of the recorded and modeled waveforms. In this manner the leading waves in the DART data and those from the simulations arrive at the gauges at the same time. The time shift (100 to 200 s) corresponds to an EW displacement of the location of the source of 15-30 km.

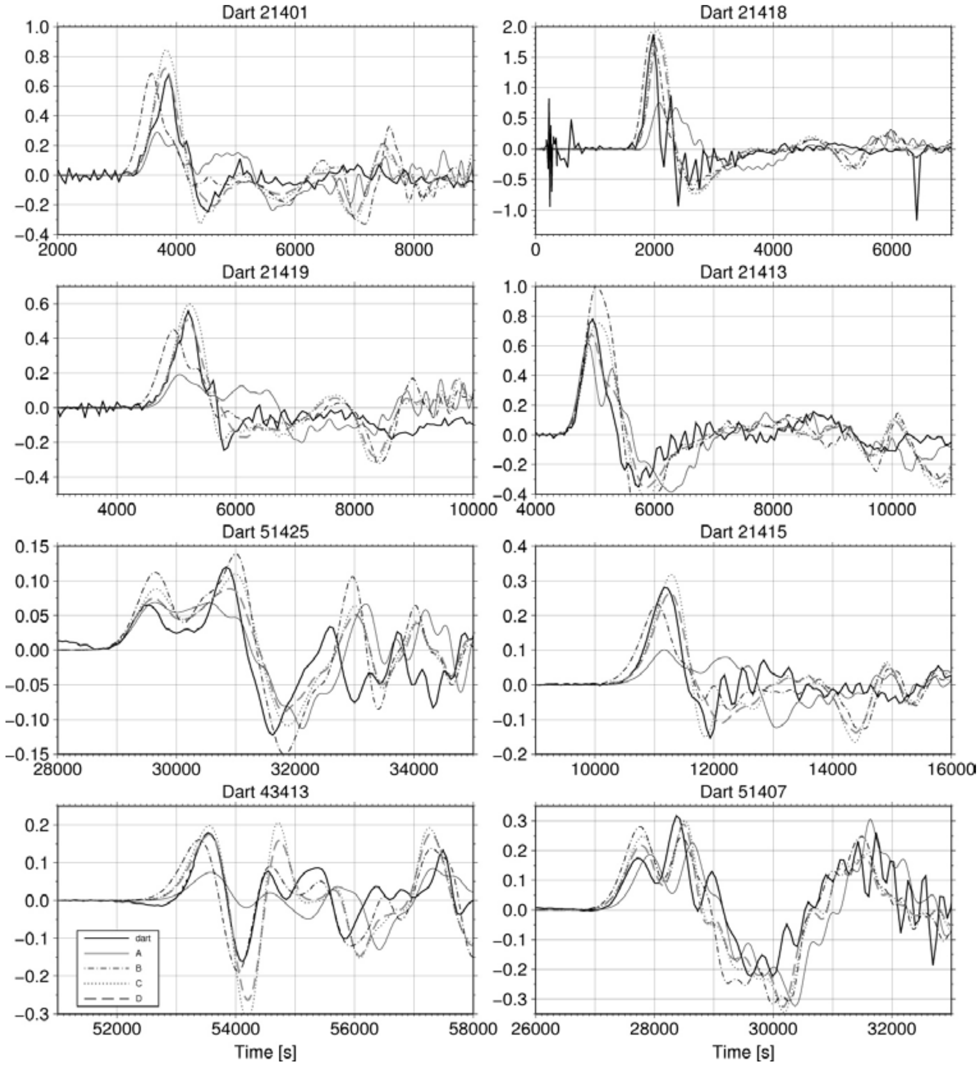

Figure 4: Source sensitivity for a range of DART locations exemplified for scenarios A-D, dispersive solution (Løvholt et al. 2012).

2.2 Inundation modeling and validation

Inundation simulations were conducted for ten study areas with different morphological and topographical settings along the Sanriku coast. The study areas are located in the floodplains of Minamisoma, Soma and Sendai, Ishinomaki city, and along the ria* coasts of Minamisanriku, Kesennuma, Rikuzentakata, Otsuchi, Miyako, and Kuji (Figure 8). The size of the study areas varies from 298 km^2 to 1969 km^2. The General Bathymetry Chart of the Oceans (GEBCO) with a resolution of 30'' (~910 m) was applied and 90 m resolution data from the Shuttle Radar Topography Mission (SRTM, Jarvis et al. 2008) were used to represent land elevation in the model. It is stressed that the SRTM dataset is not corrected for the subsidence due to the earthquake, which is in the order of 1.2 m (Mimura

* submerged river valley open to the sea, partly with steep slopes

et al. 2011a). This gives rise to a slight underestimation of the run-up, but the subsidence is clearly less than the typical mean run-up.

Several studies on tsunami inundation modeling depicted the need for high resolution elevation data to simulate inundation sufficiently well by accounting for changes in local topography (e.g. Taubenböck et al. 2009). However, high resolution data are not available in many parts of the world and often not suitable for rapid assessments due to computational demands. For this reasons freely available data are an option for many tsunami risk studies.

We tested two different Digital Elevation Models (DEMs), the ASTER Global Digital Elevation Model (ASTER GDEM, 30 m) and the SRTM (90 m) for selected study areas in order to get the most accurate elevation data set for this study. A description of the technical specifications of both elevation models is given in Table 1.

Table 1: Elevation data sets applied in this study.

	SRTM	***ASTER GDEM***
Type	Digital Surface Model (DSM)	Digital Surface Model (DSM)
System	Synthetic Aperture Radar (C-Band-SAR) data, space-borne, NASA Endeavour	Advanced Spaceborne Thermal Emission and Reflection Radiometer, NASA Terra
Resolution	Horizontal: 90 m Vertical: ~ 6.2m (Rodriguez et al. 2006), 16 m according to mission specifications	Horizontal: 30 m Vertical: 10-25m
Acquisition date	February 2000	1999 to 2008
Availability	free	free
Spatial scale	global (60°N - 56°S)	global (83°N - 83°S)
Source	Jarvis et al. (2011)	METI/NASA/ERSDAC LP DAAC

A comparison of the terrain height information provides more realistic values for the SRTM and also test simulations showed that using the SRTM leads to better matches between the run-ups measured in the field and the modeled inundation simulation (Figure 5). Therefore, the SRTM was chosen for further analysis in this work.

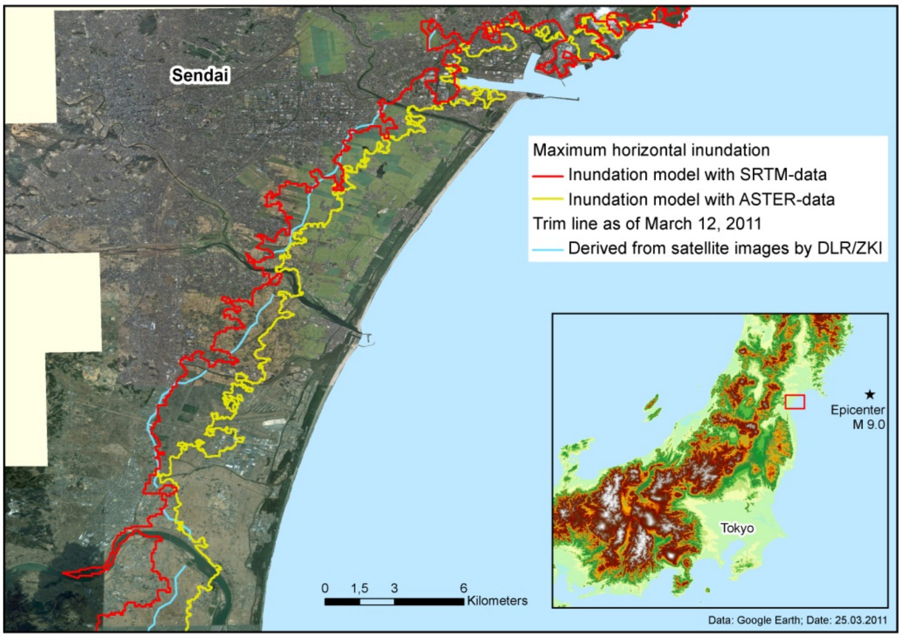

Figure 5: Comparison of modelled inundation based on ASTER GDEM and SRTM for a test scenario (figure produced by Lasse Scheele).

As many other terrain models derived from space-/airborne sensors, the SRTM data describe the earth surface, including vegetation and settlement structures in the height description (Sun et al. 2003, Hofton et al. 2006). In some of the study areas this required manual adjustments of the SRTM data to remove significant offsets (i.e. coastal forests) which would influence the inundation simulations considerably and lead to false (underestimated) water levels. This was done in GIS by correcting offset pixels to the surrounding ground level pixels based on land cover information from satellite images. Since no detailed land use data were available this correction was done very conservatively and only for obvious green belts and artifacts (Figure 6). General offsets due to housing in urbanized areas were not removed. Despite removing the most prominent forests there are still considerable inaccuracies related to the coarse horizontal and the vertical resolution of the elevation data, which have to be kept in mind when analyzing the results.

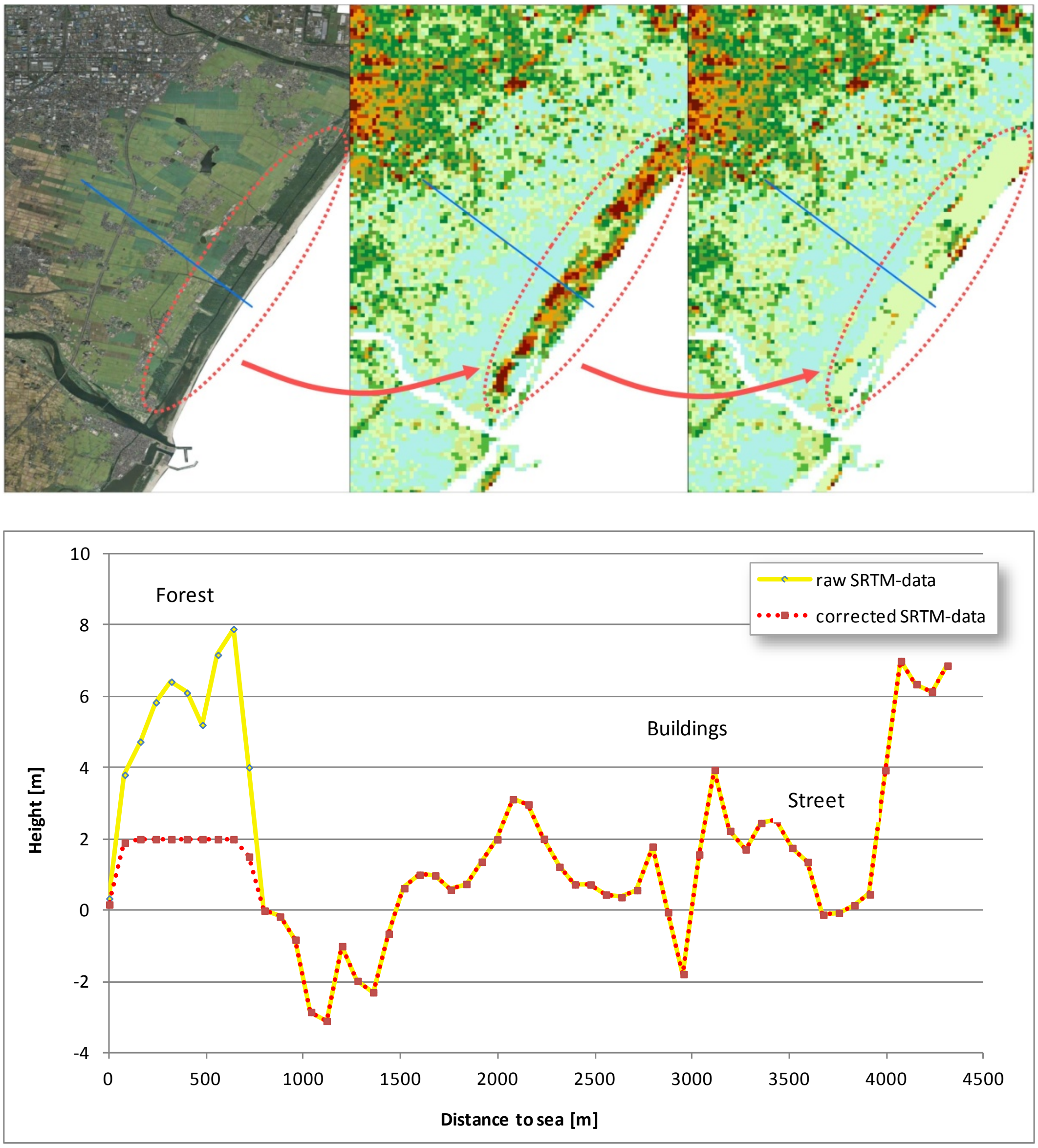

Figure 6: Correction of vegetation offset from a coastal forest in Sendai. The left panel shows an example of a coastal forest parallel to the coast. In the middle panel the height offset of the forest in the SRTM data is illustrated, which causes elevations up to 8 m above ground. The right panel shows the manually corrected SRTM data, where forest offsets have been removed. In the lower panel a profile is drawn (from SE to NW along the blue line in the upper data panels) through both the original and the corrected SRTM elevation data sets (figure produced by Lasse Scheele; data source: SRTM, Google Earth).

Besides the topography land cover is influencing inundation patterns (Gayer et al. 2010, Kaiser et al. 2011, Mimura et al. 2011a). Thus different friction coefficients were tested (Figure 7) in ComMIT to account for wave attenuation caused by land cover roughness such as forests or human-made structures. From the Manning coefficients n^2 = 0.0009, n^2 = 0.0017, and n^2 = 0.0012 the last one provides the best results when validating the simulations against run-up measurements from the field. Land cover roughness has shown to particularly influence flow velocities and only to a minor degree the inundation extent (Kaiser et al. 2011). Hence, differences in the modeling results for different roughness values are not very significant, where only the extent is considered (Figure 7). Tides were not considered in the analyses.

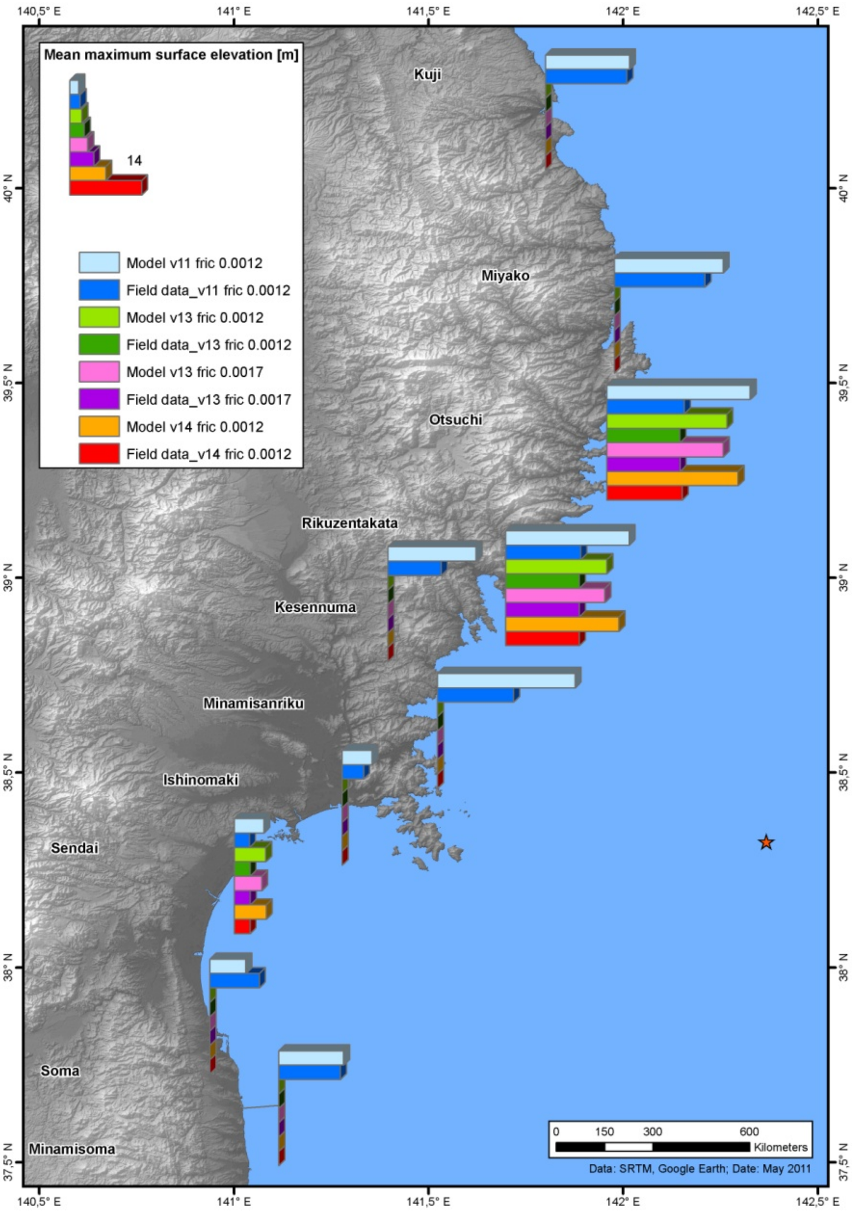

Figure 7: Model runs for scenario D (dispersive) based on different values for bottom friction. The model results are compared to the field observations for each bar (figure produced by Lasse Scheele).

The results of the ComMIT simulations for scenario D were compared to (a) 442 run-up measurements derived from the Coastal Engineering Committee of the Japan Society of Civil Engineers (2011) and (b) trim lines derived from the Tsunami Damage Mapping Team, Association of Japanese Geographers (2011). The field survey, which is now published in Mori et al. (2011), comprises more than 5300 field measurements in its final version. However, during our investigation we could only use the first measurements of this study available online in the early phase after the tsunami. Within each study area (Figure 8) a mean value was created from the measured points in the field and compared to a corresponding mean value of the modeled surface elevation in these points. In doing so, extreme water levels were smoothened in both the measurements and the modeled inundation. Thus, the water levels in the study areas were directly comparable.

Results from the ComMIT simulations show mean maximum water levels of 5.5 m in the Sendai area, whereas mean maximum water levels of approximately 20 m could be observed in the steep valleys of Rikuzentakata and Otsuchi (Figure 8). The maximum modeled run-up value occurred in Otsuchi with 49.8 m. The maximum modeled inundation distance is approximately 6 km in Otsuchi, Rikuzentakata and Sendai, which agrees with observations provided by Mimura et al. (2011a), while the water reaches 15 km inland at the Kitakami River close to Minamisanriku.

In total in Minamisoma, Soma, Kesennuma, Miyako, and Kuji good results have been achieved with a deviation of the mean modeled values from the measurements of 5-13%. In Sendai and Otsuchi, however, there is a significant overestimation (191%, 157%) in the modeled surface elevation, which likely results from inaccuracies in the topography/ bathymetry, the disregard of coastal infrastructure as well as a local source peak offshore Otsuchi (see Figure 1). The slip concentration does not affect the far field tsunami simulation, but the overestimation in Otsuchi may suggest that this local peak is artificial.

A comparison with the trim lines (Figure 9) shows good agreement in almost all study areas, even in those, where the point measurements are dissent (e.g. in Rikuzentakata and Sendai). However, a good match with the trim lines in the steep valleys of Rikuzentakata, and Otsuchi was expected since the topography changes significantly over a short distance and thus directs water flow narrowly through the valley.

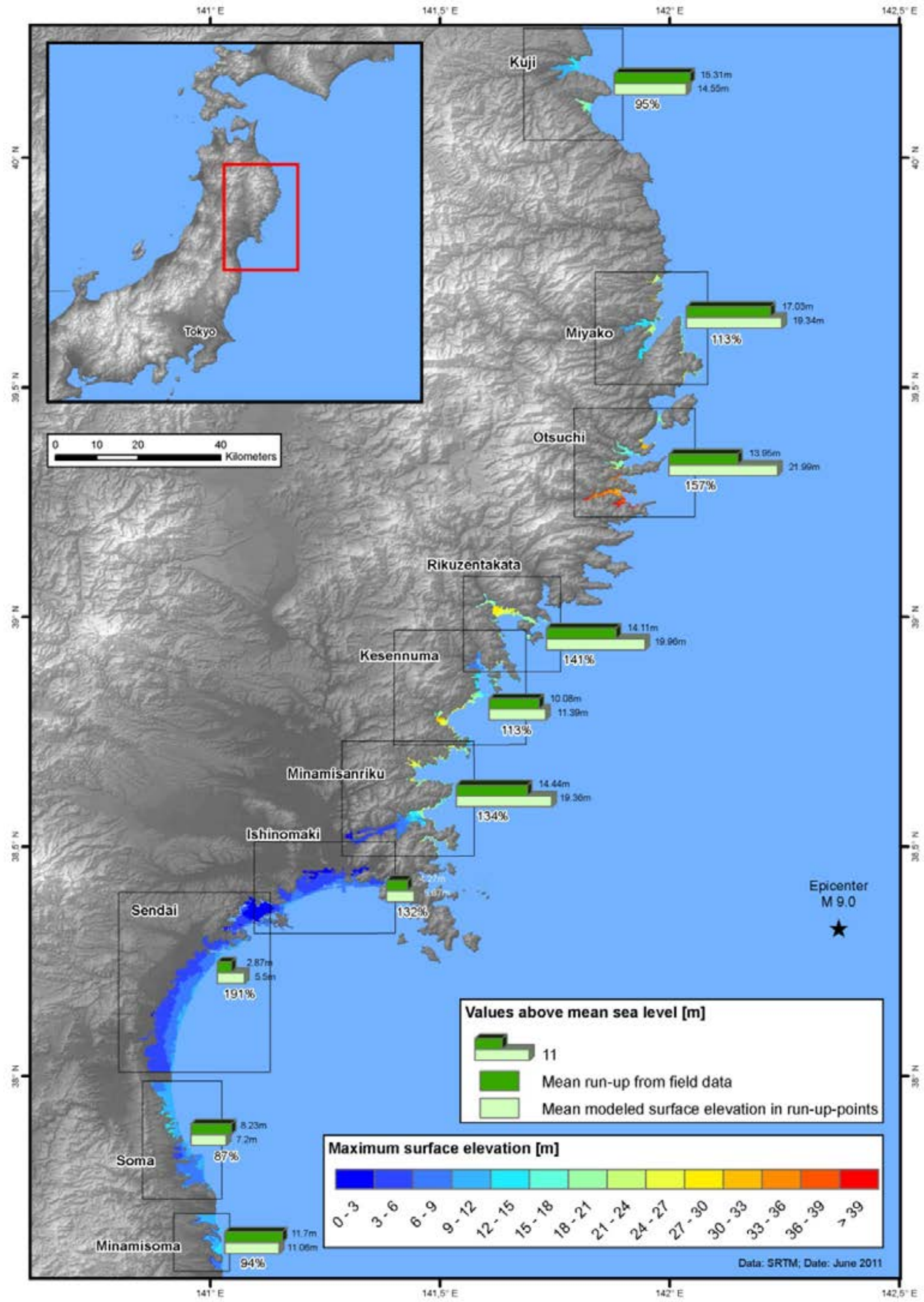

Figure 8: Comparison of the modeled maximum surface elevation of scenario D (dispersive) with field measurements published by the Coastal Engineering Committee of the Japan Society of Civil Engineers (2011). Mean values summarizing point measurements in each study area and the corresponding mean values of the modeled surface elevation in these points are shown (Løvholt et al. 2012).

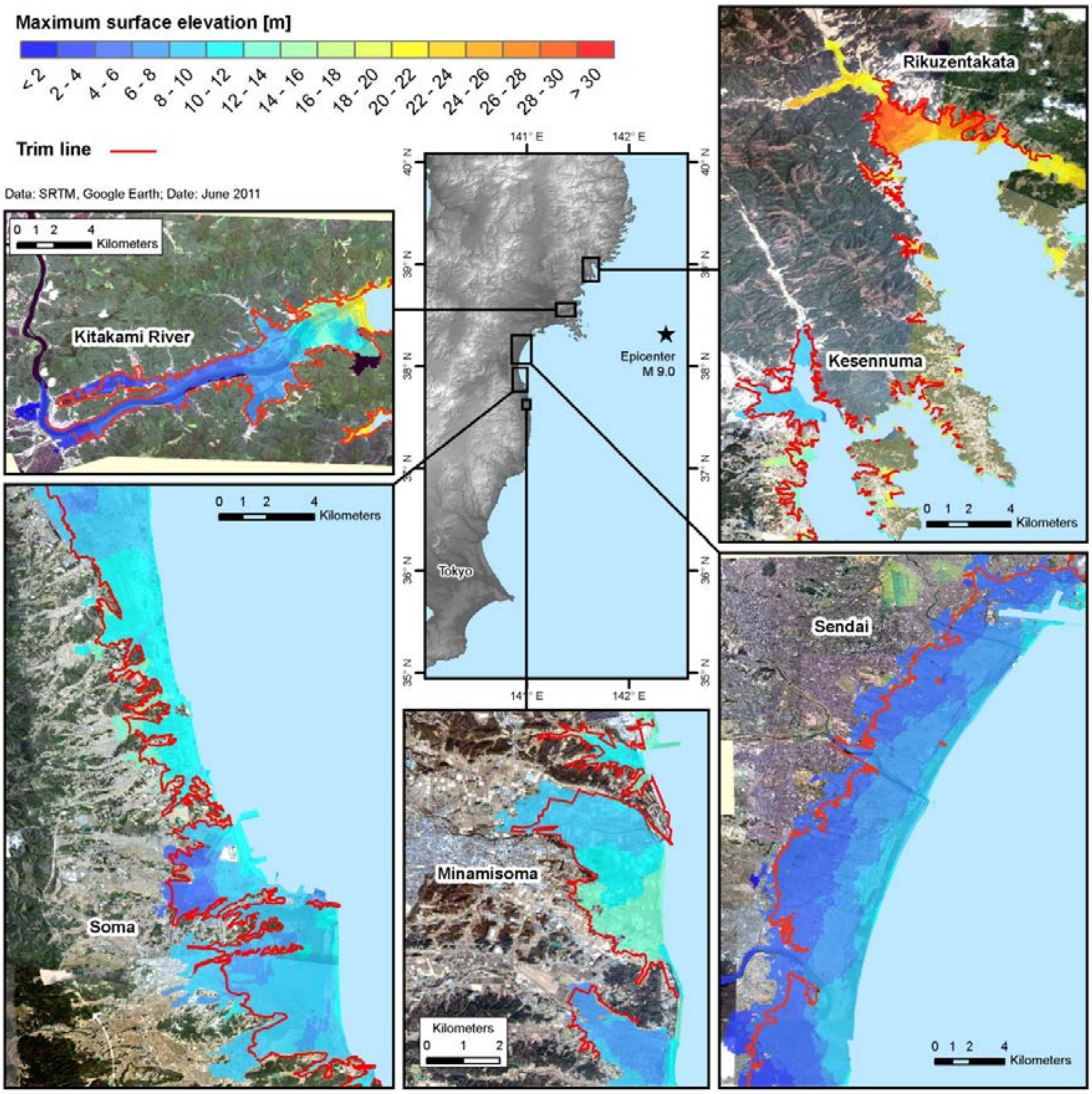

Figure 9: Comparison of the maximum modelled inundation extent (scenario D dispersive) with trim lines derived from pre-/post-tsunami satellite images by the Tsunami Damage Mapping Team, Association of Japanese Geographers (2011). Results are shown for the Kitakami River close to Minamisanriku, Soma, Kesennuma, Minamisoma, and Sendai (Løvholt et al. 2012).

3 Impact and damage assessment

The Tohoku tsunami caused severe damages to buildings and infrastructure along the 2000 km coastline affected. However, tsunami impacts vary according to local conditions (Mori et al. 2011). It could for instance be observed that the first wave was not always the largest one, and that huge differences in tsunami run-up and inundation extent occurred between the Sendai plains and the northern Sanriku coast. Especially in the narrow bays of the ria coast amplifications due to topography could be observed. While the inundation extent is much larger in the floodplains of Sendai, run-up is considerably higher along the Sanriku coast. Moreover urban areas, coastal structures, geomorphology, and rivers have influenced inundation patterns (Mori et al. 2011). Along rivers the inundation distance was longer and water has been transported far into the hinterland. Due to locally varying hazard conditions, but also due to local factors determining vulnerabilities, including population density, coastal protection measures, building material or early warning capacities, impacts and damages were different at different locations.

In the aftermath of the event several survey teams have been mapping and quantifying fatalities and damages in the affected areas (e.g. EERI 2011, Vervaeck and Daniell 2011, Goto et al. 2011).
Main results are summarized in the following.

3.1 Loss of life

In total 20,000 people are recorded dead or missing, and 400,000 people are homeless (Vervaeck and Daniell 2011, EERI 2011, Dunbar et al. 2011). 92.5% of the deaths are supposed to have drowned, while the others were crushed by collapsed houses or died from fire (Seeds 2011, Vervaeck and Daniell 2011).
Most fatalities occurred in the prefectures Iwate (4664/1628 missing), Miyagi (9487/2092 missing), and Fukushima (1604/238 missing) (Dunbar et al. 2011, Figure 10). Table 2 summarizes fatality statistics together with inundation data.

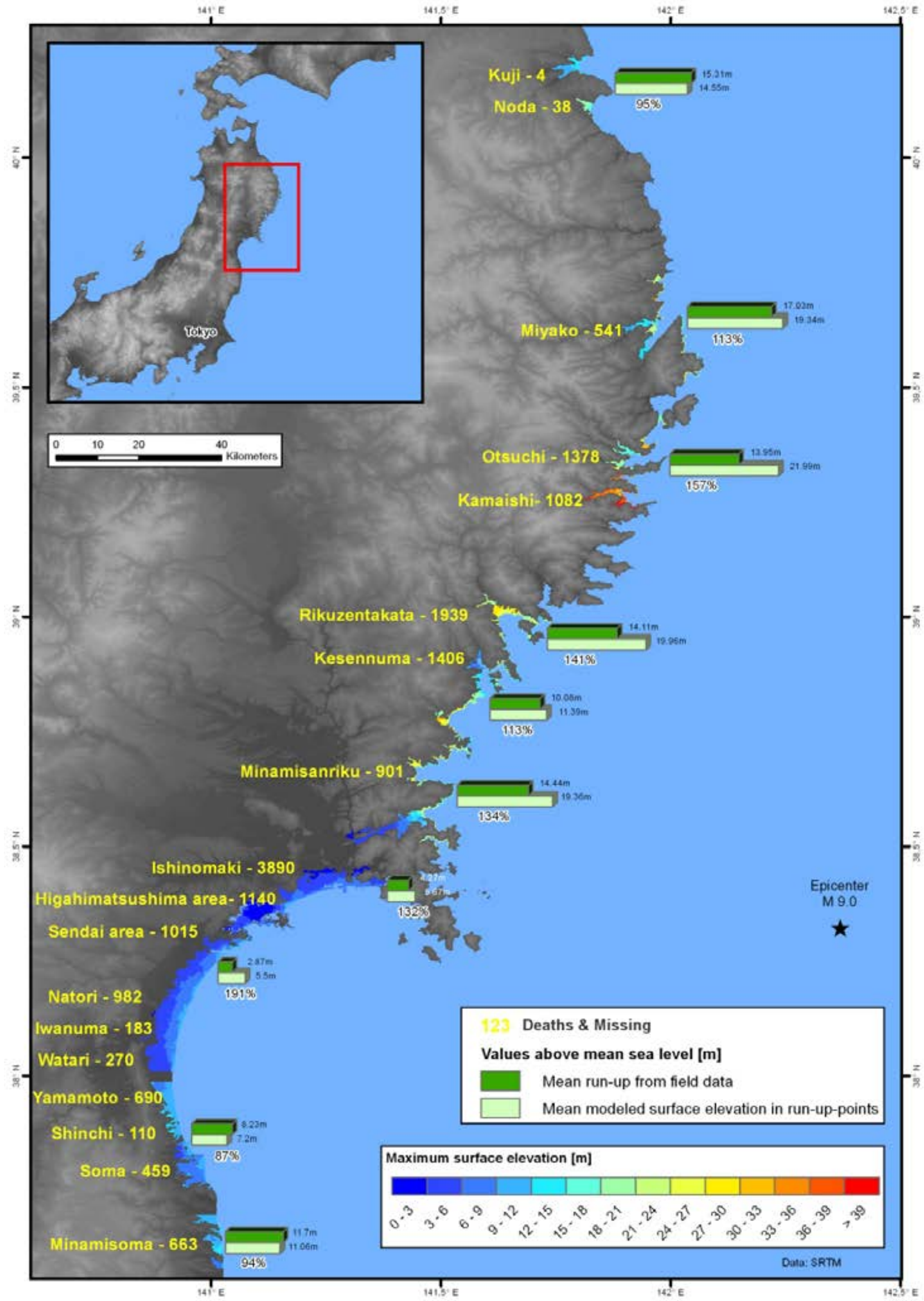

Figure 10: Number of fatalities by community (based on EERI 2011) combined with mean measured and modelled run up (scenario D dispersive) (modified from Løvholt et al. 2012).

Table 2: Casualties and water levels at the study sites (extracted from EERI 2011, based on IOC/UNESCO bulletins (2011), NGDC, Mori et al. 2011, Dunbar et al. 2011)

City	Exposed population	Population in 2010	Deaths & Missing	% Casualties of exposed population	Peak water height	Total area (km^2)	Inundation area (km^2)	% inunated	Arrival time (minutes)
Kuji	3177	36900	4	0.13	18.6	623	4	0.64	
Noda	1115		38	3.41	17	81	2	2.47	
Miyako	18378	59400	541	2.94	37.88	1260	9	0.71	31
Otsuchi	11915	15300	1378	11.57	19	201	4	1.99	
Kamaishi	13164	39600	1082	8.22	9	441	7	1.59	35
Rikuzentakata	16640	23300	1939	11.65	19	232	9	3.88	20
Kesennuma	40331	73500	1406	3.49	22.2	333	15	4.50	20
Minamisanriku	14389	17400	901	6.26	15.5	164	7	4.27	25
Ishinomaki	112276	160700	3890	3.46	16	556	7	1.26	
Higashimats.	34014		1138	3.35	10.4	102	36	35.29	
Matsushima	4053		2	0.05	2.4	54	2	3.70	
Shiogama	18718		21	0.11	4	18	5	27.78	
Shichigahama	9149		75	0.82	10	13	6	46.15	

Tagaiyo	17144		189	1.10	7	20	6	30.00	
Sendai (S) City	29962	1046000	730	2.44	9.9				65
S-Miyagino	17375					58	20	34.48	
S-Wakabayashi	9386				9.4	48	29	60.42	
S-Taihaku	3201					228	3	1.32	
Natori	12155	73100	982	8.08	12	100	27	27.00	74
Iwanuma	8051		183	2.27	7.6	61	29	47.54	
Watari	14080		270	1.92	8	75	35	46.67	
Yamamoto	8990		690	7.68	5	64	24	37.50	
Shinchi	4666		110	2.36	7.9	46	11	23.91	
Soma	10436		459	4.40	8	198	29	14.65	
Minamisoma	13377		663	4.96	4.5	399	27	6.77	

3.2 Structural damage and economic losses

The costs of the damages are not finally assessed until today, but sum up to an order of magnitude of $300 billion in direct losses (EM-DAT 2011, Mimura et al. 2011a, Mori et al. 2011). An extraordinarily high number of indirect losses in terms of reduced economic activity and interruption of supply chains for a longer period is also expected. After all, damages are estimated to be the highest economical loss from an earthquake/tsunami ever (Vervaeck and Daniell 2011, EERI 2011). The structural damages, especially those to buildings, were particularly high (Table 3), which is supposed to be due to the fact that most buildings in the area were wooden and only some major buildings were of concrete material, as could be seen from videos available online. In general three types of buildings are common in Japan (Gomez et al. 2011): a) timber, b) metallic structure, and c) (steel) reinforced concrete buildings. Although building regulations are very strict in Japan due to the extraordinary exposure to natural hazards, buildings in the area are mainly constructed to withstand earthquakes. This resulted in very little damage to buildings caused by the earthquake but major damages caused by the tsunami, since wooden, earthquake resistant houses are not well fitted to withstand a tsunami. For the first 3 km inland, however, most of the buildings have been destroyed, regardless of their structure (Gomez et al. 2011).

Vervaeck and Daniell (2011) summarize the damages to 1,000,000 buildings, 3559 roads, 77 bridges, 45 dikes, and 29 railway locations. Suppasri et al. (2012b) specified this further for Miyagi prefecture where 80,000 buildings were completely destroyed, 130,000 moderately destroyed, and 210,000 partially damaged. Gokon and Koshimura (2012) analyzed multi-temporal aerial photographs detecting ‘washed-away’ and ‘surviving’ buildings based on the existence of the roofs in Miyagi prefecture. They found that from 162,025 buildings 31.5% were washed away, most of them in the northern ria coast valleys. The distribution of destroyed buildings varied though. In some places, e.g. in Minamisanriku 80% of the buildings were washed away, while in others, e.g. Ishinomaki, these damages amount to 20%.

Table 3: Damage to buildings in Miyagi prefecture (from Suppasri et al. 2012a).

Location	Estimated household in inundated area	Completely destroyed	Half destroyed	Partially destroyed	Completely destroyed (%)
Kesennuma	13,974	8,383	1,861	428	59.99
Minami-Sanriku	4,375	3,877	N/A	N/A	88.62
Onagawa	3,155	4,372	256	462	138.57
Ishinomaki	42,157	28,000	N/A	N/A	66.42
Higashi-Matsushima	11,251	4,791	4,410	1,032	42.58
Matsushima	1,477	163	752	657	11.04
Rifu	192	31	260	800	16.15
Shiogama	6,973	386	1,217	1,598	5.54
Shichigahama	2,751	667	381	595	24.25
Tagajo	6,648	1,500	3,000	N/A	22.56
Sendai	10,385	11,158	12,315	11,101	107.44
Natori	3,974	2,735	791	4,376	68.82
Iwanuma	2,337	699	1,057	1,010	29.91
Watari	4,196	2,369	823	633	56.46

Lekkas et al. (2011) and EERI (2011) observed that residential wood houses (typical building, low-cost housing solution with two storeys, wood, and roofs with corrugated steel sheets) coped with the earthquake, but not with the tsunami. They were destructed and swept away. Engineered reinforced concrete tall mid-rise constructions suffered only from minor damages and coped best with the tsunami. In Rikuzentakata, for example, the tsunami reached 19 m height flooding and destroying all buildings to the fifth floor. Only two buildings resisted: a seven-story hotel and a tsunami evacuation building (EERI 2011, Lekkas et al. 2011). Moreover, debris contributed significantly to damage.

Besides buildings also port facilities and related constructions were severely damaged (e.g. in Ishinomaki). Quay walls and piers were widely destroyed by the waves or the impact of objects such as boats and containers. The Sendai port was out of function for four weeks (Lekkas et al. 2011, EERI 2011). Liquefication has been a problem in ports and also other areas.

Critical infrastructure was heavily damaged and traffic interrupted along the coast which caused not only material damage, but also led to difficulties in disaster management. 200 highways, bridges, and numerous rail bridges were damaged by the earthquake (EERI 2011). The coastal road network has been destroyed by waves or debris, railways and telecommunication were destroyed, and an interruption of water supply occurred due to broken pipes. Since the restoration of water supply took over two months, consequences for the sanitation system and the inhabitants occurred (EERI 2011).

Besides the material damages, also the fishing industry and the livelihoods of fishermen were affected by the tsunami, since most of the coastal communities are depending on fisheries. Fishermen lost facilities, equipment, stock, harvesting grounds and 90% of the fishing boats were unusable after the event (Seeds 2011, EERI 2011).

3.3 Environmental impacts

Besides the loss of life and the material damage, environmental impacts occurred. The most significant environmental impact is of course related to the leak of nuclear radiation from the Fukushima power plant. The extent of the nuclear disaster is still not fully clear. However, it is supposed to be one of the worst nuclear power plant disasters ever. As seen in Chernobyl already, it will take decades to clear the area from radioactive contamination. Long-term impacts on people and environment are unforeseeable.

Another environmental impact related to the tsunami is the pollution by waste and debris. According to UNEP (2011) the total amount of waste has been estimated to be between 80 and 200 million tons. In addition 18 waste water treatment plants were damaged and pipeline damages caused additional pollution (EERI 2011).

Morphological changes have been investigated by Udo and Sugawara (2012) as well as by Tanaka et al. (2012) by using remote sensing data. They found changes in coastal morphology and erosion due to destroyed structures. Udo and Sugawara (2012) used laser DEM data to compare beach morphology before and after the tsunami. They observed land subsidence of 0.2-0.5 m due to the event and erosion at several places.

Gomez et al. (2011) investigated erosion in Rikuzentakata based on GIS and earth observation techniques, observing a beach retreat of 345 m in average with maximum values of 501 m at the lagoon barrier. They summed up the total loss of the surface of land to 0.37 km^2. They also found that the Kesan River was widened from 79 to 88 m in average. Riparian trees were uprooted to a large extent at the coast and along the river (Gomez et al. 2011). The uprooted coastal forest at the lagoon was 0.26 km^2 which corresponds to 100% loss. The 70,000 pine trees planted for protection with 25-40 cm diameter were destroyed. Only one tree, “the tree of hope”, survived (EERI 2011).

In agricultural areas land was inundated and salt water intrusion is going to affect future cropping (e.g. in Rikuzentakata, over 70% of the land was affected by salinization, EERI 2011).

The earthquake triggered also secondary environmental impacts, such as e.g. 200 landslides (Vervaeck and Daniell 2011).

4 Lessons learned for risk and vulnerability assessment

The Tohoku tsunami clearly pointed out the vulnerability of people, assets, and the environment. However, to what degree a region or community is vulnerable depends on a variety of aspects rising from the social, cultural, institutional, economic, or environmental conditions (Birkmann 2006, Taubenböck et al. 2008). Hence, local conditions have to be considered, when analyzing vulnerability.

4.1 Influence of coastal structures and early warning

The affected areas were well prepared for a possible tsunami event. Preparedness programs, evacuation plans, loudspeakers, and hard coastal protection structures were in place (Dunbar et al. 2011, Arcas and Segur 2012). All ports and many bays were protected, partly by huge breakwaters or by seawalls, revetments and coastal forests. Moreover a huge number of shelters and buildings constructed for evacuation were in place (Table 4).

Table 4: Tsunami countermeasures at the Tohoku coast (EERI 2011).

	Countermeasure	Locations Observed
Structural	Seawalls and Tsunami Gates	Kuji, Noda, Fudai, Tarou, Miyako, Otsuchi, Kamaishi and Rikuzentakata
	Breakwaters	Hachinohe, Kuji, Otsuchi, Kamaishi, Ofunato, Minamisanriku
	Tsunami Mitigation Forests	Rikuzentakata, Natori south of Sendai Airport
Evacuation	Designated Vertical Evacuation Buildings	Kamaishi, Kesunnuma, Minamisanriku, Rikuzentakata
	Evacuation Sites on Higher Ground	Miyako, Rikuzentakata, Minamisanriku, Onagawa
	Evacuation Signage & Warning Sirens	Observed in numerous locations in all communities visited

It is obvious from the massive devastation that most of these structures failed to some extent or completely. According to Ogasawara et al. (2012) 25 of 55 tsunami barriers in Iwate prefecture were damaged and also almost half of the disaster prevention infrastructure has been destroyed. Even the breakwater installed in Kamaishi, being the deepest break water in the world (1950 m long and 63 m deep), was heavily damaged (Figure 11).

Nevertheless, although sea walls were partly overtopped by twice their height, and dikes were heavily damaged, these structures reduced the wave height and avoided a greater damage (EERI 2011, Seeds 2011). Mori et al. (2011) did some first investigations for two similar bays (Otsuchi and Kamaishi Bay) with similar settings and tsunami heights. According to their investigation in Kamaishi Bay the barrier probably decreased the tsunami height from about 22 m to 10 m, whereas in Otsuchi bay where no barrier was present tsunami surface elevations were constantly around 17 m. The same phenomenon could be expected for many of the coastal and urban structures, revetments, or dikes. Therefore, they concluded that hard protection structures may have reduced inundation heights. However, the insufficient structures may also have caused a false perception of safety.

EERI (2011) also investigated the impacts on structures in their report, concluding that flow velocities (mean 6.34 m/s in the Sendai plains) are important, when it comes to loads on structures (which are mainly (i) hydrostatic pressure, (ii) viscous drag, (iii) debris, and (iv) scour effects). Seawalls using reinforced concrete constructions with sound foundations proved to be most efficient, while offshore breakwaters or coastal forests failed (EERI 2011).

Figure 11: Damage of the worlds' deepest breakwater in Kamaishi, left before damage, right, after damage (Source: www.nytimes.com, http://community.guinessworldsrecords.com).

Coastal forests have not performed very well during this event. As extensively and controversially discussed after the 2004 tsunami (Dahdouh-Guebas et al. 2005, Danielsen et al. 2005, Wolanski 2007, Kathiresan and Rajendran 2005, Kerr et al. 2006, Kerr and Baird 2007) dense coastal forests have a damping effect on tsunami waves, especially on their flow velocities. However, this effect decreases significantly with increasing wave heights (Tanaka et al. 2007). The coastal forests at the Japanese coast were not very dense (e.g. no mangroves) and the tsunami water levels were extremely high, leading to an uprooting and wash away of most of the coastal forests. Gomez et al. (2011) stated that the coastal forests in Rikuzentakata might have provided some wave dissipation, if they wouldn't have been destroyed. However, since the coastal forests were washed away Gomez et al. (2011) supposed that they contributed to the opposite by providing flotsam that further destroyed buildings. Moreover, coastal forests might also have led to a false safety feeling for the inhabitants (Leone et al. 2010). It should also be noted that the real effect of mangroves is still disputable. There is no doubt that tsunami impact may be reduced by mangroves, but perhaps mangroves also grow in already protected areas. Maybe the flat areas favoring mangroves also favor wave breaking (with corresponding energy dissipation) further out? Furthermore, the mangroves grow in river deltas possibly forming an alluvial fan that might favor wave refraction or reflection. Finally, the mangroves will produce lots of nutrition that is brought to the ocean. Will this enhance the build-up of coral reefs? If so, the mangroves are feeding the reefs while the reefs again protect the growth of mangrove forests, which again implies more nutrition, bigger reefs, and so on.

Besides the structural measures also other emergency planning and disaster reduction strategies were in place. Regularly disaster drills were conducted in schools and other places, the last one was one week before the event (Seeds 2011). Early warning systems worked well, launching tsunami warnings three minutes after the earthquake (Seeds 2011). Risk awareness and evacuation training helped to save lives (Suppasri et al. 2012a). However, some of them failed since communication was interrupted in many places.

It can be concluded that both structural and non-structural measures helped to a large extent to protect coastal communities during the Tohoku tsunami (EERI 2011). However, considering the magnitude of the event, hard structures were not high and strong enough to fully withstand the wave impact and also people underestimated the power of the tsunami. The extensive failure of coastal structures led EERI (2011) to suggest that the planning design for a 100 year event was not sufficient in this area.

Seeds (2011) recommend to further adapt risk reduction measures to local conditions to improve them and combine hard and soft measures. They observed that tsunami warnings were received, but people underestimated the water level and felt safe. Seeds (2011) also concluded that it would help evacuation management, if people would get information on expected tsunami height/water levels to cope with. Here scenario based hazard mapping could be a useful tool for disaster risk management.

4.2 Correlation between flow depths and fatalities/ damages

A correlation has been shown to exist between local flow depths and the fatalities/damages that occurred (Berryman et al. 2005, Reese et al. 2007, Ruangrassamee et al. 2006, Saatcioglu et al. 2006, Koshimura et al. 2009, Suppasri et al. 2011, Valencia et al. 2011). Plenty of field data have been collected in the aftermath of the 2004 tsunami in Indonesia, Thailand, and other affected countries and fragility functions have been derived from these data. Koshimura et al. (2009), Suppasri et al. (2011), and Ruangrassamee et al. (2006) found that wooden houses collapsed when water levels exceed 3 m, and brick houses when water levels exceed 7 m. From the 2006 Java tsunami in Indonesia Reese et al. (2007) concluded that buildings were totally damaged or seriously damaged with water levels > 2 m for wooden houses and > 4 m for brick houses. As water levels were extra-ordinarily high during the Tohoku tsunami and mostly exceeded 2 m, a massive destruction had to be expected. Suppasri et al. (2012b) found that in Japan minor damage occurred at flow depths of 2.5 - 3.0 m, moderate damage at flow depths of 3.0 - 4.0 m, major damages at flow depths of 4.0 - 4.5 m, and complete damage at flow depths > 4.5 m. They developed fragility functions from 189 buildings (150 thereof were wooden houses) for Miyagi prefecture (Figure 12) concluding that wooden houses performed better in Japan than in other areas, mainly because of a more advanced construction.

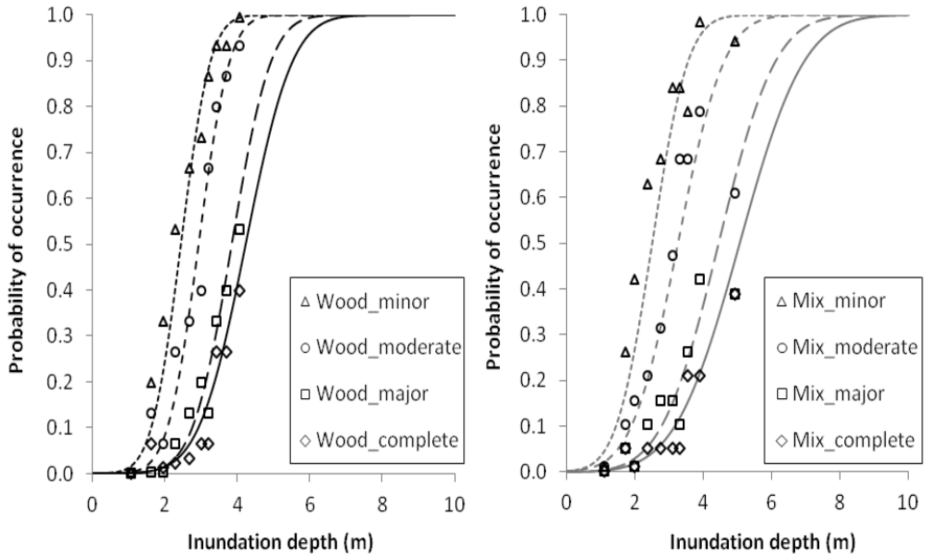

Figure 12: Fragility functions developed from the Tohoku tsunami for Miyagi prefecture developed by Suppasri et al. (2012b).

Dunbar et al. (2011) made a first analysis of the correlation between the number of fatalities and the measured run-up and inundation heights in Japan. Figure 13 shows, that there is a correlation between the number of deaths and the water level, which is rather obvious, considering that more than 90% of the fatalities were due to drowning.

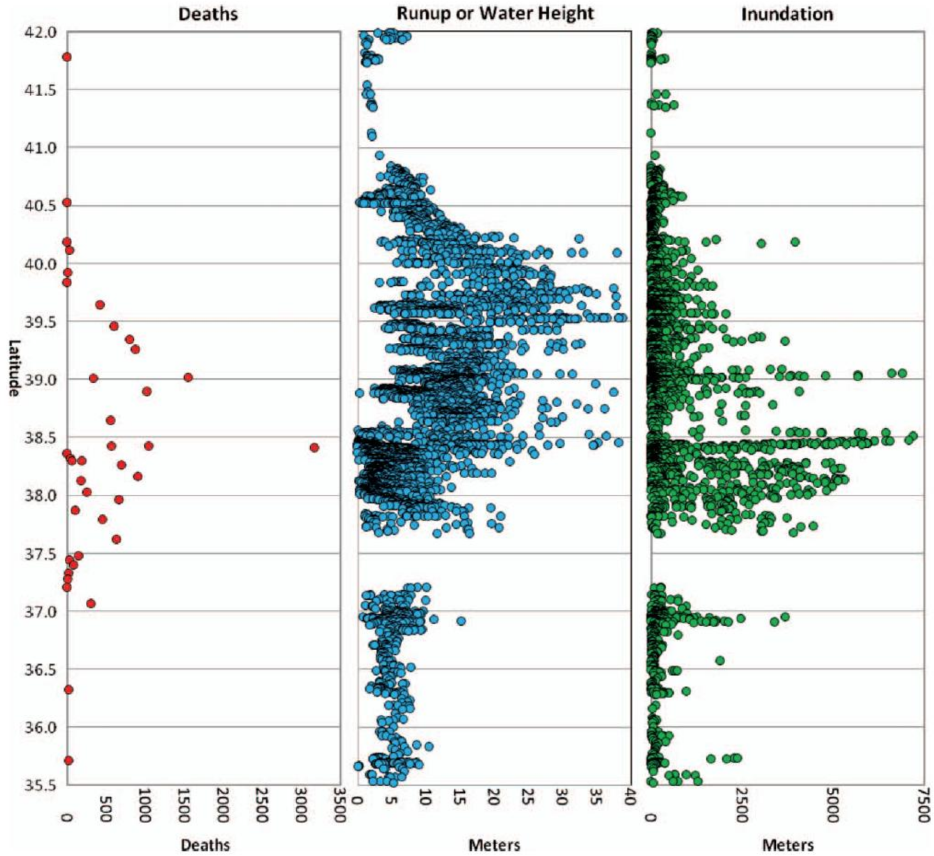

Figure 13: Latitude-based graphs of total deaths for selected principalities and prefectures, run-up or maximum water height, and maximum inundation distance from the 2011 Tohoku tsunami (Source: Dunbar et al. 2011, after IOC 2011 – deaths; Mori et al. 2011 – run-up or water height and inundation distance).

Based on the modeling performed in our work, only rough estimates could be made on a correlation between flow depths and the number of fatalities in certain villages. In Figure 10 the modeled surface elevation as well as the measured run-up heights are plotted in bars. The yellow numbers provide the number of deaths and missing by community according to EERI (2011), see also Table 2.

Figure 10 shows the highest absolute number of deaths and missing in Ishinomaki, which is a densely populated town close to the shore. Although water levels were lower here than in many other areas, the high population density and most likely also debris from collapsed buildings, that has shown to considerably contribute to loss of life and damage (Dalrymple et al. 2006), are supposed to have contributed to the high number of fatalities. Videos from the Tohoku tsunami available online showed that a huge amount of wooden houses collapsed in the area. After collapsing they were transported inland with the water causing further damages by crushing into other buildings and crumpling people. Also according to Table 2 Ishinomaki has the highest absolute number of fatalities, while the percentage is quite small due to the size of city. The fact that a comparably small area was flooded might underpin that the effect of flotsam is rather significant. The highest percental number of fatalities occurred in Rikuzentakta (11.65%) and Otsuchi (11.57%). In these places also the highest water levels were measured, because of the steep ria coast valleys channeling the water and leading to a huge pile up of water. The strong wave impact and the high water levels have led to a total destruction of the coastal communities, which just flushed away, including all refugee locations (Leone et al. 2010). Since only 1.99% of the city Otsuchi were inundated (Table 2) the destructive wave height is obviously the reason for the high number of fatalities in a rather small area. Also here flotsam from destroyed houses, structures, and forests is supposed to have contributed to the number of fatalities (Figure 14).

Figure 14: Rikuzentakata was totally flushed away by the tsunami (Photo: M. Sato, Wikicommons).

Flow depth maps have been produced for selected villages in order to get a detailed overview on the spatial distribution of water depths over land and a correlation with damages and the location of fatalities (Figure 15). Since the ComMIT model provides only the modeled surface elevation (water level above mean sea level) flow depths were derived by subtracting the SRTM elevation model from the modeled surface elevation. As a result the spatial distribution of flow depths could be represented in a 90 m raster.

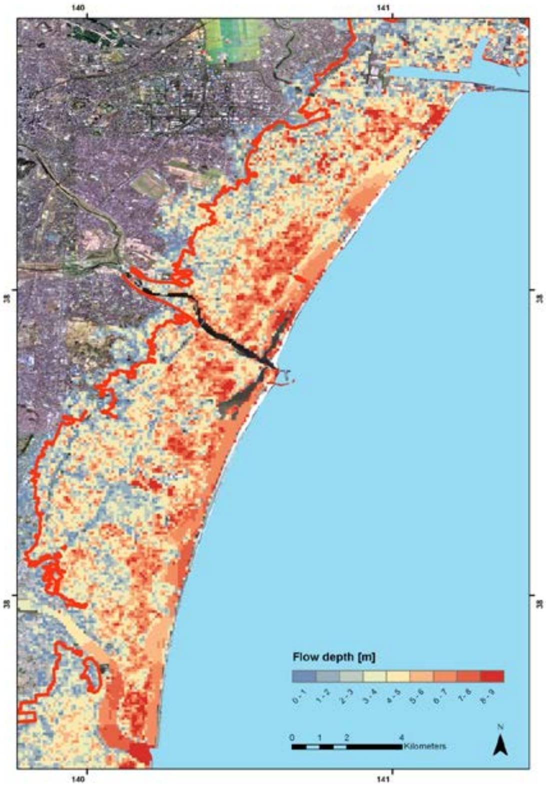

Figure 15: Total water depth in Sendai. Map generated by a subtraction of the modelled surface elevation and the SRTM elevation model (figure produced by Lasse Scheele).

However, it turned out that the accuracy of the SRTM data set is not detailed enough to derive pixel based accurate information on water levels with an accuracy necessary to deduce information on the drowning of people. Moreover the number of fatalities is availbale from community statistics only. Detailed information on the spatial distribution of people such as their working place, or location of people during the tsunami event would have been necessary, though. Moreover, capabilities of people to escape from the water would have to be taken into account. Suppasri et al. (2012a) developed some basic fatality ratio curves based on statistics and their field data (Figure 16).

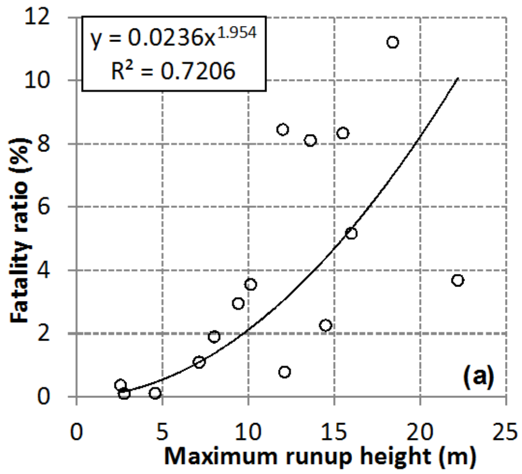

Figure 16: Relationship between maximum run-up height and fatality ratio based on data from Miyagi prefecture (Suppasri et al., 2012a).

Fragility curves for buildings are normally developed from field survey data collected directly after the event where signs of water marks could be measured at remaining houses. Due to the coarse resolution of the data and without field measurements a detailed correlation between water levels and building damage could not be made.

4.3 People exposure and risk to life

People exposure and loss of life are difficult to predict due to the mobility of people during the day and during different times of the year, and due to peoples different behavior during a disaster. Many circumstances have shown to influence the risk to life of individuals: flow depth and velocities, distribution of people, age of people, preparedness, risk perception, and many more (Penning-Rowsell 2005).

An analysis of the Tohoku tsunami showed that in total 77.6% of the people who died in the tsunami were older than 50 years, and 46.5% were older than 70 years (Vervaeck and Daniell 2011). Only 15% were younger than 30 years (Ogasawara et al. 2012). A distribution of age among the fatalities is given in Figure 17. This confirms the general statement that old people are more vulnerable since they often cannot evacuate themselves as fast as younger ones (and often do not want to). Seasonal changes can have influence on people exposure as the 2004 tsunami in Thailand showed. Therefore, for more accurate risk and vulnerability assessment people exposure and the other circumstances listed above have to be taken into account for different scenarios.

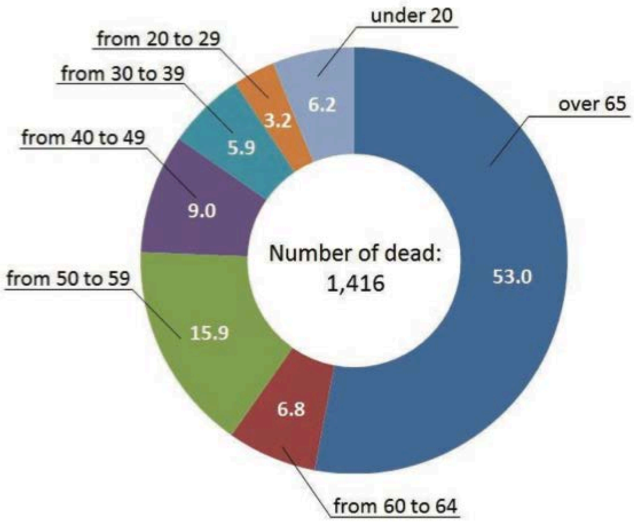

Figure 17: Ages distribution among fatalities (Ogasawara et al. 2012).

4.4 Critical infrastructure

Critical infrastructure plays a major role in disaster mitigation, but also as a potential source for negative impacts. This could also be seen during the Tohoku tsunami. Critical infrastructure includes places where many people are allocated, such as schools, hospitals, hotels, or large industrial production sites. It also includes banks, telecommunication systems, water and power supply, railway, and other locations essential for the functionality of the society. Interruption of traffic due to destroyed roads and bridges as well as telecommunication systems were a major problem during and after the Tohoku tsunami. Moreover, many evacuation shelters were destroyed, again suggesting a false safety to people hiding there. As a conclusion from Japan and from many other tsunami events the location and the setup of critical infrastructure have to be considered in more detail and also included in an ex-ante vulnerability assessment. Learning from the severe damages to critical infrastructure and their impact on disaster management, Lekkas et al. (2011) propose a new design of critical infrastructure coping with lateral hydrodynamic forces and flotsam.

4.5 Environmental impacts

Environmental impacts are often neglected in risk evaluations, which mainly focus on people at risk and economic damage potentials including structural damages to buildings, and infrastructure as well as economic losses. Environmental impacts can occur directly by pollution, contamination of soils and water bodies, by erosion of beaches or by uprooting of forests. Often environmental impacts also occur a long time after an impact. For example impacts on coastal forests can, besides uprooting, also result in long-term defoliation or dying of trees (Roemer et al. 2010).

The deterioration of ecosystems may lead to a loss of ecosystem services and functions that are important for the functioning and the sustainability of livelihoods. As an example in many reports (Seeds 2011, EERI 2011) it was stated that fishermen lost their livelihoods due to loss of fishing grounds and fishing environment.

When industrial sites are hit by tsunami waves, there is a potential for leakage of chemicals or other ingredients, that my harm soils, air, or water bodies. The Fukushima case showed an example of environmental impacts by the destruction of a nuclear power plant and a leak of nuclear radiation, which will have environmental and health effects in the region and beyond for decades (Brumfiel 2011).

Other environmental impacts of tsunami inundation might be (UNEP 2011):

- Pollution by debris and waste transported and distributed by water
- Salinization and infiltration from other water ingredients in soils and ground water. This affects water quality (e.g. drinking water) and agricultural areas, where harvest might be destroyed and agricultural use may not be possible for a longer period
- Sedimentation and silting on land, in channels, and at coastal structures might induce further impacts
- Damage to urban water supply and sewage networks can result in cross contamination, leading to health impacts for the population.

5 Approach for developing an extended tsunami risk model

NGI has developed and applied a GIS based model to assess tsunami vulnerability and mortality risk. The model has been applied in a demonstration project in Bridgetown, Barbados (NGI 2009a) and in a reduced version in a case study for Batangas Bay, the Philippines (NGI 2009b). The model includes exposure analysis and mortality risk analysis based on structural building vulnerability.

Population statistics were used together with digitized building polygons to distribute the number of people per building in the whole study area. As a result exposure maps show the spatial distribution of people. To account for structural vulnerability a sampled number of buildings have been mapped in the field and four vulnerability criteria were assigned to each of the mapped buildings: (i) number of floors (height), (ii) barriers in place, (iii) material, and (iv) use. To gather a spatial distribution for the whole study area building information was extrapolated to all buildings in the study area using GIS tools. Finally, a weightening scheme was applied to provide vulnerability scores to each building according to the four vulnerability criteria. Results provided by this analysis are (a) a critical facility map (short and long-term impacts), and (b) a mortality risk map based on flow depths, vulnerability score per building, empirical data on fatalities as a function of flow depth, and the population distribution.

During these studies and learning from events like the Samoa tsunami in 2009 or the Tohoku tsunami in 2011 some limitations of the model and demands for future improvements of the model became obvious:

1. In the existing model people exposure is determined by distributing people to buildings, according to their size. In this case it is assumed, that people are in their houses during a tsunami event. As this is not necessarily the case during daytime, taking into account peoples' mobility would be of importance. This would include scenarios for different people exposure day/night/seasonal distribution, and mobility aspects (working places).

2. Besides the loss of life socio-economic damages are the major impact of natural disasters. Economic impacts comprise direct material damage to infrastructure, and loss of economic goods, but also indirect losses such as interruption of supply chains, loss of production, reduced spending power, loss of reputation, and other long-term impacts (Willroth et al. 2010). Beyond that, a variety of factors exists that indicate social or socio-economic vulnerability, e.g. age of the people, education, risk awareness, existence of insurances, GDP, preparedness and response capacity, early warning capacity, etc. (Birkmann 2006, Penning-Rowsell et al. 2005, Taubenböck et al. 2008, Tapsell et al. 2005). Also social networks and socio-cultural characteristics within a family or community have in some cases shown to influence the livelihood and disaster response (Willroth et al. 2010, EERI 2010). Since many of these factors are difficult to quantify they are often not included in quantitative risk and vulnerability models. However, socio-economic factors make some people or communities more vulnerable than others and therefore should be considered in a vulnerability assessment.

3. Both the 2004 Indian Ocean tsunami and the 2011 Tohoku tsunami caused some environmental impacts and consequences, which may lead to further vulnerability. A healthy and functioning environment is crucial for coastal communities, which are using services and functions of nature for their livelihood. Evaluating the pre-disaster environmental conditions and considering possible environmental impacts are therefore recommended in a risk assessment. Besides exposure analysis of coastal ecosystems and possible dangerous critical infrastructure such as e.g. nuclear power plants or industrial sites, the renewable capacity of the existing environmental stage should be considered as well as the consequence of an interruption of the provision of ecosystem services.

4. To estimate the potential loss of life and damages, aspects of risk mitigation have to be taken into account since they may reduce the overall vulnerability. This includes structural measures, protection of private houses, preparedness, risk awareness, and the ability to cope with an event. The 2011 Tohoku tsunami showed that even well prepared societies might suffer from tsunami impacts because measures do not work out or fail. On the other hand structures have considerably reduced the number of fatalities.

A suggestion for an improved tsunami model is depicted in Figure 18. To be applicable for quantitative risk assessment and mapping the model is kept rather simple. It includes a GIS procedure for:

Risk to people based on buildings, working places, care facilities, and flow depths:

- Extraction of building polygons
- Population statistics (age, mobility, distribution to buildings)
- Information on seasonal and working conditions (statistics or interviews) – scenario-based distribution of people
- Extraction of care facilities and schools, number of people from statistics
- Building vulnerability (material, height, barriers)
- Flow depths from numerical model
- Flow depth vulnerability (expected number of fatalities as a function of flow depth)
- Mortality risk

Damage potential based on private households and companies:

- Extraction of building polygons of private buildings and companies/industries
- Values of private households from statistics
- Values of companies from statistics (GDP, number of employees, other economic indicators)
- Flow depths from numerical model
- Flow depth vulnerability (expected damage as a function of flow depth)
- Economic losses

Environmental impacts based on pollution and loss of ecosystem services and functions:

- Land cover classification (remote sensing or GIS based)
- Mapping of industrial sites with a potential for harm
- Assessing ecosystem services and functions in the study area
- Flow depths from numerical model
- Environmental impacts and loss of ecosystem services and functions

In addition, critical facilities including lifelines (water supply, telecommunication, railway, etc.) should be mapped and included in the risk estimation.

The model does not include social or preparedness factors such as education, risk awareness, coping capacity of individuals, personal income, political or cultural aspects. Although these factors are supposed to influence vulnerability, they are difficult to assess in a quantitative, GIS-based model and often require e.g. interviews with local people. For a complete understanding of vulnerability they should be considered, though.

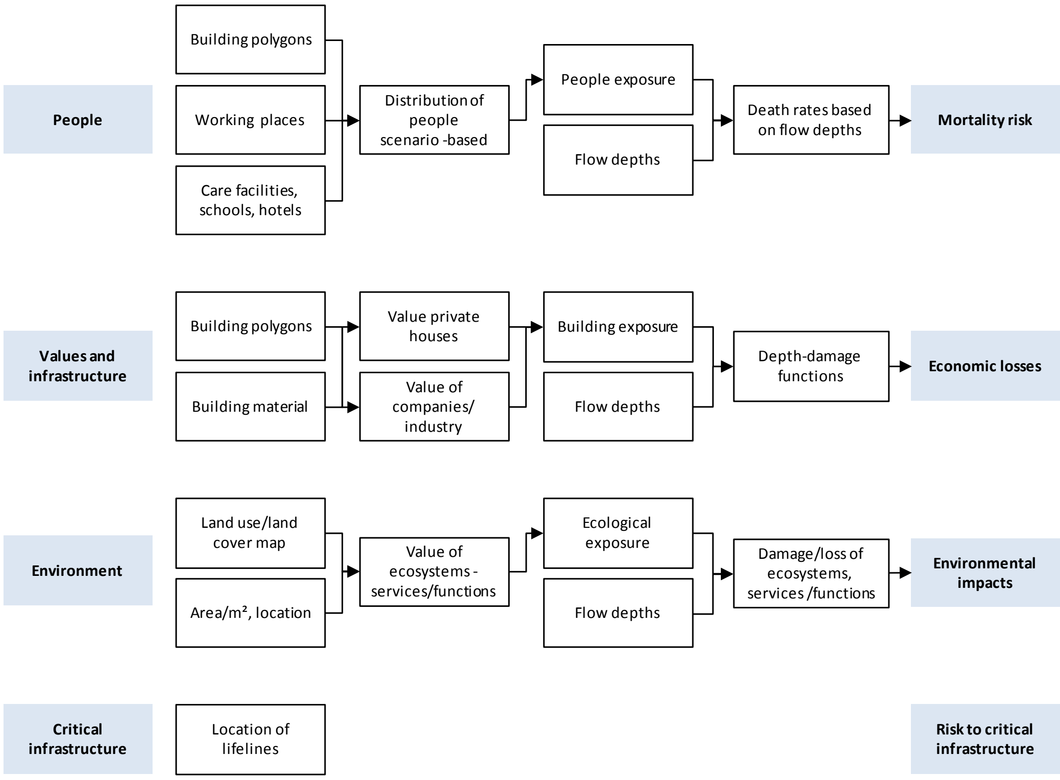

Figure 18: Sketch on the overall approach for tsunami risk assessment.

6 Conclusions

A thorough analysis of the 2011 Tohoku tsunami in Japan is valuable for the scientific community, mainly for two reasons: First, the coincidence of an earthquake, a tsunami, and a subsequent nuclear accident - all of them in an unexpected magnitude and dimension - made it an extraordinary event and an outstanding example of a multi-hazard situation. Second, due to the increased tsunami awareness in the scientific community since 2004 and new media and broadcasting possibilities, this event is very well documented enabling a validation of numerical models or risk models.

We conducted tsunami propagation and inundation modeling in the first weeks after the event, using the very first data available from the internet (Løvholt et al. 2012). Results from the numerical simulations show a good match with the field data available for this type of rapid assessment, particularly compared to offshore DART buoys. The influence of dispersion is shown to be important for the transoceanic propagation, significantly reducing the leading wave compared to traditional linear shallow water (LSW) wave models. There are some uncertainties and sources of errors in the model and the data which should be considered when evaluating the results, including the earthquake source model, the horizontal and vertical resolution of the SRTM, the limited consideration of bottom friction and flotsam, as well as the ignorance of coastal structures like walls or revetments, which might have attenuated the wave impact (EERI 2011, Mori et al. 2011, Mimura et al. 2011a). Despite these uncertainties the study highlights the feasibility of earthquake seabed displacement combined with tsunami generation, propagation, and inundation in a rapid tsunami hazard assessment based on medium resolution data sets. Some information on land cover needs to be available though in order to interpret inaccuracies in digital elevation models and to account for the influence of bottom roughness caused by settlement and vegetation. The approach is considered to be useful for modeling tsunami scenarios and impacts in areas potentially exposed to tsunamis and thus support risk management.

A further analysis of the correlation between flow velocities/depths and people at risk/building fragility turned out to be difficult with simulations based on the SRTM data and with only general statistics about the distribution of fatalities. The general conclusions that could be made go along with the conclusions drawn in literature. The highest total number of deaths occurred in Ishinomaki where the highest population density is located close to the shore with 3.46% fatality rate (Table 2). Flotsam is supposed to be a major contribution to loss of life in this area. The highest percental number of fatalities occurred in the steep valleys at the northern Sanriku coast. The relatively small inundated area shows that the very high water levels in this area are the main cause for the high number of fatalities. A critical water level at which people drowned could not be determined from the model results due to the coarse resolution of the topography (and with that lacking information on local flow depths) and the missing information on the distribution of people during the event.

Coastal structures to mitigate tsunami impacts were present at many places. Most of them were overtopped or failed due to an insufficient design level. But the structures in place, although partly destroyed by the tsunami, reduced inundation to some extent. However, many authors made aware of the negative side effects of hard structures, such as reflection and wave set up at other places, or the impression of a false safety to the inhabitants, who trusted the structure without taking additional precautionary measures.

Based on the lessons learned from Japan further research and tsunami risk assessments should therefore consider:

- detailed assessment of the distribution of people (people exposure),
- structural damages to coastal protection measures,
- indirect economic damages such as interruption of supply chain, reduced economic activities,
- environmental impacts, e.g. by evaluating a potential loss of ecosystem services,
- aspects of risk mitigation that reduce vulnerability,
- social/socio-economic vulnerability criteria, and
- a better correlation between the damage/fatality rate and flow depths.

EERI (2011) also proposes that paleo-tsunami studies should be considered in more detail. Taken the example from the Tohoku coast, paleo-seismologists have shown larger tsunami events in the area, which have not been considered in hazard mapping (EERI 2011).

Moreover, risk perception is an issue in highly developed areas, where huge coastal structures and elaborated tsunami early warning systems are in place. As many other natural disasters before, also the 2011 Tohoku event showed that people feel safe, believe that they can escape by cars, or do not think they live in a flood prone area (EERI 2011). It is therefore important to develop adequate personal preparedness strategies also in highly developed areas.

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