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# Response to the 2011 Great East Japan Earthquake and Tsunami disaster

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We revisited the lessons of the 2011 Great East Japan Earthquake Tsunami disaster specifically on the response and impact, and discussed the paradigm shift of Japan's tsunami disaster management policies and the perspectives for reconstruction. Revisiting the modern histories of Tohoku tsunami disasters and pre-2011 tsunami countermeasures, we clarified how Japan's coastal communities have prepared for tsunamis. The discussion mainly focuses on structural measures such as seawalls and breakwaters and non-structural measures of hazard map and evacuation. The responses to the 2011 event are discussed specifically on the tsunami warning system and efforts to identify the tsunami impacts. The nation-wide post-tsunami survey results shed light on the mechanisms of structural destruction, tsunami loads and structural vulnerability to inform structural rehabilitation measures and land-use planning. Remarkable paradigm shifts in designing coastal protection and disaster mitigation measures were introduced, leading with a new concept of potential tsunami levels: Prevention (Level 1) and Mitigation (Level 2) levels according to the level of 'protection'. The seawall is designed with reference to Level 1 tsunami scenario, while comprehensive disaster management measures should refer to Level 2 tsunami for protection of human lives and reducing potential losses and damage. Throughout the case study in Sendai city, the proposed reconstruction plan was evaluated from the tsunami engineering point of view to discuss how the post 2011 paradigm was implemented in coastal communities for future disaster mitigation.

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The analysis revealed that Sendai city's multiple protection measures for Level 2 tsunami will contribute to a substantial reduction of the tsunami inundation zone and potential losses, combined with an effective tsunami evacuation plan.





# 1. Introduction

On 11 March, 2011 a devastating tsunami triggered by a Mw 9.0 earthquake struck the northern Pacific coast of Japan, and completely destroyed many coastal communities, particularly in Iwate, Miyagi and Fukushima prefectures. The tsunami flooded 561 $km^2$ of land along the Pacific coast of Japan (Geospatial Information Authority of Japan, www.gsi.go.jp) and affected 602 200 residents and killed 3.5% of them (Statistics Bureau of Japan, www.stat.go.jp/info/shinsai/index.htm).

Several nuclear power plant facilities were affected by the strong ground motions and great tsunamis: the Tokai, Higashi Dori, Onagawa and Fukushima Dai-ichi and Dai-ni plants. An unexpectedly large tsunami 14 m high attacked the Fukushima Dai-ichi facilities and caused the loss of the emergency diesel generators that had been working in the situation of no off-site power available [1]. Consequently, all the instrumentation and control systems at reactors 1–4 were lost, and a series of explosions occurred, causing extensive radioactive contamination. The geological and historical evidence of irregularly recurring earthquakes in Japan is discussed elsewhere in this issue [2], while the Fukushima accident is discussed in [3].

The 2011 Great East Japan Earthquake and Tsunami disaster left many lessons to be learned regarding Japan's disaster management policies. As a result, they have been drastically changed to promote initiatives for building national resilience with the aim of creating safe and secure national lands, regions and economic society that have strength and flexibility, in any disasters. For disaster-affected areas, the central government has amended policies of coastal protection from the viewpoint of reducing risks and enhancing disaster resilience, and local governments have completed drafting reconstruction plans including infrastructure design, transportation, land-use management, urban design, relocation, economic and industrial outlooks. Four years have passed since the event occurred, and a national budget of 25 000 billion yen has been allocated for 5 year reconstruction efforts.

This contribution revisits the lessons of the 2011 Great East Japan Earthquake and Tsunami disaster specifically focusing on the response, impact and paradigm shift of Japan's disaster management policies and discusses perspectives for enhancing national resilience. First, we review the pre-2011 Japan tsunami countermeasures developed from the experience of the past Sanriku tsunami events. Second, we revisit the responses to the 2011 event, specifically on the tsunami warning system and efforts to identify the tsunami impacts and lessons learned. Third, the post-disaster paradigm shifts in reconstruction are discussed through a case study in Sendai city, Miyagi prefecture.

# 2. Pre-2011 paradigm

## (a) History of Sanriku Tsunamis

The Sanriku Coast lies on the north-eastern side of the island of Honshu (in the Tohoku region), corresponding to Aomori, Iwate and Miyagi prefectures. The Sanriku coastline is particularly vulnerable to tsunamis because it has many V-shaped bays, which cause tsunami energy to focus and amplify.

During the night of 15 June 1896, the Meiji Great Sanriku Tsunami hit the Sanriku Coast. The highest tsunami run-up height was 38 m at Ryori Shirahama in Iwate prefecture. The earthquake was a typical 'tsunami earthquake' that had negligibly weak ground shaking, and, therefore, no residents tried to evacuate. This resulted in the death toll of 22 000. The economic losses reached about 10% of the national budget of the time [4]. After this tsunami, several villages were relocated to high ground at the personal expenses of individuals or village leaders [5].

In the early morning on 3 March 1933, another major tsunami struck the Sanriku Coast. The maximum run-up height was 29 m at Ryori Shirahama. Most of the coastal villages on the Sanriku Coast were devastated again. Because ground shaking was strong this time, many residents were awakened and evacuated to high ground; however, the death toll reached 3000.

Before the 1933 Showa Great Sanriku Tsunami, the countermeasures taken were simply the relocation of residences to higher ground. Three months after the 1933 event, the Council on Earthquake Disaster Prevention (CEDP) of the Ministry of Education proposed a total system of tsunami disaster mitigation that consisted of 10 countermeasures: relocation of dwelling houses to high ground, coastal dykes, tsunami control forests, seawalls, tsunami-resistant areas, buffer zones, evacuation routes, tsunami watch, tsunami evacuation, memorial events. Coastal dykes were constructed at five sites only, because of expensive construction costs.

In 1941, a tsunami warning organization was founded for the Sanriku Coast. A tsunami forecasting chart was drafted empirically. After the Meteorological Business Act was enacted in 1952 [5], the forecasting system covered the whole coast of Japan.

On 23 May 1960 (JST), a huge earthquake occurred off the Chilean coast. The tsunami generated by the earthquake attacked the Japanese coast the next morning. Coastal residents did not feel any ground shaking and the Japan Metrological Agency did not issue a tsunami warning. Thus, the residents were suddenly attacked by the tsunami. Among the Japanese Pacific coasts from Hokkaido down to Okinawa, the Sanriku Coast suffered the most serious damage. The tsunami height of 3–6 m was not so high in as the near-field tsunamis of the Meiji and Showa events.

## (b) Pre-2011 Tsunami countermeasures

Japan's tsunami countermeasures after the 1960 tsunami consisted mainly of the construction of seawalls and coastal dykes, based on the tsunami height in the 1960 event, 3–6 m at most. At the same time, rapid economic growth resulted from the 'Income-Doubling Plan' that started in 1960, an age of rapid growth, could cover the expensive construction costs.

In addition to the 1896 Meiji and the 1933 Sanriku tsunamis which killed 22 000 and 3000 people, respectively, the experiences of the 1959 Ise-wan super typhoon (Vera) and the 1960 Chilean earthquake tsunami strongly motivated Japan to develop coastal protection infrastructures of seawalls and breakwaters. Especially in Iwate prefecture, 10 m high seawalls have been built along the coast to protect communities that have been devastated many times throughout history.

The first tsunami breakwater was constructed at the mouth of Ofunato Bay, Iwate prefecture, where the maximum water depth was 38 m. The functionality of this breakwater for protection was investigated through numerical analysis [6]. This was the first stage of using computer simulations in tsunami science and engineering.

The Kamaishi tsunami breakwater is in the Guinness Book of World Records as the deepest tsunami breakwater at nearly 63 m deep, and was designed to protect the densely populated area in Kamaishi city located at the bottom of the bay. Its construction started in 1978 and was completed in 2009, requiring an investment of almost 30 years and 120 billion yen. But even this barrier could not protect citizens from the 2011 tsunami, although it earned them a 6 min delay before the tsunami penetrated Kamaishi city, and 40% tsunami height reduction (13.7–8.1 m) in the harbour [7]. One can understand how, with this huge concrete breakwater, people in Kamaishi would feel well protected, and yet the 2011 tsunami caused 1253 fatalities in the city.

Concrete seawalls and coastal dykes were covered with concrete at the front, top and back. However, hard protection at the dyke toes was not mentioned. It was found in the 2011 event that this lack of toe protection became a weak point, once overflowed.

At night on 12 July 1993, an earthquake off the west coast of Hokkaido generated a huge tsunami. The southernmost area of Okushiri Island was completely devastated by the 11 m tsunami, even though the area was protected by 4.5 m seawalls. This fact called for serious reflection on the conventional method that was used after 1960 which relied mainly on coastal structures. Field measurements of extreme inundation are now used for validating numerical models [8,9].

In 1997, the Japan central government council, which consists of seven ministries, issued a guideline for comprehensive tsunami countermeasures that should be taken as part of regional tsunami disaster prevention. In those guidelines, three basic concepts of tsunami countermeasures were recommended: (i) building seawalls, breakwaters and flood gates to protect lives and properties; (ii) urban planning to create a tsunami-resilient community through effective land-use management and arrangement of redundant facilities to increase the safe area, such as vertical evacuation buildings; (iii) disaster information dissemination, evacuation planning and public education.

The 2011 Tohoku event provided the first real test of the various technologies and countermeasures that Japan has been using to protect people during tsunamis. Some have probably worked well, while others appear to have failed.

## (c) Tsunami source scenarios and hazard maps

Most tsunamis are generated by earthquakes that occur in subduction zones, the areas where oceanic plates subduct beneath overriding continental plates. The tsunami source scenarios considered in preparing hazard maps are determined by the results of long-term evaluation of seismic activities. Thirty-year monitoring and measurement of seismic activity around Japan have revealed the seismotectonic structure [10]. It was thus suggested that in the Tohoku region the Pacific plate was moving westwards with a convergence rate of 8.5 cm $year^{-1}$ and was subducting beneath the North American plate at the Japan Trench; interpretation of the seismotectonic features were believed to be divided into three seismotectonic provinces [10] and their characteristic earthquakes. On this basis, the maximum potential earthquake in the Tohoku region was estimated as Mw 8.5. The March 11 Tohoku earthquake was caused by thrust faulting at the plate boundary between the Pacific and North American plates as expected. However, its size was unexpectedly large (Mw 9.0). Earthquake source studies indicate that the fault ruptured with a maximum slip of 60–80 m [11] over an area approximately 450 km by 200 km [12], making the pre-2011 estimates irrelevant.

Paleoseismological studies suggested the predecessor of the 2011 Tohoku earthquake had been the 869 Jogan earthquake [13,14]. The variability in size and recurrence interval of great earthquakes in subduction zones cannot be well resolved with seismological studies only, especially for the occurrence of extreme events with a 500- to 1000-year recurrence interval.

It was widely believed that Japan was one of the most prepared countries in the world for tsunami events. In one sense, the belief was right. The 2004 Sumatra–Andaman earthquake tsunami (Mw 9.0–9.3) killed 220 000 people, while the 2011 event (Mw 9.0) caused over 18 000 fatalities. Both events are probably similar with regard to the size of the earthquake and the height of the tsunami. One reason for the striking difference in the number of fatalities was the level of preparedness.

After the 1990s, many local governments published tsunami hazard maps, prepared from numerical simulations. As a national guideline of preparing flood hazard maps, the Cabinet Office published 'Tsunami and Storm Surge Hazard Map Manual' in 2004 [15]. This manual recommends hazard maps not only for residents but also for companies and fishermen. A hazard map shows the flooded area by past tsunamis and by the most likely tsunami in the near future. Following the guideline, coastal cities and towns in Japan had prepared tsunami hazard maps

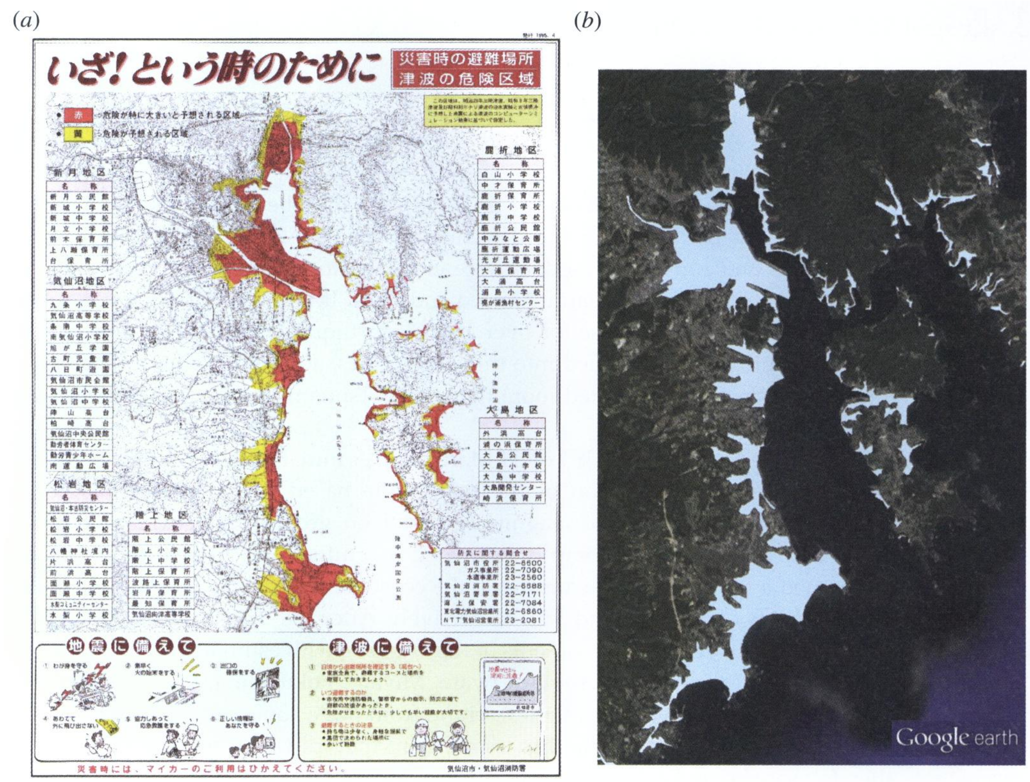


**Figure 1.** (*a*) Tsunami hazard map published for Kesennuma city, Miyagi prefecture. The map was delivered to every household before the 2011 event to announce the tsunami inundation zone in past events, list of evacuation facilities, and brief instructions for earthquake and tsunami preparedness. (*b*) The map of tsunami inundation extent in the 2011 event (www.gsi.go.jp). The tsunami caused 1280 dead or missing even in this well-prepared community.

with estimated inundation zones, the list of shelters where people could evacuate and instructions on how to survive a tsunami. In many coastal communities, people have conducted regular evacuation drills and have held workshops to learn which areas are at risk, by referring to a hazard map prepared by the local government. Figure 1 contrasts one hazard map for Kesennuma city, in Miyagi prefecture, with the actual extent of inundation in the 2011 tsunami. The maps seem quite similar in terms of the tsunami inundation extent.

In addition, in Sanriku coastal communities, people were taught the lesson or maxim of 'Tsunami Tendenko', which means that people should run without taking care of others, even family members [16]. This phrase encourages people to escape by making individual decisions and taking personal responsibility; every individual effort increases the possibility of surviving. Note that 'Tsunami Tendenko' is not an egoistic maxim, with the importance of trust among loved ones to achieve the aim of maximizing the number of lives saved [17].

The 2011 tsunami disaster also implied that hazard maps have two functional aspects. One is to inform people that they are at risk. It is through such opportunities to know their risk that people learn that they must try to escape an at-risk area as soon as possible, when they feel strong ground motion or hear the tsunami warning or evacuation order issued. On the other hand, a hazard map can function to assure residents living outside of the expected inundation zone that their area is NOT at risk. This is one negative aspect of relying heavily on a hazard map. In the 2011 event, hazard maps failed to offer accurate predictions in some areas and may have increased the number of fatalities, as people believed that they did not have to evacuate immediately, even though these maps indicated the uncertainty of estimations based on past events and state-of-the-art computer simulations.

## 3. Response to the 2011 event





### (a) Tsunami warning

The Japan Meteorological Agency (JMA), which is responsible for issuing tsunami warnings/ advisories and for estimating tsunami height, employed a new system in 1999 [18] and updated it using Earthquake Early Warnings (EEWs) in 2006 [19]. Japan believed that JMA's tsunami warning system was using the most advanced technology in the world. In fact, its tsunami forecasting technologies and numerical models were exported to many foreign countries that needed support, such as Indonesia, Thailand, Mexico and Peru. JMA prepared a pre-conducted tsunami propagation simulation database for over 100 000 earthquake scenarios around Japan. The contents of the warning were classified into three categories, according to the estimation of tsunami height: 'Major tsunami' (estimated more than 3 m), 'Tsunami' (estimated 1 or 2 m) and 'Advisory' (0.5 m or less).

When the 2011 event occurred at 14.46 JST on 11 March, JMA's initial estimate of the magnitude (Mjma) was 7.9, which is a combination of the magnitude based on ground displacement for relatively large earthquakes and the magnitude based on ground velocity for relatively small earthquakes [20]. Based on the promptly estimated magnitude 7.9, 3 min after the quake (14.49 JST), JMA issued a Major tsunami warning to the coasts of Iwate, Miyagi and Fukushima prefectures with estimates of 3 m, 6 m and 3 m, respectively. After the tsunami was observed at offshore tsunami buoys, JMA revised the contents of the warning with estimates of 3 m, 6 m, over 10 m, 6 m, 4 m and 4 m to the coasts of Aomori, Iwate, Miyagi, Fukushima, Ibaraki and Chiba prefectures, respectively. Receiving the tsunami warning from JMA, some residents claimed that they thought they were safe based on the 3 m estimation: they did not feel that they had to evacuate, as they felt safe behind a 10 m seawall. Even worse, in several communities, the radio or speaker system did not work because of the blackout caused by the earthquake.

Now, JMA has expanded its seismic/tsunami monitoring network by installing broadband seismometers and an offshore tsunami monitoring system, to increase its capability for quicker and more accurate estimation of earthquake magnitude and tsunami [21]. Still, it is difficult to determine a precise magnitude within around 3 min for large earthquakes with a magnitude of 8 or more and for 'tsunami earthquakes' generating much larger tsunamis than their magnitude would suggest. For such cases, JMA has introduced methods to quickly highlight the possibility of underestimation in magnitude estimation and issues an initial tsunami warning based on the largest seismic fault expected in the area where the earthquake was triggered [21].

Learning lessons, we should note that there are still limitations on the reliability of technologies that can be used in a very short time. Tsunami warning information can inform people that they are in danger, but it cannot guarantee people's safety. The most important lesson is that one should not wait for official information to act: strong ground shaking is the first alert to take action.

### (b) Witnessed tsunami height and inundation flow

After the 2011 Tohoku tsunami attack, the international post-tsunami survey team was established and conducted a nation-wide survey [22,23] to record the tsunami run-up heights, flow depths, inundation extent and the impacts. Tsunami height measurements are most dense from previous post-tsunami survey teams and are now widely used for understanding features the local tsunami amplification and for benchmarks of tsunami modelling. Figure 2 illustrates the measured tsunami inundation and run-up heights by the survey team, with plots of historical tsunami heights of the 1611 Keicho Sanriku, 1896 Meiji Sanriku, and 1933 Showa Sanriku earthquake tsunamis [24]. Northeast of Tohoku, the maximum run-up height in this event was similar to the events of both 1896 and 1933, especially of the 1896 Meiji Sanriku tsunami. However, the affected area of this event was much more extensive than in those historical events. In this sense, the 11 March 2011 event was the largest known tsunami event in Japan. In addition, a

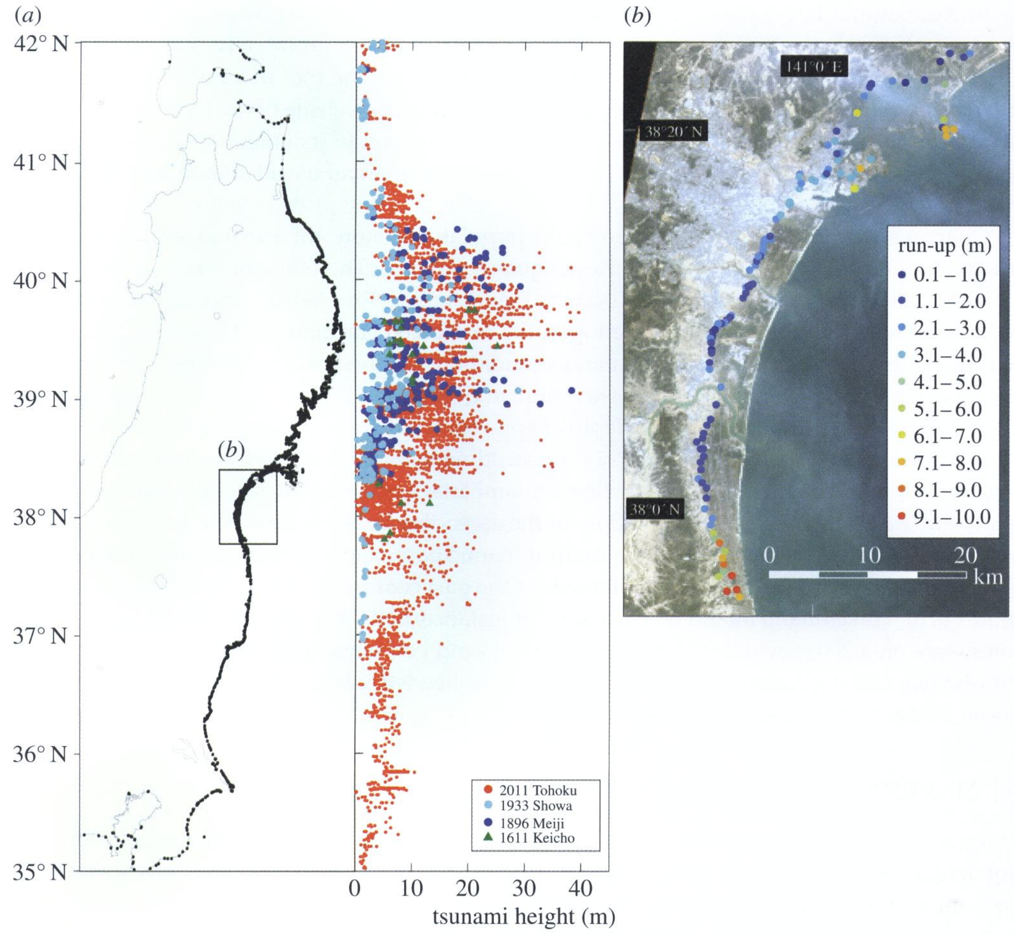


**Figure 2.** (*a*) The measured heights of the 2011 Tohoku tsunami [22] and historical Sanriku earthquake tsunamis (1611, 1896 and 1933 events). The historical tsunami data were provided by Japan Tsunami Trace Database [24] maintained by Tohoku University and the Japan Nuclear Energy Safety Organization (JNES). Black dots on the coastline indicate the points of the 2011 tsunami height measurement. The tsunami run-up height reached up to 40 m in Iwate prefecture. (*b*) The extent of the tsunami inundation zone with the measurement of the run-up heights at tsunami inundation limit in Sendai Coast [23].

significant feature of the 2011 tsunami was the wide extent of the inundation zone; for example, on the Sendai plain (figure 2*b*), the tsunami inundated more than 5 km inland, causing devastating damage to populated areas and rice fields. These features implied that the 2011 earthquake was probably a combination of the 1896 Sanriku 'tsunami earthquake' and a Jogan-type deeper interplate earthquake [14].

Tsunami inland penetration with strong inundation flow causes damage to infrastructures, forests, buildings and humans. Measurements of tsunami inundation flow velocities on land were quite rare, and it was thus difficult to understand what really happened in the devastated area and to identify the cause and mechanisms of structural destruction by tsunami inundation flow. Thanks to the recent advances of hand-held video cameras and mobile phones, however, many tsunami survivors have attempted to capture the moment of tsunami attack on their communities and have uploaded videos to the Internet (we should note that taking photos or videos of a tsunami should only ever be done from a position uphill, never from a beach). Applying a video analysis technique, the tsunami flow velocity can be determined to understand the characteristics of tsunami inland penetration and impact on structures [25–30].

In Kesennuma Bay, Fritz *et al.* [26] analysed survivor videos and measured flow velocities of about $10\,\mathrm{m\,s^{-1}}$ for the inundation flow that penetrated through the city [26], and produced a hydrograph of the tsunami. Another video was taken from the roof of a building in Onagawa town by one survivor. A part of this video was uploaded to the website of the Japanese newspaper company Yomiuri Shimbun [31]. It captured the moment of tsunami attack and contains important information of how the tsunami penetrated inland and local tsunami inundation flow characteristics.

Onagawa town, Miyagi prefecture (10 014 population before the earthquake), is one of the towns devastated by the 2011 Tohoku earthquake tsunami. The tsunami attacked the town at 15.20 JST (34 min after the earthquake occurred) and caused 816 fatalities and 125 missing. Using the video taken by a resident from the top of the reinforced concrete (RC) building in Onagawa harbour, the flow velocity of the tsunami inundation in Onagawa town when the houses in the town started being washed away was estimated as $6.3\,\mathrm{m\,s^{-1}}$ for the ascending tsunami and $7.5\,\mathrm{m\,s^{-1}}$ for the return flow at a flow depth of approximately 5 m. This observation implies, as the flow conditions of the subcritical flow of the ascending tsunami and the super-critical flow of the return flow, that the return flow in the first tsunami attack was slightly stronger than the leading tsunami. The $6.3\,\mathrm{m\,s^{-1}}$ of inundation flow of the ascending tsunami caused a drag force per unit meter width of $100\,\mathrm{kN\,m^{-1}}$ [32]. These hydrodynamic parameters appear capable of devastation for the coastal forests that have been planted for the past centuries. Often, the destroyed trees did more harm with tsunami inland penetration. For instance, in the city of Rikuzentakata, 70 000 pine trees were on a 200 m wide, 1.7 km long beautiful sand beach and were totally destroyed except for one tree [33]. Consequently, the devastated trees headed inland producing large amounts of waste, and may have caused more destruction.

## (c) Structural vulnerability to tsunamis

Many field surveys were conducted to identify the damage mechanisms of structures and their impact [27,34,35]. Structural vulnerability to tsunamis is a critical issue in planning for tsunami-resilient communities. Integrating structural damage information [36] with field survey data, such as flow depths, produces a new measure of structural vulnerability to tsunamis, as a form of tsunami fragility curve or tsunami fragility function [37]. In general, a tsunami fragility curve is defined as structural damage probability or fatality rate with particular regard to the hydrodynamic features of tsunami inundation flow, such as flow depth obtained from field measurements, current velocity and hydrodynamic force estimated with tsunami numerical modelling [38].

Figure 3 shows an example of a tsunami fragility curve obtained in the 2011 Tohoku event. Note that this fragility curve was obtained using the form of probability of structural destruction as a function of measured tsunami flow depth. As observed in the tsunami fragility curves, structures were especially vulnerable when the local flow depth exceeded 2 m, while a 6 m flow depth would cause everything to be washed away. This finding can inform land-use planning, so that residential areas will not be inundated more than 2 m. Also, we found high-rise RC buildings with robust columns and walls withstood tsunami flow depths over 2 m and can be used for vertical evacuation.

Before the 2011 event, the general belief of a safe place to survive a tsunami attack was robust RC buildings. In the past, nothing has been reported about the devastation of RC structures except for the case of the Scotch Cap lighthouse in Unimak island that was destroyed by the 1946 Aleutian tsunami [40]. This 18 m tall lighthouse built on a cliff 10 m a.s.l. was hit by an approximately 30 m tsunami. All that remains of the lighthouse is the foundation and part of the concrete seawall. Details of the inundation are discussed by Okal *et al.* [41].

In the 2011 Tohoku event, at least eight RC or steel construction buildings were found overturned or washed away in Onagawa town and Miyako city. Even in Onagawa town, 28 people were saved inside the boiler room of a five-storey RC building which was totally submerged by the tsunami inundation flow.

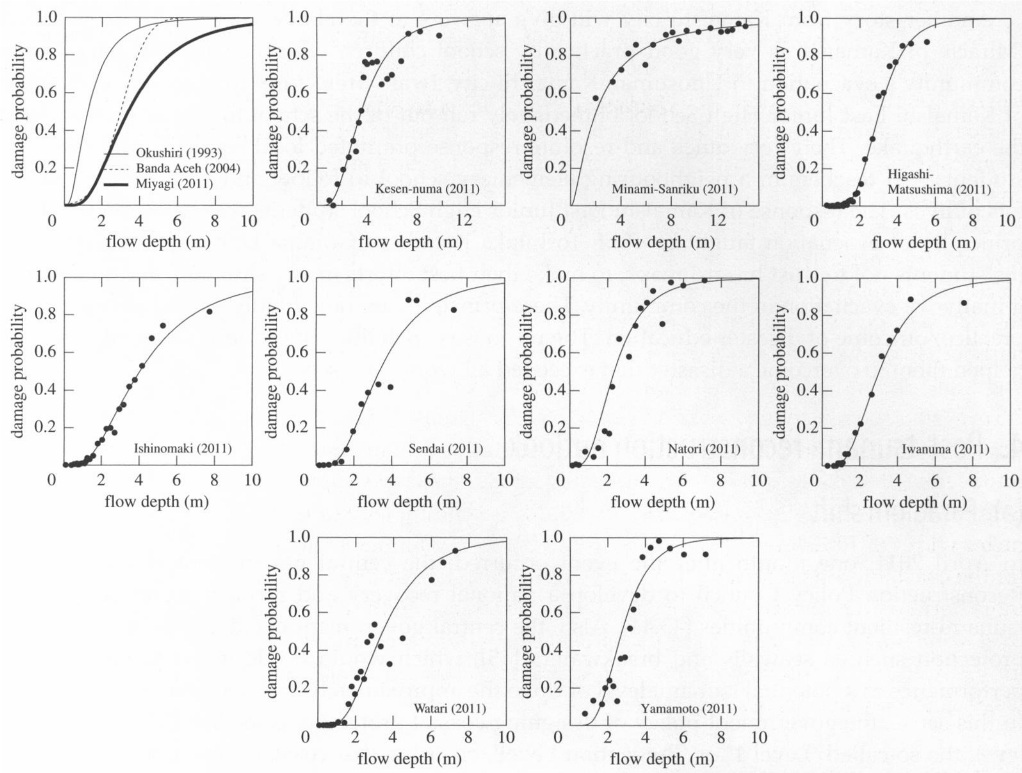


**Figure 3.** Tsunami fragility curves for structural destruction (washed-away structures) [39]. The solid lines are obtained from the devastated municipalities of Miyagi prefecture (from the 2011 event) and the dashed one is from Banda Aceh, Indonesia (the 2004 Indian Ocean tsunami) [37].

## (d) Tsunami's impact on schools

Many pupils and teachers were affected by the 2011 Tohoku earthquake and tsunami. On 6 October 2011, the Ministry of Education, Culture, Sports, Science & Technology published a report of student fatalities and injuries: in total, 635 children, students and teachers were killed by the tsunami, and 221 were injured.

Especially hard hit was the Okawa elementary school in Ishinomaki city, located 5 km inland along the Kitakami River: the school lost 74 pupils (70 killed and 4 still missing) out of a total of 108 and 10 teachers in the 2011 tsunami. At least 50 min elapsed after the earthquake before the tsunami attacked the school. After the strong ground shaking had stopped and the tsunami warning had been issued, the teachers and pupils gathered on school grounds to discuss where to evacuate to. They had two options. One option was a hill with a steep slope behind the school, which looked difficult for small children to climb. The other was a small overlook at the river bridge, 200 m away from the school. Consequently, teachers decided to head for the bridge, walking along the river. Shortly thereafter, the tsunami penetrated along the river and overtopped the riverbank, sweeping away pupils and teachers.

We must learn lessons from the incidents. What is the requirement that should be put into place for safer school buildings that can withstand both strong ground shaking and a devastating tsunami? How high should buildings be, so that the inhabitants can survive? (The Okawa elementary school building withstood the devastating tsunami inundation flow, but was totally submerged.) How can we educate children to be prepared? How should teachers be trained to provide appropriate guidance to save children's lives and their own?

Another story from Kamaishi city will give answers to the above questions. The so-called 'Miracle of Kamaish' is very good practice by school children who took the initiatives for a community's evacuation in Unosumai, Kamaishi city, Iwate prefecture. In Unosumai, students of Kamaishi East Junior High School immediately ran out of the school to higher ground after the earthquake. Their very quick and resolute response prompted local residents and even the students and teachers in a neighbouring elementary school to follow and consequently saved lots of lives. The response of Kamaishi East Junior High School students was based on the three principles of evacuation taught by Prof. Toshitaka Katada of Gumma University [42]. He told the students not to trust hazard maps, to make their best efforts in any situation, and to take the initiative of evacuation in the community. These principles are now highly valued as one of best practice/outcome of disaster education. The response capabilities the children learned at school helped them to overcome a disaster that exceeded all worst-case scenarios.

## 4. Post-tsunami reconstruction outlook

### (a) Paradigm shift

In April 2011, one month after the event occurred, the central government established the Reconstruction Policy Council to develop a national recovery and reconstruction outlook for tsunami-resilient communities [43,44]. Also, the central government decided a policy of coastal protection such as seawalls and breakwaters [45], which would be designed to ensure their performance to a potential tsunami level of up to the approximately 150 year recurrence interval. In this sense, the government policy of designing coastal protection is for the 150 year tsunami level, the so-called 'Level 1' or 'Prevention Level', ensuring that coastal protection will prevent tsunamis from penetrating inland to protect lives and properties (or economic activities). For the largest-possible tsunami level of the more than 150 year recurrence interval, the so-called extreme event (such as the 2011 Tohoku event), the government refers to this as 'Level 2' or 'Preparedness/Mitigation Level' to protect human lives and to reduce the losses and damage with comprehensive disaster management measures including coastal protection, urban planning, evacuation and public education.

A remarkable paradigm shift in coastal protection policies is on seawall design. The lesson learned was that coastal infrastructure such as breakwaters and seawalls cannot always protect life and property: even great seawalls can fail. Seawalls should be designed with the assumption of overtopping and destruction, and communities should not rely on coastal infrastructures alone for protection.

In December 2011, the central government enacted the 'Act on the Development of Tsunami-resilient Communities'. According to the principle of 'Human life is most important', this law promotes a development of tsunami-resistant communities based on the concept of multiple defences which combines infrastructure development and other forms of measures targeting the largest class tsunami [46]. The act is based on the following new principles: (i) properly combine structural and non-structural measures to minimize damage; (ii) with sufficient consideration to socioeconomic conditions, coastal protection facilities should be aimed at protecting people's lives, property, industrial and economic activities, and national land against a certain scale of relatively frequent tsunamis; (iii) tsunami disaster mitigation strategies should be based on multiple protection that combines structural and non-structural measures, with consideration of regional characteristics.

### (b) Evaluation of reconstruction plan

All the municipalities in the 2011 tsunami-affected areas needed to draft their reconstruction plans following the 'Act on the Development of Tsunami-resilient Communities'. When verifying the proposed reconstruction plan, numerical modelling is useful. For Sendai city, we performed numerical modelling of tsunami inundation in the city by setting several tsunami source

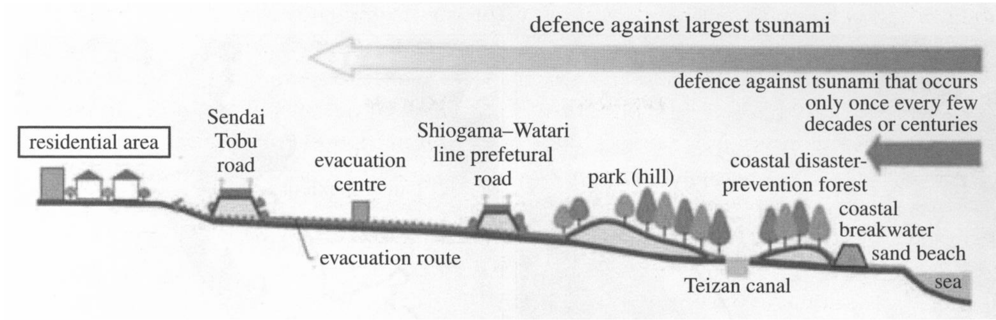


**Figure 4.** Conceptual image of tsunami-prevention facilities in Sendai city [49]. The seawall was designed for Level 1 tsunami (the height equivalent to the historical tsunami heights in the past 150 years and storm surge heights in the past 50 years). The other measures secure multiple protection. (Online version in colour.)

scenarios [47,48]. The nonlinear shallow water equations are discretized by the staggered leap-frog finite difference scheme with bottom friction in the form of Manning's formula according to the land-use condition [37]. The inundation model results are validated through the comparison with field data in terms of local inundation depths, inundation heights [22,23].

Under the limitations and uncertain conditions of funding, prefectural and local governments have developed their own recovery and reconstruction plans, which require 10 years to be completed (National budget is allocated for the first 5 years). These plans consist of the combination of structural prevention/mitigation, urban planning, preparedness and provide suggestions for land-use management, relocation, housing reconstruction and tsunami disaster mitigation plans. The key role of academia, from the engineering point of view, is to verify and evaluate if these plans will really work for future disaster reduction. For instance, based on the findings regarding the structural vulnerability (figure 3), Sendai city determined a reconstruction plan [49] to reduce the tsunami flow depth to less than 2 m in the populated area with a conceptual image of multiple coastal protection (figure 4). A significant feature of Sendai city's reconstruction plan is integrating several coastal protection facilities, such as seawalls, coastal forests, park (artificial hill) and elevated roads to minimize the potential losses. Figure 5*a* indicates the plan view for the multiple protection of Sendai city with a 7.2 m seawall and river dyke and 6 m elevated prefectural road. The seawall's height was determined by considering historical tsunami heights in the past 150 years and storm surge heights in the past 50 years (Level 1). For the largest possible tsunami (Level 2), the city secures multiple facilities of coastal forest, artificial hill, raised road and evacuation sites to protect citizens' lives.

To evaluate how these protection measures will work in terms of tsunami disaster reduction, we conducted tsunami numerical modelling with the 2011 tsunami source scenarios, namely 'Level 2 tsunami' scenarios of the largest-possible tsunamis, and the present reconstruction plan. Figure 5*b* shows one example from preliminary results. As indicated in the figure, we found that the multiple protection measures for Level 2 tsunami will contribute to substantially reduce the tsunami inundation zone and flow depth on Sendai plain especially at the western side of 6 m elevated prefectural road. Using this result, Sendai city determined the land-used plan and the area of housing reconstruction and relocation. However, note that the tsunami (the 2011 scenario) will overtop even a 7.2 m seawall (designed for Level 1 tsunami) and the 6 m elevated road, and the model assumes no destruction of structures. In this sense, the model cannot reproduce all the aspects of tsunami inland penetration. Coastal infrastructure such as breakwaters and seawalls cannot always protect life and property. Seawalls or coastal structures should be designed with the assumption of overtopping and resiliency, and communities should not rely on coastal infrastructures alone for protection. Based on this new reconstruction plan in the tsunami-affected area, Sendai city has formulated its tsunami evacuation plan [50] to protect lives.

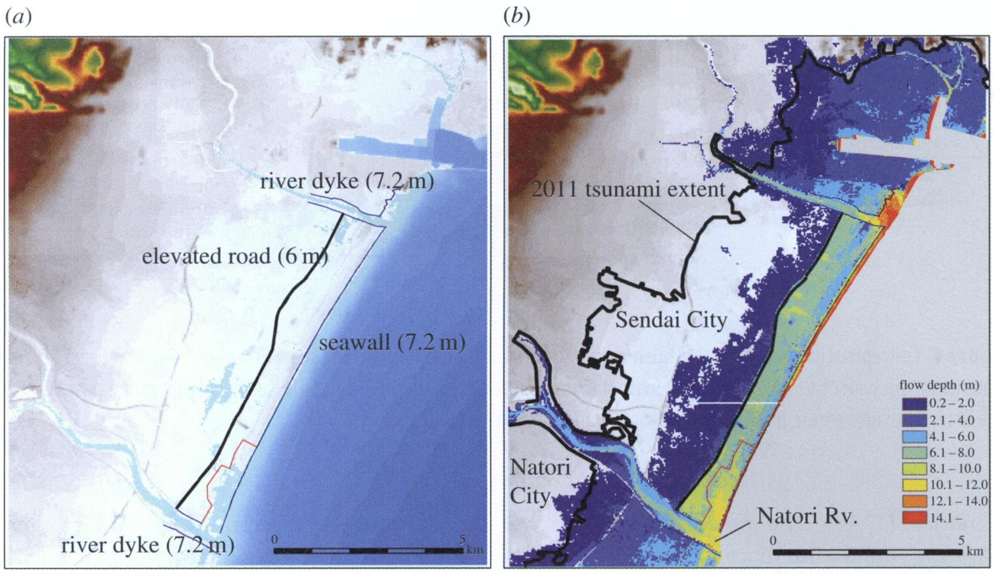


**Figure 5.** (*a*) Setting of tsunami prevention facilities in Sendai city reconstruction plan [49]. (*b*) Result of tsunami numerical modelling to evaluate the effect of the proposed reconstruction plan in Sendai city (maximum flow depth).

## 5. Conclusion

The devastating tsunami followed by the 2011 Great East Japan Earthquake and Tsunami left many lessons to be learned that have led the paradigm shift of Japan's tsunami disaster management.

On tsunami hazard maps, knowing which areas are at risk is critical, but one must also recognize the predictive limits of science and technology; hazard maps cannot always accurately predict areas at risk. Governments can reduce risk, but communities must not become complacent. Even now, numerical simulations cannot predict everything that will happen in a disaster. Hazard maps have two functional aspects. One is to tell people that they are at risk. On the other hand, a hazard map can function to assure residents living outside of the expected inundation zone that their area is not at risk. This is one negative aspect of relying too completely on a hazard map.

Coastal infrastructure such as breakwaters and seawalls cannot always protect life and property: even great seawalls can fail. Seawalls should be designed with the assumption of overtopping and destruction, and communities should not rely on coastal infrastructures alone for protection. A new paradigm of coastal structural design has caused significant arguments in some Sanriku coastal communities. The design policy of coastal defence structures sets the height of seawalls to ensure their performance to a potential tsunami level of up to approximately the 150 year recurrence interval (Level 1 or 'Prevention Level'). However, when implementing, this design paradigm has triggered conflict and debate. Even when protected by great seawalls of 8–10 m, the government often prohibits the lower part of town to redevelop as a residential area, as the low land is reserved for commercial and industrial purposes. Many coastal communities on low-land devastated areas are thus moving uphill by applying for relocation and buy-out programme. Scattering residential areas will isolate people and weaken community connections, and consequently, undermine the community's sustainability with shrinking population in rural areas. Then the question is 'what are the great seawalls for?'. This problem is not yet solved.

As observed in devastated areas in Japan, tsunami flow depths over 2 m have the potential to severely damage houses. High rise RC buildings with robust columns and walls can withstand tsunami flow depths over 2 m and can be used for vertical evacuation. However, at the same time, at least eight RC or steel construction buildings have been found overturned or washed away. This fact led to a revision of the requirement for structural design of tsunami evacuation buildings [51], specifically focusing on the tsunami loading effect. School buildings should have similar construction requirements, in order to ensure children's safety. Teachers, parents and children should have more opportunities to learn about their risk and how to survive in emergency situations.

Following the expanded seismic/tsunami monitoring network by installing broadband seismometers and offshore tsunami monitoring systems, JMA's tsunami warning increased its capability for quicker and more accurate estimation of earthquake magnitude and tsunami. However, learning the lessons, we should note that there are still limitations on the reliability of technologies that can be used in such a limited amount of time. Tsunami warning information can inform people that they are in danger, but it cannot guarantee people's safety. The most important lesson is that one should not wait for official information to act: strong ground shaking is the first alert to take action.

Lastly, public education is the most important part of tsunami disaster management. Prof. Katada's three principles: not to trust hazard maps (recognize the predictive limits), make the best efforts in any situation and take the initiative of evacuation in a community; these are highly recommended attitudes to overcome a disaster that exceeds all worst-case scenarios.

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