Available online at www.sciencedirect.com

Public Health

journal homepage: www.elsevier.com/puhe

Original Research

Tsunami inundation after the Great East Japan Earthquake and mortality of affected communities

A. Ishiguro [a], E. Yano [b,*]

[a] Department of Hygiene and Public Health, Teikyo University School of Medicine, Tokyo, Japan
[b] Teikyo University Graduate School of Public Health, Tokyo, Japan

ARTICLE INFO

Article history:
Received 24 March 2014
Received in revised form
12 February 2015
Accepted 23 June 2015
Available online 20 July 2015

Keywords:
Natural disaster
Tsunami
Mortality
Inundation depth
Landform

ABSTRACT

Objective: To examine the relationship between mortality rate and tsunami inundation after the Great East Japan Earthquake (GEJE) in 2011.

Study design: Cross-sectional study.

Methods: One hundred and fifty-five town or village sections in Ishinomaki, Myagi Prefecture, were included in this study. Three areas in the city were classified by characteristic landforms: plains area ($n = 114$), ria coastal area ($n = 27$) and Kitakami riverside ($n = 14$). The correlation coefficient between tsunami inundation depth and mortality rate was calculated for each area, and the differences between the areas were examined. Furthermore, multivariate analyses adjusted for the characteristics of the sections were conducted using census data taken before the GEJE.

Results: An association was found between inundation depth and mortality rate for Ishinomaki as a whole ($r = 0.65$, $P < 0.001$), Kitakami riverside ($r = 0.85$, $P < 0.001$) and the plains area ($r = 0.75$, $P < 0.001$) in separate analyses. However, no association was detected between inundation depth and mortality rate for the ria coastal area ($r = 0.14$, $P = 0.47$).

Conclusion: The ria coastal area has good accessibility to the hills and tight bonding between members of the community. These factors seemed to play crucial roles in the lower mortality rate in this area despite the deep inundation.

Introduction

There are numerous vacant lots along the coast of northeastern Japan that formerly contained communities comprised of houses, ports and workplaces. On 11 March 2011, a huge tsunami caused by the Great East Japan Earthquake (GEJE, magnitude 9.0) wreaked havoc on the area.[1,2] Nearly 400,000 houses and 20,000 public buildings were completely or partially destroyed, and 400,000 people were forced to evacuate.[2–4] The catastrophic power of the GEJE took nearly 20,000 lives.[2,5] Among the municipalities, Ishinomaki in Miyagi Prefecture suffered the greatest number of deaths ($n = 3471$).

There is a need to investigate factors that mitigated the human mortality rate, regardless of the physical damage, in order to prepare for the next disaster. Of nearly 20,000 casualties, more than three-quarters of deaths were due to

* Corresponding author.
E-mail address: eyano@med.teikyo-u.ac.jp (E. Yano).
http://dx.doi.org/10.1016/j.puhe.2015.06.016

drowning in the tsunami rather than collapsed buildings.[6] Some perished while attempting to rescue their families, while others had no knowledge of the impending tsunami and were unable to escape in time.

The mortality rate increased with the inundation depth,[7] and a relationship has been reported between the mortality rate and the proportion of the population that lived in the area of inundation.[8] In contrast, some communities in the ria coastal area of Ishinomaki reported no fatalities, despite the fact that almost all houses were destroyed by the tsunami. The Japanese Government reported that the average mortality rate in the ria coastal area was lower than that of the plains area at the same inundation depth.[7]

Mortality rate trends in inundated areas of past disasters have been reported, but to the authors' knowledge, this is the first study to investigate the relationship between inundation depth and mortality rate.[9–13] It was hypothesized that the mortality rate experienced by a community is not determined solely by the inundation depth of a tsunami. This study investigated the relationship between the inundation depth of the GEJE tsunami and mortality rate, and explored the factors, including landforms, that affected the degree of mortality.

Methods

Setting

A cross-sectional study was performed to examine the study hypothesis using data from Ishinomaki, Miyagi Prefecture. Ishinomaki is one of the major port cities in Tohoku District, and its main industries include fishing, marine product processing and paper manufacturing. The population of Ishinomaki used to be 160,000, but it decreased by >5% following the GEJE due to the large number of deaths ($n = 3471$).[14]

Ishinomaki can be divided into three geographical areas based on characteristic landforms: plain, ria coast and Kitakami riverside (see Fig. 1). The plains area, which contains the largest population among the three areas, is located in the southern part of the city and includes the main administrative functions, a residential area, a major port, and a fishing and paper industrial region. The ria coastal area, which is comprised of a number of rural fishing villages, is on the north-eastern coast. Each village was divided by a steep landscape with coves and valleys, and the population density was low. The Kitakami riverside, along the Kitakami River, is located at the northern border of the city and is comprised of mixed agricultural and residential areas.

Sample population

Ishinomaki is comprised of seven areas, each of which used to consist of old towns. However, the area now contains 177 town or village sections (hereafter ‘sections’), and is further divided into 354 blocks. The populations in the sections classified by the 2010 Census were included in this study.[15]

Five sections from the plains area were excluded as their population data were missing from the 2010 Census: Shiomi-cho, Mikawa-cho, Shigeyoshi-cho, Nishihama-cho and Aza-Yokotsutsumi. The 15 sections in Ogatsu-cho were consolidated into a single section (Total-Ogatsu) as the exact addresses of 103 residents killed in the GEJE (out of 158 deaths) were unknown. Four sections in Kitakami-cho were consolidated into a single section (Total-Kitakami) as the exact addresses of 154 residents killed in the GEJE (out of 194 deaths) were unknown. Therefore, 155 sections were included in the final analysis: 114, 27 and 14 for the plains area, ria coastal area and Kitakami riverside, respectively.

Inundation depth of the tsunami

Using data from the Ministry of Land, Infrastructure and Transport,[16] the tsunami inundation level for each block was evaluated and classified into the following seven levels: 0, not flooded; 1, ~0.5 m; 2, 0.5–1 m; 3, 1–2 m; 4, 2–4 m; 5, 4–8 m; and 6, ~8 m. The mean inundation depth of each section was calculated based on the values of the block members of each section.

Mortality rate

The mortality rate of each section was calculated by dividing the number of deaths caused directly by the GEJE by the population before the GEJE, obtained from the 2010 Census.[15] Data from the census were used because it was impossible to know the exact locations of the deaths. Nearly 80% of the deaths in Miyagi Prefecture were caused by drowning,[6] and it is speculated that most were washed away by the huge tsunami. Thus, it may be assumed that the locations where the bodies were found were not the same as where they were at the time of the tsunami. Some deaths were witnessed, or the location was reported, but many cases only included information on where the body was found or no report existed. Thus, the location of the deaths was estimated based on residential addresses.

Miyagi Prefectural Government formally recognised 3471 GEJE-related deaths from 11 March 2011 to 30 September 2012, of which 3251 fatalities were caused directly by the tsunami or collapsed buildings.[14] Miyagi Prefectural Police Department reported 3158 deaths with detailed information (age, sex and address) after obtaining permission from the families.[17]

From these data, 30 deaths that could not be classified into sections based on the 2010 Census, and 49 deaths that lacked an exact address were excluded. Ultimately, 3079 deaths were included in the mortality rate estimate.

Other features of the sections

Using the 2010 Census data,[15] 16 representative variables that were relevant in the analysis of factors affecting mortality in the communities were selected. In Japan, a census is conducted every 5 years and is a count of all residents and households. This provides initial insight into local populations. In addition to sex and age distributions, the proportions of people or households in the following categories were calculated: marital status (widowed or divorced), number of people who lived in the same section continuously (born or lived in the section for >20 years, or lived in the section for <five years), the industry in which individuals were engaged (agriculture/forestry/fisheries, manufacturing), education

(completed senior high school or more), transportation (commute by foot or bicycle), family type (one-person household, nuclear family, three-generation family), households with children <18 years of age, households with elderly persons (≥65 years of age), and households consisting solely of elderly people.

Statistical methods

Spearman's correlation coefficients between tsunami inundation depth and mortality rate were calculated for the 155 sections, and the results for the entire city and each of the three geographical areas were examined. Furthermore, logistic regression analyses were conducted to identify factors other than inundation depth that were related to mortality rate. After examination of the interaction between landform type and inundation depth for mortality rate, logistic regression analyses were performed for each landform. The variables were inundation depth and the basic demographic characteristics of the sections based on census data. Odds ratios (ORs) were calculated for each factor mentioned above, and significant variables with OR >1.05 or <0.95 were selected. As a result, three variables were included as covariates (proportions of young people, males and manufacturing workers) in the multivariate logistic regression analyses.

All analyses were performed using SAS Version 9.3 (SAS Institute, Cary, NC, USA). All tests were two-sided, with $P < 0.05$ considered to indicate significance.

Results

The characteristics of Ishinomaki before the GEJE are shown in Table 1. Compared with the national average, the proportion of elderly people (≥65 years old) in Ishinomaki as a whole was relatively high (27.2% vs 23.3%).[15] The proportion was 41.2% in the ria coastal area, which was much higher than that in the plains area (25.9%) and Kitakami riverside (30.4%). The ria coastal area and Kitakami riverside had a higher percentage of households with elderly members (69.1% and 71.0%),and a higher percentage of people who had lived there from birth or for >20 years (76.3% and 77.6%) compared with the plains area (47.1% and 51.7%, respectively).

Table 2 shows the damage caused by the GEJE. The mortality rate was higher among females than males in all areas, and the elderly mortality rate was the highest among all age groups. The mortality rate of young people (<15 years) in Kitakami riverside (5.2%) was considerably higher compared with that in the plains area (0.8%) and the ria coastal area (1.1%).

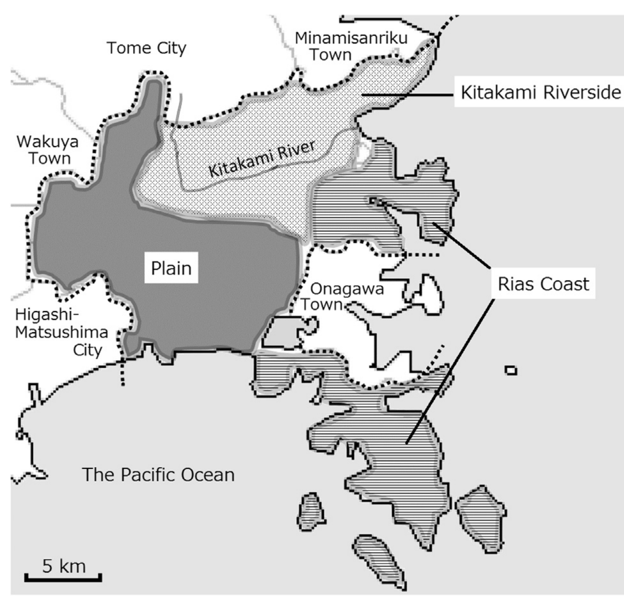
Fig. 2 shows the relationship between inundation depth (m) and mortality rate for the 155 sections. Significant correlation was found between inundation depth and mortality rate (Spearman's $r = 0.65$, $P < 0.001$). In contrast, several sections had low mortality rates but high inundation depths, most of which were in the ria coastal area. The correlation coefficient for each landform was calculated separately. A significant correlation between inundation depth and mortality rate was found for the plains area ($r = 0.75$, $P < 0.001$), and an even stronger association was found for Kitakami riverside ($r = 0.85$, $P < 0.001$), but no association was found for the ria coastal area ($r = 0.14$, $P = 0.47$). The terms that interacted with landform were found to be statistically significant in the regression analyses, suggesting that the landform acted as an effect modifier for the relationship between inundation depth and mortality rate (see Fig. 2).

Table 3 shows the results of logistic regression analyses for Ishinomaki as a whole and each area. In a simple regression analysis, inundation depth was significantly associated with mortality rate in Ishinomaki as a whole [OR 1.27, 95% confidence interval (CI) 1.26–1.28] and each area (plain: OR 1.50, 95% CI 1.48–1.52; ria coast: OR 1.11, 95% CI 1.04–1.19; Kitakami riverside: OR 1.30, 95% CI 1.28–1.32). In a model adjusted for multiple variables, inundation depth was significantly associated with mortality rate in the plains area (OR 1.49, 95% CI 1.46–1.51) and Kitakami riverside (OR 1.24, 95% CI 1.21–1.27), but not in the ria coastal area (OR 1.06, 95% CI 0.98–1.16).

Discussion

A general association was found between tsunami inundation depth and mortality rate in Ishinomaki. Inundation depth was strongly associated with mortality rate in the plains area and Kitakami riverside, but not in the ria coastal area. Other factors were found to be associated with mortality rate in each region, such as landform. The ria coast landform may have played a crucial role in the lower mortality rate despite the deep inundation.

There have been many discussions on mortality rate and inundation depth in past disasters. The flood after Hurricane Katrina in 2005 caused more than 1100 fatalities in the state of Louisiana, USA. Although mortality rates were highest in areas with large water depths, and two-thirds of the analysed



The area surrounded by the dotted line and coastline is Ishinomaki. Onagawa, a separate municipality, is surrounded by Ishinomaki.

Fig. 1 – Map of Ishinomaki and each of the three areas.

Table 1 – Characteristics of Ishinomaki as a whole and each area.

Characteristic	Ishinomaki	Plain	Ria coast	Kitakami riverside
	n (%)	n (%)	n (%)	n (%)
Population total	160,826	136,351	9650	14,825
Sex				
Male	77,143 (48.0)	65,269 (47.9)	4703 (48.7)	7171 (48.4)
Female	83,683 (52.0)	71,082 (52.1)	4947 (51.3)	7654 (51.6)
Age group (years)				
<15	20,214 (12.6)	17,704 (13.0)	732 (7.6)	1778 (12.0)
15–64	96,297 (59.9)	82,821 (60.7)	4942 (51.2)	8534 (57.6)
≥65	43,747 (27.2)	35,258 (25.9)	3976 (41.2)	4513 (30.4)
Unknown	568 (0.3)	568 (0.4)	0 (0.0)	0 (0.0)
Period of residence				
≤20 years	69,976 (43.5)	64,398 (47.2)	2278 (23.6)	3300 (22.3)
>20 years or from birth	89,403 (55.6)	70,528 (51.7)	7362 (76.3)	11,513 (77.6)
Unknown	1447 (0.9)	1425 (1.1)	10 (0.1)	10 (0.1)
Occupation				
Total workers	71,623	60,565	4405	6653
Agriculture, forestry and fisheries	5450 (7.6)	3349 (5.5)	1360 (30.9)	741 (11.1)
Manufacturing	13,388 (18.7)	11,184 (18.5)	870 (19.8)	1334 (20.1)
Transportation				
Total workers	71,623	60,565	4405	6653
None (home workers)	10,921 (15.2)	7745 (12.8)	1795 (40.7)	1381 (20.8)
Walk only	3263 (4.6)	2761 (4.6)	345 (7.8)	157 (2.4)
Bicycle	4499 (6.3)	4338 (7.2)	88 (2.0)	73 (1.1)
Private car	47,849 (66.8)	41,191 (68.0)	1817 (41.2)	4841 (72.8)
Total students	7032	6153	266	613
Walk only	751 (10.7)	726 (11.8)	14 (5.3)	11 (1.8)
Bicycle	3433 (48.8)	3235 (52.6)	12 (4.5)	186 (30.3)
Private car	955 (13.6)	675 (11.0)	64 (24.1)	216 (35.2)
Households				
Total	57,796	49,802	3808	4186
Family form				
One-person household	14,509 (25.1)	12,810 (25.7)	1137 (29.8)	562 (13.4)
Nuclear family	30,614 (53.0)	27,161 (54.5)	1729 (45.4)	1724 (41.2)
Three-generation family	9150 (15.8)	7068 (14.2)	585 (15.4)	1497 (35.8)
Others[a]	3523 (6.1)	2763 (5.6)	357 (9.4)	403 (9.6)
Composition				
Including people <18 years of age	14,589 (25.2)	12,833 (25.8)	538 (14.1)	1218 (29.1)
Including people ≥65 years of age	29,039 (50.2)	23,436 (47.1)	2632 (69.1)	2971 (71.0)
Only elderly people in the household	10,999 (19.0)	9111 (18.3)	1209 (31.7)	679 (16.2)
Sections				
Total	155	114	27	14
Inundation depth (m)				
0	46 (29.7)	35 (30.7)	2 (7.4)	9 (64.3)
0.1–1.9	43 (27.7)	40 (35.1)	1 (3.7)	2 (14.3)
2.0–3.9	19 (12.3)	17 (14.9)	1 (3.7)	1 (7.1)
4.0–5.9	17 (11.0)	15 (13.2)	2 (7.4)	0 (0.0)
6.0–7.9	3 (1.9)	2 (1.7)	1 (3.7)	0 (0.0)
≥8.0	27 (17.4)	5 (3.4)	20 (74.1)	2 (14.3)

[a] Including unknown (0.7%).

fatalities were most likely associated with the direct physical impact of the flood, one-third of the analysed fatalities were not caused directly by the flood but by the critical public health conditions.[12] During the great flood on the east coast of Britain in 1953, 307 people were killed, with two-thirds of the deaths occurring in vulnerable buildings, such as post-war prefabricated buildings, bungalows and chalets. In contrast, the empathetic response of the local residents in providing shelter, warmth and food was a mitigating factor.[13] On 26 December 2004, a tsunami in the Indian Ocean caused 220,000 deaths and missing persons in the Indian Ocean region. The mortality rate was 11.5–27.0% in each Indonesian district[9–11,18] and 12.9% in Ampara, Sri Lanka.[19] However, oral histories from Simeulue Island recounted a massive tsunami in 1907 in which residents were advised to head to the hills after significant shaking; an extraordinarily powerful mitigation tool that saved countless lives.[20]

Many plans have been initiated to prepare for future disasters, particularly for the Nankai Trough Earthquake, which is predicted with >90% certainty to occur within the next 50

Table 2 – Number of deaths and mortality rates in each area by sex and age group.

	Ishinomaki			Plain			Ria coast			Kitakami riverside		
	Population (%)	Number of deaths (%)	Mortality rate	Population (%)	Number of deaths (%)	Mortality rate	Population (%)	Number of deaths (%)	Mortality rate	Population (%)	Number of deaths (%)	Mortality rate
Total	160,826	3079	1.9%	136,351	2249	1.6%	9650	246	2.5%	14,825	584	3.9%
Sex												
Male	77,143 (48.0)	1365 (44.3)	1.8%	65,269 (47.9)	1002 (44.6)	1.5%	4703 (48.7)	110 (44.7)	2.3%	7171 (48.4)	253 (43.3)	3.5%
Female	83,683 (52.0)	1714 (55.7)	2.0%	71,082 (52.1)	1247 (55.4)	1.8%	4947 (51.3)	136 (55.3)	2.7%	7654 (51.6)	331 (56.7)	4.3%
Age group (years)												
<15	20,214 (12.6)	242 (7.9)	1.2%	17,704 (13.0)	142 (6.3)	0.8%	732 (7.6)	8 (3.3)	1.1%	1778 (12.0)	92 (15.8)	5.2%
15–64	96,297 (59.9)	1142 (37.1)	1.2%	82,821 (60.7)	863 (38.4)	1.0%	4942 (51.2)	79 (32.1)	1.6%	8534 (57.6)	200 (34.2)	2.3%
≥65	43,747 (27.2)	1692 (55.0)	3.9%	35,258 (25.9)	1244 (55.3)	3.5%	3976 (41.2)	156 (63.4)	3.9%	4513 (30.4)	292 (50.0)	6.5%
Unknown	568 (0.3)	3 (0.1)		568 (0.4)	0 (0.0)		0 (0.0)	3 (1.2)		0 (0.0)	0 (0.0)	

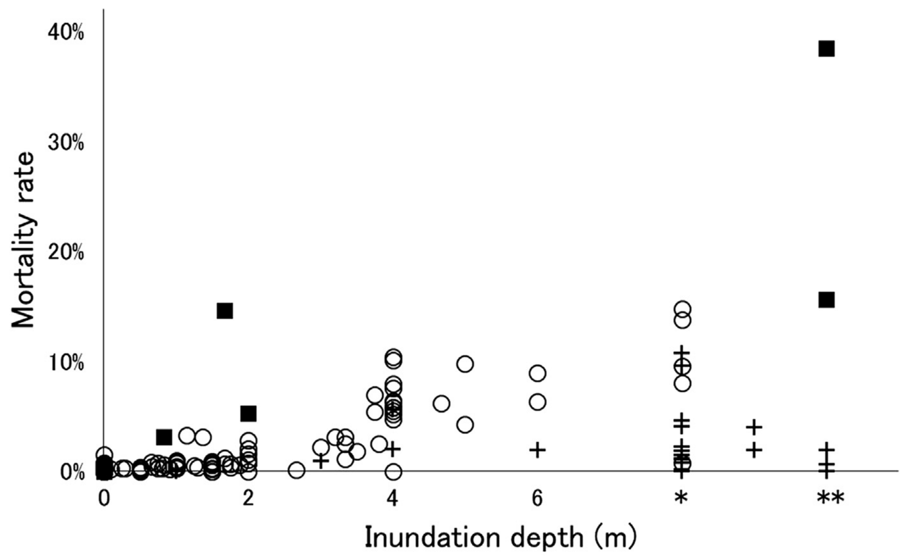
years in south-western Japan.[21] Discussing characteristics of individual landforms is beneficial to provide more suitable plans for individual communities in the future.

There are no nearby hills for escape in the plains area, and there are urban communities with higher population density. Traffic jams delayed escape because of the lack of evacuation routes, and some three-story buildings were flooded far beyond the expected level.[2] The finding that the mortality rate in the plains area was determined by inundation depth indicated the indispensability of providing adequate infrastructure. In fact, the Japanese Government had already planned to construct tall towers in coastal areas to protect against tsunamis.[22]

Several factors in the ria coastal area could have accounted for the lower mortality rate despite the deep inundation. This area contains small coves suitable for fishing that are distant from other villages. There are nearby hills, and old buildings (e.g. shrines and temples) were built at higher altitude due to prior tsunamis. Low urbanization and the sense of community in fishing villages, as well as high proportions of people who engage in agriculture, forestry or fisheries, led to improved evacuation and a lower mortality rate. In Kitakami riverside, which is 8 km from the estuary, the tsunami flowed up the Kitakami River at a depth of 4 m almost 1 h after the earthquake and reached 49 km upstream from the estuary.[23] Most of these areas are so far from the coast that people cannot see the ocean, and they never expected the tsunami to reverse the flow of the Kitakami River. Although there are hills near the residential areas, there are no direct escape routes. People in this region delayed their escape as they were taken completely by surprise.

The limitations of this study must be considered before generalizing the results and applying them in preparation for future disasters. These include misclassification of both inundation depth and mortality rate, confounding factors and ecological fallacy. There is no actual information regarding the exact location of the deaths that occurred when the tsunami hit, so residential addresses were used. As the GEJE occurred on a weekday afternoon, children may have been in school and adults would have been working. There are many workplaces in the plains area, such as fish processing plants near the coast, so some of the workers who lived in inland areas with a small inundation depth may have been killed at their workplace where there was a deeper inundation depth. If location misclassifications of this type occurred, the association between inundation depth and mortality rate may have been weakened. As non-differential misclassification could have resulted in an underestimate, the true associations may have been even stronger.[24] In contrast, the sections in the ria coastal area were separated by steep hills, and many residents worked near their homes, which introduced less misclassification of the location of the deceased.

The force of the tsunami must be considered as a potential confounding factor. Coastal areas with deep inundation were hit directly by the strongest force of the tsunami, and more deaths are caused by stronger tsunamis compared with weaker tsunamis with the same inundation depth. It was not possible to adjust for the strength of the tsunami in each section due to the lack of information.



○, plain; +, ria coast; ■, Kitakami riverside. * indicates the part of the section inundated over 8 m, and ** indicates the whole area of the section inundated over 8 m.

Fig. 2 – Relationship between tsunami inundation depth and mortality rate for each of the three regions.

Table 3 – Association between inundation depth and other factors and mortality rate in Ishinomaki as a whole and the three areas according to correlation and logistic regression analyses.

	Correlation analysis		Logistic regression analysis			
			Simple regression model		Multivariate adjusted model[a]	
	R	P-value	OR[b]	95% CI	OR[b]	95% CI
Ishinomaki						
Inundation depth	0.65	<0.001	1.27	(1.26–1.28)	1.30	(1.29–1.32)
Proportion of people in the section (%)						
Young people (<15 years)			0.95	(0.94–0.96)	1.07	(1.05–1.08)
Males			0.92	(0.91–0.94)	0.91	(0.89–0.93)
Manufacturing workers			1.06	(1.06–1.07)	1.04	(1.03–1.04)
Plain						
Inundation depth	0.75	<0.001	1.50	(1.48–1.52)	1.49	(1.46–1.51)
Proportion of people in the section (%)						
Young people (<15 years)			1.03	(1.02–1.03)	1.02	(1.00–1.03)
Males			0.92	(0.90–0.95)	1.05	(1.02–1.08)
Manufacturing workers			1.08	(1.08–1.09)	1.04	(1.03–1.05)
Ria coast						
Inundation depth	0.14	0.47	1.11	(1.04–1.19)	1.06	(0.98–1.16)
Proportion of people in the section (%)						
Young people (<15 years)			1.05	(1.01–1.09)	1.17	(1.09–1.26)
Males			0.89	(0.85–0.93)	0.83	(0.78–0.88)
Manufacturing workers			1.01	(1.00–1.02)	0.99	(0.97–1.01)
Kitakami riverside						
Inundation depth	0.85	<0.001	1.30	(1.28–1.32)	1.24	(1.21–1.27)
Proportion of people in the section (%)						
Young people (<15 years)			0.67	(0.64–0.71)	0.75	(0.70–0.81)
Males			0.73	(0.68–0.79)	1.07	(0.94–1.22)
Manufacturing workers			1.41	(1.35–1.47)	1.19	(1.14–1.25)

OR, odds ratio; CI, confidence interval.

[a] Adjusted variables include the proportion of young people (<15 years), males and manufacturing workers.

[b] ORs indicate an increase in mortality rate for each 1-m increase in inundation depth.

Furthermore, this study considered sections rather than individuals, which could have introduced ecological fallacy. In contrast, Tanaka et al.[8] reported a significant correlation between the proportion of a population living in the inundation range and mortality rate ($r = 0.746$, $P < 0.001$) after analysing 44 coastal municipalities in the three prefectures in Tohoku District. This result indicates that municipalities with a larger inundated area had higher mortality rates, suggesting that greater inundation caused more deaths. The present results were similar but this study involved smaller areas of 155 sections in Ishinomaki, and a general relationship between inundation depth and mortality rate was identified.

The quantitative aspect of the GEJE mortality rate must be considered in order to understand the factors affecting mortality rate, which was not very high despite the huge physical damage. Of course, the efforts of medical teams specializing in disaster medicine saved lives during the acute phase,[25] and disaster prevention awareness and evacuation drills also contributed to the lower relative mortality rate. People have learned from past experiences of earthquakes and tsunamis; the proverb of ‘Tsunami Tendenko’ (‘when a tsunami comes, forget others and escape individually’) saved people in some communities.[26] However, hazard maps and sea walls underestimated the level of the tsunami, and gave some people a false sense of security which delayed their evacuation.[27] Compared with past disasters, the ratio of people injured to people missing or dead was much lower (GEJE, 0.31; Indian Ocean Tsunami of 2004 in Thailand, 1.01; Great Hanshin-Awaji Earthquake of 1995 in Japan, 6.80).[28] The low ratio of injuries to deaths could explain the importance of rapid evacuation from tsunami inundation areas.

These results confirmed the hypothesis that the mortality rate of individual communities was not determined solely by the tsunami inundation depth; an unmodifiable physical factor. Thus, there is still much room for improving disaster preparedness.

Based on these findings, it is vital to improve and maintain evacuation routes to hills or higher areas. If there are no hills, tall buildings strong enough to withstand a tsunami are needed. In addition, risk awareness depends on both education and appropriate risk communication based on accurate assessment. The hazard maps prepared by the local governments of some Tohoku communities may have increased mortality rates because the actual inundation depth far exceeded any predicted by a plan. In contrast, thanks to repeated classroom education about the risks of natural disasters and the importance of escape, even schoolchildren who had never experienced a tsunami persuaded adults to escape, as reported from Kamaishi in Iwate Prefecture.[26] Tighter community bonds should be maintained to help people to share their awareness for preparing for disasters during ordinary times and to cooperate in an emergency.

Considering the advantages and weaknesses of each community, these measures must be adapted to increase preparedness for future disasters.

In conclusion, a general correlation was found between inundation depth and mortality rate for Ishinomaki as a whole. Inundation depth was strongly associated with mortality rate in the plains area and Kitakami riverside, but not in the ria coastal area. The landforms and community characteristics in the ria coastal area played crucial roles in the lower mortality rate despite the deep inundation.

Author statements

Acknowledgements

The authors are very grateful to Dr Peter Baxter from the University of Cambridge for his critical reading and valuable comments about the study.

Ethical approval

Institutional Review Board of Teikyo University Ethics Committee (Ref. No.: 12-079).

Funding

This study was supported financially by the Ministry of Education, Culture, Sports, Science and Technology through Grant-in-Aid for Young Scientists (B) 26870596 ‘Disaster and Gender: Women's empowerment in the community for building resilience (PI: Aya Ishiguro)’ and the Japan Public Health Society through a Special Grant for Public Health for the Great East Japan Earthquake in 2012. The grant had no role in the study design, data collection, data analysis, data interpretation, writing of the manuscript or decision to submit the manuscript.

Competing interests

None declared.

REFERENCES

1. Cyrabiski D. Japan faces up to failure of its earthquake preparations. *Nature* 2011;**471**:556–7.
2. Cabinet Office. Bosai Hakusho, disaster prevention white paper. Available at: http://www.bousai.go.jp/kaigirep/hakusho/pdf/H24_gaiyou.pdf (last accessed 19 June 2013).
3. Emergency Disaster Countermeasures Headquarters, National Police Agency. Damage situation and police countermeasures associated with 2011 Tohoku district – off the Pacific Ocean Earthquake. Available at: http://www.npa.go.jp/archive/keibi/biki/higaijokyo_e.pdf (last accessed 19 June 2013).
4. Cabinet Office. Higashi-Nihon Daishinsai no hinanjoseikatsushasu no suii nitsuite. Available at: http://www.bousai.go.jp/taisaku/hinanjo/h24_kentoukai/1/pdf/8.pdf (last accessed 19 June 2013).
5. Nakahara S, Ichikawa M. Mortality in the 2011 tsunami in Japan. *J Epidemiol* 2013;**23**:70–3.
6. Ministry of Health, Labour and Welfare. The vital statistics of Japan yearly survey 2011. Available at: http://www.mhlw.go.jp/toukei/saikin/hw/jinkou/kakutei11/dl/14_x34.pdf (last accessed 19 June 2013).
7. City Bureau, Ministry of Land, Infrastructure, Transport and Tourism. Tsunami situation survey of the Great East Japan Earthquake. 2nd Report. Available at: http://www.mlit.go.jp/common/000168249.pdf (last accessed 19 June 2013).

8. Tanaka M, Shineha R, Maruyama K. *Saigaijakusha to jouhoujakusha. Chikuma Sensho*. Taito-ku Tokyo: Chikuma Shobo; 201249 [in Japanese].
9. Doocy S, Gorokhovich Y, Burnham G, Balk D, Robinson C. Tsunami mortality estimates and vulnerability mapping in Aceh, Indonesia. *Am J Publ Health* 2007;**97**:146–51.
10. Rofi A, Doocy H, Robinson C. Tsunami mortality and displacement in Aceh Province, Indonesia. *Disasters* 2006;**30**:340–50.
11. Doocy S, Robinson C, Moodie C, Burnhama G. Tsunami-related injury in Aceh Province, Indonesia. *Glob Public Health* 2009;**4**:205–14.
12. Jonkman SN, Maaskant B, Boyd E, Levitan ML. Loss of life caused by the flooding of New Orleans after hurricane Katrina: analysis of the relationship between flood characteristics and mortality. *Risk Anal* 2009;**29**:676–98.
13. Baxter PJ. The east coast big Flood, 31 January–1 February 1953: a summary of the human disaster. *Philos Trans Ser A Math Phys Eng Sci* 2005;**363**:1293–312.
14. Miyagi Prefecture, Crisis Division. Higashi-Nishon Daishinsai niokeru higaitou jokyo. Available at: http://www.pref.miyagi.jp/uploaded/attachment/90212.pdf (last accessed 7 May 2013).
15. Statistics Bureau, Ministry of Internal Affairs and Communications. 2010 Population Census. Available at: http://www.e-stat.go.jp/SG1/estat/eStatTopPortalE.do (last accessed 7 May 2013).
16. City Bureau, Ministry of Land, Infrastructure and Transport. Higashi-Nihon Daishinsai tsunamihisai shigaichi fukkoushien chousa. Available at: http://fukkou.csis.u-tokyo.ac.jp/dataset/show/id/1111 (last accessed 19 June 2013).
17. Miyagi Prefectural Police. Mimoto ga kakunin sareta giseisha no katagata. Available at: http://www.police.pref.miyagi.jp/hp/jishin/itai/kakunin/itai_kakunin.html (last accessed 1 March 2013).
18. Doocy S, Rofi A, Moodie C, Spring E, Bradley S, Burnham G, et al. Tsunami mortality in Aceh Province, Indonesia. *Bull World Health Organ* 2007;**85**:273–8.
19. Nishikiori N, Abe T, Costa DGM, Dharmaratne SD, Kunii O, Moji K. Who died as a result of the tsunami? Risk factors of mortality among internally displaced persons in Sri Lanka. *BMC Public Health* 2006;**6**:73.
20. McAdoo BG, Dengler L, Prasetya G, Titov V. Smong: how an oral history saved thousands on Indonesia's Simeulue Island during the December 2004 and March 2005 tsunamis. *Earthq Spectra* 2006;**22**:661–9.
21. Headquarters for Earthquake Research Promotion. List of long-term evaluation. Available at: http://www.jishin.go.jp/main/choukihyoka/ichiran.pdf (last accessed 19 June 2013).
22. Cabinet Office. Nankaitorafu kyodaijishin de soutei sareru higai. Available at: http://www.bousai.go.jp/jishin/nankai/taisaku_wg/pdf/20130528_houkoku_s2.pdf (last accessed 11 June 2013).
23. Ministry of Land, Infrastructure and Transport, Tohoku Regional Bureau. Kitakamigawa suikeikasen seibikeikaku. Available at: http://www.thr.mlit.go.jp/karyuu/info/kitakami_kasenseibi/121120_sakutei/kitakamihonbun.pdf (last accessed 11 June 2013).
24. Rothman KJ. *Epidemiology: an introduction*. 2nd ed. New York: Oxford University Press; 2012135. p.
25. Nagamatsu S, Maekawa T, Ujike Y, Hashimoto S, Fuke N. The earthquake and tsunami – observations by Japanese physicians since the 11 march catastrophe. *Crit Care* 2011;**15**:167.
26. Ministry of Education. White paper on education, culture, sports, science and technology, restoration and revival following the Great East Japan Earthquake. Available at: http://www.mext.go.jp/b_menu/hakusho/html/hpab201101/detail/1330449.htm (last accessed 19 June 2013).
27. Nakahara S. Lessons learnt from the recent tsunami in Japan: necessity of epidemiological evidence to strengthen community-based preparation and emergency response plans. *Inj Prev* 2011;**17**:361–4.
28. Fuse A, Yokota H. Lessons learned from the Japan earthquake and tsunami. *J Nippon Med Sch* 2011;**2012**(79):312–5.