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Report on the 2014 Winter Cyclone Storm Surge in Nemuro, Japan

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From Tuesday, December 16, 2014, until Thursday, December 18, Hokkaido was battered by strong winds and high sea waves caused by a passing low pressure system intensified to typhoon levels. In the city of Nemuro, a rise in sea level influenced by the storm surge which exceeded quay height in port areas was observed from predawn Wednesday, December 17, 2014. Flooding was experienced in areas of central Nemuro, the Nemuro Port and estuaries of rivers. This technical note provides a comprehensive meteorological analysis and the results of a local flood survey carried out by the authors from December 19 to 21, 2014, and summarizes the characteristics of the 2014 Nemuro storm surge disaster.

Keywords: 2014 Nemuro storm surge, inundation, river flooding

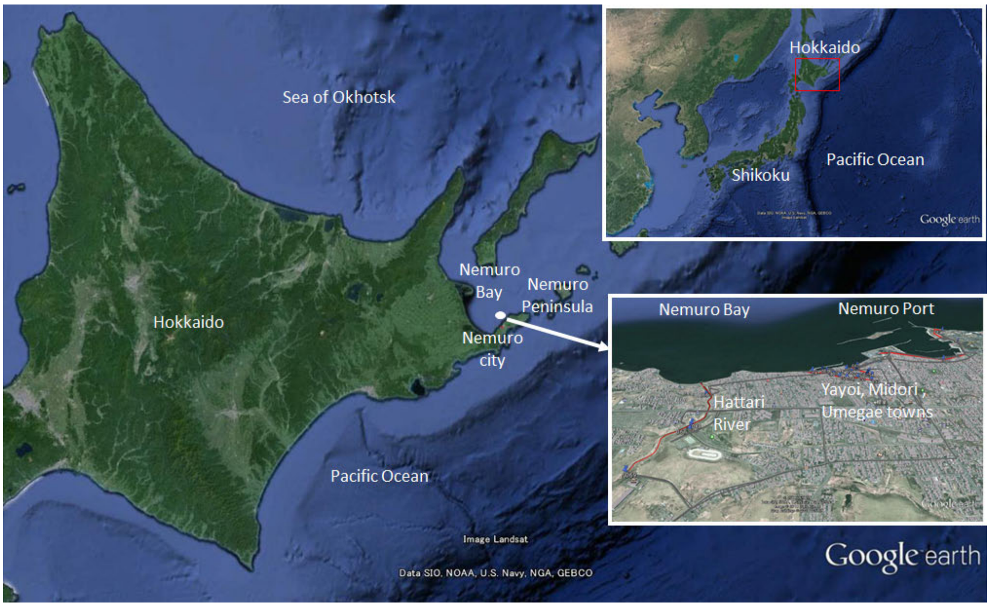

Fig. 1. Map of the area affected by the 2014 Nemuro storm surge.

1. Introduction

Japanese coasts have been often affected by storm surges induced by typhoons ([Isozaki, 1970; Makino, 1992]). In 1959, Typhoon Vera induced a storm surge in Ise Bay and caused high inundation around coastal areas, resulting in the deadliest typhoon disaster in Japan (e.g. [Bessho et al., 2010]). The more recent storm surges due to the 1999 Typhoon Bart and the 2004 Typhoon Chaba also caused significant flood damages to coasts of Japan (e.g. [Fujii et al., 2002; Kohno et al., 2010]). Because typhoons which reach Japan commonly take recurving paths toward northeast and are attenuated by the move into the belt of westerlies, Hokkaido, the northernmost island of Japan, is usually away from the paths of strong typhoons ([Elsner and Liu, 2003]). As a consequence, Hokkaido had never experienced any recorded storm surge disaster, and hardly any measure to reduce tidal flood impacts had been taken there.

On December 16, 2014, an extratropical cyclone located off Shikoku island was rapidly intensified by a typical winter monsoon system and moved toward northeast over the Pacific Ocean. The central pressure was recorded to decrease, during one day, from 1006 hPa to 946 hPa, when the pressure reached off the Nemuro Peninsula, eastern Hokkaido, on December 17 (Fig. 4). The city of Nemuro, which faces the Nemuro Bay in the center of the Nemuro Peninsula, was affected by strong winds and a storm surge. A significant sea level rise exceeding quay height in port areas of Nemuro (see Fig. 1) was observed from predawn December 17. Afterwards, flooding was experienced in certain areas, including central Nemuro (Kaigan, Yayoi, Midori

Fig. 2. Photographs of (a)–(b) inundated streets in central Nemuro (locations indicated in Fig. 10), and (c)–(d) inundated quays in the Nemuro Port (locations indicated in Fig. 9). Fishing boats and cars were drifted by the flood. All photos were taken by the Hokkaido Regional Development Bureau during the flood event on December 17, 2014.

towns), causing about $20 million damage to ports and harbors, fishery facilities, commercial buildings, fishing boats, residences and vehicles (Fig. 2). An overview of the flood damages was reported by the Hokkaido Regional Development Bureau [Hokkaido Regional Development Breau, 2015].

While coasts of Northeast Asia facing the Northwestern Pacific Ocean have rarely experienced storm surges during winter season, there is a number of disaster reports on winter storm surges in coasts of Europe along the North Sea and the Northeastern Atlantic Ocean, e.g., [Lamb and Frydendahl, 1991; Bertin et al., 2012; Sibley et al., 2015]. Langenberg [Langenberg et al., 1999] found that there is an increasing tendency in extreme sea level events induced by winter storms in coasts in the North Sea and related it to changes in climate which may be enhanced by global warming. The fact that global warming also enhances the migration of tropical cyclones toward higher latitudes (Kossin et al. 2001) suggests possible modifications in the frequency of intensified storms over the world regardless of the season. In fact, the number of extratropical cyclones over the northern Pacific in winter tends to increase at the rate of 0.21 per year, along with an increase in the induced wind velocity and ocean wave height ([Graham and Diaz, 2001]). Additionally, Iwao et al. [Iwao et al., 2012] found that there is an increasing tendency of occurrence of winter cyclones with

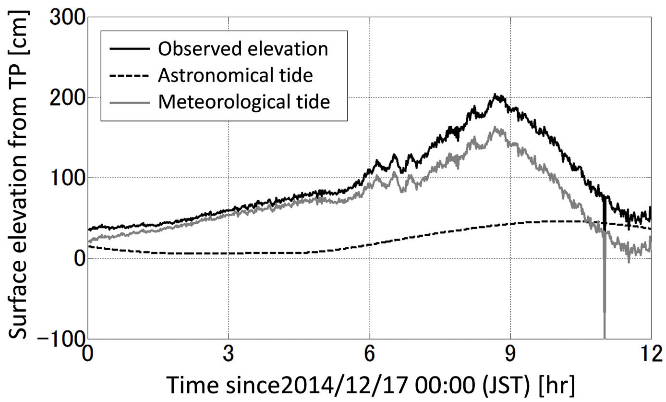

Fig. 3. Evolution of the sea surface level observed at the Nemuro Port (provided by the Hokkaido Regional Development Bureau).

rapid growth in the western Pacific, especially near Japan. The storm surge event reported in this paper may fall into such recent trend of occurrences affected by global climate change.

Previous storm surges in Japan were typically caused by abnormal tides during the passage of typhoons. These events were usually enhanced by river flood, as typhoons are commonly accompanied by intense precipitation. Similar inundation mechanisms were observed in the disaster induced by the 2005 Hurricane Katrina, where rivers swelled by intense precipitation and the storm tide propagated along the Mississippi River ([Dietrich et al., 2010]). The 2014 Nemuro storm surge, on the other hand, was caused by a monsoon system with low precipitation, resulting in features distinct from those owing to tropical cyclones: the inundation was induced only by meteorological and astronomical tides without any effect of inland floods or river swelling. The present paper provides all observed data obtained during the local flood survey carried out by the authors from December 19 to 21, 2014 with aiming to promote further disaster analyses and investigations of disaster prevention for future storm surges.

This paper is organized as follows: meteorological features associated with the onset of the storm surge are described in Section 2; features of the storm surge flood are described in Section 3 and the results are summarized in Section 4.

2. Meteorological Features

In this section, the meteorological mechanisms which induced the 2014 Nemuro storm surge are discussed in terms of tide and weather conditions.

The sea surface level measured at Nemuro Port, provided by the Hokkaido Regional Development Bureau, is shown in Fig. 3. The observed sea level was corrected to the height of the standard mean sea level of Tokyo Bay (Tokyo Peil, TP). The

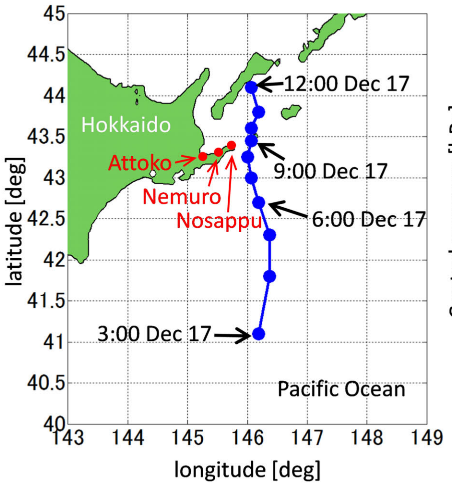

Fig. 4. The computed trajectory (left) and central pressure (right) of the extratropical cyclone, provided by JMA. The locations of the AMeDAS stations in the Nemuro Peninsula are indicated.

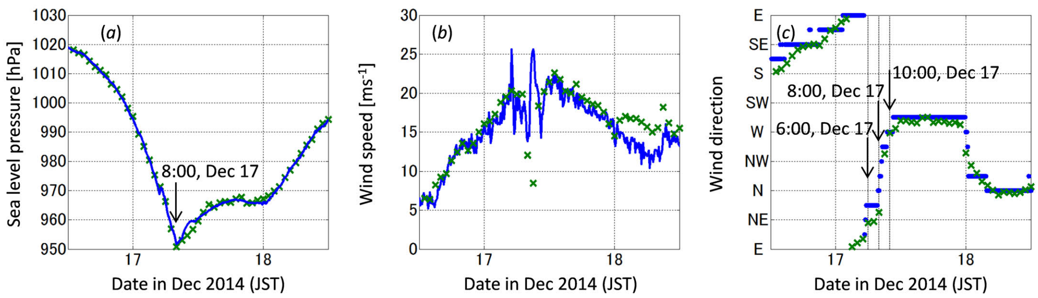

Fig. 5. Comparison between the forecast results by JMA-MSM (green) and observed data by AMeDAS (blue) for the (*a*) sea level pressure, (*b*) wind speed and (*c*) wind direction at the Nemuro AMeDAS station.

gradual sea level rise was observed from the predawn of December 17, and exceeded the lowest quay height of the port (113 cm) at 6:00 (Japan Standard Time, JST). The rapid increase of the sea surface level commenced at about 7:00, while the maximum sea level $H_m = 204$ cm was reached at about 8:40 when the astronomical rising tide was $H_t = 41$ cm. The maximum meteorological tide component H_w was then estimated to be $H_w = H_m - H_t = 163$ cm.

The effect of major meteorological factors on the storm tide, including local distributions of air pressure and wind directions over the sea around the affected area, is analyzed using forecast results of the Meso-Scale Model (MSM) of the Japan Meteorological Agency (JMA) ([Hara et al., 2007]).

Fig. 4 shows the computed central locations and central pressures of the extrat-

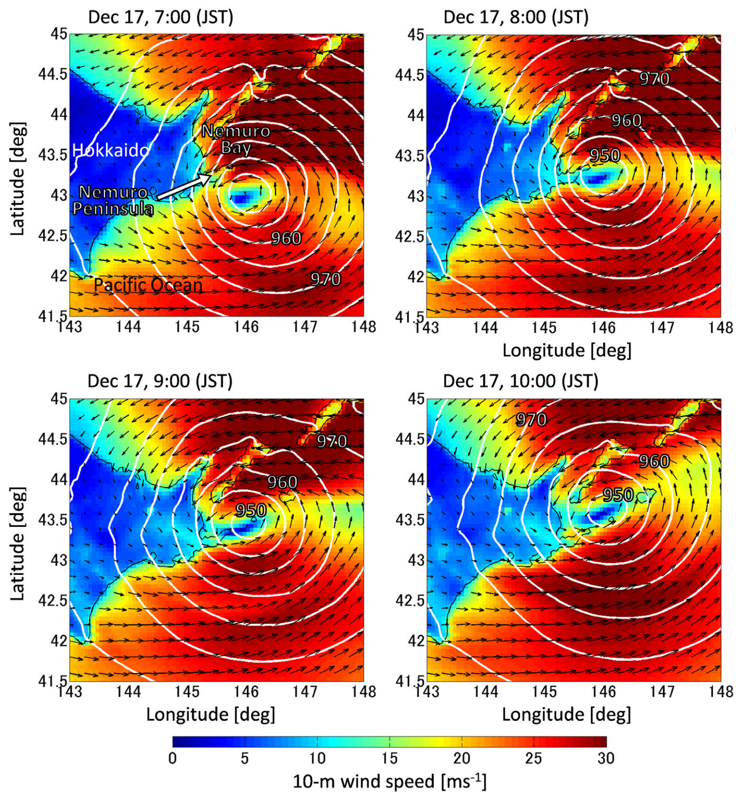

Fig. 6. Distribution of the air pressure and wind velocity obtained in the present meteorological simulation. Color and arrows indicate wind speed at 10 m above the surface, isobars represent the pressure at sea level.

ropical cyclone during the storm surge (see also the tide level in Fig. 3). In the early morning of December 17, 2014 (3:00 – 8:00 JST), the cyclone was intensified over the Pacific Ocean during its way up to the north toward off the Nemuro Peninsula. The extremely low pressure below 950 hPa lasted from approximately 6:00 to 13:00, while the minimum central pressure of 946.5 hPa was attained at 8:00, about when the cyclone reached its nearest location to the affected area, leading to an estimated maximum sea level rise of about 65 cm owing to the static low atmospheric pressure suction effect. Both the JMA-MSM forecast and the AMeDAS observed data indicate a minimum pressure of about 952 hPa at 8:00 at the Nemuro AMeDAS station (Fig. 5).

Root-mean-square (RMS) errors of 1.18 hPa for the atmospheric pressure and 3.83 ms^{-1} for the wind velocity were calculated for the predictions at Nemuro AMeDAS station. The RMS wind velocity errors at the other stations located in the Nemuro Peninsula, Attoko and Nosappu stations (Fig. 4), were estimated to be 4.38 and 6.33 ms^{-1}, respectively. The authors confirmed that the errors of the wind directions at these three stations, which ranged between 12^o and 18^o, were smaller than the maximum resolution of the observed data (22.5^o).

Fig. 6 shows distributions of the wind velocity and contours of the atmospheric pressure. While the eastern wind predominated over the Nemuro Bay at 6:00, the wind direction changed to northeast at 7:00 and then to north at 8:00 (see also Fig. 5) when the rapid sea level rise was observed (Fig. 3). The strong northerly wind with velocity over 20 ms^{-1} in the wide area off the Nemuro Peninsula drove a drift current toward the shores along the Nemuro Bay. Because the wind-driven current was blocked by the east coast of Hokkaido facing Nemuro Bay and the north coast of the Nemuro Peninsula, and stagnated there, the sea surface along the coast was lifted by the accumulated mass flux of the current. The observed tide record (Fig. 3) provides a rough estimate of the sea level rise due to wind stress H_c, $H_c = H_w - H_s =$ 98 cm, where H_s is the pressure-induced sea level rise, although detailed analyses of local flow dynamics and atmosphere-ocean responses are necessary to identify the precise mechanical contributions. When the wind direction changed from northwest to west between 9:00 and 10:00, the accumulated flux was released to east off the peninsula, causing the sea level to decrease rapidly (Fig. 3).

An hourly snowfall of less than 1.5 mm was observed in Nemuro in the uprushing period from 6:00 to 9:00, and thus no inland river flood occurred during the storm surge event. Because tropical cyclones commonly bring heavy rain and river floods in addition to storm surge floods, a detailed analysis of various inland and ocean factors which affect the inundation is generally required. The present observed data is useful for examining storm surge models without effects of precipitation-induced flooding.

It should be noted that, since the extratropical cyclone was driven by baroclinic effects, it was intensified during the northward movement of the monsoon pressure system. Tropical cyclones, on the other hand, require heat supply from the ocean for growing, and commonly decrease while traveling toward north. This suggests a higher risk of storm surges in northeast Asia to be caused by seasonal extratropical cyclones rather than typhoons.

3. Inundation Survey

The combined factors of the pressure-induced surface rise, wind-driven current and astronomical tide caused flood damage to lowland areas and lower river areas along the north coast of Nemuro peninsula, which are the target areas of the survey explained in this section.

3.1. *Methods of the survey*

The field survey was conducted from December 19 to 21, 2014, in three areas: central Nemuro, the Nemuro Port and along the downstream end of Hattari River (Fig. 1). The inundation had receded completely when the survey was carried out. However,

Fig. 7. Photographs of streets in central Nemuro after the disaster: (a)–(b) inundated houses and shops, (c) debris and a fishing boat brought ashore, (d) fallen shed (locations shown in the photos in Fig. 10). All photos were taken during the survey on December 20, 2014.

because the cleaning works of the affected areas were not sufficiently advanced, large amounts of debris carried inland by the storm surge remained untouched (see Fig. 7 and Fig. 8). Additionally, watermarks in buildings, indicated by locals who witnessed the event, were still visible (Fig. 7 a). There were, thus, a number of traces of flooding. For instance, lines of debris from which no debris were observed further upstream were clear vestiges of the extent of the runup (Fig. 8 a and b).

The inundation and runup heights were estimated by measuring, with a level, the heights of the watermarks and the ground elevation of the limit of the extension of the debris, respectively. The location and time of the measurements were recorded by GPS. The sea surface level at the time of the survey was taken as a reference level for the measured elevation. The measured levels were later corrected by the tidal level data of the time of the survey.

3.2. *Survey results*

Table 1 presents the inundation or runup heights for selected survey points in Yayoi Town, located in Central Nemuro, and the Nemuro Port. The survey points corresponding to runup limits are summarized in Table 2.

According to the results, an average 2.2 m deep flood (with a meteorological

Fig. 8. Debris brought ashore by (a) high tide at Site 4 (see map in Fig. 9) and (b) by wave overtopping at Site 8 (see map in Fig. 10), (c) debris and buoys transported through Hattari River and (d) wooden river-side benches plucked out due to buoyancy (see map in Fig. 11). All photos were taken during the survey on December 20, 2014.

component of approximately 1.8 m (T.P.), Fig. 9) covering approximately 15 ha took place in the pier and other areas surrounding the Nemuro Port, which is located at the lowest ground level of the city. In the present survey, debris from the flood were found at T.P. 3.55 m at site 8, which is located behind the north seawall of the Nemuro Port (Fig. 9 and also Fig. 8 b). Since the traces at site 8 were more than 1 m higher than the highest inundation level of TP 2.24 m observed among the other surveyed sites at Nemuro Port (sites 6 and 7 in Table 1), the flooding at site 8 is attributed to high overtopping waves which developed outside of the port. Seawater influx overtopping the seawall crest (height of 3.13 m) above the sea level rise during the storm surge was found to have inundated areas adjacent to the seawall. No other place affected by overtopping was observed, as the multiple breakwaters surrounding the port, shown in Fig. 9, intercepted the northerly ocean waves from propagating to the affected areas. Thus overtopping waves were effectively reduced and extra damage may have been minimized.

Fig. 10 shows the runup area and inundation heights in urban areas of Nemuro (Yayoi and Midori towns) where significant flood damage to houses and shops occurred. Seawater flew and spread through sloping streets (see Fig. 2 a and b), causing

Table 1. Runup and inundation heights (TP)

Survey Area	Site*1	Latitude	Longitude	Flood Type	Flood Height (m)	Meteorological Component (m)*2
Yayoi town	1	N 43°19'54.599"	E 145°34'26.843"	Inundation	1.86	1.42
Yayoi town	2	N 43°19'56.250"	E 145°34'29.622"	Inundation	1.80	1.36
Yayoi town	3	N 43°19'58.501"	E 145°34'40.084"	Inundation	2.14	1.69
Yayoi town	4	N 43°19'57.014"	E 145°34'43.558"	Runup	1.96	1.52
Yayoi town	5	N 43°20'3.160"	E 145°34'39.896"	Runup	2.29	1.84
Nemuro Port	6	N 43°20'37.515"	E 145°35'10.262"	Runup	2.08	1.64
Nemuro Port	7	N 43°20'20.252"	E 145°35'7.577"	Runup	2.24	1.80
Nemuro Port	8	N 43°20'47.224"	E 145°35'1.795"	Overtopping	3.55	3.10

*1 The site number corresponds to the ones shown in Fig. 9 and Fig. 10.
*2 The meteorological component of local flood height is estimated to be (flood height) - (astronomic tidal height at the time when the maximum sea elevation was achieved).

above floor and underground inundation, damage to fishing boats and equipment (Fig. 2), and sewage blockage. We estimated a 1.8-2.1 m deep (T.P.) flood covering approximately 7 ha over streets with a relatively low ground level (Fig. 10).

The inundation heights in areas near sites 3, 6 and 7 were also measured by several other survey groups ([MLIT, 2014] and [Shibayama et al.]).

The inundation and runup heights observed in both the Nemuro Port and the Nemuro central area are consistent with the maximum sea surface elevation measured at the tide station (H_m = 204 cm, with local fluctuations of about ± 20 cm).

Flooding was also observed around the mouth and downstream areas of Hattari River, which flows through Misaki and Nishihama towns (Fig. 8 c and d). Since the hourly precipitation (snowfall) during the storm surge was less than 1.5 mm, river swelling was not significant. Increased seawater level due to the storm surge spread upstream (Fig. 11) and caused the flood. The inland runup possibly reached approximately 1 km. As in general tropical cyclones accompany heavy rain and cause river flood ([Dietrich et al., 2010; Fritz et al., 2010]), river propagation of the tide had yet to be explicitly observed. A storm tide propagation in the river, which potentially extends the flood area inland away from the coast, is a disaster scenario which should be taken into account for warning and evacuation in future storm surge events.

Table 2. Runup limits

Survey Area	Site[*1]	Latitude	Longitude
Yayoi Town	4	N 43°19'57.014"	E 145°34'43.558"
Yayoi Town	9	N 43°19'57.295"	E 145°34'48.472"
Yayoi Town	10	N 43°19'59.322"	E 145°34'47.496"
Yayoi Town	11	N 43°20'1.036"	E 145°34'45.552"
Yayoi Town	12	N 43°20'1.115"	E 145°34'40.418"
Yayoi Town	13	N 43°19'55.794"	E 145°34'39.929"
Yayoi Town	14	N 43°19'55.085"	E 145°34'37.515"
Yayoi Town	15	N 43°19'55.225"	E 145°34'34.846"
Yayoi Town	16	N 43°19'56.010"	E 145°34'31.728"
Nemuro Port	6	N 43°20'37.515"	E 145°35'10.262"
Nemuro Port	7	N 43°20'20.252"	E 145°35'7.577"
Nemuro Port	8	N 43°20'47.224"	E 145°35'1.795"
Hattari River	17	N 43°19'30.371"	E 145°34'5.394"
Hattari River	18	N 43°19'18.689"	E 145°34'14.696"
Hattari River	19	N 43°19'20.136"	E 145°34'13.343"
Hattari River	20	N 43°19'4.458"	E 145°34'14.164"

[*1] The site number corresponds to the ones shown in Fig. 9, Fig. 10 and Fig. 11.

4. Summary

This paper reports results of the inundation survey and meteorological analysis of the 2014 Nemuro storm surge with aiming to enhance further disaster analyses for possible future storm surges.

The contributions of the meteorological factors to the sea surface rise measured at Nemuro Port were estimated, based on weather forecast results, as being: the pressure-induced elevation $H_s = 65$ cm, the effect of the wind stress $H_c = 98$ cm, and the astronomic tide $H_t = 41$ cm. The inundation covered an estimated area of 22 ha in the surroundings of Nemuro Port and in streets with relatively low ground level in central Nemuro. Both the inundation and runup heights estimated from the survey in Nemuro Port and central Nemuro are consistent with the maximum tide recorded. Propagation of the storm tide along Hattari River, causing significant floods in the estuary and the riverside around the downstream reach, was observed.

Further detailed analyses are required to improve understanding and modeling of mechanisms of storm surge floods and potential scenarios of flood disasters in areas adjacent to rivers.

Acknowledgments

We thank Hokkaido Regional Development Bureau for providing tidal observation data (Fig. 3) and private photographs (Fig. 2).

Fig. 9. Estimated runup limits (indicated by a red line) and surveyed sites at Nemuro Port. Flood heights at Sites 6–8 are listed in Table 1. The locations where the photographs of Fig. 2 (c–d) and Fig. 8 (b) were taken and the location of the tide gage (Fig. 3) are indicated in the map. The ground elevation estimated from 5-m topographic data of the Geospatial Information Authority of Japan (GSI) is indicated by the blue (1 m), green (2 m), yellow (4 m) and brown (6 m) contours.

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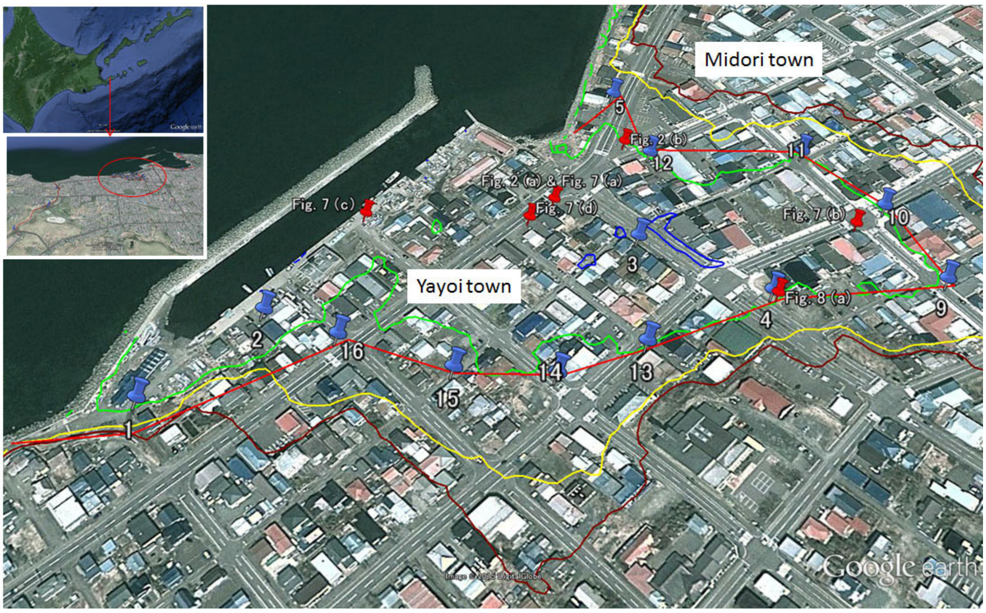

Fig. 10. Estimated runup limits (indicated by a red line) and surveyed sites at central Nemuro. Flood heights at sites 1 - 5 are listed in Table 1, and the locations of the runup limit sites are shown in Table 2. The locations where the photographs were taken (Fig. 2 a, b, Fig. 7 and Fig. 8 a) are indicated in the map. The ground elevation estimated from 5-m topographic data of GSI is indicated by the blue (1 m), green (2 m), yellow (4 m) and brown (6 m) contours.

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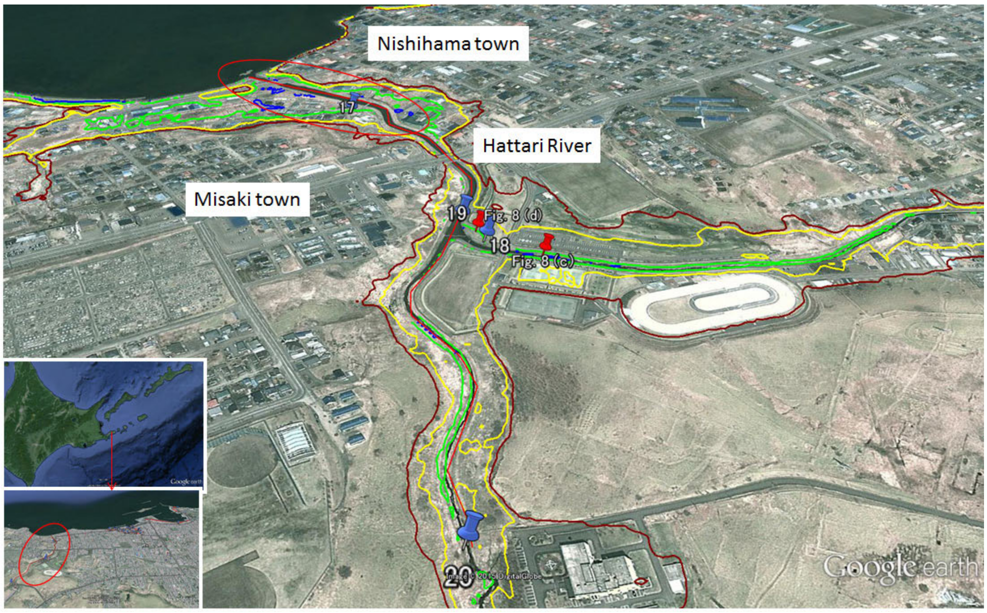

Fig. 11. Location of the survey (red line) and survey sites along Hattari River. The inundated area is marked by a circle. Site locations where debris were observed are shown in Table 2. The locations where the photographs were taken (Fig. 8 c, d) are indicated in the map. The ground elevation estimated from 5-m topographic data of GSI is indicated by the blue (1 m), green (2 m), yellow (4 m) and brown (6 m) contours.

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