Validation of a GIS-based attenuation rule for indicative tsunami evacuation zone mapping

S. A. Fraser W. L. Power

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S. A. Fraser, GNS Science, PO Box 30368, Lower Hutt 5040
W. L. Power, GNS Science, PO Box 30368, Lower Hutt 5040

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ABSTRACT

A GIS-calculated attenuation rule for development of indicative tsunami evacuation zone has been previously developed and presented by Leonard et al. (2008). This provides a solution for tsunami evacuation zone planning where a lack of resources or detailed topographic and bathymetric data precludes full hydrodynamic simulation of tsunami to develop evacuation zones. Attenuation of tsunami flow over land is considered to occur at different rates, dependent on the flow path – i.e. over land from the coast, along a river channel and laterally from the river, or into a harbour then over land. The attenuation relationships applied in the method were calibrated using inundation data collected during several post-tsunami field surveys. The method has been applied in several cases of evacuation zone mapping in New Zealand and the Pacific. However, since its development and application there has been no validation of the method with recorded inundation data.

The present study succeeds in validating the approach by comparing outputs of the attenuation-rule based method against inundation and run-up data points surveyed following the Great East Japan Tsunami (11th March 2011). To validate the method, firstly the inundation height versus distance inland (according to the attenuation rules for overland flow from the coast and via rivers) is directly compared against the survey data points of inundation and run-up height. Secondly, GIS-calculated evacuation zones are developed for two contrasting study areas in Miyagi Prefecture, Tōhoku, Japan, representing coastal plain topography and a rias (drowned river valley) with harbour topography. These are then compared to the recorded survey data and satellite imagery indicating tsunami inundation extent at the same locations. The evacuation zones generated using the GIS-calculated attenuation rule successfully incorporate the zone of inundation due to the Great East Japan tsunami at both study areas, giving confidence that the method is suitable for derivation of indicative evacuation zones elsewhere.

KEYWORDS

Tsunami, evacuation, zone, GIS, validation, Great East Japan

1.0 INTRODUCTON

This report presents validation of a GIS-based attenuation rule for mapping indicative tsunami evacuation zones in New Zealand, developed by Leonard et al. (2008). The attenuation rule method relies on definition of maximum possible run-up height at the coast and application of rules for attenuation of potential run-up height with horizontal distance inland (see Figure 1 for definitions of tsunami parameters). The rules are applied in a GIS method using basic topographic data, enabling production of indicative evacuation zones in cases where it is not possible to carry out probabilistic detailed hydrological simulation, for example where there is an absence of sufficiently detailed topographic and bathymetric data or a lack of available resources. The current report will not describe in detail the GIS method already covered by Leonard et al. (2008), but summarises the process below.

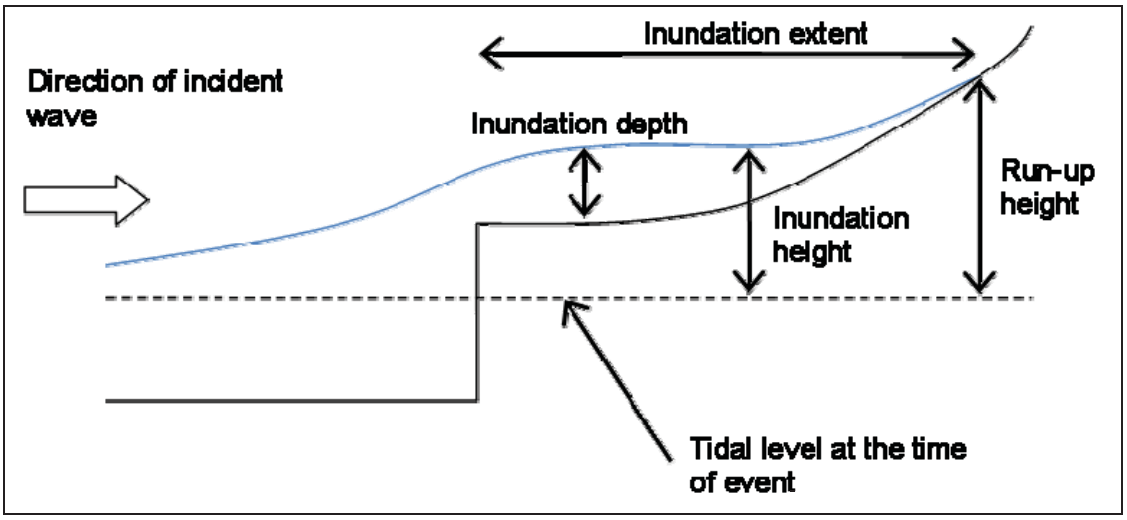

Figure 1 Graphic to define parameters of tsunami (after PARI, 2011 and EEFIT, 2011).

Maximum possible run-up at the coast is used as input to the attenuation rule calculation. This value represents the maximum possible run-up on land if no attenuation were to occur and if ideal topographic and bathymetric conditions for focussing and amplifying wave height exist, for example, in a steep, narrow bay immediately at the shore. Leonard et al. (2008) apply maximum possible run-up as two times the 84th percentile of probabilistic wave height at the coast, derived from modelling of sources considered in the first national tsunami hazard review (Berryman, 2005). A factor of two is applied to represent the effects of wave amplification due to wave-focussing by shoreline and onshore topographic features, and is an appropriate equivalent (Power, Downes and Stirling, 2007) to statistics proposed for Japanese tsunami (Kajiura, 1983, 1986). This run-up factor can underestimate run-up in some situations, for example in extremely narrow bays (e.g. Didenkulova, 2013), or for tsunami earthquakes (Satake, 1994). The maximum possible run-up is capped at a maximum of 35 m based on the range of modelled wave heights at the New Zealand coast and the rarity of tsunami above this height in international tsunami data.

Once the maximum possible run-up at the coast is defined, linear attenuation relationships are applied to determine potential run-up height inland, according to the coastal features of the study area:

- Following overland flow direct from the coast, the potential run-up height attenuates at a rate of 1 m for every 200 m horizontal inland (attenuation of 1:200, 0.5%). The initial

level is the maximum possible run-up (at the coast) plus the maximum tidal level, derived from tide gauge records.

- Potential run-up height within a harbour does not diminish within the first 1000 m from the harbour mouth. It attenuates at an exponential rate thereafter within the harbour as follows, where R is maximum possible run-up at harbour mouth (m) and D is distance (m) from harbour mouth:

  *Potential run-up height = R * exp((-0.0433 * D) / 1000)*

  The initial level at the harbour mouth is the maximum possible run-up (at the coast) plus the maximum tidal level, derived from tide gauge records. Potential run-up height for overland flow from the harbour edge attenuates at a rate of 1 m for every 200 m inland (1:200, 0.5%), starting from the potential run-up level at the harbour edge derived using the above relationship.

- Potential run-up height within a river channel attenuates at a rate of 1 m for every 400 m up river (1:400, 0.25%) and potential run-up height for flow over land from the river channel attenuates at a rate of 1 m for every 50 m (1:50, 2.0%). Initial level at the river mouth is the maximum possible run-up (at the coast) plus tidal level if the river flows directly into the sea. Where a river flows into a harbour, the initial level is the potential run-up at the closest harbour grid cell to the river mouth, derived using the above relationship.

Potential run-up height derived from the attenuation relationships is then intersected with local topography in a digital elevation model (DEM) to determine the maximum potential inundation extent (Figure 2). The resulting evacuation zones are presented on evacuation maps and signage in New Zealand as an ‘Orange Zone’ and a ‘Yellow Zone’ (MCDEM, 2008, p.7; Figure 3). The ‘Orange Zone’ represents the zone to be evacuated following an event in which most official evacuation warnings will be issued – this represents the estimated maximum inundation extent due to most regional or distant source events. The maximum possible run-up (at the coast) used to derive the ‘Orange Zone’ has by most local councils been chosen as two times the 84th percentile of the probabilistic at-shore wave height with a 500 year return period from regional and distant sources. The probabilistic at-shore wave height is usually rounded up to the next tsunami-warning threat-level threshold (Power and Gale, 2011) before it is doubled, in order that exceptional events that might exceed the ‘Orange Zone’ can be identified from tsunami forecasts. The ‘Yellow Zone’ is defined as two times the 84th percentile of the probabilistic at-shore wave height from maximum credible event(s) (for most local councils this has been a 2500 year return period) and encompasses all credible tsunami, including local events (within 1 hour travel time to the point of observation) for which no official warning would be issued. Here, validation will be carried out for the maximum credible event only, due to the absence of detailed information about probabilistic wave heights for the Tōhoku coastline.

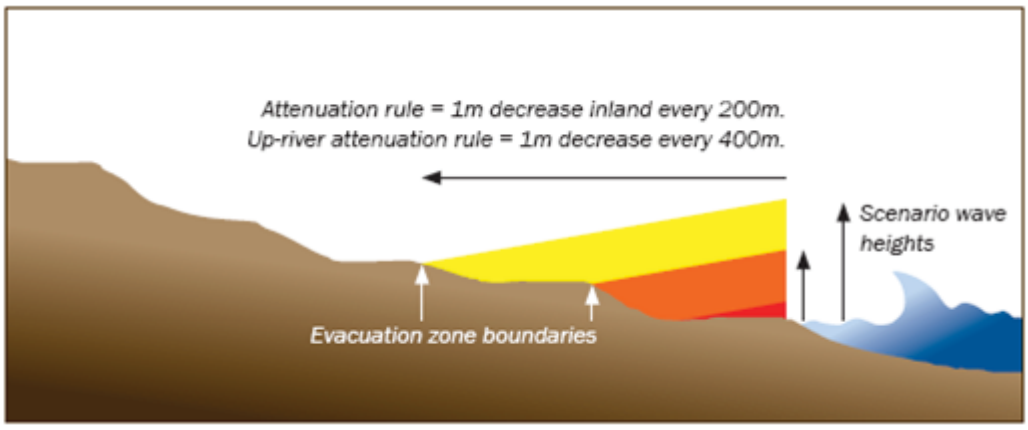

Figure 2 Illustration of the relation between maximum potential run-up at the coast (here, 'Scenario wave heights'), the attenuation rule giving potential run-up height inland and the intersection of potential run-up height with topography to produce evacuation zones (MCDEM, 2008).

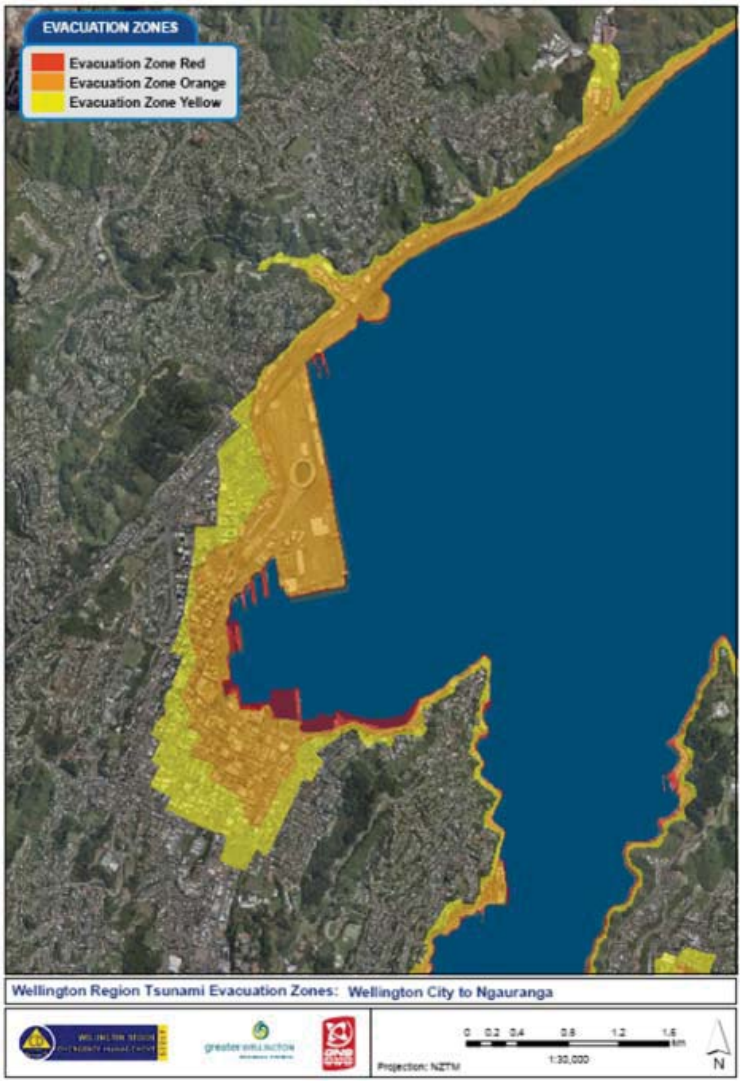

Figure 3 An example of maps produced by the attenuation rule based method: Tsunami evacuation zones for Wellington City to Ngauranga (Source: http://www.gw.govt.nz/assets/Emergencies--Hazards/Tsunami-Maps/12wellington-ngauranga.pdf).

GNS Science has applied the method to several regions in New Zealand, where it fulfils Development Level 2 of national tsunami evacuation zoning guidelines (MCDEM, 2008) and to the islands of Samoa (Wright et al., 2011). The method has also been used as the basis

for painting of evacuation zone lines in the Wellington Blue Line Project (Wellington City Council, 2011). Leonard et al. (2008, p.8) calibrated the attenuation rules against tsunami inundation data collected during several international post-tsunami field surveys including Banda Aceh in 2004 and Java in 2005, however, the 2011 Great East Japan tsunami presents an opportunity to validate the method with respect to extensive survey data (Mori et al., 2011, 2012) following a tsunami with significant damaging inundation heights.

In the validation, it is important to consider not only whether mapped zones successfully encompass the inundated area, to ensure evacuation of all affected areas, but that they do not encourage significant over-evacuation by vastly overestimating the area of expected inundation. Two aspects of the methodology were validated:

1. Linear attenuation relationship, to check that the applied relationships remain adequate when compared against a large detailed dataset of recorded inundation and run-up heights.
2. Zone mapping methodology, to ensure that evacuation zones produced by the method encompass all areas of tsunami inundation which occurred at the study areas in the 2011 Great East Japan tsunami.

1.1 STUDY AREA

The study areas used in validating the evacuation mapping methodology are the Sendai Plains and Kesennuma City, both in Miyagi Prefecture, Japan (Figure 4). A wider region around Kesennuma City is considered for validation of the attenuation relationship, encompassing the coastline from Kesennuma City to Ōfunato City, Iwate Prefecture. These study areas represent two contrasting topographies, ensuring the attenuation-based method is validated for different coastal environments.

The Sendai Plains study area is a low-lying coastal region (Figure 5), which was inundated to a depth of 20 m at the coast and to a distance of 5 km inland on March 11th 2011 (Mori et al., 2011). Relevant features of this study area include the harbour of Sendai Port, Lake Tourinoumi (connected to the sea and treated as a harbour for this analysis) and three major rivers (Abukuma, Natori and Nanakita Rivers), which are included in the validation. The majority of the study area is flat agricultural and sparsely-developed residential land subject to direct inundation from the coast.

Kesennuma City is a harbour city situated in a drowned river valley with two rivers (Oh and Shikaori Rivers) flowing into the harbour (Figure 6). Maximum inundation at the coast in this city was approximately 25 m (Mori et al., 2012). Damage in Kesennuma City was observed to 1.1 km inland (EEFIT, 2011), although survey data also indicates a maximum inundation extent of 2.5 km north up the Shikaori River (Mori et al., 2012). Prior to the Great East Japan tsunami there was high-density development of the harbour area, comprising a mix of industrial, commercial and residential uses.

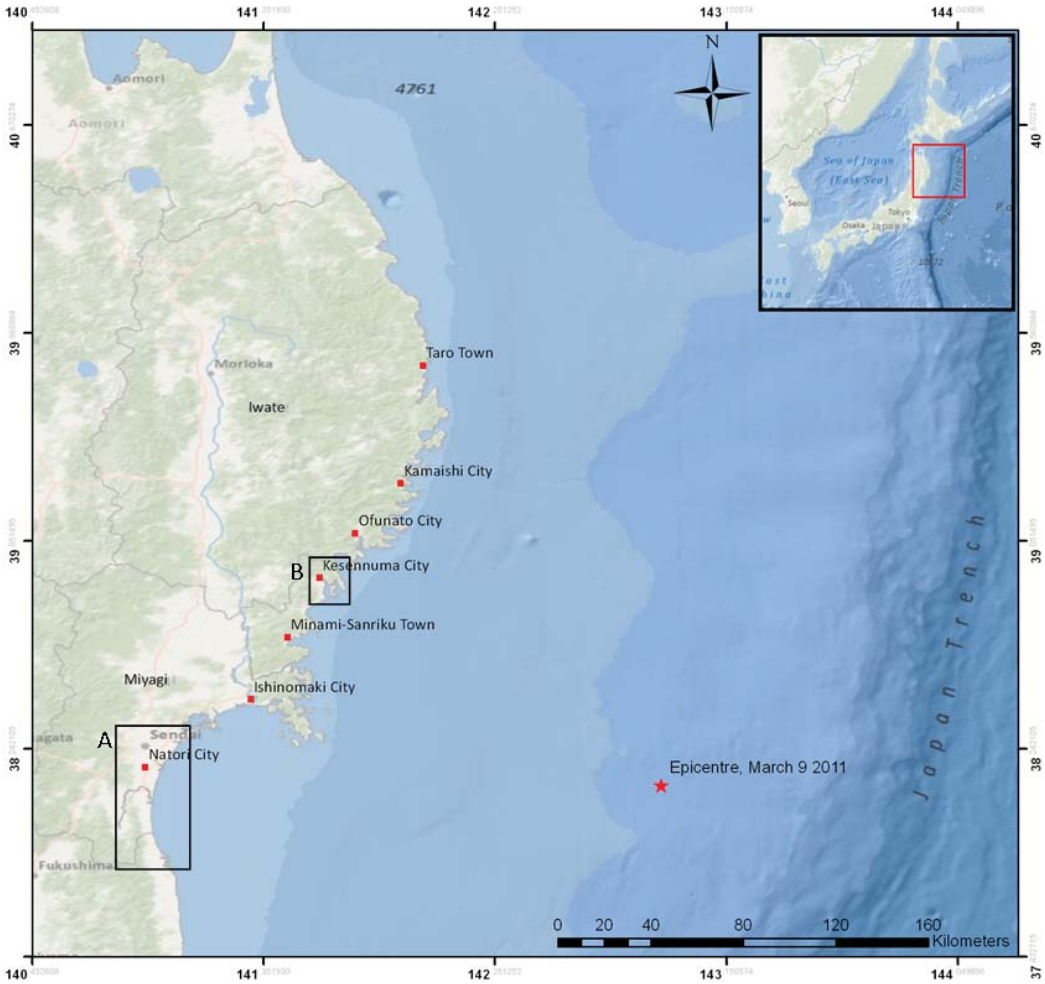

Figure 4 Map indicating the Study areas: Sendai Plains (A), Kesennuma City (B). Other major coastal towns and cities of Miyagi and Iwate Prefectures are also indicated.

Figure 5 Photograph taken post-tsunami, looking east across Sendai Plains towards the coast. The coastal forest, visible in the distance, indicates the position of the coastline. Photograph credit: G.S. Leonard, 27th October 2011.

Figure 6 Photograph looking southeast across Kesennuma City. The harbour entrance is at top right. Photograph credit: S.A. Fraser, 24th October 2011.

2.0 LINEAR ATTENUATION RELATIONSHIP

The linear attenuation relationships applied to determine maximum potential run-up for inland flow directly from the coast and via flow along rivers then over land, have been validated by comparing the linear relationships against comprehensive inundation and run-up data published by The 2011 Tōhoku Earthquake Tsunami Joint Survey Group (TTJT) (http://www.coastal.jp/tsunami2011/; Mori et al., 2012). The survey data were filtered by area of interest and then by reliability as rated by the survey group, to retain only data points with the highest reliability for the validation. The reliability measures selected were '*A: High, clear mark, small error of measurement*' and '*B: Middle, not clear mark but reliable information from witness, small error of measurement*'. Spatial filtering to select only the data points in our study areas was carried out in ArcGIS using the survey point coordinates provided in the original data.

Where a survey data point includes values for height above mean sea level and distance to coast, the data point is plotted on a chart of inundation height versus distance from coast. Many data points had not been assigned a distance to coast by the survey team. Prior to chart plotting, these data points were assigned a distance to coast in ArcGIS, using spatial analysis of their location in relation to a 10 m resolution raster with values indicating distance inland from the coast. This grid was generated as part of the accompanying evacuation zone GIS process. The appropriate linear relationship was plotted on the same chart, according to the rate of attenuation and maximum possible run-up value at the coast (35 m for the maximum evacuation zone).

A probabilistic calculation was not conducted to derive the 35 m maximum possible run-up value at the coast in Japan. The value of 35 m was taken as a global maximum credible level, based on the historical rarity with which that height has been exceeded. We propose that this level be used as a default value for the maximum evacuation zone along coasts directly adjacent to subduction zones, in the absence of probabilistic studies.

For the Sendai Plains, only the coastal attenuation of 0.5% (1:200) is considered in the comparison because the TTJT survey data does not indicate significantly greater inundation extent along river channels, than direct from the coast. Survey data points along major rivers in the Kesennuma study area were identified and compared separately to those judged to be from direct coastal flooding, against the attenuation-based rule for river channels (0.25%, 1:400).

2.1 RESULTS

Inundation height and inland distance of the TTJT survey points from the Sendai Plains are compared to the linear attenuation relationship of 0.5% (1:200) in Figure 7. For a maximum possible run-up value at the coast of 35 m, corresponding to the evacuation envelope of the maximum credible tsunami ('Yellow Zone'), this linear attenuation relationship encompasses all survey data points and produces an additional evacuation margin of approximately 1.5 km, to 7 km inland from the coast. The trend line of observed inundation points (where inland distance is measured by the survey team) yields attenuation of 0.13% and the trend line of run-up data yields attenuation of 0.15%, suggesting that the relationship uses a more rapid rate of attenuation than observed on the Sendai Plains in 2011.

The same relationship, plotted against TTJT data from the rias coastline of Kesennuma City to Ōfunato City (Figure 8), encompasses all TTJT data points with 1.2 km additional

evacuation. Again, the trend lines of TTJT data show a more gradual linear attenuation of inundation than the 1:200 (0.5%) applied to generate the evacuation zone: 0.15% for inundation and 0.10% for run-up.

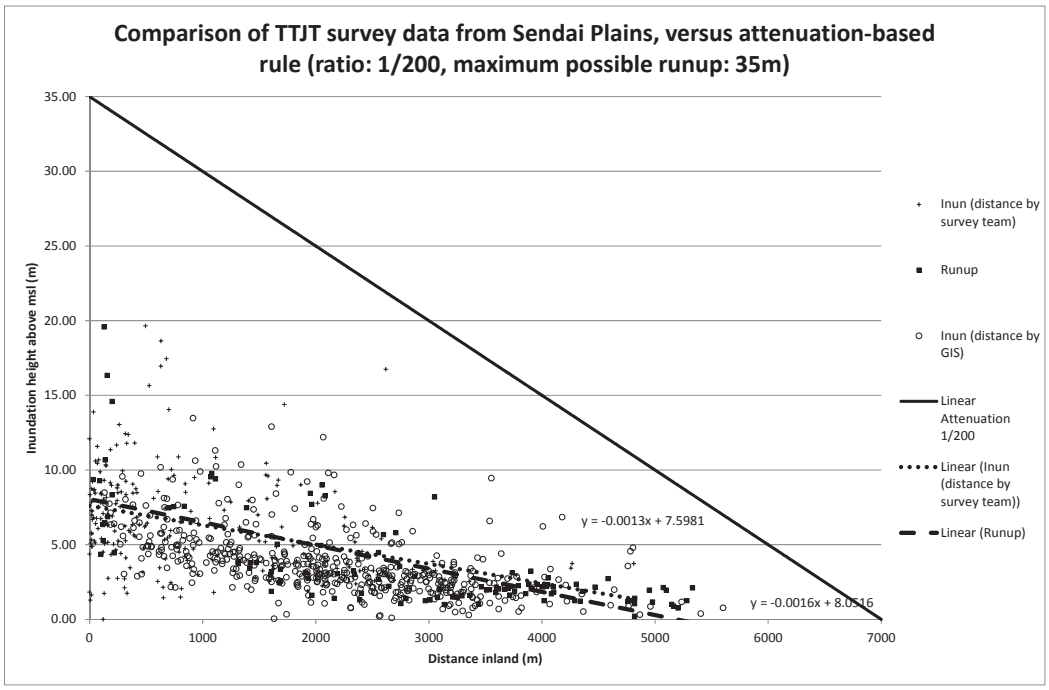

Figure 7 Comparison of The 2011 Tōhoku Earthquake Tsunami Joint Survey Group (TTJT) survey data (inundation height with distance inland measured by survey team, *cross*; inundation height with distance inland derived from GIS, *hollow circle*; run-up height, *square*) from the Sendai Plains area of Japan, versus the linear attenuation relationship for potential run-up, of 0.5% (1:200) (*solid line*). Trend lines of survey data are also shown (*dotted* and *dashed lines*).

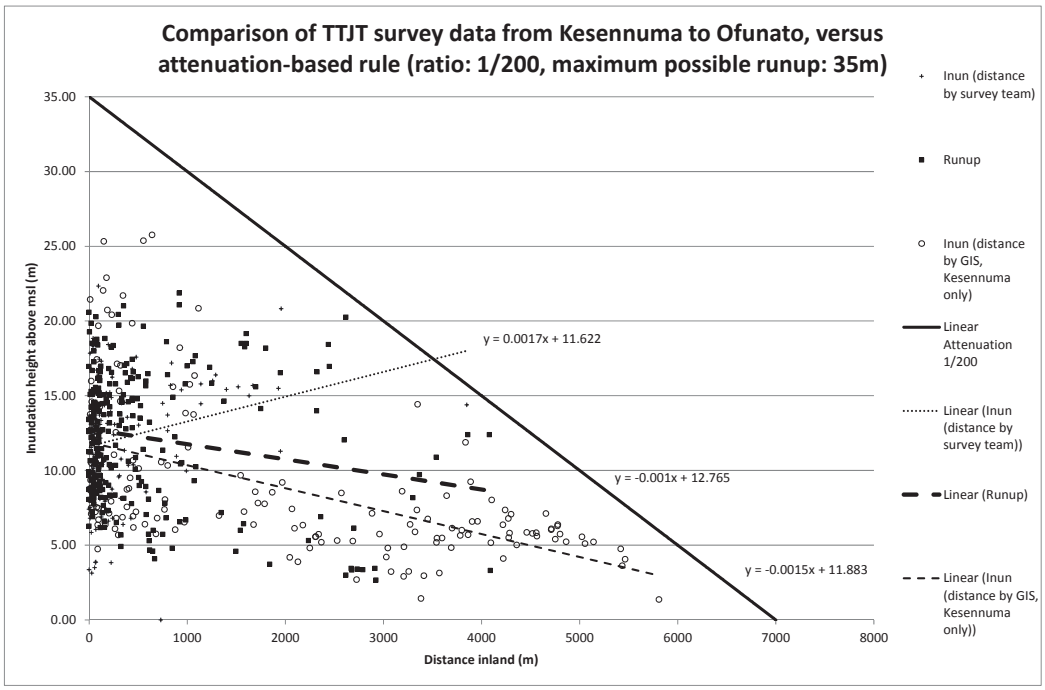

Figure 8 Comparison of The 2011 Tōhoku Earthquake Tsunami Joint Survey Group (TTJT) survey data (inundation height with distance inland measured by survey team, *cross*; inundation height with distance inland derived from GIS, *hollow circle*; run-up height, *square*) between Kesennuma City and Ōfunato City. The survey data are shown against the linear attenuation relationship for potential run-up, of 0.5% (1:200) attenuation (*solid line*). Trend lines of survey data are also shown (*dotted* and *dashed lines*).

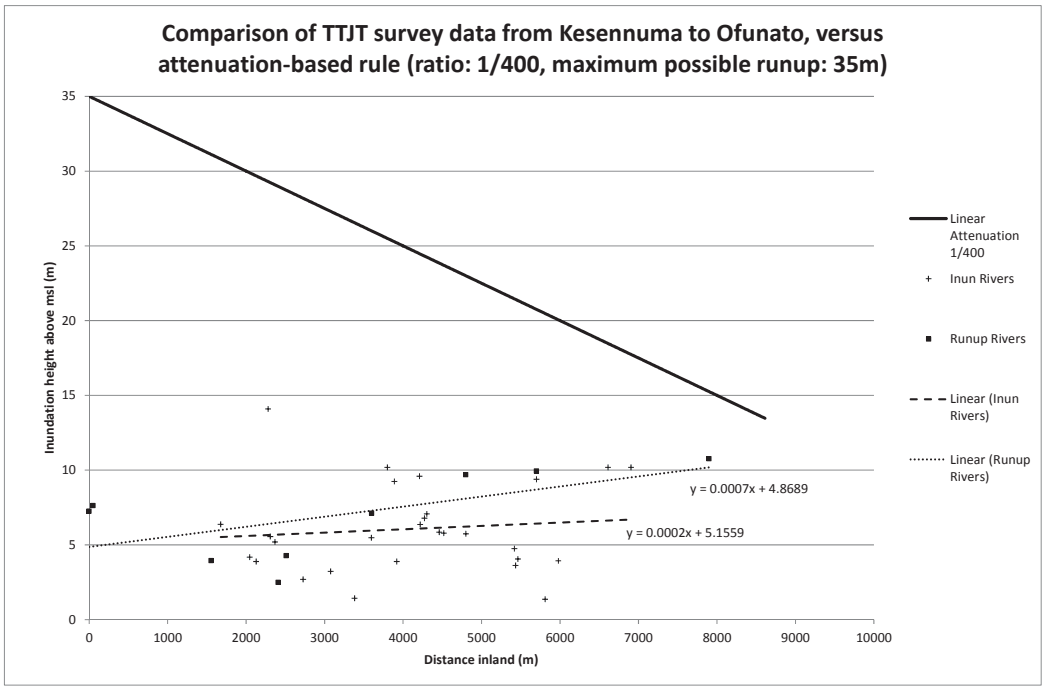

Figure 9 Comparison of The 2011 Tōhoku Earthquake Tsunami Joint Survey Group (TTJT) survey data for rivers only (inundation height with distance inland along rivers measured by survey team, *cross*; run-up height, *square*) between Kesennuma City and Ōfunato City. The survey data are shown against the linear attenuation relationship for potential run-up, of 0.25% (1:400) attenuation (*solid line*). Trend lines of survey data are also shown (*dotted* and *dashed lines*).

The attenuation relationship for potential run-up height via river channels (0.25%, 1:400) also encompasses the TTJT data surveyed along the rivers in Kesennuma City (Figure 9). In this case, the attenuation relationship indicates a much larger inland distance, to a maximum of 14 km, compared to the maximum surveyed inundation of 8 km. The slight upwards trend of both inundation and run-up survey data in Figure 9 is due to the absence of data points close to the river mouth – these points are included in the coastal data plotted in Figure 8, as it was not possible to identify those data points as being derived from over-bank flow via the river.

3.0 EVACUATION ZONE MAPPING

3.1 METHODOLOGY

This stage of validation applies the original method of Leonard et al. (2008), which is summarised in this report but detailed in full in the prior report. ESRI ArcGIS 10.0 and Arc Macro Language (AML) scripts executed in ArcInfo Workstation are used for preparation of the digital elevation model (DEM) and other raster input, and subsequent processing of potential run-up calculations also uses AML scripts. All calculations are based on gridded data, which is used to represent the DEM (land values only) and the areas covered by the sea, each harbour and each river.

DEM preparation differs in some respects from Leonard et al. (2008), as dictated by the different topographic data available for the study area. Topography data is obtained from the Geo Spatial Authority of Japan (http://fgd.gsi.go.jp/download/GsiDLLoginServlet) in .gml file format at horizontal resolution of 0.000111 decimal degrees (approximately 11 m) and vertical datum relative to the mean sea level of Tokyo Bay ('Tokyo Peil') (Geo-Spatial Information Authority of Japan, n.d.). These data are prepared for subsequent processing with 11 m grid cells as follows. Each .gml file is converted to ASCII grid text format using a Python script written by the authors, as no readily available solution existed to convert these data or import these data directly into ArcGIS. ASCII grid text files are imported to GIS as raster datasets and converted from decimal degrees coordinates (spatial reference: WGS 1984) into Universal Transverse Mercator (UTM) coordinates (spatial reference: JGD_2000_UTM_Zone54N). The individual rasters are mosaicked into a single raster at resolution of 11 m. Where gaps occur between individual rasters (due to transformation from decimal degree to UTM coordinates) resulting in cells with 'NoData' values, additional processing is required. First, a new raster is created with each new cell value representing the mean elevation of neighbouring cells of the DEM, within a distance of 3 cells. The mosaicked raster DEM is then subject to a calculation to replace any cell of 'NoData' value with the corresponding mean elevation.

No amendments are made to the topography data to represent high resolution features such as road embankments, which traverse the Sendai Plains from north to south at a distance of around 4 km inland. This embankment is shown to impede tsunami flow during the Great East Japan Tsunami, but as there are gaps in the embankment (at road bridges) through which water can flow, this is not considered for the indicative tsunami evacuation map. Similarly, no sea defences or buildings are included this analysis. The DEMs used in the validation indicate the contrasting topography of our study areas (Figure 10).

Digital Elevation Models used in analysis

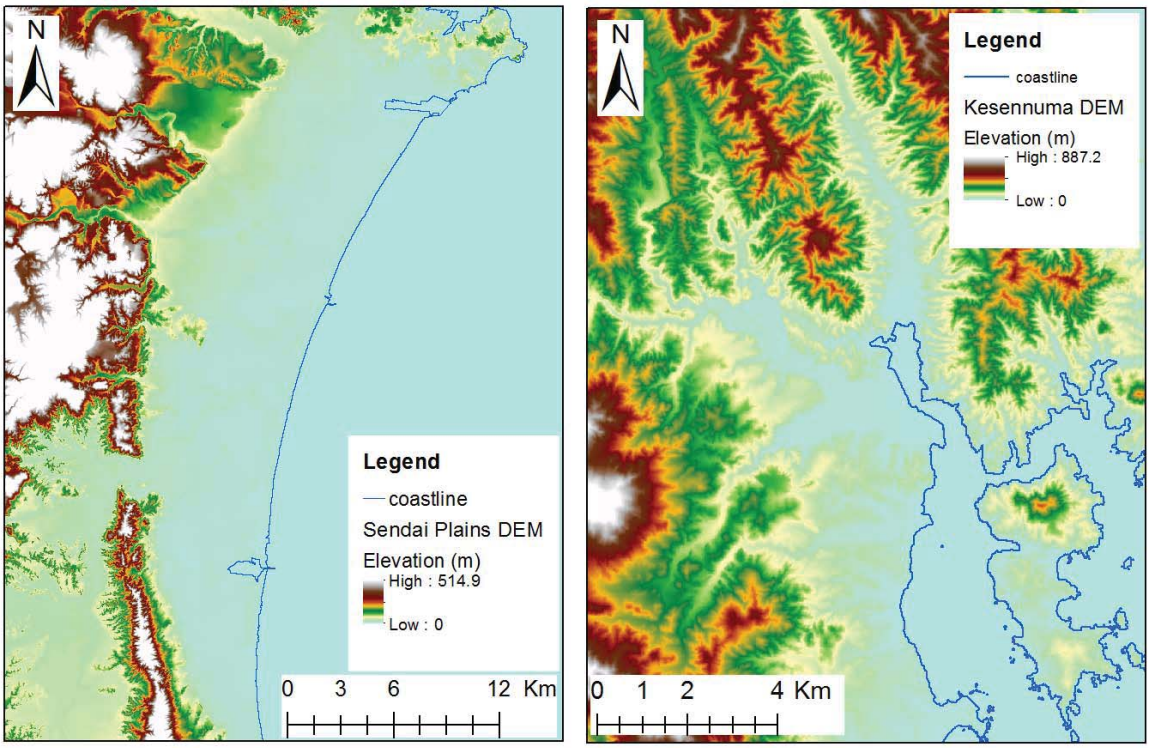

Figure 10 Digital Elevation Model for Sendai Plains study area (left) and Kesennuma study area (right). The DEM was developed using 11 m resolution elevation data obtained from the Geo Spatial Authority of Japan (http://fgd.gsi.go.jp/download/GsiDLLoginServlet).

Polygons representing water bodies in the study area are manually digitised in ArcGIS, based on the DEM and aerial imagery available in ESRI ArcGIS 10.0. These features are buffered according to the known horizontal limit of potential run-up according to attenuation rules and specified maximum possible run-up value to minimise analysis time (to 8000 m around each harbour and to 2000 m around each river). Using the grid preparation AML scripts, these polygons are converted into raster format. A 'distance grid' is also generated for the overland area and each water body. The value of each cell in these grids represents the distance from the coast overland, distance from coast within the harbour or along the river channel respectively. These provide the distance value used in subsequent attenuation rule based calculations of potential run-up at each grid cell.

Three AML scripts are then executed in turn, to generate an attenuation-based evacuation zone for flow directly inland from the coast and via each water body, with the appropriate attenuation rate and specified tidal value and maximum possible run-up height at the coast (35 m for the maximum evacuation zone). Tidal level is applied as the maximum tidal height for each study area. For the Sendai study area, applied tidal level is 1.798 m and represents the maximum tidal level at the Sendaiko tide gauge (38 16 N, 141 01 E) relative to Tokyo Peil in the years 2004-2008 (Japan Oceanographic Data Center, 2012). The tidal level applied for Kesennuma study area is 1.065 m and represents the maximum tidal level at the Ōfunato tide gauge (39 01 N, 141 45 E) relative to Tokyo Peil in the years 2004-2009 (Japan Oceanographic Data Center, 2012). Output from each AML script, providing area of potential run-up after intersection with elevation data (therefore maximum potential inundation extent) from each water body in the study area, are merged in ArcGIS to create a single evacuation zone. This is then plotted against TTJT survey data and inundation data derived from satellite imagery.

3.2 RESULTS

The indicative evacuation zone for the Sendai Plains study area, for maximum possible run-up (at the coast) of 35 m is shown in Figure 11 and Figure 12. The evacuation zone encompasses all land inundated during the Great East Japan tsunami in this study area. This is illustrated by the comparison against mapped areas of standing water derived from UNOSAT satellite imagery, recorded on 12th March 2011, the line of maximum inundation (data obtained from the Geographical Survey Institute, Japan; http://stlab.iis.u-tokyo.ac.jp/eq_data/eq_line/) (Figure 11) and all TTJT survey points (Figure 12).

The evacuation zone generally extends to a maximum of 6.5 km inland across the plains (where unimpeded by high land) and to approximately 9 km along the river channels. The only area in the study area where UNOSAT data show inundation further inland than the evacuation zone is on a golf course in the south of the study area. As this land exceeds 20 m elevation at a distance of over 2.5 km inland, we infer that the standing water on the golf course at the time of satellite image capture is unrelated to tsunami inundation. This inference is supported by the absence of surveyed inundation data points at this location in the TTJT data, which otherwise agrees very well with the UNOSAT data.

At Kesennuma City, the inland extent of the evacuation zone derived from 35 m maximum possible run-up is constrained by steep terrain. The evacuation zone extends over 5 km inland along the rivers, encompassing all TTJT survey points and the line of maximum inundation (data obtained from the Geographical Survey Institute, Japan; http://stlab.iis.u-tokyo.ac.jp/eq_data/eq_line/) (Figure 13). A substantial area in the western part of the city is incorporated in the indicative evacuation zone indicating conservative zoning compared to the inundation observed from the Great East Japan tsunami. In more peripheral parts of the study area, the attenuation rule method successfully includes numerous small coastal valleys in the zone.

4.0 CONCLUSIONS

The GIS-based attenuation rule methodology developed by Leonard et al. (2008) has been validated against observations from the 2011 Great East Japan tsunami. The indicative evacuation zone generated, using a methodology previously established and applied in New Zealand and Samoa, was compared against survey data and satellite imagery of inundated areas on maps and plotted against a large number of survey data points.

This validation indicates that the attenuation rule method, applied for a maximum possible run-up (at the coast) of 35 m generates an evacuation zone of sufficient extent to encompass all areas of inundation in the Sendai Plains and Kesennuma City. This value for the maximum possible run-up has only very rarely, and in very small areas, been exceeded by tsunami following historical subduction zone earthquakes. It has been used as an upper limit of the maximum run-up derived in probabilistic calculations of tsunami hazard around New Zealand and is assumed to represent the largest waves that could be expected in New Zealand. We propose that 35 m maximum run-up be used as a default value for defining the maximum evacuation zone along coasts directly adjacent to subduction zones, in the absence of probabilistic studies.

Comparison of the linear attenuation relationships with survey data points indicates that the attenuation rule-based approach is conservative, as it delineates the evacuation zone further inland than recorded inundation by over 1 km, potentially resulting in unnecessary ‘over-evacuation’. However, this is preferable to an approach which under-estimates potential inundation.

The methodology succeeds in providing a sufficiently accurate indicative evacuation zone, which can be progressively refined by more detailed inundation modelling as data and resources allow, as specified by MCDEM (2008). Results of the validation provide confidence that the indicative evacuation zones that are currently in place in New Zealand are appropriate for the maximum credible tsunami in New Zealand and support continued use of the current attenuation relationships where data or resources preclude the use of more detailed hydrological simulation to derive evacuation zones.

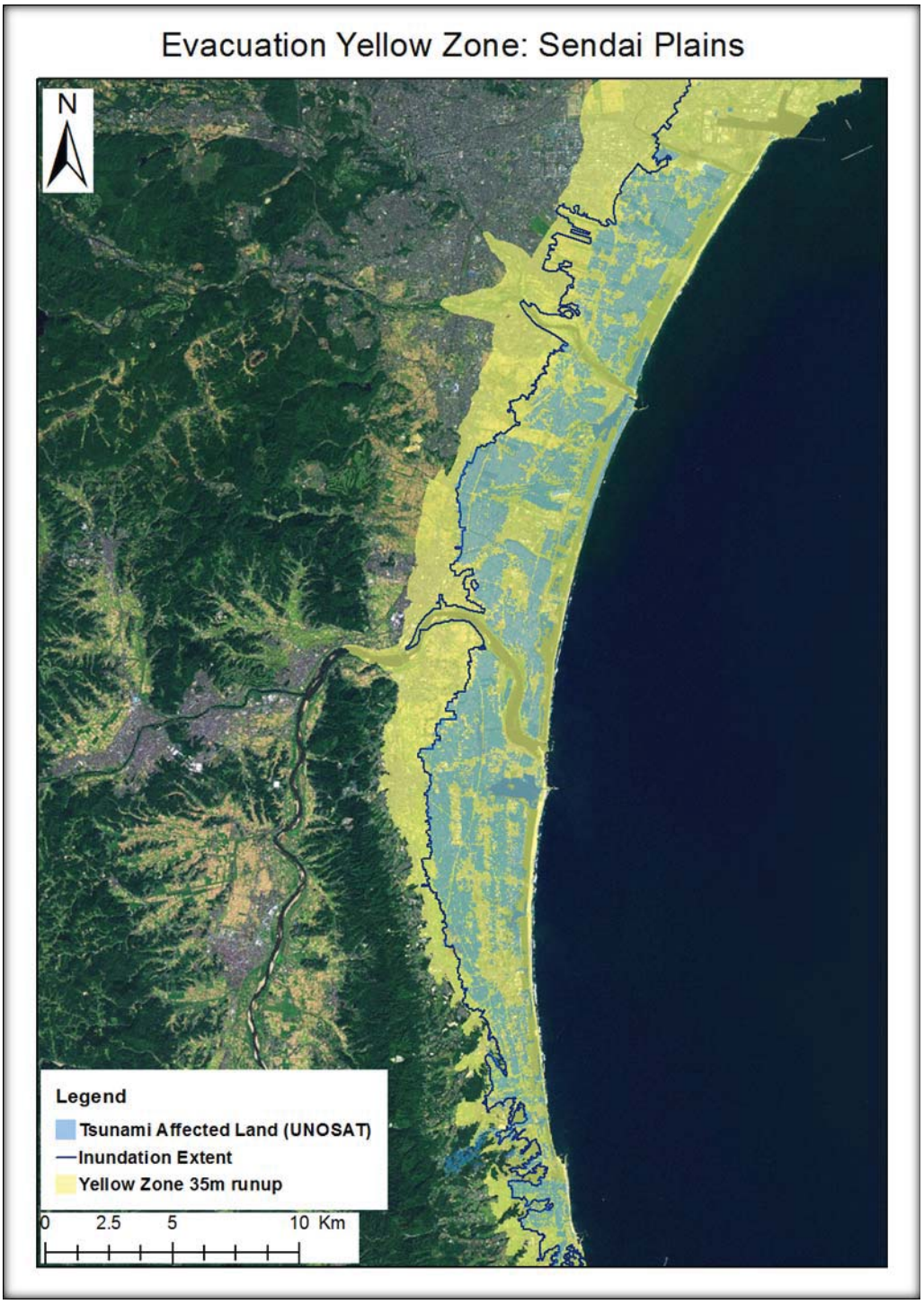

Figure 11 Evacuation zone (*yellow shaded*) for the Sendai Plains, produced using a maximum possible run-up (at the coast) of 35 m and tidal level of 1.798 m relative to Tokyo Peil datum. The footprint of tsunami-related standing water bodies (*blue shaded*) is derived from UNOSAT satellite imagery (http://www.unitar.org/unosat/node/44/1549). Maximum inundation extent (*blue line*, copyright: Geographical Survey Institute, Japan) is also shown for comparison.

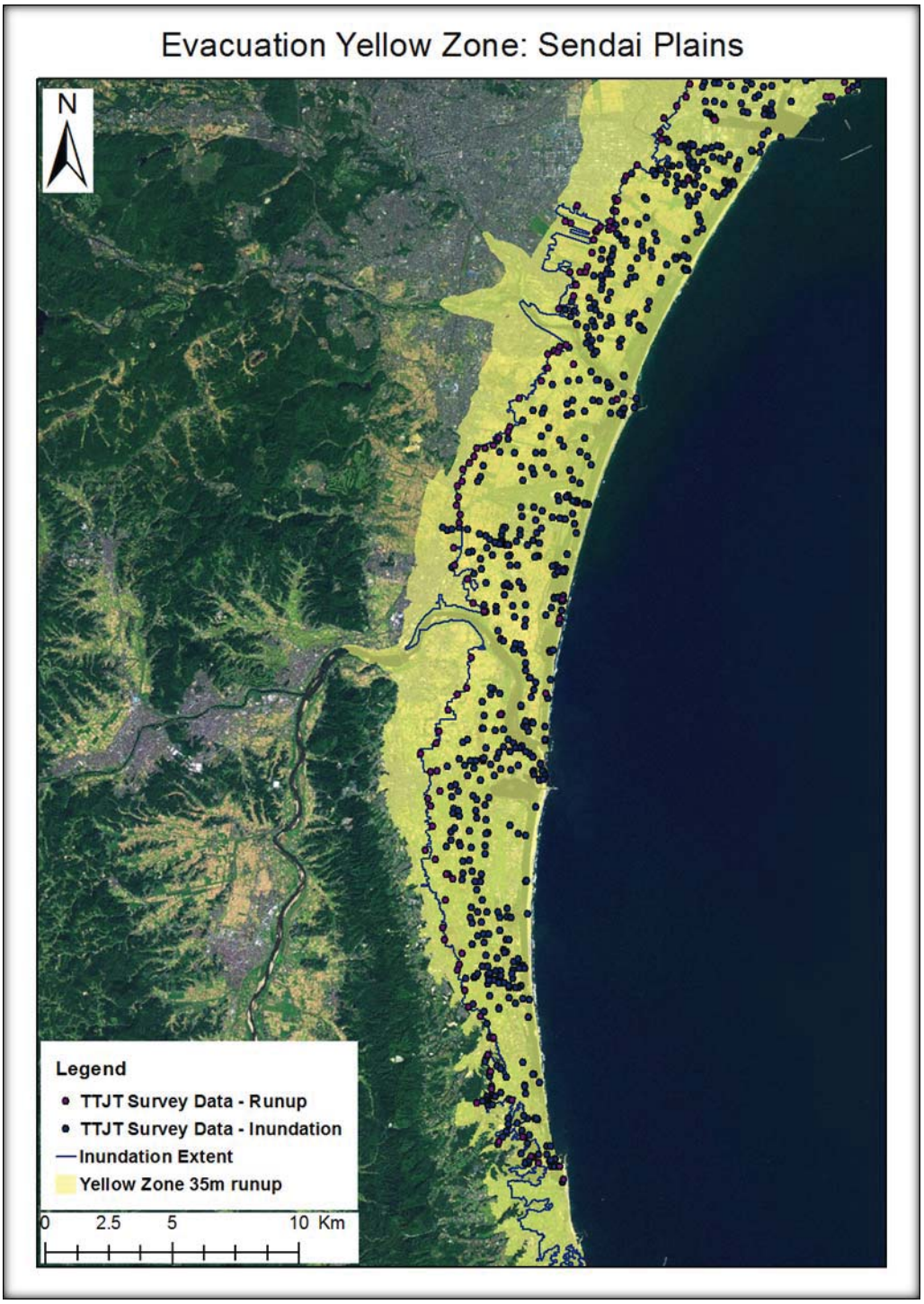

Figure 12 Evacuation zone (*yellow shaded*) for the Sendai Plains, produced using a maximum possible run-up (at the coast) of 35 m and tidal level of 1.798 m relative to Tokyo Peil datum. TTJT survey data points (inundation and run-up height; Mori et al., 2012) and maximum inundation extent (*blue,* copyright: Geographical Survey Institute, Japan) are shown for comparison.

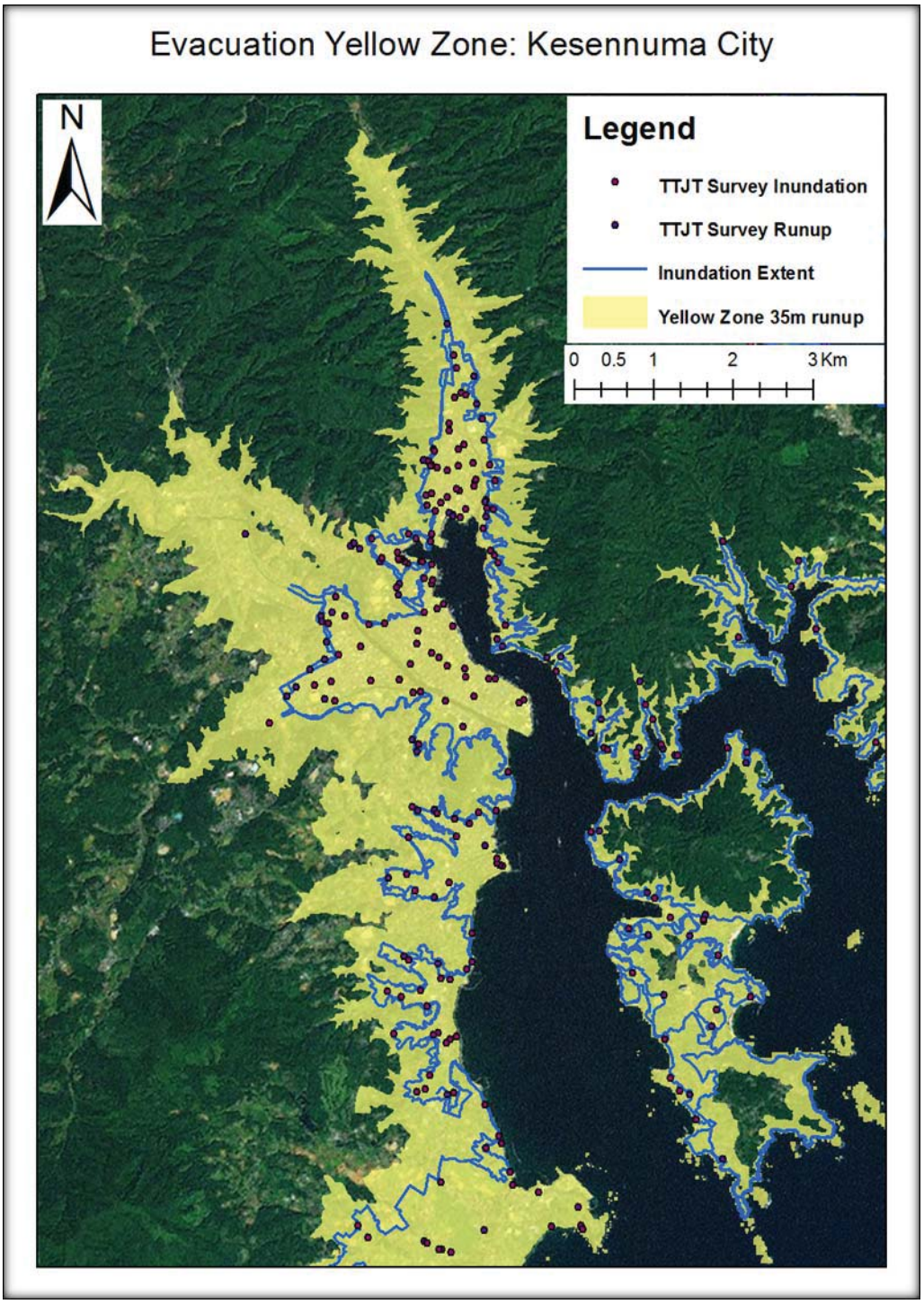

Figure 13 Evacuation zone (*yellow shaded*) for Kesennuma City (Oshima Island is also shown) produced using a maximum possible run-up (at the coast) of 35 m and tidal level 1.065 m relative to Tokyo Peil datum. TTJT surveyed inundation and run-up data points (Mori et al., 2012) and the extent of maximum inundation (*blue,* copyright: Geographical Survey Institute, Japan) are shown for comparison.

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www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657