Water

Capital Regional District

Modelling of Potential Tsunami Inundation Limits and Run-Up

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15 April, 2013

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15 April, 2013 **Project No: 60242933 Task ID #400.1**

Travis Whiting
CRD Protective Services
Capital Regional District
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Dear Mr. Whiting:

Re: Modelling of Potential Tsunami Inundation Limits and Run-Up

AECOM Canada Ltd. (AECOM) is pleased to submit this FINAL report, "Modelling of Potential Tsunami Inundation Limits and Run-Up", summarizing the work performed, tsunami modelling results, and suggested next steps related to use of the information and emergency planning.

As you are aware, this project has been a collaboration between AECOM and Applied Research International (ARILLC), a sole proprietorship firm of Dr. K.F. Cheung, a professor of Ocean Engineering at University of Hawaii. ARILLC's involvement in this project has been a key to the tsunami modelling and the successful completion of the work.

This has been a very interesting, yet complex, project and we are confident that the CRD will find the project deliverables of significant value.

Sincerely,
AECOM Canada Ltd.

Mike Brady, P.Eng.
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MB/bl

Encl.

Distribution List

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Revision Log

Revision #	Revised By	Date	Issue / Revision Description

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Executive Summary

This report, “Modelling of Potential Tsunami Inundation Limits and Run-Up” summarizes the work performed and the results of modelling the tsunami impacts along the entire coastline within the Capital Regional District (CRD) that would result from a possible, predicted Cascadia Subduction Zone (CSZ) earthquake occurring off the west coast of Vancouver Island. Cascadia Subduction Zone earthquakes have occurred, on average, every 500 years and the most recent 1-in-500-year earthquake for this zone is thought to have occurred in the year 1700.

The US National Seismic Hazard Maps shows 12 possible combinations of earthquake magnitudes and rupture configuration scenarios that would each represent a 1-in-500-year earthquake. Amongst these, the combination having the highest joint probability, which comprises a magnitude Mw 9.0 and global analog (GA) rupture scenario, was selected as the event to be analyzed.

The model used to analyze the tsunami wave generation and their impacts when reaching land was NEOWAVE. It is a model developed by researchers at the University of Hawaii and University of Alaska led by Dr. Kwok Fai Cheung, who was the lead modeller for this project. In 2009, NEOWAVE competed and won against seven other tsunami numerical models and it has been validated against data obtained from a number of recent tsunami events, including the 2011 Tohoku tsunami in Japan. It is the official model for tsunami inundation mapping in Hawaii, American Samoa, the US Gulf of Mexico coastal states and Puerto Rico.

In order to perform the tsunami modelling, a complete and seamless digital elevation model (DEM) containing both topographic (land) and bathymetric (sea-floor) information was first required. To accurately model the propagation of the tsunami through the Strait of Juan de Fuca the area to be covered included shoreline areas of the entire CRD and, within the USA, the Olympic Peninsula, San Juan Islands and portions of Puget Sound. This whole process required the compilation of data from multiple original sources (sometimes overlapping), having varying accuracies and reliabilities that needed to be resolved. Some of the challenges encountered and overcome included differences in both coordinates and elevations used in Canada and USA; use of differing elevation datums within the various sources; overlapping data providing differing elevations; and shoreline discontinuities, all of which could have had a significant impact on the modelling results.

The NEOWAVE model was applied to the DEM in a series of nested grids, with increasing accuracy applied to smaller grid areas as follows:

- The complete CRD was modelled at a 90-m grid size
- Esquimalt Harbour, including the area from Albert Head to Clover Point was further modelled at an 18-m grid size; and
- Victoria Harbour including Inner Harbour, Upper Harbour and Selkirk Waterway was then further modelled at a 9-m grid size.

The models were run using the Higher High Water Mean Tide (HHWMT) at Victoria as the base water level, which is approximately 0.732 m above Mean Water Level (MWL). Modelling results are presented in a series of colour-scaled figures or maps showing:

- Maximum water level – this includes, and is not additive to, the HHWMT (i.e. this is not the wave height, which is smaller)
- Maximum Drawdown of Water - this value is relative to the base water level (HHWMT)
- Maximum water flow speed – similar to the water current
- Tsunami Arrival Time – time to first positive wave
- Time to Maximum Water Level – time that water reaches its maximum (impacted by resonating wave effects)

Table ES-1 provides a summary of these values for several selected locations within the CRD. The values in the tables have been inferred from Figures 5.1 through 5.5 – the reader is encouraged to refer to the figures for these and any other specific values.

Table ES1 – Summary of Tsunami Model Results at Selected Locations

Location	Maximum Water Level (m)	Maximum Drawdown of Water (m)	Maximum Water Flow Speed (m/s)	Tsunami Arrival Time (min)	Time to Maximum Water Level (min)
Port San Juan (entrance near Port Renfrew)	3.5	-1.0	0.7	35	50
Sooke Harbour (entrance)	2.5	-0.2	0.6	60	75
Esquimalt Harbour (entrance)	2.7	-1.2	2.0	77	96
Victoria Harbour (entrance)	2.5	-1.05	1.0	76	95
Cadboro Bay	2.0	-0.2	0.8	90	160
Sidney	2.0	-0.2	0.6	110	150

As can be seen from the figures in the report, for much of Greater Victoria, the maximum water level is predicted to be less than 3.5 m and the maximum flow speed is predicted to be in the order of 1 m/s, excluding areas with narrows or waterway constrictions. To provide a comparative reference, the 2011 Tohoku tsunami resulted in a maximum water level of 40 m (recorded at a cliff on the Iwate coast) and a maximum water flow speed of approximately 12 m/s (inferred from video images taken in Myagi).

Based upon the modelling results, a Tsunami Hazard Line has been prepared for all coastline areas within the CRD. The Tsunami Hazard Line has been developed based upon the model-predicted Maximum Water Level, with consideration for earthquake-induced land subsidence and a Factor for Public Safety, as follows:

- Maximum water level, plus
- Land subsidence (since lowering of the ground surface effectively adds to the water level), plus
- An allowance of 50% added to the total of maximum water level and subsidence.

The 50% allowance has been included as a Factor for Public Safety to account for a) uncertainty related to the magnitude of the earthquake event that occurs; b) possible variations in the initial tide condition; and c) variability of the available topographic information.

The resulting Tsunami Hazard Line has been created as a layer to be added to CRD's GIS mapping.

To further benefit from the model developed and its results, a series of potential next steps has been suggested. These include:

- Using the results and Tsunami Hazard Line for other emergency considerations, including:
    - Evacuation planning
    - Emergency response planning
    - Infrastructure design
    - Transportation planning

List of Acronyms

ARILLC	Applied Research International
BT	Base Transition
CD	Chart Datum
CGVD28	Canadian Geodetic Vertical Datum of 1928
CRD	Capital Regional District
CSZ	Cascadia Subduction Zone
CVN	US Nuclear Aircraft Carrier
DEM	Digital Elevation Model
ETOPO1	1 Arc-Minute Global Relief Model
GA	Global Analogs
GIS	Geographic Information System
HHWLT	Higher High Water Large Tide
HHWMT	Higher High Water Mean Tide (MMHW in USA)
ISEC	Inundation Science and Engineering Cooperative
LG EPAC	Local Government Emergency Program Advisory Commission
LiDAR	Light Detection And Ranging
LLWLT	Lower Low Water, Large Tide (MLLW in the USA)
LZ	Locked Zone
MHHW	Mean Highest High Water (HHWLT in Canada)
MLLW	Mean Lower Low Water (USA - LLWMT in Canada)
MSL	Mean Sea Level (USA - MWL in Canada)
MT	Midpoint Transition
MWL	Mean Water Level (MSL in the USA)
NAVD29	North American Vertical Datum 1929
NAVD88	North American Vertical Datum 1988
NAVFAC	Naval Facilities Engineering Command
NEOWAVE	Non-hydrostatic Evolution of Ocean WAVE
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NTHMP	National Tsunami Hazard Mitigation Program
ODOT	Oregon Department of Transportation
TIN	Triangulated Irregular Network
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
UTM	Universal Transverse Mercator (Coordinate System)

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1. Background

The Capital Regional District (CRD) is located on the southern tip of Vancouver Island adjacent to the Cascadia Subduction Zone (CSZ) that runs from the coast of Northern California to Northern Vancouver Island and separates the Juan de Fuca and North America plates. This zone can produce very large earthquakes with magnitudes of 9.0 or greater which are known as Great Subduction Zone Earthquakes. This type of earthquake poses the largest tsunami threat to the area, and several studies and models have been completed in other areas adjacent to this zone using 9.0 magnitude CSZ earthquake scenarios. The importance of the 9.0 magnitude event was recognized at the project outset and identified as a requirement in the CRD's Request for Proposals.

Data from various studies shows a recurrence interval for great earthquakes of between 300 and 700 years with an average return period of 500 years. The last great rupture in 1700 generated a destructive tsunami reaching as far as Japan and reportedly produced extensive geological evidence on the west coast of North America. Despite the uncertainty associated with seismic activities, paleoseismic studies of tsunami deposits, tree rings, and coastal subsidence have established that at least seven great earthquakes might have occurred in the Cascadia Subduction Zone during the last 3500 years .

Many residents of the Capital Region live in coastal areas, and the region is also home to many parks and beaches that receive intensive recreational use from both residents and tourists. The combination of the high tsunami hazard, coastal habitation, and intensive recreational use creates the potential for very high tsunami hazard risk levels in the coastal regions in the Capital Region.

Previously the CRD had prepared simple mapping for a selected few areas within the region, including Greater Victoria, Saanich Peninsula and Port Renfrew/San Juan River estuary, which were considered to be at higher risk. However, these maps were based upon a single elevation for each area (4 m for Greater Victoria and Saanich Peninsula, and 20 m for Port Renfrew), and, in order to more properly help mitigate risk the CRD wanted tsunami mapping developed that would be based upon a more detailed, scientific approach and would specify potential tsunami inundation limits and run-up elevations. These could then be used for determining evacuation zones and for other emergency planning purposes.

Numerical modelling can provide an effective means to assess the impact of a great Cascadia tsunami for hazard mitigation and emergency planning. This report describes:

- selection of a 500-year earthquake scenario,
- numerical model used,
- development of digital elevation model (DEM) covering CRD,
- computed flow conditions along the CRD coasts,
- development of a continuous Tsunami Hazard Line, and
- other outputs and considerations for emergency planning and management.

2. Selection of 500-Year Earthquake Scenario

The Cascadia subduction zone extends 1100 km from Cape Mendocino in northern California to Vancouver Island in British Columbia. The US National Seismic Hazard Maps includes four rupture configurations at moment magnitude Mw 8.8, 9.0, and 9.2, each with a return period of 500 years.

Table 2.1 provides the joint probability distribution of the rupture configuration and magnitude in the event of a 500-year earthquake. Each configuration includes the entire locked zone (LZ), but may extend to the midpoint (MT) or the base (BT) of a plastic transition zone. In addition, global analogs (GA) of shallow-dipping subduction zones place the eastern boundary of the rupture at 123.8°W (near the Pacific coastline of Washington and Oregon states) around a depth of 30 km below the earth surface.

In all four configurations, the slip follows a uniform distribution in the locked zone and decreases linearly to zero across the respective transition zone (if present).

Table 2.1 – Relative Probability of Rupture Scenarios for a 500-Year Earthquake (from 2008 US National Seismic Hazard Maps)

Rupture	Moment Magnitude Mw			Total
	8.8	9.0	9.2	
LZ	0.02	0.06	0.02	0.10
MT	0.04	0.12	0.04	0.20
BT	0.04	0.12	0.04	0.20
GA	0.10	0.30	0.10	0.50
Total	0.20	0.60	0.20	1.00

The logic tree in the Pacific Northwest seismic source model assigns the highest occurrence probability of 0.5 to the GA rupture configurations and a total probability of 0.6 to the magnitude of Mw 9.0. In addition, the GA rupture at Mw 9.0 has the highest occurrence probability of 0.3 among the 12 scenarios for tsunami modelling, thus representing the most likely magnitude and rupture for a 500-year earthquake. This then represents the rupture scenario selected for tsunami modelling.

Figure 2.1 shows the slip distribution over the rupture area and the vertical displacement of the earth surface. The rupture is modelled by 550 planar faults and the slip distribution is computed from the seismic moment using 3×10^{11} dyne/cm^2 for the rigidity. The 15.4 m slip in the locked zone is equivalent to 428 years of strain at the current subduction rate of 36 mm/year and is representative of a great Cascadia earthquake that might occur within the next 100 years.

Superposition of the planar fault solution provides the earth surface deformation. The rupture produces 6.2 m of uplift along the trench and up to 1.5 m of subsidence (sinking of land level) on the western side of Vancouver Island. **Figure 2.2** provides a close-up view of the earth surface deformation around Vancouver Island. The subsidence decreases from approximately 1 m at Port Renfrew to 0.2 m at Victoria. When considering tsunami impacts on ocean water level, subsidence of the land effectively acts to raise the water level due to tsunamis; that is, subsided lands will be more at risk to tsunami inundation than prior to the earthquake and land subsidence.

Judging from the uplift and subsidence, the tsunami modelled from the selected earthquake should cover the lower 50th percentile (half) of the 12 rupture scenarios in terms of the potential tsunami impact. It also produces the best agreement with the extent of 3,500 years of paleotsunami deposits in Siletz Bay, Oregon (Cheung et al., 2011).

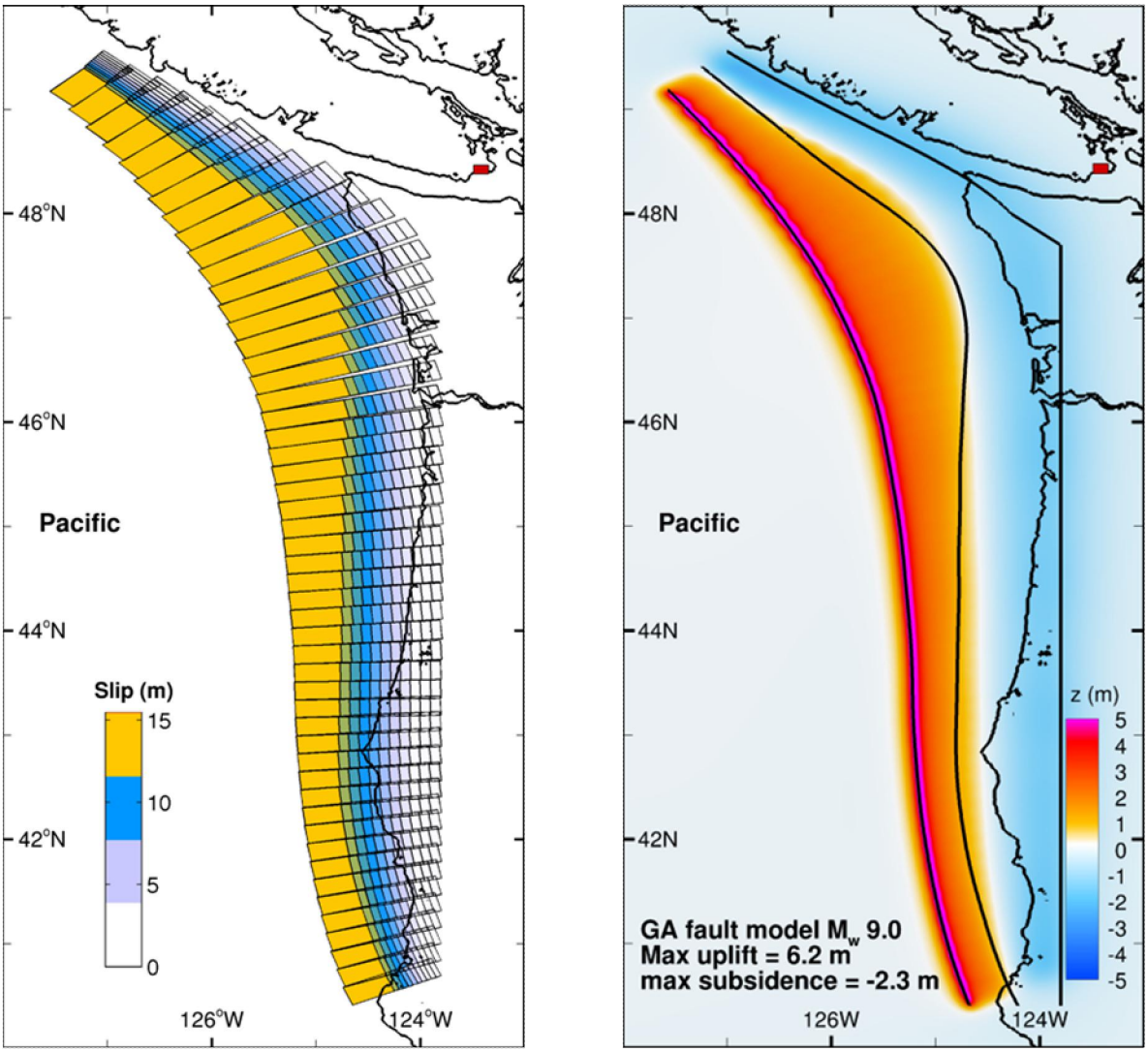

Figure 2.1 – Slip Distribution at the Rupture Plane and Vertical Displacement of the Earth Surface

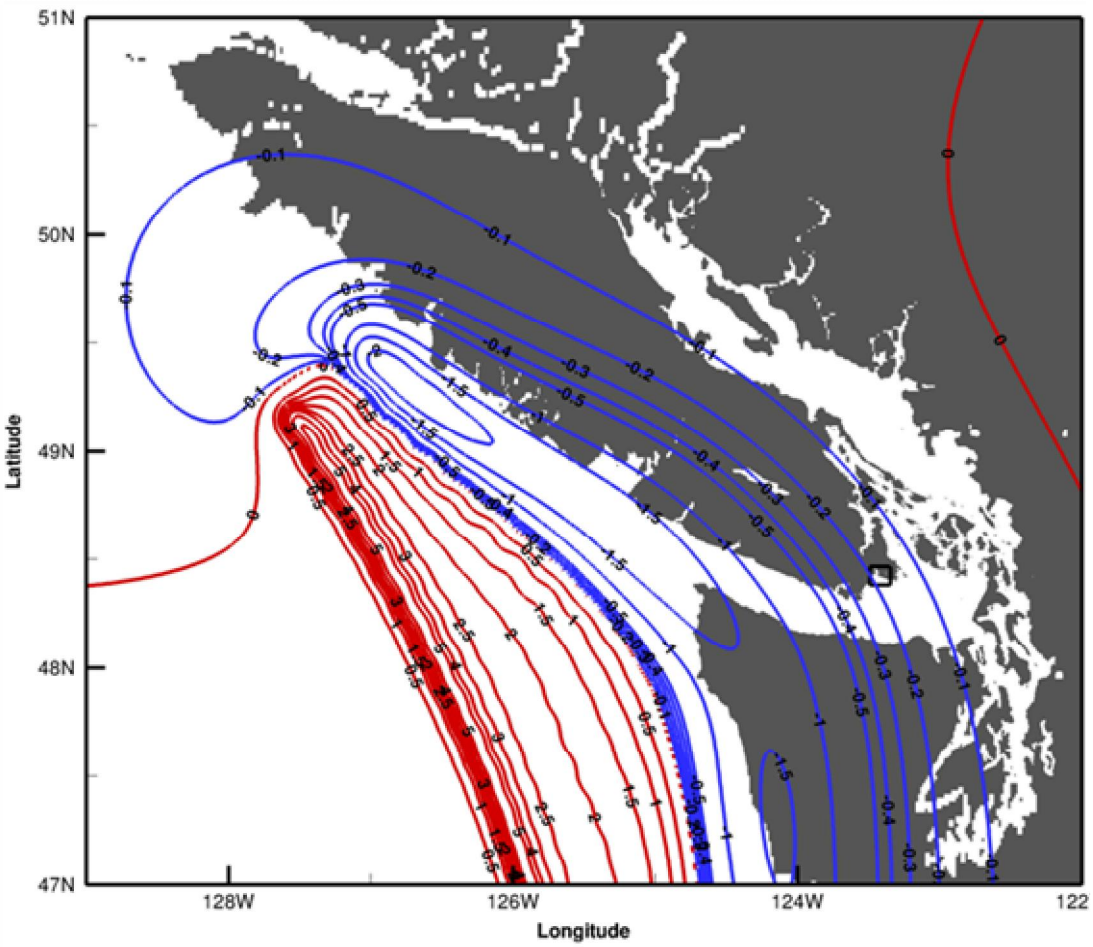

Figure 2.2 – Uplift and Subsidence in metres - near Vancouver Island

For comparison, it should be noted that Cherniawsky et al (2007) utilized a rupture scenario similar to BT to investigate impacts of tsunami waves and currents on southern Vancouver Island coasts. They considered 19 m of slip in the locked zone for a 520-year earthquake and admitted their value represents an overestimate for an event that might possibly occur in the immediate future.

3. Tsunami Model

The model selected and used for the tsunami inundation mapping of the Capital Region District is NEOWAVE (Non-hydrostatic Evolution of Ocean WAVE). This is a depth integrated model for wave propagation, transformation, breaking and run-up developed by researchers at University of Hawaii and University of Alaska led by Dr. Cheung, who was the lead modeller for this project.

NEOWAVE was entered in the 2009 Benchmark Challenge at the Inundation Science and Engineering Cooperative (ISEC) community workshop sponsored by National Science Foundation. This is the premier workshop in the tsunami inundation modelling community that was held only four times since 1990. NEOWAVE correctly reproduced the energetic breaking waves and hydraulic processes over a complex reef system in the Tsunami Wave Basin at Oregon State University and won the competition from the seven numerical models developed in the U.S. and Europe, including: GeoCLAW, Bouss2d, Delft3d, MOST, FUNWAVE, and SELFE.

NEOWAVE has been validated against the benchmarks put forth by the National Tsunami Hazard Mitigation Program (NTHMP) and is approved by NOAA for use in tsunami flood hazard mapping for evacuation and planning purposes. It also has been validated against water level and/or run-up data from recent tsunamis generated by the 2009 Samoa Earthquake, the 2010 Mentawai Earthquake, the 2010 Chile Tsunami, and the 2011 Tohoku Tsunami with a wide range of magnitudes from Mw 7.8 to 9.0.

Oregon Department of Transportation (ODOT) used NEOWAVE for modelling of 500-year tsunami for probabilistic design of coastal infrastructure in the Pacific Northwest. This study involved investigating tsunami design criteria for four bridges at Siletz Bay, Oregon by utilizing 12 scenarios of the 500 year Cascadia earthquake in the Pacific Northwest seismic source model of the National Seismic Hazard Maps. The model utilized four levels of two way grids with varying resolution to capture bathymetric features of a scale appropriate to the physical processes.

NEOWAVE has provided engineering design criteria for CVN (Aircraft Carrier) berthing facilities at Apra Harbor, Naval Facilities Engineering Command (NAVFAC) Guam. It is the official model for tsunami inundation mapping in Hawaii, American Samoa, the US Gulf coast states, and Puerto Rico. In addition, the UNESCO Inter-government Oceanographic Commission has distributed NEOWAVE to Chile, Peru, Eduardo, Colombia, and Nicaragua for development of tsunami warning guidance and inundation maps.

4. Development of Digital Elevation Model (DEM)

The NTHMP guidelines call for a grid size of 90 m or smaller for inundation mapping. The modelling for this project was performed using five levels of two-way nested grids as follows:

- Level 1 – northeastern Pacific Ocean using 1800 m grid size,
- Level 2 – Juan de Fuca Strait to the continental margin using 450 m grid size,
- Level 3 – entire CRD using 90 m grid size,
- Level 4 – Esquimalt Harbour, including Victoria Harbour, using 18 m grid size,
- Level 5 – Victoria Harbour, using 9 m grid size.

The decreasing grid size and area covered reflects an increasing level of detail to be applied to the analysis and results, which at the Level 3, 4, and 5 grids includes computation of inundation and wave run-up on initially dry land.

Modelling of tsunami propagation and inundation requires accurate bathymetry across the ocean and high-resolution topography near the coast. Due to there being several sources of information with varying degrees of accuracy, this was not completely the case for the CRD tsunami model.

AECOM used topographic and bathymetric data provided by the CRD and public sources to develop a seamless topographic-bathymetric (topo-bathy) Digital Elevation Model (DEM). The DEM forms a single surface that extends from open water up to a specified interior land surface elevation; an interior contour elevation of 10 m CGVD28 was used as the upland cutoff.

4.1 Approach

Six important steps in the development of the seamless topo-bathy DEM included:

1. Obtain and review data,
2. Establish a uniform horizontal and vertical reference frame (datum) for all of the various data sets by applying an appropriate datum conversion technique,
3. Prioritize and integrate (e.g., merge) the various data sets together into a single seamless surface,
4. Delineate a zero metre contour shoreline,
5. Build a TIN surface and sample the various model DEM grids from that surface,
6. Provide a bare-earth surface.

Each of these steps, along with challenges and hurdles, is described briefly in the following paragraphs.

4.2 Available Data

Data were obtained from many sources and adjustments were made to prepare the data for use. The following summarizes the data, sources, and adjustments, with the colour references indicating the spatial extent of the different datasets as shown in **Figure 4.1**.

1. CRD LiDAR (light green with outline) – AECOM received 483 text files containing LiDAR data (XYZ format); however, no metadata (e.g., data accuracy, projections, acquisition dates, 1 & 2 classifications) were available and without attribute field matching names on LiDAR files, a conversion had to be run to develop an index file.
2. CRD Mass Points and breaklines (red) – AECOM converted these data from a geodatabase format to a 3D shapefile; issues were discovered with some breaklines that were fixed.
3. Canadian NRC DEM (Canadian land area)(orange) – AECOM converted these data from 2D shapefiles to 3D shapefiles; a bounding polygon for these data was not provided and had to be created.
4. USGS DEM (US land area)(grey hillshade) – AECOM obtained these data from public sources; however, the data had to be reprojected from geographic to UTM coordinates and a bounding polygon had to be created for these data also.
5. CRD Victoria Bathymetric Data (light blue) –this information was obtained by CRD from the National Resources Canada, Canadian Hydrographic Service, Pacific Region; AECOM transferred into UTM coordinates and elevations were available as Chart Datum referenced to Victoria Harbour.
6. NOAA Coastal Relief Bathymetry Data (dark blue) – available as UTM coordinates but vertical datum did not match with Canadian sources and there is no direct transformation from US to Canadian elevations (see discussion that follows).

Several challenges were presented for the direct use of these data including:

- inconsistent vertical and horizontal datums,
- lack of bare-earth topography in LIDAR data,
- terrestrial and bathymetric data discontinuities, and,
- discontinuous zero metre shoreline delineation.

These challenges and resolutions are described in the following sections.

4.3 Establishing Vertical and Horizontal Datums

The methodologies selected for creating the seamless topo-bathy DEM required a uniform vertical and horizontal datum to integrate the various datasets into a single seamless surface. AECOM confirmed with the CRD that the vertical datum and units of the CRD data provided are in CGVD 28 (Canadian Geodetic Vertical Datum of 1928) and in metres, and that the horizontal datum and units of the CRD data provided are in UTM Zone 10N and that units are in metres.

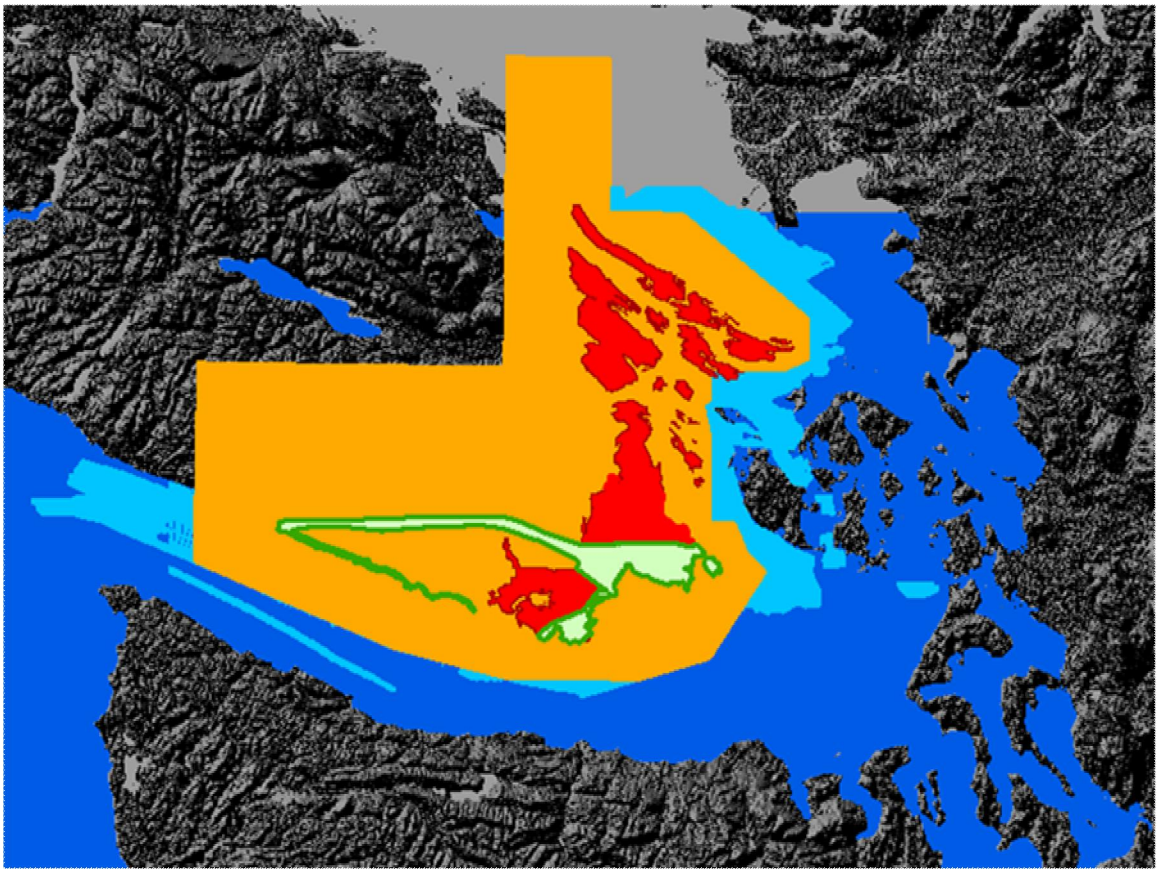

Figure 4.1 – Datasets Used in the Development of the DEM

4.3.1 U.S and Canadian Vertical Datums

Literature searches and discussions with U.S and Canadian government staff indicated merged U.S and Canadian topo-bathy datasets have been compiled only down to a 6 arcsecond level of resolution; however, this project required a 3 arcsecond (90 m) dataset. Therefore, finer resolution datasets were joined together, but vertical datum differences were observed between U.S and Canadian data. **Figure 4.2** shows a section across the Strait of Juan de Fuca and a sampling of U.S (blue) and Canadian (red) bathymetric data points within the red circle are shown in the bottom portion of the figure.

Inquiries with NOAA on 06/11/12 indicated, “there is no direct transformation from CGVD 28 to NAVD 88. In general CGVD 28 is considered about the same as NGVD 29…”. Therefore AECOM used the NOAA VERTCON tool (National Geodetic Survey, 2013) to estimate that NAVD88 elevations are approximately 1.09 m higher than NGVD29, and by association CGVD28. We also observed that the U.S. data are not always consistently higher in elevation than the Canadian data. However, this difference in bathymetric elevations was deemed insignificant for offshore tsunami wave modelling in strait with 90 m grid and depths greater than 100 m, and the values were used as presented.

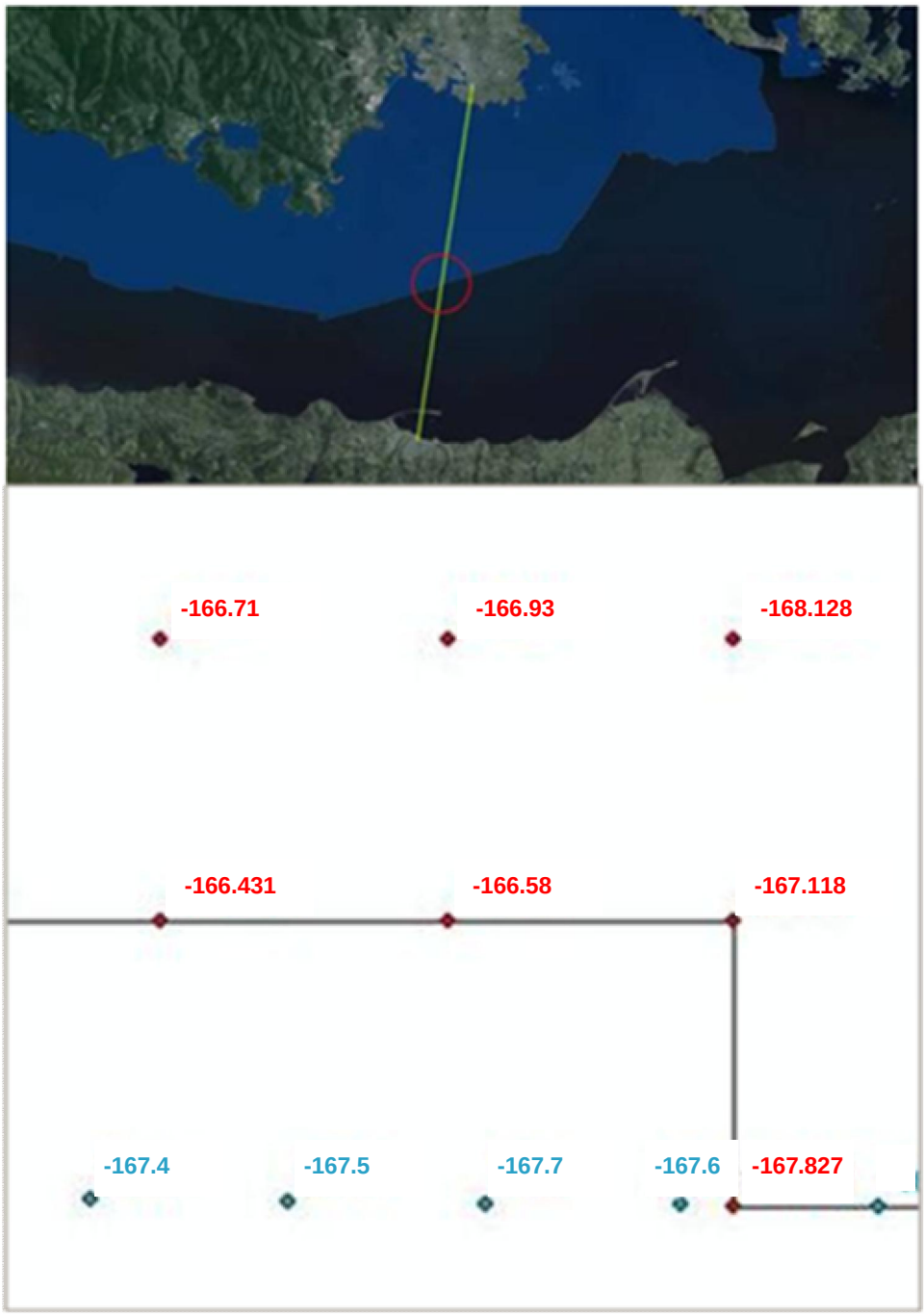

Figure 4.2 – US and Canadian Bathymetric Data

4.3.2 Local Tidal Datums

Modelling of tsunami propagation and inundation requires accurate bathymetry across the ocean and high-resolution topography near the coast. The source data includes the ETOPO1 Global Relief Model and Coastal Relief Model at 1 arcmin and 3 arcsec (~1800 and ~90 m) resolution obtained from the US National Geophysical Data Center. AECOM also prepared elevation datasets of the Juan de Fuca Strait, the Greater Victoria area, and Victoria Harbour at 50, 18, and 9 m resolution.

While the Global and Coastal Relief Models reference the mean sea level, the AECOM datasets use the chart datum (CD) in Canadian waters that were adjusted in the development of the digital elevation model. **Table 4.1** summarizes the benchmark elevation and water levels at Victoria Harbour from the Canadian Hydrographic Services. Contrary to U.S. practice, the water levels in Canada are derived from 19 years of predicted tides. The present sea levels are based on the 2010-2027 epoch.

The Canadian Chart Datum (CD) target is the Lower Low Water, Large Tide (LLWLT) as opposed to the Mean Lower Low Water (MLLW) used in the US. The AECOM datasets are adjusted uniformly to reference the Mean Water Level (MWL) at Victoria Harbour. This provides a reasonable approximation of the water level along the CRD coasts. However, due to variations in chart datums, the adjustment might not produce representative results for outlying areas such as the San Juan Islands and U.S. land areas in Puget Sound.

Table 4.1 - Benchmark Elevation and Water Levels at Victoria Harbour, British Columbia.

Reference	Elev (m) Referenced to Chart Datum	Elev (m) Referenced to Geodetic Datum
Benchmark 87C9766	7.282	5.401
HHWLT (average of annual highest tides)	3.124	1.243
HHWMT (MHHW in US)	2.613	0.732
CGVD28	1.966	0.085
MWL (MSL in US)	1.881	0.000
LLWMT (MLLW in US)	0.769	-1.112
CD	0.000	-1.881
LLWLT (average of annual lowest tides)	-0.083	-1.964

Bathymetry is usually referenced to the CD, while topography is referenced to the MWL or geodetic datum; however, the MWL and geodetic datum are practically the same at Victoria (difference is 0.085 m or 8.5 cm). Since the CRD LiDAR elevations are based on the CD, land elevations were reduced by 1.881 m to align with MWL in the vicinity of Victoria Harbour.

This resulted in a potential downward offset of 1.881 m in the land elevations in the Level 3, 90 m grid areas, depending upon the source of original data. This was considered reasonable for general hazard assessment since it was expected that this offset would not noticeably change tsunami wave heights and, ultimately, maximum water levels. The lack of a significant variation in predicted maximum water levels was confirmed by performing the tsunami modelling using both datums. It is the maximum water level that is later used to derive the Tsunami Hazard Line, which is entirely referenced to the geodetic datum.

4.3.3 Terrestrial and Bathymetric Data Discontinuities

As the datasets were converted to a common vertical and horizontal datum, it was observed that the CRD terrestrial LiDAR data overlapped with the Canadian NRC DEM bathymetric data. As a result, LiDAR data created an unnatural "shelf" **(Figure 4.3)** because the water surface at the time of flight was captured in the LIDAR data, showing a "flat" surface at approximately 2 m elevation for all ocean areas. Because the LiDAR was considered to be most accurate and therefore assigned a higher priority in terms of which data could be relied upon at which locations, the unnatural flat surface or shelf resulted in erroneous data that would significantly impact the shoreline effects of the tsunami model. To correct this a zero metre elevation shoreline was used to trim the LiDAR terrain data back and allow the merged bathymetric data to take priority in those areas, as approximated by the red dashed line in **Figure 4.3**.

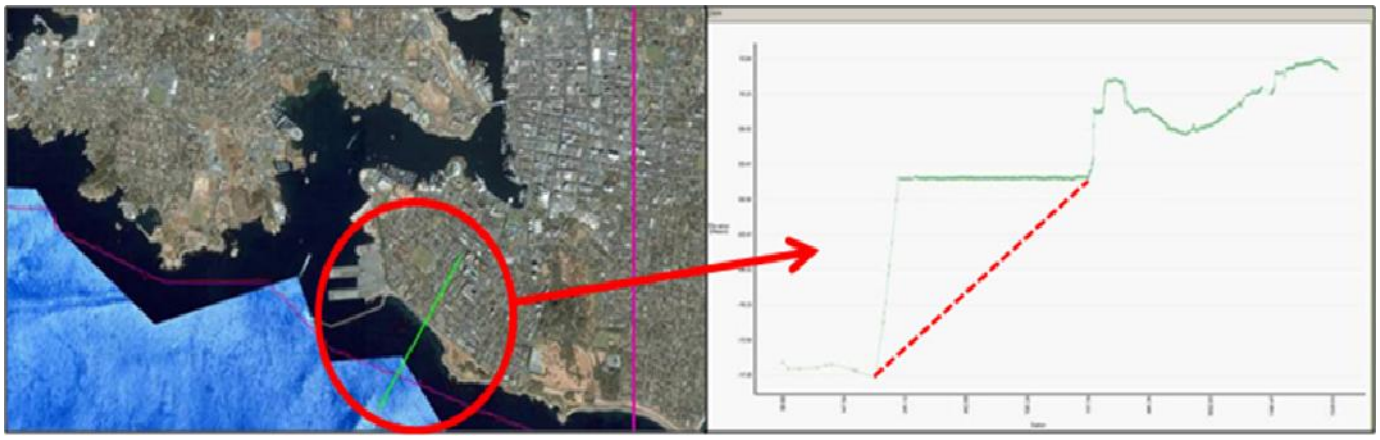

Figure 4.3 – Example of Topo-Bathy Data Overlap Challenges

4.4 Data Integration

Integrating all of the various survey data was a significant and major step in developing the seamless topo-bathy DEM. Data integration consisted of combining or merging data sets into a single, continuous surface. **Figure 4.1** shown earlier, shows how the various datasets were merged with the prioritized data on top of other data; the following data were used in prioritized order:

1. CRD LiDAR – Light Green with Outline
2. CRD Mass Points and breaklines – Red
3. Canadian NRC DEM (Canadian SIDE) – Orange
4. CRD Victoria Bathymetric Data –Light Blue
5. NOAA Coastal Relief Bathymetric Data – Dark Blue

4.5 Shoreline Delineation

As noted, the delineation of a shoreline, defined as the zero metre contour, was intended to be used to clip back the LiDAR data to prevent the erroneous points reflected back from the water surface from being used in the final DEM. However, on the zero metre contour made available to AECOM as a shapefile from the CRD, the shoreline was discontinuous along the coast **(Figure 4.4- left)** and some islands were not included in the zero metre contour **(Figure 4.4 - right)**.

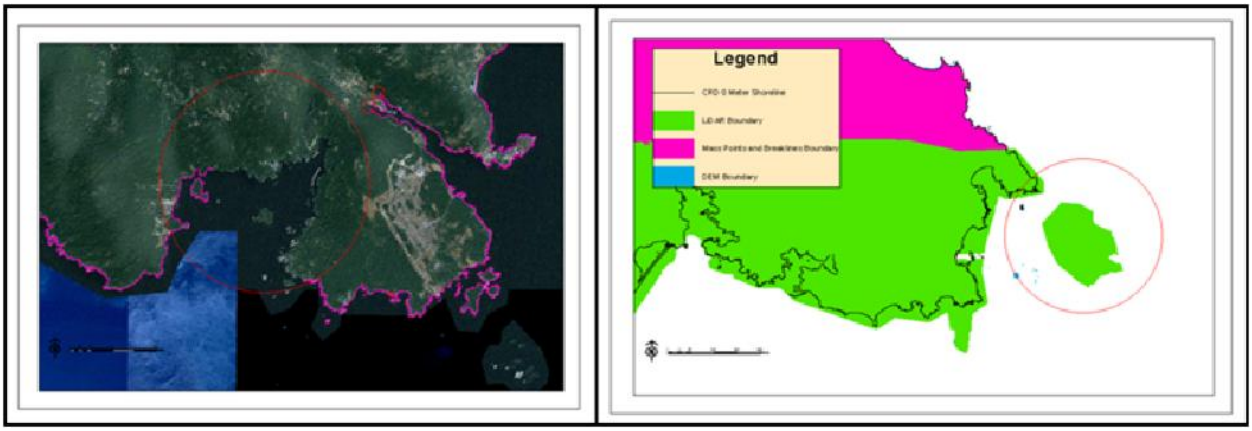

Figure 4.4 – Shoreline Challenges including Discontinuities (left) and Missing Islands (right)

At the request of the CRD, AECOM completed the process of establishing the zero metre contour in the areas with LiDAR, including:

- closing all gaps in the CRD coastline;
- adding the river at Port Renfrew; extending the Inner Harbour; and,
- adding large islands that were not previously included in the CRD DEM.

Figure 4.4 (right) shows an example of a large missing island (missing from the shoreline file) and this was digitized where LiDAR data exist; i.e., the green areas. Islands were included where they are larger than approximately 270 m (or three 90-m Level 3 DEM grid cells); e.g., as a rule of thumb, islands that are smaller than about 3 times the grid size can be omitted from the tsunami model grid.

Once the LiDAR topography was separated from the bathymetry using the zero metre contour in the areas with LiDAR, the continuous zero metre shoreline was used to separate bathymetry from topography in the areas with mass-points/breaklines. The shoreline for the mass-points and breaklines data is over 65,000 m in length.

4.6 Build TIN Surface

Then the CRD and USGS DEMs were clipped to the new shoreline and the more dense bathymetric data in the new 9 m and 18 m grids were added, prioritizing it into the CRD and NOAA bathymetric data, and removing all the bathymetric data that has topographic data on top. At this point the TIN surface was built using an automated computer process from which the various grid sizes of the DEM were sampled. Due to the large amount of data involved this process required the use of four very powerful micro-computers calculating continuously for approximately two weeks.

Figure 4.5 provides a screenshot of the resulting DEM including the 9 m grid (red border), 18 m grid (black border), within the 50 m grid and with the shoreline shown for reference.

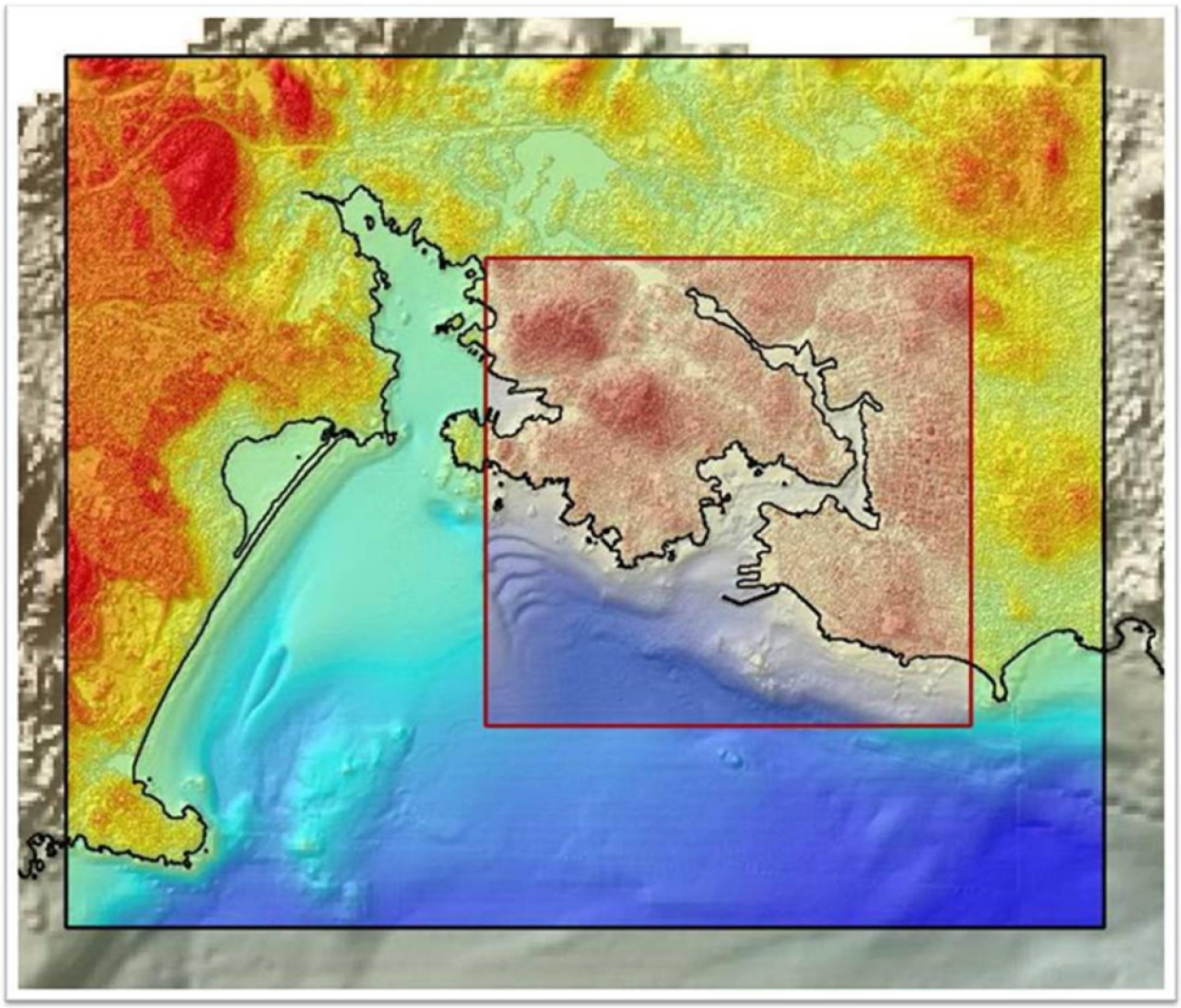

Figure 4.5 – Nested Model Grids with Final Shoreline

4.7 Bare-Earth Topography

The final step in the processing of land-side topographic data was to prepare the DEM for bare-earth topography. In the original data, buildings and vegetation from LiDAR surveys were visible in the LIDAR datasets. Since tsunami models treat buildings and vegetation as solid blocks, their inclusion would artificially reflect incoming waves and unduly restrict flows. With permission from CRD, buildings and vegetation were filtered out from the DEM. The algorithm systematically replaced building and canopy elevations by those of adjacent roadways and open areas. **Figure 4.6** shows the unfiltered (left panel) and filtered (right panel) land surface for inundation modelling in the Greater Victoria area. A comparison with the original data shows minimal effects of the filtering algorithm on the topography. The use of bare-earth topography is consistent with, and recommended by, the NTHMP Modeling and Mapping Guidelines.

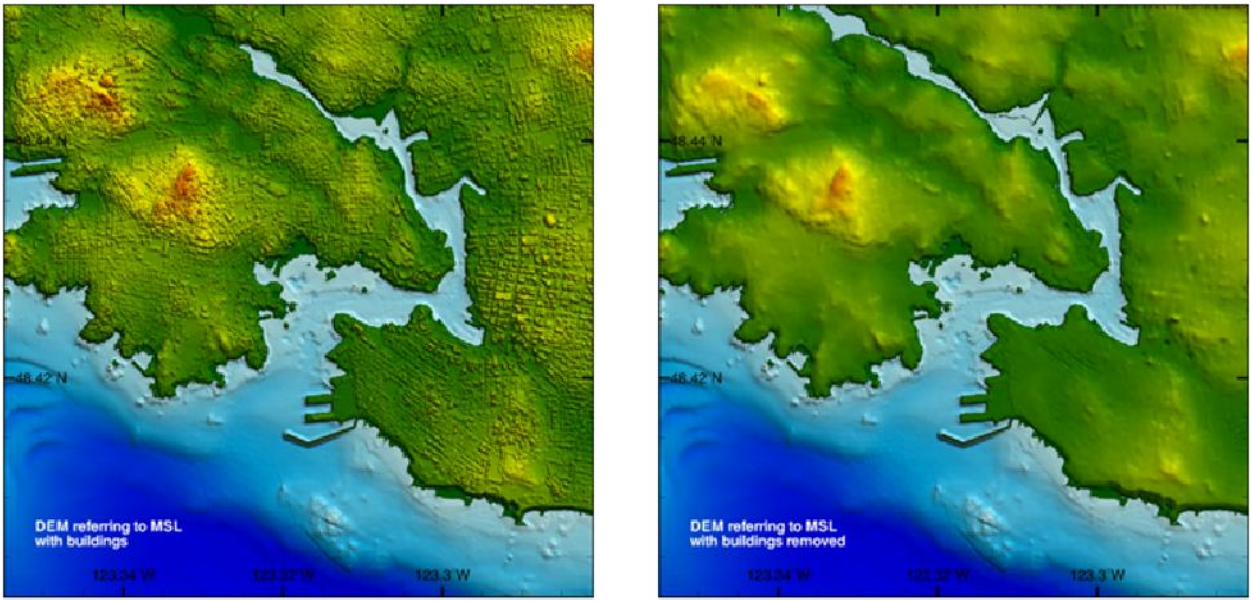

Figure 4.6 – Conversion to Bare-Earth Topography

4.8 Summary

The preceding pages summarize what proved to be an extensive and, at times, labour-intensive process. However, the effort required to provide a continuous coastline and seamless topographic-bathymetric DEM was essential for the tsunami modelling, to provide accurate and realistic results.

The process of assembling the DEM is never simple, and it is inevitable that inconsistencies will exist. Although establishing a uniform reference frame will reduce the error in the final DEM, it will not eliminate all data mismatches in the merged data set. Additional potential sources of errors stem from differences in the collection date, as the morphology and topology of the area is likely to change over time, particularly in dynamic coastal systems, and after extreme events such as floods.

Having stated that, it should also be noted that the assembled continuous, seamless dataset is much better information than the CRD possessed prior to this assignment and effort. Its existence now creates other opportunities for the CRD (and possibly, its member municipalities and stakeholders) to undertake other investigations and reviews or, simply, related to mapping purposes near the coasts. However, it should be noted that the DEM still relies on some old topography (NRC DEM) for a large portion of the region outside of the Level 4 (18 m) and level 5 (9 m) grid areas, and that the original source(s) of this information are often unknown.

5. Tsunami Modelling Results

5.1 Maximum Water Levels

The NEOWAVE model was run for 8 hours of event time to capture potential resonance over the continental margin and in the Strait of Juan de Fuca. The computation was performed using the base water level of Higher High Water Mean Tide (HHWMT). **Figure 5.1** shows the maximum surface elevation from the five levels of nested grids. The maximum surface elevation references the MWL and thus includes 0.732 m of tides corresponding to the HHWMT, i.e., maximum water level is not the wave height, which is smaller. While subsidence will also have an impact, it acts to lower the land elevation, making subsided land more at risk to tsunami impacts; however, it does not change the water level calculations, so that the water-level definitions, such as MWL and HHWMT, remain unchanged by the earth surface deformation.

5.1.1 Levels 1 and 2 Grids

The tsunami transforms over the continental shelf and maximum water levels reach 6 to 9 m elevation along the open coast of western Vancouver Island modelled at 15 arcsec (~450 m) resolution. After subtracting the tide level, the coastal wave amplitude is consistent with the 5 m of run-up inferred by Clague et al. (2000) from the spatial distribution of the deposits of the 1700 Cascadia tsunami. Although the run-up would be higher at heads of inlets and embayment, the agreement of the results along the open coasts of Vancouver Island renders additional support for the selection of the GA rupture scenario for the tsunami hazard assessment.

5.1.2 Level 3 Grid

The Level 3 results provide a reasonable depiction of the water level along open coasts, but might underestimate the run-up at inlets and waterways not resolvable at the 90 m grid. The model shows rapid attenuation of the energy as the tsunami enters the Strait of Juan de Fuca. The maximum water level reduces from 3.1 m at Port Renfrew to approximately 2.4 m at Victoria.

The maximum water level continues at 2.2 m along the relatively sheltered Saanich Peninsula coast because of local shoaling. Similarly, the water level builds up to over 3 m on either side of the Strait of Juan de Fuca with shallow water along the coast. An exception is at Race Rocks, where the shoals and outcrops accelerate the flow and lower the water surface locally. The model captures the build-up of the water level at Sooke Inlet and the formation of a weir at the entrance to Sooke Basin, where the water level is discontinuous.

As the tsunami exits the Strait of Juan de Fuca and enters the Strait of Georgia, its amplitude decreases to less than 1 m along the coasts. The lack of energetic wave activities provides an explanation for the absence of tsunami deposits in the region as reported by Clague et al. (2000).

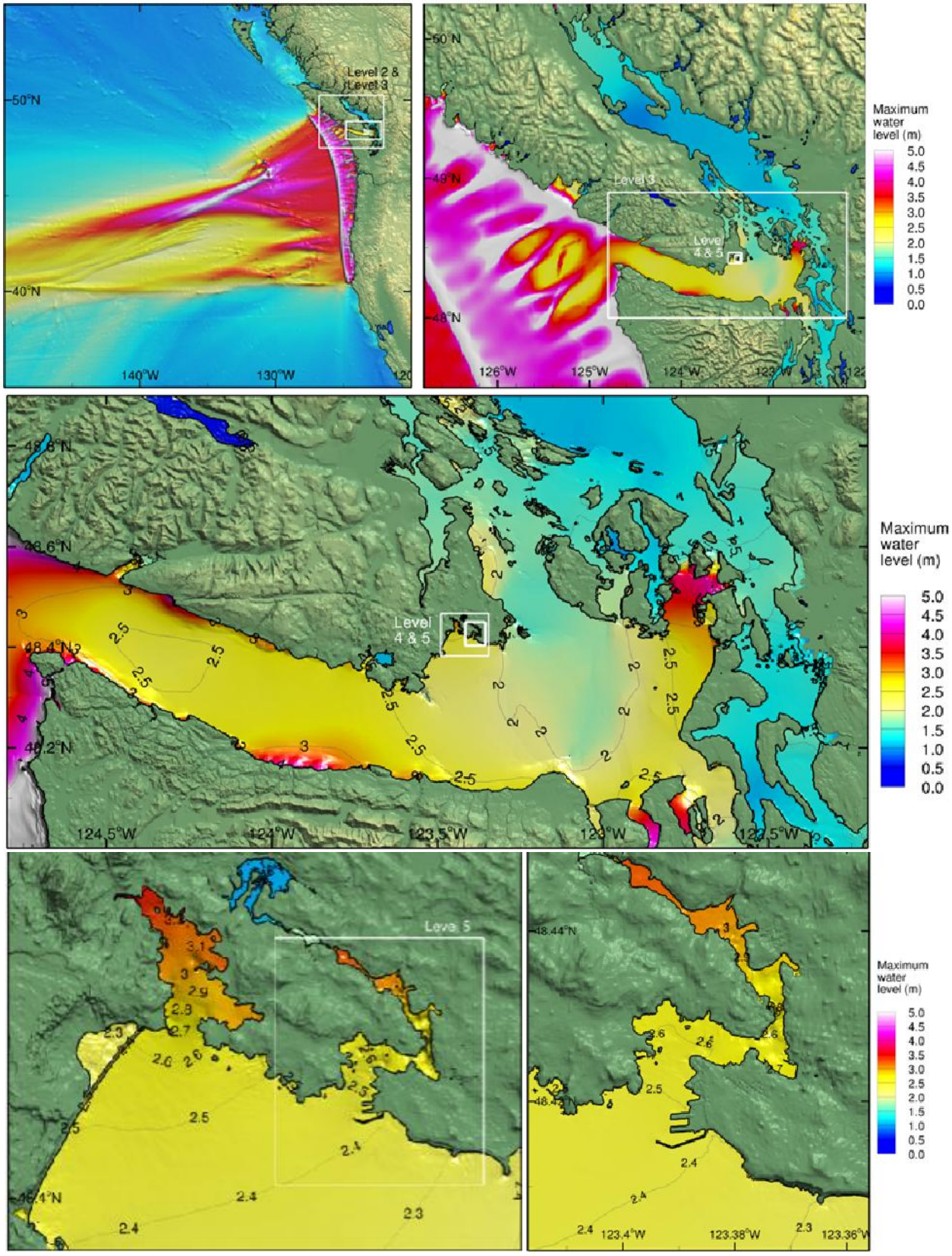

Figure 5.1 – Maximum Surface Elevation above MWL

5.1.3 Levels 4 and 5 Grids

The Level 4 to 5 grids provide detailed flow conditions in the Esquimalt Harbour and Victoria Harbour areas that cannot be resolved by the 90 m grid at Level 3. The computed maximum water levels, which are consistent with those from Cherniawsky et al. (2007), do not show widespread inundation in these areas. The tsunami overtops the barrier of Esquimalt Lagoon, where the water level increases to 2.3 m, and there are resonance effects in Esquimalt Harbour, so that the surge at the head of the embayment reaches 4.3 m above MWL. The water level increases from 2.5 m at Victoria Harbour to 3.1 m in Gorge Waterway with minor inundation at pockets of low-lying areas. Weirs are formed at a couple of locations along the waterway, where the flow is discontinuous. The tsunami does not overtop the cruise ship terminals and the harbour promenade areas, which have a pre-rupture elevation of about 3 m above the MWL.

For comparison, the maximum water level associated with the 2011 Tohoku tsunami was approximately 40 m measured at a cliff on the Iwate coast.

5.2 Water Level Drawdown

Along with potential flooding and inundation there are also effects due to water levels dropping during the complete tsunami cycle. The drawdown in harbours and waterways during a tsunami may ground vessels and damage berthing facilities.

Figure 5.2 shows the computed drawdown from the initial still water level in the level 3 to 5 grids. Although the computation was performed at HHWMT, the results provide an indication of navigational hazards should a tsunami occur at a lower tide level. The drawdown is much smaller than the wave amplitude along the Strait of Juan de Fuca, but increases dramatically over shallow shoals and embayments. Port Renfrew experiences up to 1.4 m of drawdown. The value increases from 1.2 m at the Esquimalt Harbour entrance to 2.0 m at the head of the embayment in association with the first mode of resonance oscillation. Victoria Harbour, which is less prone to resonance because of its irregular geometry, experiences relatively uniform drawdown of 1.1 m extending through most of the Inner Harbour, Upper Harbour, and Gorge Waterway.

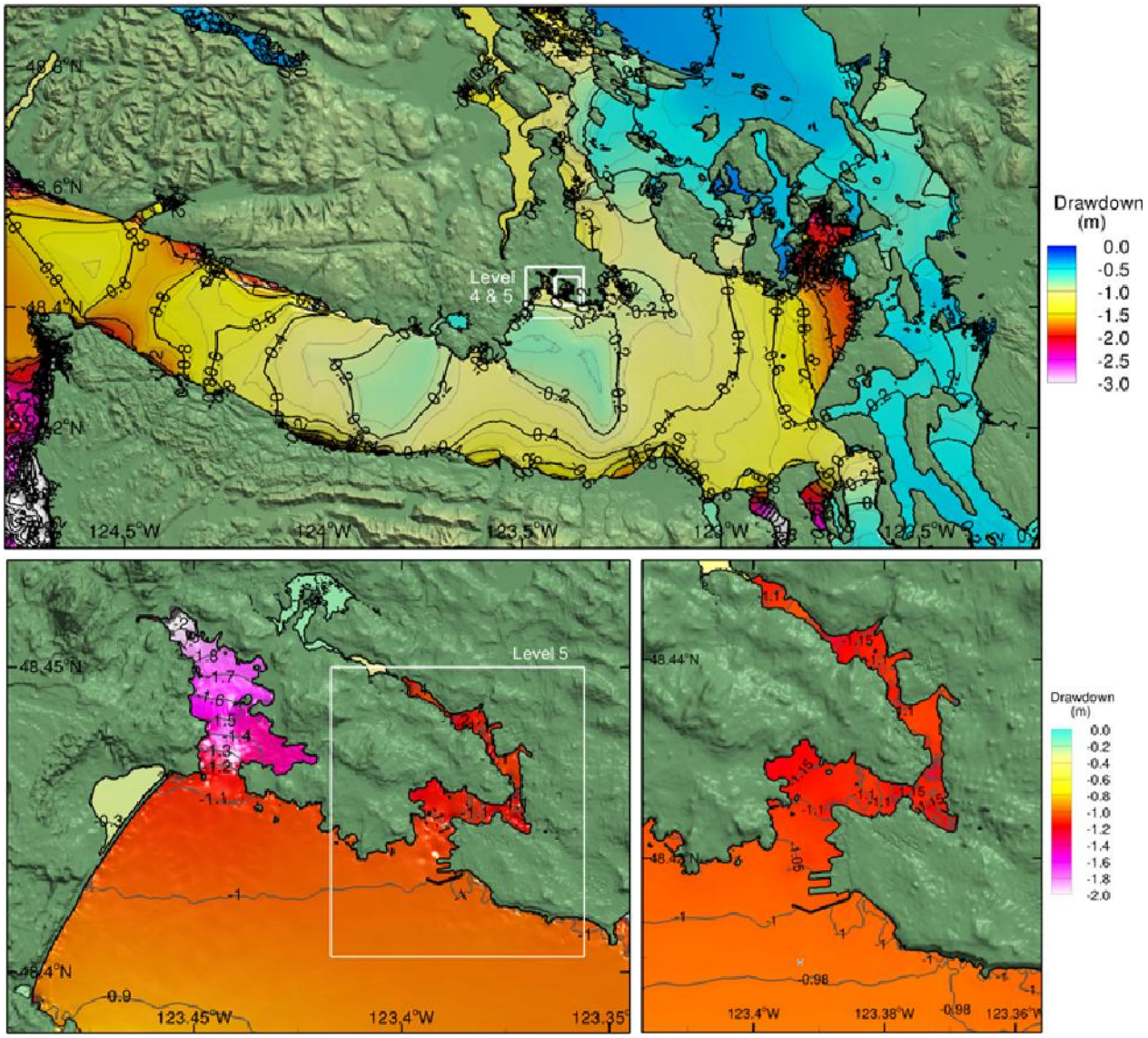

Figure 5.2 – Maximum Drawdown of Water Level

5.3 Tsunami Water Flow Velocities

Tsunamis can generate damaging flow velocity conditions (similar to water currents) in harbours and waterways even when there is only nominal inundation on land. NEOWAVE is the only NTHMP-approved model that has been validated with measurements of coastal currents generated by a tsunami (Yamazaki et al., 2012b).

Figure 5.3 plots the maximum water flow speed in the Level 3, 4, and 5 grids. The Level 3 grid at 90 m resolution provides a reasonable depiction of the currents over large coastal features. The current in the Strait of Juan de Fuca is typically less than 1 m/s, but increases to over 2 m/s in inlets and waterways. High flow speeds of 2.7 and 2.4 m/s develop at Port Renfrew and Sooke. The jet into Sooke Basin is reasonably determined and depicted.

Further east, the model captures the flow speed increase 3.1 m/s at Race Rocks, where the tidal currents are known to generate strong eddies. Tolkova (2012) indicated that a tsunami in a strong tidal river can be amplified when propagating into the ebb flow after a high tide. However, recent studies by Tolkova (personal communication) showed that the nonlinear tide-tsunami interaction is almost negligible in the Strait of Juan de Fuca

The Level 4 grid at 18-m resolution provides the water flow speed at more refined coastal features. The model depicts the inflow and outflow jets at Witty's Lagoon near Albert Head as well as high speed flows over the barrier and at the inlet of Esquimalt Lagoon. The flow speed increases to 3.2 m/s at the entrance to Esquimalt Harbour, where a node is developed from the standing wave. Local acceleration of the flow is evident in the upper reach of the basin, where small islands and outcrops produce constrictions of the flow.

The level 5 grid provides detailed water flow conditions at 9-m resolution in Victoria Harbour and Gorge Waterway. The inner and outer harbours show strong outflow jets reaching 3.4 and 3.1 m/s due to ponding of floodwater in the upper reach of Gorge Waterway and rapid withdrawal of the tsunami in Victoria Harbour after the initial wave.

The high-speed water flow from the tsunami could conceivably damage dock facilities and generate debris in the downstream region. The flow might also erode channels and inlets that in turn might modify the flood conditions computed from the current (fixed-bed) model. The impacts of these possible changes is unknown.

For comparison, the maximum water flow velocity associated with the 2011 Tohoku tsunami was approximately 12 m/s, as inferred from video images taken in Myagi.

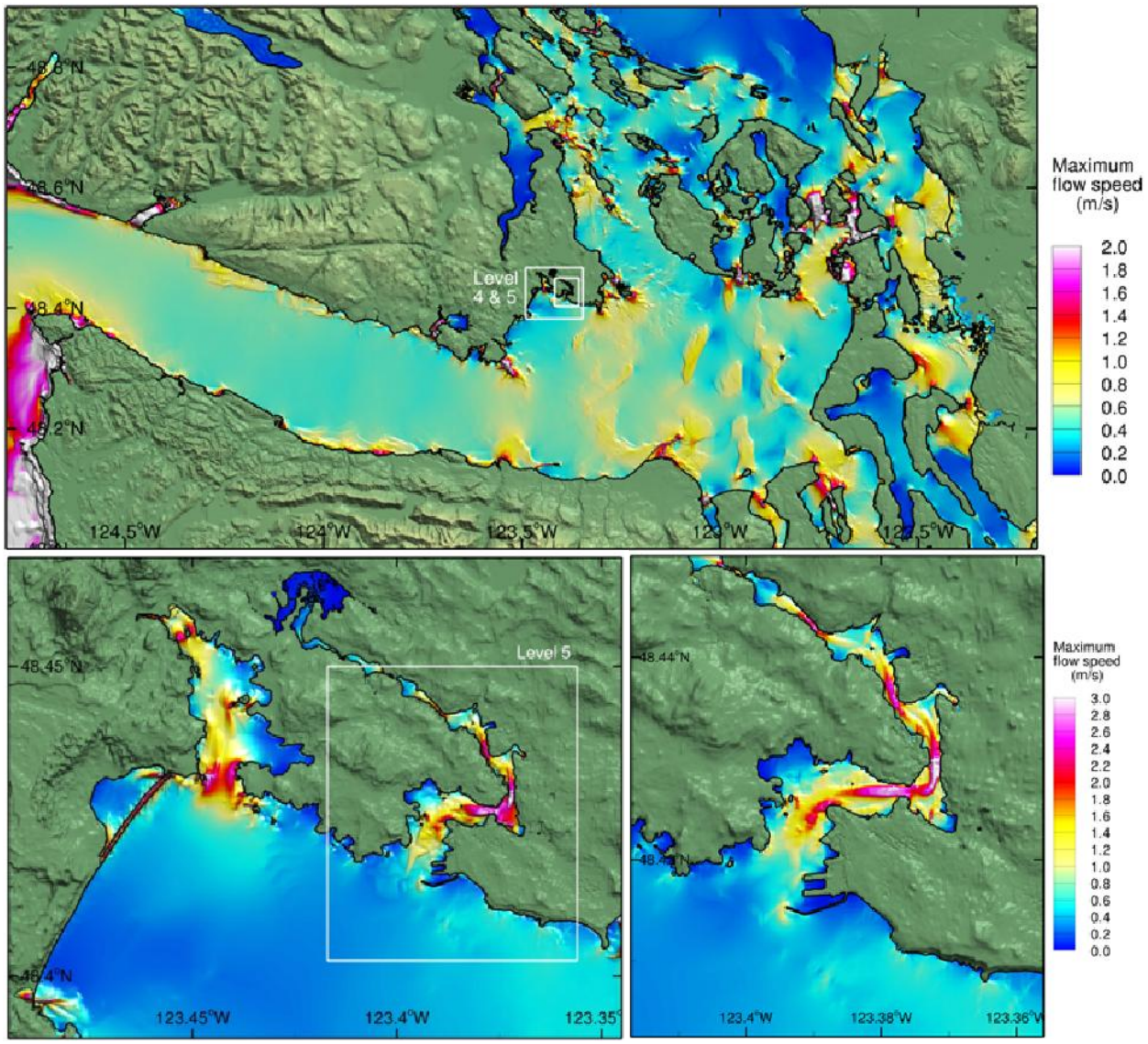

Figure 5.3 – Maximum Flow Speed in the Level 3, 4, and 5 grids

5.4 Tsunami Arrival Time

Tsunami arrival time is an important consideration in emergency planning and management.

Because of greater subsidence over the continental shelf, the water in the Strait of Juan de Fuca will retreat to the Pacific Ocean immediately after the rupture. Part of the initial wave generated by uplift of the continental slope will propagate toward the coastlines. Tsunamis are shallow-water waves, whose propagation speed given by $\sqrt{\boldsymbol{gd}}$, where $\boldsymbol{g}$ = 9.81 m/s^2 is acceleration due to gravity and d is the local water depth.

Figure 5.4 shows the time when the water surface rises above the initially subsided water level. The tsunami arrives at Port Renfrew in 45 min after the earthquake. Sooke sees the arrival of the initial positive wave 60 min after the earthquake. The wave reaches the entrances of Esquimalt Harbour and Victoria Harbour 76 min after the earthquake, while the formation of weirs delays the arrival of the flood waves along Gorge Waterway even further. Because of the shallow coastal water, the wave does not reach Sidney on the Saanich Peninsula coast until 110 min after the earthquake.

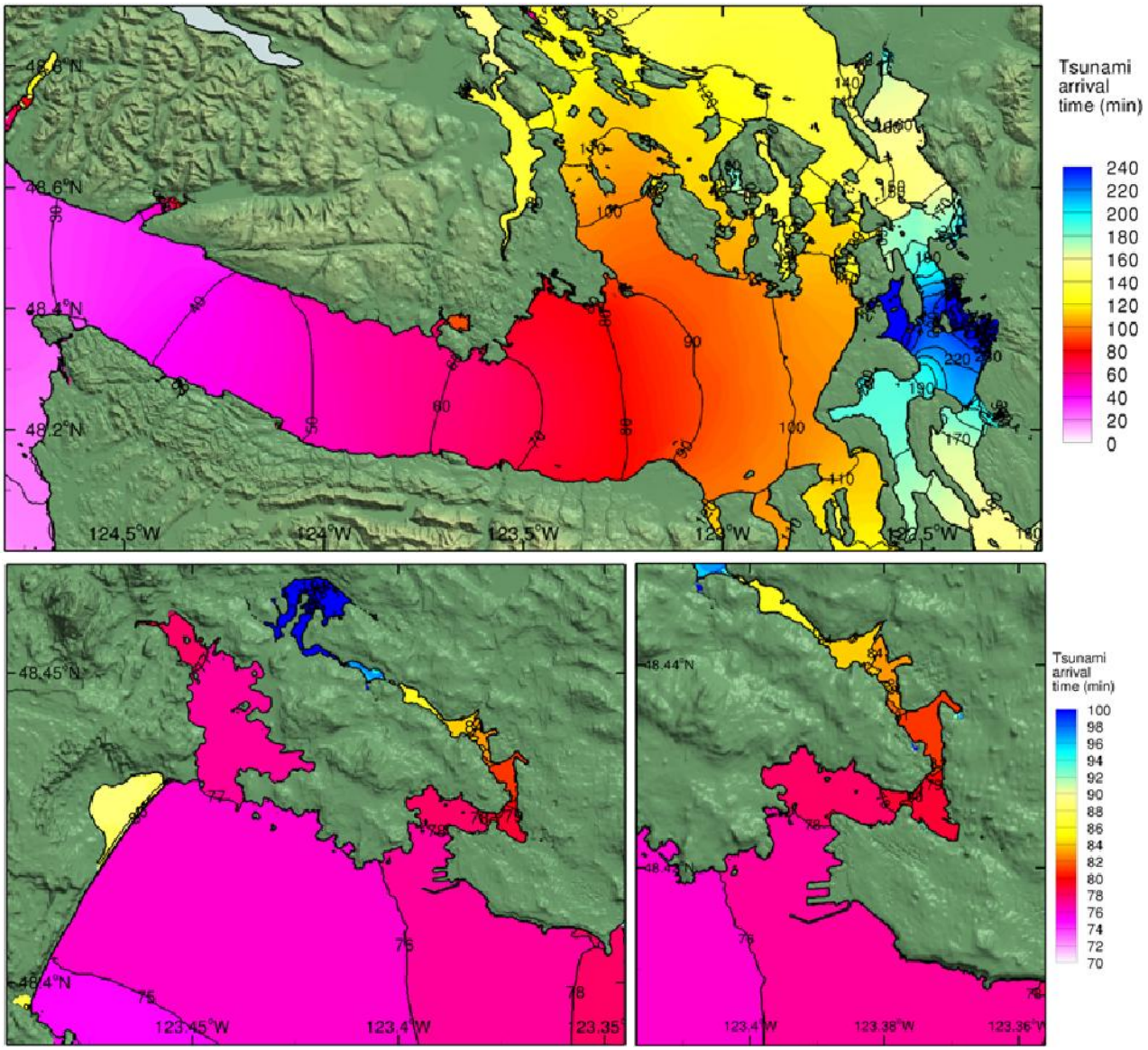

Figure 5.4 – Tsunami Arrival Time

5.5 Water Level Resonance and Time to Maximum Water Level

The continental shelves, straits, and embayments in southern Vancouver Island are prone to resonance caused by tsunamis. Constructive interferences from resonance modes have resulted in late arrivals of destructive waves in previous tsunami events.

Figure 5.5 plots the time to reach the peak water levels after the earthquake. The initial wave crest determines the peak water level at most locations along the Strait of Juan de Fuca. The water level at Port Renfrew reaches its peak in 60 min, however, the water at the head of the embayment takes another 60 min to reach the peak level. Similar, the peak flow reaches the Sooke channel in 80 min, but it takes another 60 min to fill the Sooke basin to the maximum level. This highlights the fact that a tsunami comprises a series of waves and subsequent arrivals might augment the amplitude of resonance oscillations.

The waters off Esquimalt and Victoria Harbours rise to the peak level in 95 min after the earthquake. The peak flow enters Victoria Harbour and the lower reach of Gorge Waterway almost instantaneously. In contrast, the resonance oscillation in Esquimalt Harbour reaches its peak 60 min later. Resonance and persistent wave activities occur around the Gulf Islands, so that the Saanich Peninsula coast does not see the peak flow until 166 min after the earthquake. The Strait of Georgia, which resonates with the longer period waves, does not exhibit the peak surface elevation for at least another 100 min.

Coastal resonance is a common occurrence during tsunami events. Standing edge waves formed along the continental margin have low dissipation rates and continue to send waves into the Strait of Juan de Fuca long after the rupture. Because of the semi-enclosed basin, the oscillations in the Strait of Juan de Fuca and Strait of Georgia might take many hours to subside.

From an emergency management perspective, it will be important to maintain the tsunami warning until the water level shows an obvious downward trend.

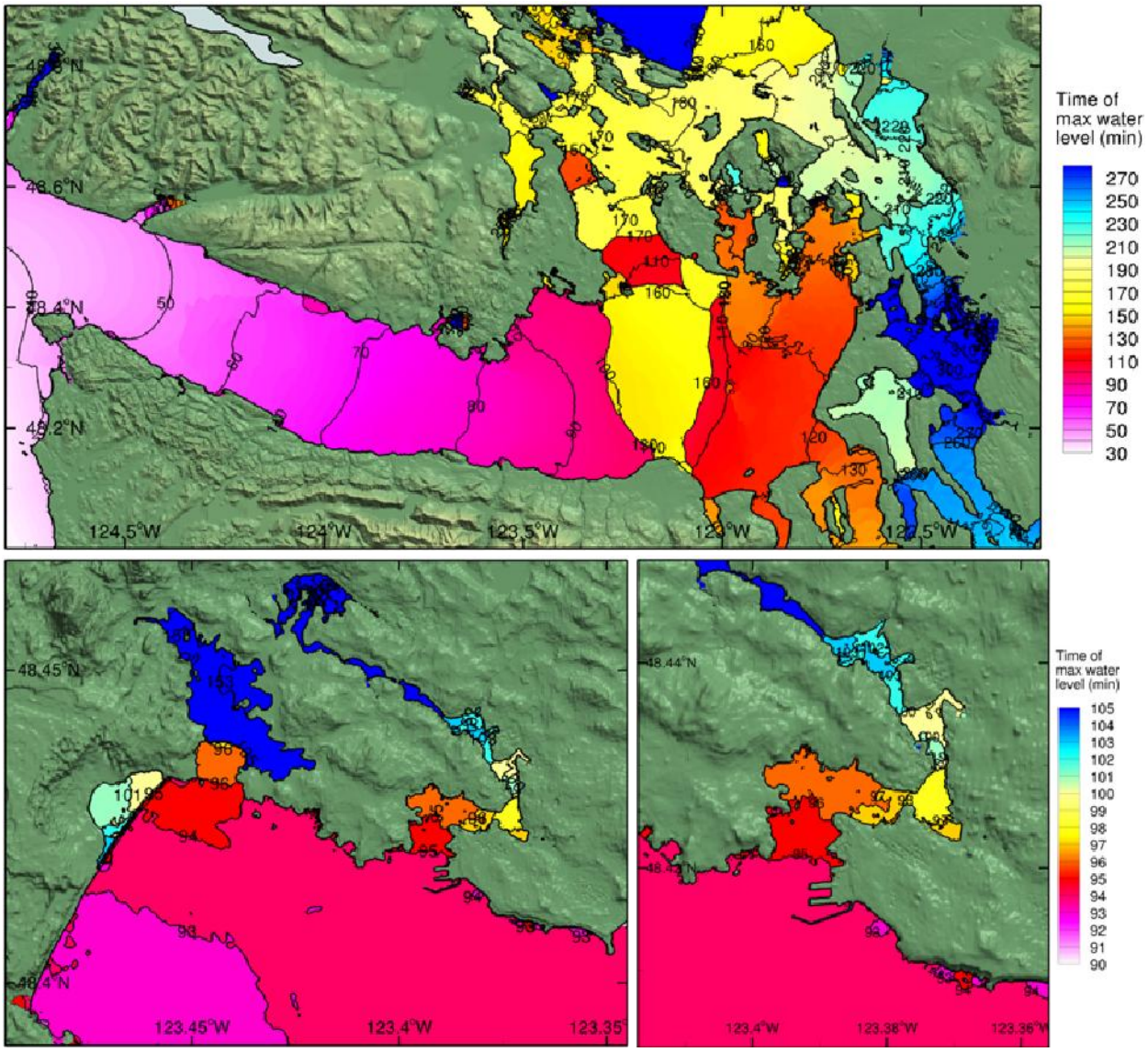

Figure 5.5 – Time to Peak Water Level After the Earthquake

6. Tsunami Hazard Line

6.1 Maximum Water in Conjunction with Subsidence

The tsunami model defines the time sequence of the event from the subsidence and uplift of the earth surface at the time of the magnitude 9.0 CSZ earthquake to propagation of the tsunami through the Straits of Juan de Fuca and Georgia. Maximum water levels and time to maximum water levels were identified in the previous section. Flood depths overland can demonstrate the risk of flooding for various CRD communities, industrial areas, waterfront facilities, critical facilities, and highway infrastructure.

Subsidence lowers the land elevation after the earthquake and exacerbates the subsequent flood hazards. Subsidence levels within the CRD were shown earlier in the discussion of the selection of the earthquake scenario, and vary from approximately 1.0 m near Port Renfrew to approximately 0.2 m near Greater Victoria.

Although the model already includes the earth surface deformation in the initial condition, presentation of the resulting water surface elevation relative to the subsided ground level provides a better indication of the tsunami flood hazard. **Figure 6.1** shows the maximum surface elevation augmented to include subsidence. Using this approach the determined flood level, which increases approximately by 1.0 m at Port Renfrew and 0.2 m at Greater Victoria, can be compared directly with the pre-event land surface elevation from the MWL for purposes of emergency planning and management.

6.2 Factor for Public Safety

As noted above, mapping has been prepared for all coastline locations within the CRD showing the combined impact of both water level rise due to tsunami and subsidence of the land mass. Both of these parameters vary across the region, so application of a single factor or total elevation is not appropriate.

To account for some of the variability of the input information AECOM also recommends that a Factor for Public Safety be included in the resulting calculations to determine the continuous Tsunami Hazard Line. Some of the variables that could impact the calculated results include:

- Uncertainty related to the magnitude event and the initial tsunami wave amplitude
    - While the earthquake event selected is the most likely event, other scenarios could result in higher initial tsunami wave amplitudes and higher maximum water levels within the CRD
- Tide variations
    - The base water level to which the tsunami wave amplitude has been added in this analysis is HHWMT (or MHHW in the US)
    - While this is supported and recommended by NTHMP, the tsunami could occur at another higher water condition
- Variablility of topographic information
    - While topographic information at the Level 4 and 5 grids is considered to have a high degree of accuracy, much of the topographic information for the CRD total coastline is of varying quality and the original source of the information is unknown.

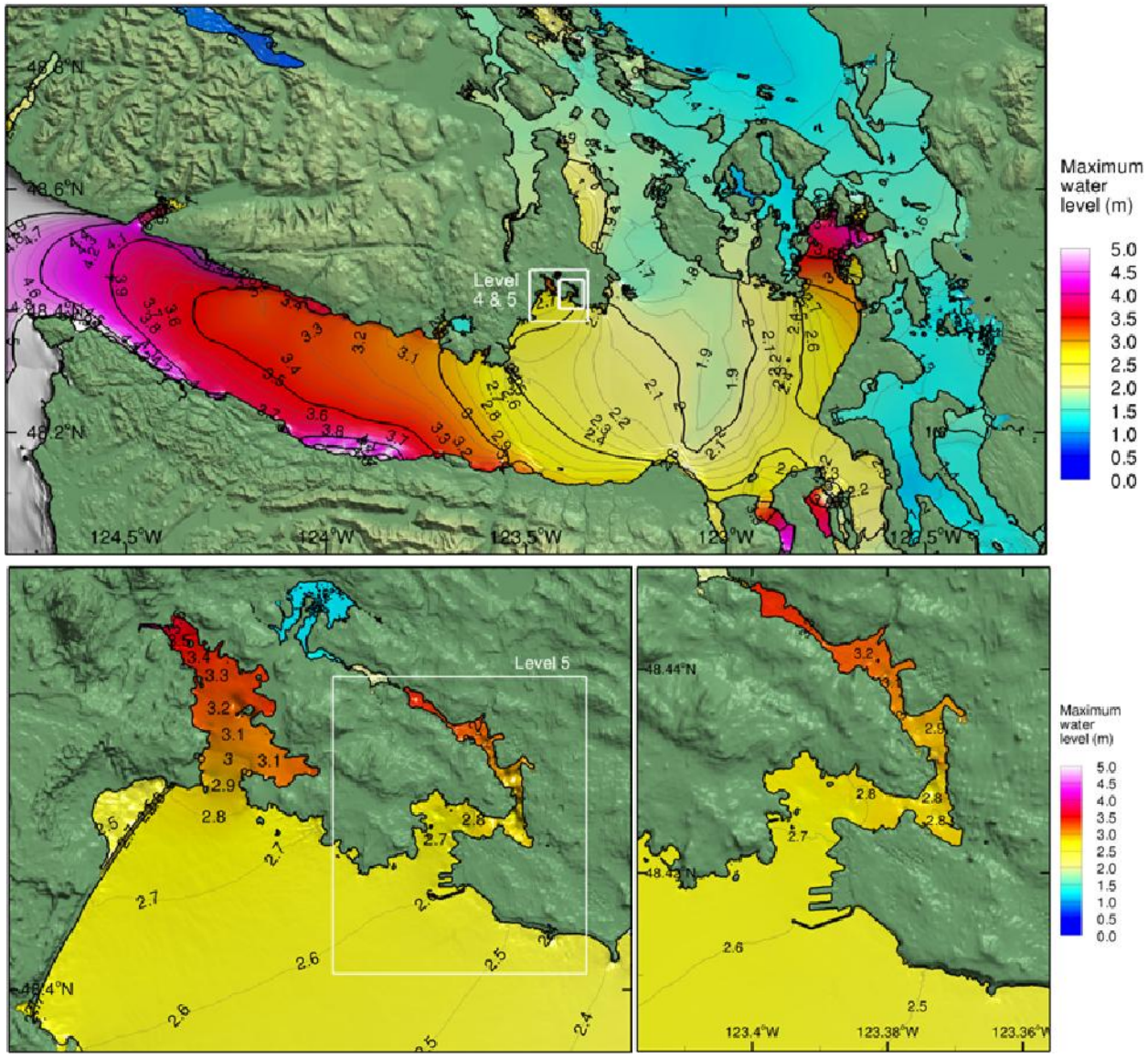

Figure 6.1 – Maximum Water Level from MWL Augmented to include Subsidence

For these reasons AECOM is recommending that a Factor for Public Safety of 50% be added to the calculated combination of maximum water level rise and land subsidence (fall), and that the resulting maximum elevation be applied as the Tsunami Hazard Line.

As examples of how this would be applied, the following sample locations are discussed:

- Using the Level 3 – 90 m grid:
    - Port Renfrew is predicted to see a Maximum Water Level of 3 m,
    - Subsidence is predicted to be approximately 1 m,
    - The calculated total water level relative to the original coastline at Mean Water Level (MWL) is then 4 m,
    - Apply a 50% factor for public safety, resulting in a Tsunami Hazard Line located at the 6 m current elevation based upon topographic information.
- Using the Level 5 – 9 m grid:
    - McLoughlin Point is predicted to see a Maximum Water Level of 2.5 m,
    - Subsidence is predicted to be approximately 0.15 m,
    - The calculated total water level relative to the original coastline at MWL is 2.65 m,
    - Apply a 50% factor for public safety, resulting in a Tsunami Hazard Line located at the 4.0 m current elevation.

6.3 Tsunami Hazard Line

Applying the above approach to all CRD coastline locations results in a completed Tsunami Hazard Line throughout the CRD and is a product of this study that has been provided to the CRD to be incorporated into its GIS mapping layers.

Figures 6.2 through 6.4 show several samples of the Tsunami Hazard Line superimposed on the land topography, showing:

- Victoria Harbour, including Inner Harbour, Upper Harbour and Gorge Waterway (using the Level 5 grid information)
- Esquimalt Harbour, showing the area from Albert Head past Victoria Harbour to Clover Point (using the Level 4 grid)
- Port Renfrew, including the San Juan River estuary (using the Level 3 grid)

Each of these examples can be compared with previous Tsunami Inundation mapping prepared for the CRD but which was based upon a single elevation for each of Greater Victoria (4 m), Saanich Peninsula (4 m) and Port Renfrew (20 m).

We would expect to see general concurrence between the mapping for Greater Victoria and Saanich Peninsula since the elevation previously chosen is similar to the calculated elevations used for the Tsunami Hazard Line in these areas. However there are differences expected as well due to the dynamic nature of this Tsunami modelling exercise and the higher precision now being applied to the data and final determined elevation.

The differences for Port Renfrew should appear significant since the NEOWAVE model has determined an overall lower total elevation (6 m) for the combination of maximum water level and subsidence, along with addition of a 50% factor for public safety, than that used for the previous mapping (20 m).

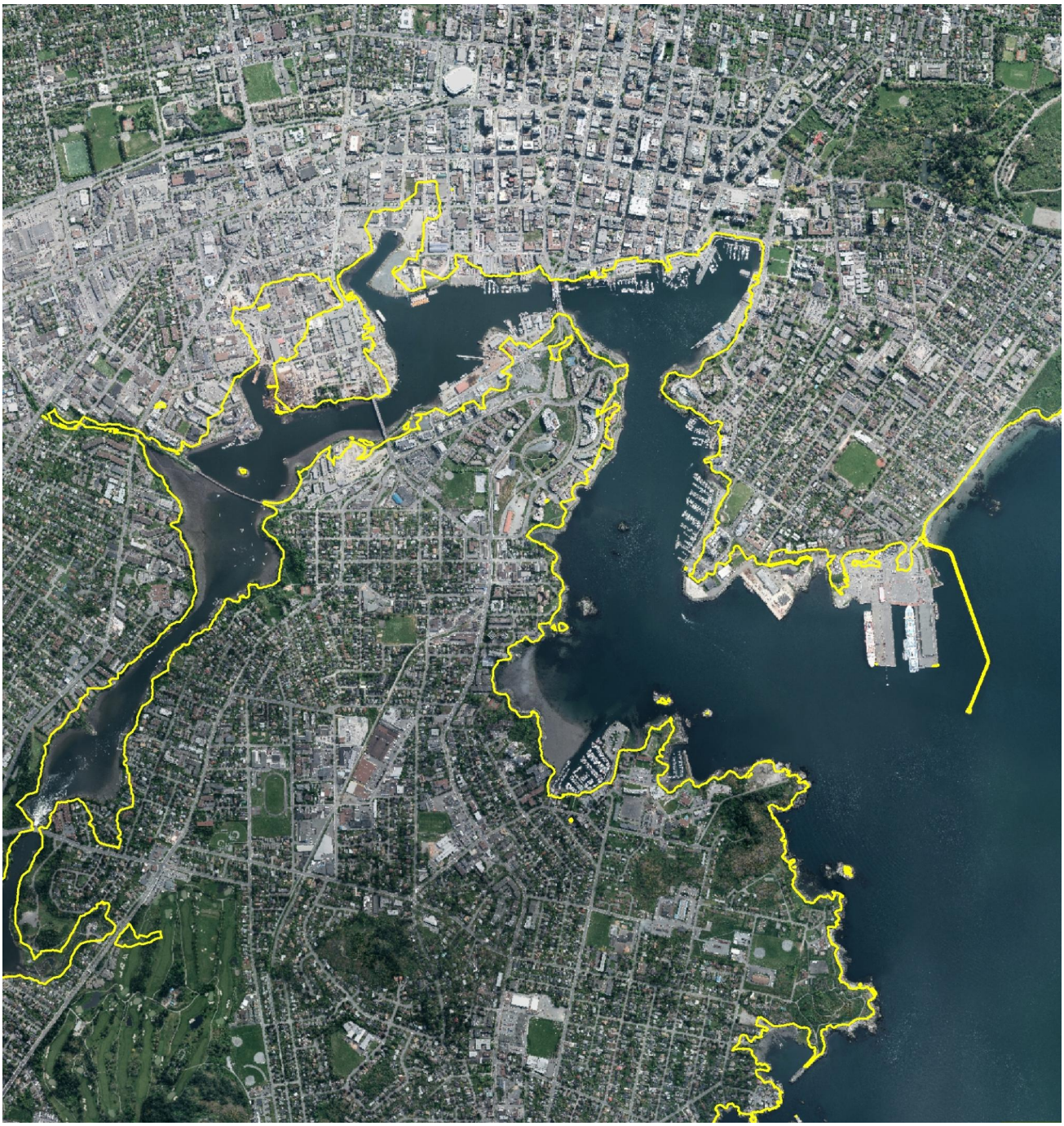

Figure 6.2 – Level 5 Grid – Tsunami Hazard Line

Figure 6.3 – Level 4 Grid – Tsunami Hazard Line

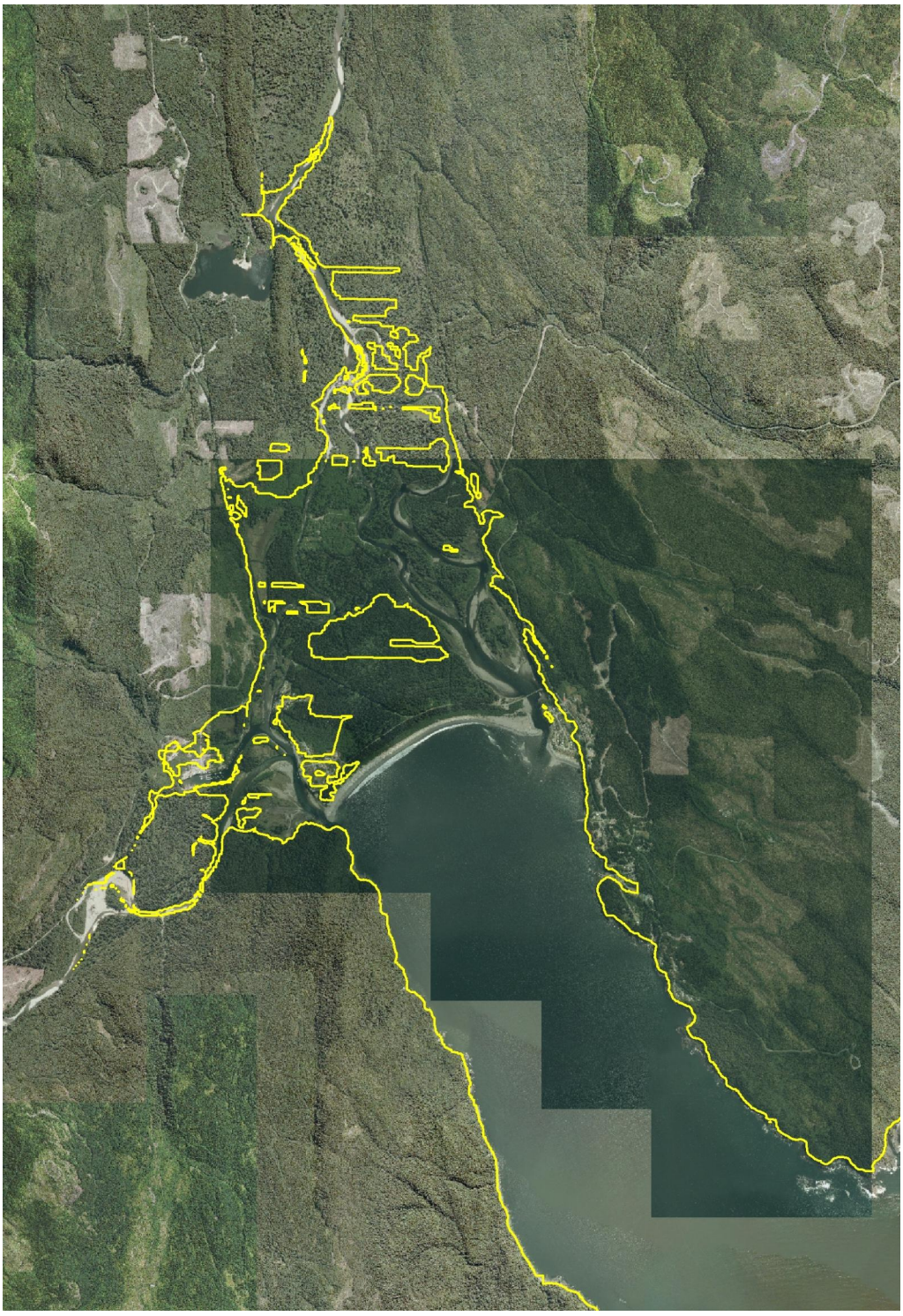

Figure 6.4 – Port Renfrew - Level 3 - Tsunami Hazard Line

7. Potential Next Steps

Within the original Request for Proposal issued for this project the CRD requested that one of the products be to "provide recommendations on potential next steps for use of data [developed as part of this project] for the purposes of risk modelling, evacuation plans, and anticipated impacts of the selected tsunami scenario."

7.1 Summary

The results from the tsunami modelling did not result in high values of maximum water levels, significant areas of inland inundation, or dramatic changes from previous mapping that had been based upon a single, set elevation (other than a significant reduction at Port Renfrew). There are a number of differences that are apparent, where the dynamic and time-variant analysis provided by the tsunami model provides greater insight into water levels, inundation and wave run-up – however, these are generally on a relatively localized geographic scale. In that sense, the modelling resulted in a confirmation that the Capital Region is not at significant risk from a tsunami generated from a 500-year Cascadia subduction zone earthquake.

And, while the results are not dramatic or dramatically different, the CRD can have greater confidence in these new results that are based upon far more-detailed, more rigorous analysis, using a multi-level nested grid analysis process that applies time- and spatially-variant results in combination with predicted subsidence values rather than a series of allowances or factors.

Importantly, due to the model's capabilities, there are other output parameters available from post-processing of the model results that provide useful information that can be used for tsunami hazard planning, or emergency planning, in general. These have been discussed previously and include:

- Spatial extent and magnitude of land subsidence
- Flow depths and flow velocities
- Tsunami arrive time
- Tsunami wave resonance and persistence
- Time to maximum water level

7.2 Potential Next Steps

The following paragraphs provide brief recommendations for how the CRD might utilize data from this project for public safety emergency planning and engineering efforts.

7.2.1 Additional Risk Modelling

Earthquake Scenario

The tsunami model was developed to simulate a 500-year Cascadia earthquake using a magnitude 9.0 rupture scenario for modelling of tsunami impacts along the CRD coasts. This rupture scenario was selected because it produces the best agreement with observed paleotsunami deposits along shorelines of the Pacific Northwest, including Vancouver Island.

It is also possible to assess the impacts and relative changes of impacts, in tsunami inundation, velocities, depths and timing due to a higher risk event, for example, the magnitude 9.2 scenario identified by the US National Seismic Hazard Maps (Refer to Table 2.1). These changes in impacts may be of interest to the CRD, however, it also has to be noted that this would be a less frequent, lower probability event.

Other Emergency Considerations

The construction of a seamless topographic-bathymetric terrain dataset as part of the tsunami modelling took considerable effort and represents a very significant achievement in combining multiple sources of data. It also provides an improvement over any existing digital mapping information related to the extensive Capital Region coastline, including southern Gulf Islands. This topographic-bathymetric dataset could also be considered for use in a number of possible coastal flood studies to assess flood risk along the open coast and sheltered water shorelines within the CRD – these could include tidal surge, wave run-up, and overtopping analyses associated with regional storm systems, as opposed to tsunami-generated.

7.2.2 Evacuation Planning

Even with the limited inland inundation estimated from this particular tsunami scenario, the uncertainty of the magnitude of an actual seismic event and resulting tsunami wave will necessitate evacuation of CRD residents within or adjacent to identified tsunami hazard areas.

The tsunami hazard line provides the predicted level of maximum water combined with subsidence, and including a factor for public safety, that is based upon a calculated elevation for all parts of the CRD coastline. However, on an urban geographic scale, the hazard line could be aligned through a City block or even a single building for example. An evacuation zone may be defined based on the inundation map and using identifiable landmarks such as major streets or highways, critical facilities such as hospitals and schools, designated refuge centres, and enforcement resources (i.e., the number of police officers available to enforce the evacuation and to maintain order). Establishment of an evacuation zone(s) can assist further planning effort; for example, by defining the spatial extent of areas at risk, reverse 911 call strategies can be better defined. In this way Evacuation Zone Mapping could build upon the Tsunami Hazard Line (possibly using GIS information) and would be expected to expand further beyond the Tsunami Hazard Line.

The tsunami model determines the arrival time of the initial wave, from the subsidence and uplift of the earth surface at the time of the earthquake to various locations along the coastlines within the CRD based on the propagation of the tsunami through the Straits of Juan de Fuca and Georgia. The model shows that some areas receive the first wave within approximately 60 minutes following the earthquake and that hazardous wave activities may last for hours. Given that there can be expected to be considerable uncertainty after the event and that communication systems may not be functional, it may be important to identify areas of “vertical evacuation” – where residents are instructed to evacuate to, say, third floors or higher in taller buildings of reinforced-concrete or structural steel frame buildings.

Given the high uncertainty of the magnitude of a seismic event and the inundation potential of the resulting tsunami wave, the ability to have an estimate of tsunami arrival times and time to maximum water level can be significant factors to guide determining priorities for evacuation of various areas within the CRD.

Another important aspect of emergency planning is public education. With potentially short arrival times and possible disruptions to communications, some consideration should be given to providing information to residents as to the steps to be taken immediately upon feeling a major tremor, similar to other jurisdictions. For areas at risk from tsunami impacts, waiting for instructions from government authorities is not a recommended course of action.

7.2.3 Emergency Response Planning

The tsunami model has the ability to estimate the spatial extent and duration of coastal resonance and persistent wave activities which may take hours to subside within the Straits of Juan de Fuca and Georgia. Emergency response planning should consider the temporal aspect of the hazard event and schedule the ingress of emergency responders to damaged areas with respect to the modelled duration of risk.

The tsunami model output of inundation, velocities, flow patterns, and resonance oscillations may help to infer tsunami debris source potential, movement, and post-event maintenance needs, when these model data are overlain with spatial land use and land cover information.

Previous devastating tsunamis showed that debris impact can be a major cause of damage to structures, and the most common form of debris is shipping containers. While this may not represent a major concern within Greater Victoria, the potential for debris to cause major damage within harbours and embayments should be considered.

7.2.4 Infrastructure Design

The results from the numerical modelling of the CSZ earthquake tsunami provide flow depths and flow velocities along coastal areas of the Capital Region District; these data will be very useful in designing infrastructure identified within the tsunami hazard areas of CRD. For example, flow depths and velocities can be used to estimate the tsunami impact forces on structures. Also, a significant amount of the damage that has been observed in previous tsunamis was due to high uplift pressures and forces acting on the underside of floor slabs, bridges and highways. The modelling can help in providing insight into better design standards for coastal infrastructure that might be exposed to this type of tsunami loading.

It is also possible to use flow velocities estimated from the modelling to investigate sediment scour characteristics along the coastline which could have an implication in terms of soil liquefaction that could cause failure of infrastructure such as shore protection structures, bridges, roads, buildings, and wharves, including those within Victoria Harbour, Inner Harbour, Upper Harbour and Gorge Waterway under various ownerships.

7.2.5 Transportation Planning

While the spatial extent of inland inundation from the modelled magnitude 9.0 rupture scenario is limited, model data related to velocities, flow patterns, and duration may assist with response plans for the evacuation or sheltering of waterway transportation vessels, such as moored ships and car ferries.

These model outputs may be used in conjunction with street network mapping, to guide the placement of tsunami evacuation signage, and a predictive transportation model to forecast roadway conditions under multiple evacuation/disaster scenarios.

If necessary, the analysis of forecast roadway conditions under evacuation scenarios may include the identification of methods to increase roadway capacity, e.g., signal optimization, reverse-laning, manual intersection control, availability and role of public transit, etc.

Yet another consideration here would be the possible evacuation of residents by foot along dedicated routes. In the event of a major earthquake and a need to evacuate a large number of residents, the possibility of major traffic jams occurring is very likely, and it will be advantageous to have alternative means for egress from the area.

8. References

Atwater, B.F. and Hemphill-Haley, E. (1997). Recurrence intervals for great earthquakes of the past 3,500 years at northeastern Willapa Bay, Washington. US Geological Survey, Professional Paper 1576, 108 p.

Cheung K.F., Wei, Y., Yamazaki, Y., and Yim, S.C. (2011). Modeling of 500-year tsunamis for probabilistic design of coastal infrastructure in the Pacific Northwest. *Coastal Engineering*, 58(10), 970-985.

Cheung, K.F., Chiou, R., and McCallister, M. (2010). Modeling of 100-year Tsunami and Typhoon Wave Conditions at Apra Harbor, Guam. Naval Facilities Engineering Command, Engineering Service Center, Site Specific Report 3541-SHR, Port Hueneme, California.

Cherniawsky, J.Y., Titov, V.V., Wang, K., and Li, J.-Y. (2007). Numerical simulations of tsunami waves and currents for southern Vancouver Island from a Cascadia megathrust earthquake. *Pure and Applied Geophysics*, 164(2/3), 465-492.

Clague, J.J. (1997). Evidence for large earthquakes at the Cascadia subduction zone. *Reviews of Geophysics*, 35(4), 439-460.

Clague, J.J., Bobrowsky, P.T., and Hutchinson, I. (2000). A review of geological records of large tsunamis at Vancouver Island, British Columbia, and implications for hazard. *Quaternary Science Review*, 19(9), 849-863.

Darienzo, M.E., Peterson, C.D., and Clough, C. (1994). Stratigraphic evidence for great subduction-zone earthquakes at four estuaries in Northern Oregon, U.S.A. *Journal of Coastal Research*, 10(4), 850-876.

Foreman, M.G.G., Walters, R.A., Henry, R.F., Keller, C.P., and Dollng, A.G. (1995). A tidal model for eastern Juan de Fuca Strait and the southern Strait of Georgia. *Journal of Geophysical Research*, 100(C1), 721-740.

Gica, E., Spillane, M., Titov, V.V., Chamberlin, C., and Newman, J.C. (2008). Development of the forecast propagation database for NOAA's Short-term Inundation Forecast for Tsunamis (SIFT). NOAA Tech. Memo. OAR PMEL-139, Seattle, Washington.

Goldfinger, C., Nelson, C.H., and Johnson, J.E. (2003). Deep-water turbidities as Holocene earthquake proxies – The Cascadia subduction zone and northern San Andreas fault systems. *Annals of Geophysics*, 46(5), 1169-1194.

Jacoby, G.C., Bunker, D.E., and Benson, B.E. (1997). Tree-ring evidence for an AD 1700 Cascadia earthquake in Washington and northern Oregon. *Geology*, 25(11), 999-1002.

Lay, T., Ammon, C.J., Kanamori, H., Yamazaki Y., Cheung, K.F., and Hutko, A.R. (2011a). The 25 October 2010 Mentawai tsunami earthquake (M_w 7.8) and the tsunami hazard presented by shallow megathrust ruptures. *Geophysical Research Letters*, 38(6), L06302, Doi: 10.1029/ 2010GL046552.

Lay, T., Yamazaki, Y., Ammon, C.J., Cheung, K.F., and Kanamori, H. (2011b). The 2011 M_w 9.0 off the Pacific coast of Tohoku earthquake: Comparison of deep-water tsunami signals with finite-fault rupture model predictions. *Earth, Planets and Space*, 63(7), 797-801.

Okada, Y. (1985). Surface deformation due to shear and tensile faults in a half space. *Bulletin of the Seismological Society of America*, 75(4), 1135-1154.

Petersen, M.D., Frankel, A.D., Harmsen, S.C., Mueller, C.S., Haller, K.M., Wheeler, R.L., Wesson, R.L., Zeng, Y., Boyd, O.S., Perkins, D.M., Luco, N., Field, E.H., Wills, C.J., and Rukstales, K.S. (2008). Documentation for the 2008 Update of the United States National Seismic Hazard Maps. US Geological Survey, Open-file Report 2008-1128.

Reiter, L. (1991). *Earthquake Hazard Analysis*. Columbia University Press, New York, N.Y., 254 p.

Roeber, V., Yamazaki, Y., and Cheung, K.F. (2010). Resonance and impact of the 2009 Samoa tsunami around Tutuila, American Samoa. *Geophysical Research Letters*, 37(21), L21604, Doi: 10.1029/2010GL044419.

Satake, K., Shimazaki, K., Tsuji, Y., and Ueda, K. (1996). Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700. *Nature*, 379, 246-249.

Tichelaar, B.W. and Ruff, L.J. (1993). Depth of seismic coupling along subduction zone. *Journal of Geophysical Research*, 98(B9), 15829-15831.

Tolkova, E. (2012) Tide-tsunami interaction in Columbia River, as implied by historical data and numerical simulations. *Pure and Applied Geophysics*, doi 10.1007/s00024-012-0518-0, in press.

Wang, K., Wells, R., Mazzotti, S., Hyndman, R.D., and Sagiya, T. (2003). A revised dislocation model of interseismic deformation of the Cascadia subduction zone. *Journal of Geophysical Research*, 108(B1), 2026, doi: 10.1029/2001JB001227.

Yamazaki, Y. and Cheung, K.F. (2011). Shelf resonance and impact of near-field tsunami generated by the 2010 Chile earthquake. *Geophysical Research Letters*, 38, L12605, Doi: 10.1029/2011GL047508.

Yamazaki, Y., Cheung, K.F., and Kowalik, Z. (2011a). Depth-integrated, non-hydrostatic model with grid nesting for tsunami generation, propagation, and run-up. *International Journal for Numerical Methods in Fluids*, 67(12), 2081-2107.

Yamazaki, Y., Cheung, K.F., Kowalik, Z., Lay, T., and Pawlak, G. (2012a). NEOWAVE. Proceedings and Results of the 2011 NTHMP Model Benchmarking Workshop, NOAA, Galveston, Texas.

Yamazaki, Y., Cheung, K.F., and Lay, T. (2013). Modeling of the 2011 Tohoku near-field tsunami from finite-fault inversion of seismic waves. *Bulletin of the Seismological Society of America*, 103, in press.

Yamazaki, Y., Cheung, K.F., Pawlak, G., and Lay, T. (2012b). Surges along the Honolulu coast from the 2010 Tohoku tsunami. *Geophysical Research Letters*, 39, L09604, Doi: 10.1029/2012GL051624.

Yamazaki, Y., Kowalik, Z., and Cheung, K.F. (2009). Depth-integrated, non-hydrostatic model for wave breaking and runup. *International Journal for Numerical Methods in Fluids*, 61(5), 473-497.

Yamazaki Y., Lay, T., Cheung, K.F., Yue, H., and Kanamori, H. (2011b). Modeling near-field tsunami observations to improve finite-fault slip models for the 11 March 2011 Tohoku earthquake. *Geophysical Research Letters*, 38, L00G15, Doi: 10.1029/2011GL049130.

National Geodetic Survey, 2013. VERTCON Orthometric Height Conversion http://www.ngs.noaa.gov/cgi-bin/VERTCON/vert_con.prl [last accessed January 13, 2013].