Probabilistic Tsunami Hazard Assessment for Point Lepreau Generating Station

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Abstract

In 2012 the Geological Survey of Canada published a preliminary probabilistic tsunami hazard assessment in Open File 7201 that presents the most up-to-date information on all potential tsunami sources in a probabilistic framework on a national level, thus providing the underlying basis for conducting site-specific tsunami hazard assessments. However, the assessment identified a poorly constrained hazard for the Atlantic Coastline and recommended further evaluation. As a result, NB Power has embarked on performing a Probabilistic Tsunami Hazard Assessment (PTHA) for Point Lepreau Generating Station. This paper provides the methodology and progress or hazard evaluation results for Point Lepreau G.S.

1. Introduction

The Canadian coastline spans three oceans, the Atlantic, Pacific and Arctic Ocean, and is exposed to hazards from tsunami generated by a wide range of mechanisms from numerous geographic source areas around the world. Far fewer tsunami have been observed on the Atlantic than on the Pacific coast of Canada, owing to the fact that the Atlantic coast is located far from plate boundaries, and due to there being fewer compressive plate boundaries around the Atlantic compared to the Pacific Rim. Nevertheless, significant tsunami events are possible from several tsunamigenic sources, as illustrated by two historic tsunami events. The 1755 Lisbon tsunami originated on the Azores-Gibraltar plate boundary, and was observed in Newfoundland [2]. A magnitude 7.2 earthquake occurred on the Grand Banks on November 18, 1929, triggering a submarine landslide-turbidity current and subsequent tsunami that claimed 28 lives and caused extensive damage on the Burin Peninsula of Newfoundland [3]. A comprehensive list of potential tsunamigenic sources was compiled by the Geological Survey of Canada [1], including submarine landslides on the continental slopes of Nova Scotia, Newfoundland and New England; megathrust earthquakes in the northeastern Caribbean; earthquakes on the Azores-Gibraltar plate boundary; large landslides caused by major volcanic flank collapses on the Canary Islands.

The generic PTHA conducted by the GSC [1] estimated the overall tsunami hazard (runup ≥1.5 m) of the outer Atlantic coastline within a 50-year period to roughly 1-15%, and for larger runup (≥ 3m) to approximately 1-5%. These estimates are equivalent to an expected recurrence of runup exceeding 1.5 m of ~300-1700 years, and of runup exceeding 3 m of ~650-4000 years. While the GSC study represents a useful first attempt to survey and summarize the known tsunami hazards, the study also identified many gaps and limitations in the available knowledge that prevent the proper quantification of the overall hazards, or application of the preliminary, generic hazard estimates to any specific site on the Canadian coastline. The GSC concluded that site-specific tsunami modelling is critically needed, in addition to more data on tsunamigenic mechanisms, to identify which sections of the coastline are at risk from each potential source.

The goal of the present study is to quantify the aggregated site-specific tsunami hazard for the Point Lepreau Generating Station (PLGS), based on the best available knowledge of tsunamigenic source mechanisms, and modelling of tsunami generation, propagation and runup in the vicinity of the PLGS. The ongoing study will take into account the aleatory and epistemic uncertainty associated with the characterization of the tsunamigenic sources, as well as those of the deterministic tsunami models. A probabilistic approach to tsunami hazard assessment is a relatively recent development ([4], [5]), and the statistical frameworks used are analogous to those traditionally employed in probabilistic seismic hazard assessment (PSHA). The present study represents the first site-specific PTHA in Canada. The following section outlines the study methodology, with a particular focus on tsunamigenic source characterization and deterministic tsunami modelling. In Section 3 preliminary results are presented from the deterministic modelling of the worst-case scenarios for multiple potential source mechanisms. Finally, discussion of the preliminary results as well as the following steps in the site-specific PTHA for PLGS, are presented in the final section.

2. Methodology

The PTHA methodology consists of three main components: characterization and screening of tsunamigenic sources; deterministic modelling of tsunami generation, propagation to the site and coastal inundation; and probabilistic assessment of the tsunami hazard based on integration of the outcome of the deterministic simulations for source scenarios, along with their recurrence rates within a probabilistic framework.

2.1 Source Characterization

2.1.1 <u>Earthquake Sources</u>

Local and transoceanic fault sources with the potential to generate tsunamis at the PLGS site were evaluated for their contribution to the tsunami hazard at the site. Transatlantic convergent plate boundaries that could generate tsunamis affecting the PLGS site include the Azores-Gibraltar plate boundary (origin of the historic 1755 tsunami) and the Caribbean-North American plate boundary (Figure 1). Of seven faults identified as potential sources for the 1755 earthquake, four were modeled in this study based on their orientation and resulting likelihood of generating a tsunami that could impact the Canadian Atlantic coast: the Gibraltar subduction zone, the Marques de Pombal-Guadalquivir fault, the Gorringe Bank fault and the Madeira Tore Rise.

Although no historical tsunamis associated with the Caribbean-North American plate boundary have impacted the Canadian Atlantic coast, the location and orientation of the plate boundary suggest that great earthquakes along this boundary could generate tsunamis at the site. As a result of the highly oblique slip along the Puerto Rico subduction zone (PRT), frequent small to moderate earthquakes occur in the PRT region, and large subduction earthquakes are rare. The largest instrumentally recorded earthquake in the PRT area was a M 7.3 in 1943, although McCann (1985, [6]) suggests that an earthquake in 1787 was as large as M 8.0-8.25. Only six > M 7 earthquakes have been observed near the PRT in the last 220 years, with only two events > M 8; twelve >M 7 earthquakes were observed in the last 500 years [7]. At least four of the above earthquakes generated tsunamis. A M 7.8 earthquake ruptured an 80 km long section of the subduction zone in 1943 [8]. Though the Puerto Rico trench has not experienced a historical great megathrust earthquake (M > 8), similarities between its relative plate motion and that of the Sumatra-Andaman plate boundary has led to the hypothesis that M 8+ thrust earthquakes could happen there [9]. The North Hispaniola fault is the continuation of the North American-Caribbean plate boundary west of the Puerto Rico trench, and is also considered in the study.

Additionally, the Oak Bay fault in the Bay of Fundy is considered to be potentially active and was assessed as a possible source of earthquake-generated tsunamis at the site. The Oak Bay fault (OBF) is an approximately 55 km long, oblique strike-slip fault that appears to control the west side of Passamaquoddy Bay (Figure 2) and the trend of the St. Croix River channel [10]. Although several investigations of geologic features in the region, both on land or beneath Passamaquoddy Bay, have failed to find evidence of Quaternary movement on the Oak Bay fault [11], Quaternary activity on the Oak Bay fault has been hypothesized based on pockmarks in Passamaquoddy Bay and historical seismicity in Passamaquoddy Bay. The Oak Bay fault is located mostly on land and in shallow water, which reduces its tsunami generation capabilities.

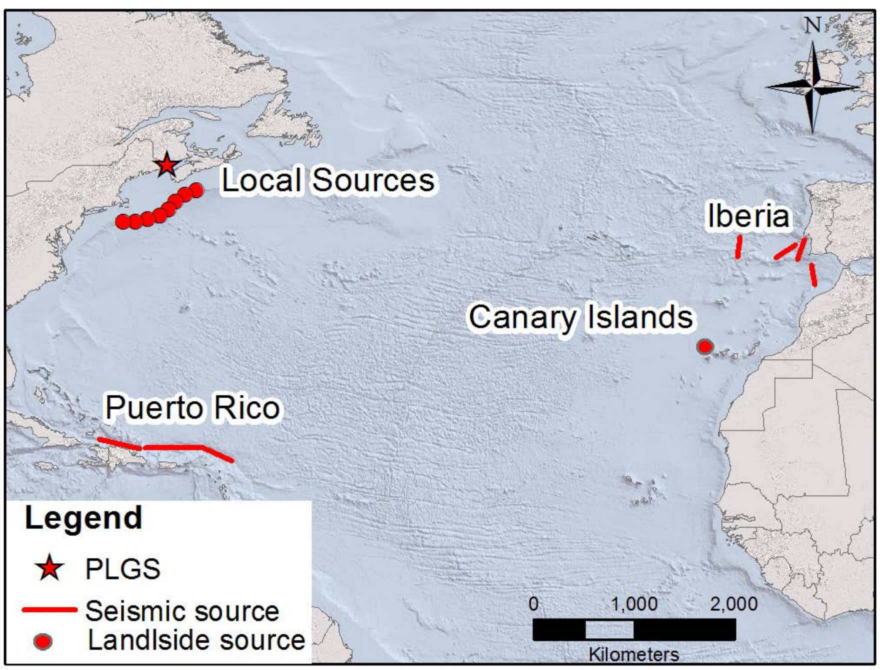

Figure 1 Potential tsunami source areas being considered in the PTHA.

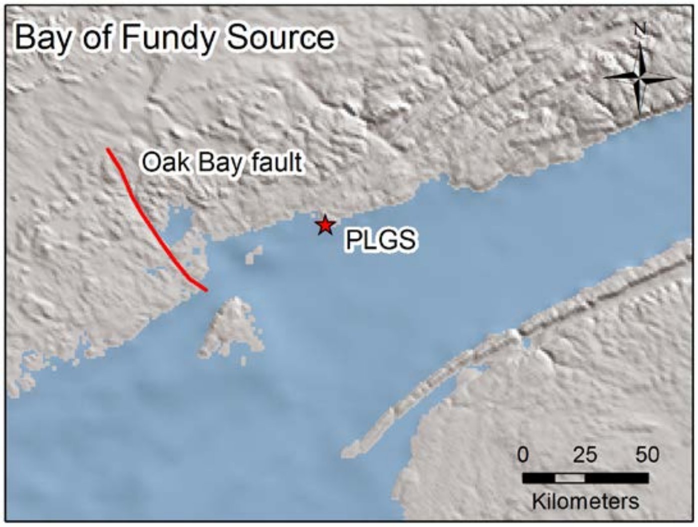

Figure 2 The Oak Bay fault in the Bay of Fundy.

2.1.2 Landslide Sources

Piper et al. (2012, [12]) compiled the most recent summary of Canadian continental slope landslides. They divided the slope into areas of erosion and deposition. In general, depositional areas are locations where glaciers reached the shelf break during the last glacial maximum and mostly occur along the Grand Banks and slopes farther to the north. Depositional slopes are characterized by large landslides that are probably triggered by large earthquakes at a rate of 1/10,000 yr. Most of the landslide sources considered in this study are within the slope zones characterized as erosional. The slope along the outlet to the Northeast Channel from the Gulf of Maine and portions of the slope along Nova Scotia are categorized as depositional. Erosional areas are characterized by large, blocky landslides occurring at a rate of 1/100,000 yr per 200 km stretch of coastline. In the last two decades the number of studies of continental slope landslides along the western Atlantic Margin has increased dramatically due to the availability of new data [13] and studies performed to determine the risk to the eastern coast from landslide-generated tsunamis ([1], [14]). These studies have identified new landslides and refined the magnitudes and ages of landslides that had been mapped previously.

The largest of these mapped landslides were considered for the credible worst case scenario for submarine landslides on the portion of the continental shelf closest to the site. Of these events, only the 1929 Grand Banks tsunami is historical and known to have generated a tsunami [15]. Other events are early Holocene to Pliestocene in age (approximately 2.5 Ma). Older events are not considered due to a change in sedimentation style and rates with the onset of Pleistocene glacial cycles [16]. Though the prehistoric events are not known to have generated a tsunami, several have been previously modeled to determine their tsunami generating potential [17].

In particular, the Currituck landslide is located on the continental slope off of northern North Carolina. This landslide was determined by the U.S. National Tsunami Hazard Mitigation Program to be a potential worst case scenario for the U.S. east coast [18]. The landslide is between 24 kyr and 50 kyr old [19]. The landslide consists of three separate failure surfaces that likely occurred nearly simultaneously and sum to a volume of 165 km^3 [19]. For the preliminary screening scenarios a Currituck-like translational landslide was considered at eight locations separated by 100 km along the continental slope (Figure 3). An additional location was considered between locations 6 and 7 that yielded the highest tsunami at the PLGS site. Preliminary results for this worst-case submarine landslide scenario are presented in Section 3.

Two sources were considered for the Cumbre Vieja Volcano flank collapse, a 450 km^3 and an 80 km^3 event. Based on studies [20] indicating previous large failures from the Canary Islands were multistage, and geotechnical work [21] indicating if there were to be a failure on Cumbre Vieja it would most likely be in the range of 38-68 km^3, the 450 km^3 case was deemed not credible and the 80 km^3 source was used as a worst case scenario from the Canary Islands.

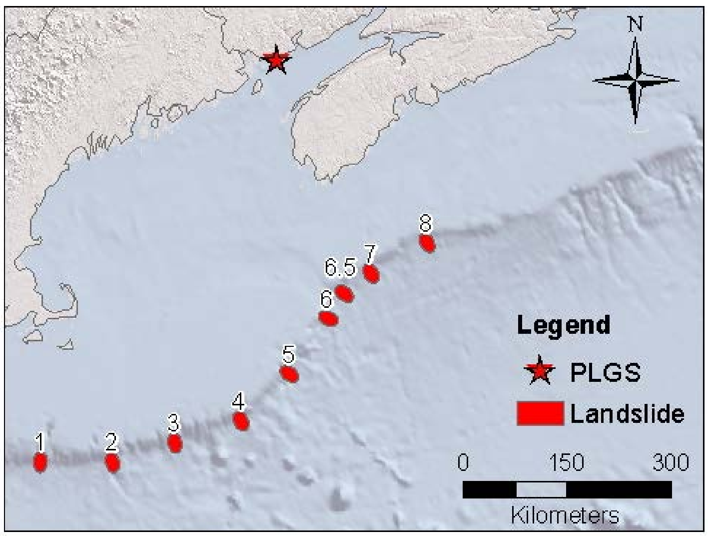

Figure 3 Submarine landslide locations based on geographic distribution, size of 165 km^3 based on largest landslides mapped on the western Atlantic slope

2.2 Deterministic Tsunami Modelling

2.2.1 Source Modelling

Earthquake-generated initial tsunami conditions were generated using the standard Okada model [22] for coseismic seafloor deformation. The model yields an initial sea surface deformation based on earthquake location, fault plane geometry, and moment magnitude. It is assumed that the coseismic displacement occurs instantaneously, and that the sea surface elevation is equivalent to the seafloor deformation.

Initial tsunami conditions for the translational submarine landslides were generated using the latest implementation of the semi-empirical model by Grilli et al. [23], based on the assumption of a semiellipsoid landslide geometry and idealized translational motion down the continental slope. The model has been validated using historical case studies ([24][25]).

The sources used to model the Cumbre Vieja landslide were supplied by Dr. Stephan Abadie [21](Universite de Pau et des Pays de l'Adour). They modeled the initial conditions using an incompressible version of a multiple-fluid/material Navier-Stokes model (THETIS-3D), using inputs derived from a comprehensive geotechnical slope stability analysis.

2.2.2 Propagation and Inundation Modelling

The deterministic modelling has been conducted using the Delft3D modeling suite by Deltares Systems, and the Funwave-TVD fully nonlinear Boussinesq model by the University of Delaware, both of which provide robust and computationally efficient methods of modeling tsunami propagation from ocean to coastal scales. The Funwave-TVD system has been benchmarked for tsunami inundation studies and hazard mapping by the US National Tsunami Hazard Mitigation Program. Delft3D has been used for tsunami inundation studies for the Australian coast (New South Wales [26]), Bay of Concepcion, Chile [27], Hawaii National Historic Sites [28], and for benchmarks against satellite observations for the 2004 Sumatra tsunami event by Deltares Systems.

The Delft3D model has been used for the transatlantic tsunami scenarios, and the Funwave-TVD model has been considered most suitable for the highly-dispersive submarine landslide scenarios. However, ongoing analyses are being conducted using both models on a subset of tsunami scenarios, in order to determine the modelling uncertainty associated with the selection of the hydrodynamic model equations. Several levels of nested and linked grids have been used with increasingly higher resolution in order to capture accurately the propagation of the tsunami toward the site: from 2' (~3.6 km) for most of the Atlantic Ocean, 15" (~500 m) for the continental shelf, 7.5" (~250 m) for the Bay of Fundy, to 2.5" and 1" (~83 m and ~28 m) in the vicinity of the PLGS. Each scenario has been modeled at a nominal initial still water level corresponding to mean sea level (MSL), and additionally with the tide level set at the highest astronomical tide (HAT) at Pt. Lepreau, in order to evaluate the sensitivity of tsunami runup to the stage of the tide.

3. Preliminary Results from Deterministic Modelling

3.1 Cumbre Vieja Volcano Flank Collapse

The 80 km^3 Cumbre Vieja Volcano flank collapse scenario (CVV80) yielded the highest tsunami runup levels of all modelled events. The initial maximum tsunami amplitude of 52.5 m near the Canary Islands is dissipated to a large degree as the waveform propagates in all directions, as shown in the plot of maximum water levels during the simulation (Figure 4). The tsunami waves become shorter and steeper as they propagate onto the continental shelf, and eventually their amplitude is further dissipated as they propagate toward the Bay of Fundy (Figure 5). Their propagation patterns are significantly influenced by the presence of the relatively shallow Georges Bank, and the relatively deeper Northeast Channel to the northeast of the Georges Bank. Finally, as the wave fronts propagate past Grand Manan Island, they begin to form more complex coastally trapped waves that persist for several hours after the initial tsunami arrival. The maximum wave runup near the PLGS is observed in Indian Cove, to the southwest of the site (Figure 6), where the waves undergo amplification and reach a level of approximately 3.4 m above the tidal level in the HAT scenario, and 2.8 m in the MSL scenario. Due to the relatively high elevation of the PLGS (13.7 m above MSL), this worst-case tsunami scenario does not cause inundation at the site.

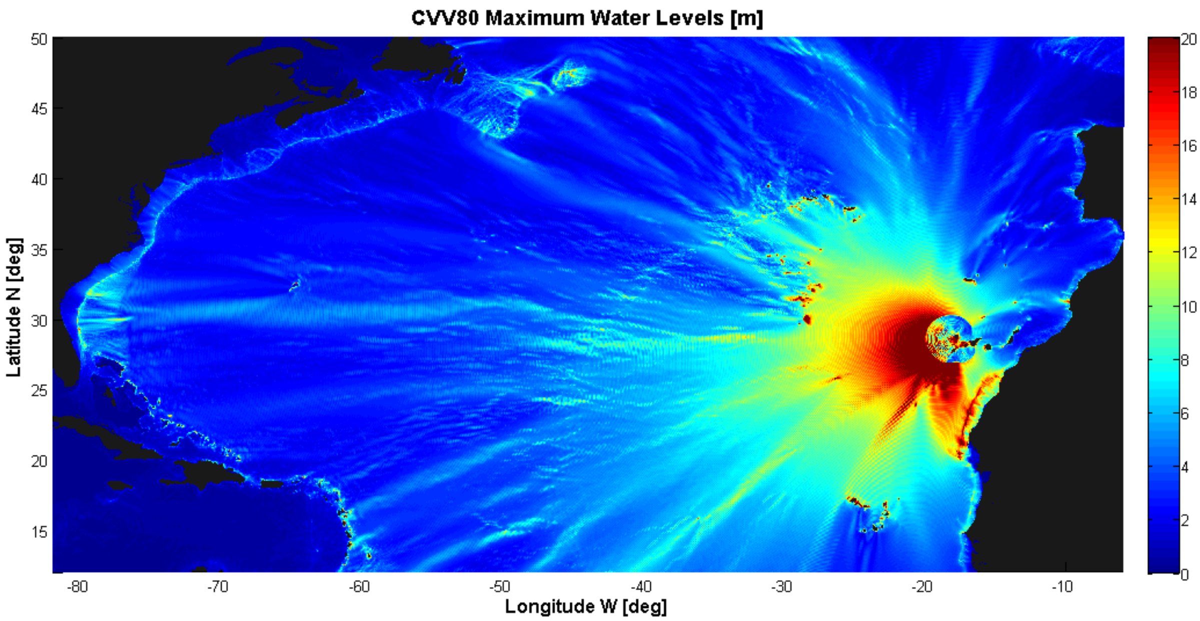

Figure 4 Maximum water levels at any time during the simulation of the 80 km^3 CVV flank collapse scenario.

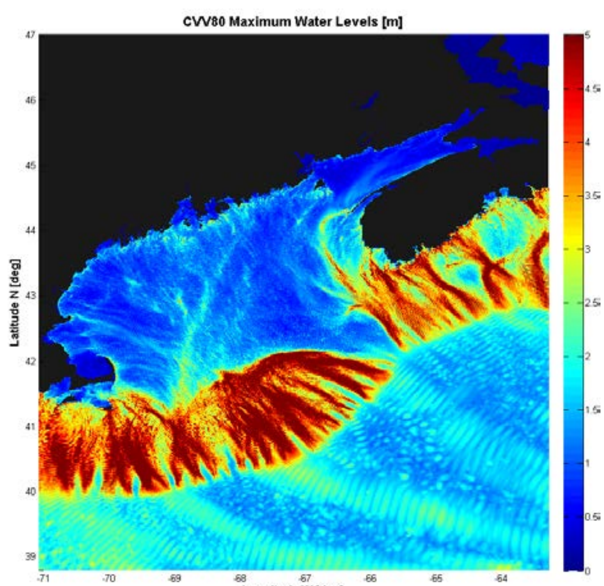

Figure 5 Maximum water levels on the continental shelf at any time during the simulation of the 80 km^3 CVV flank collapse scenario.

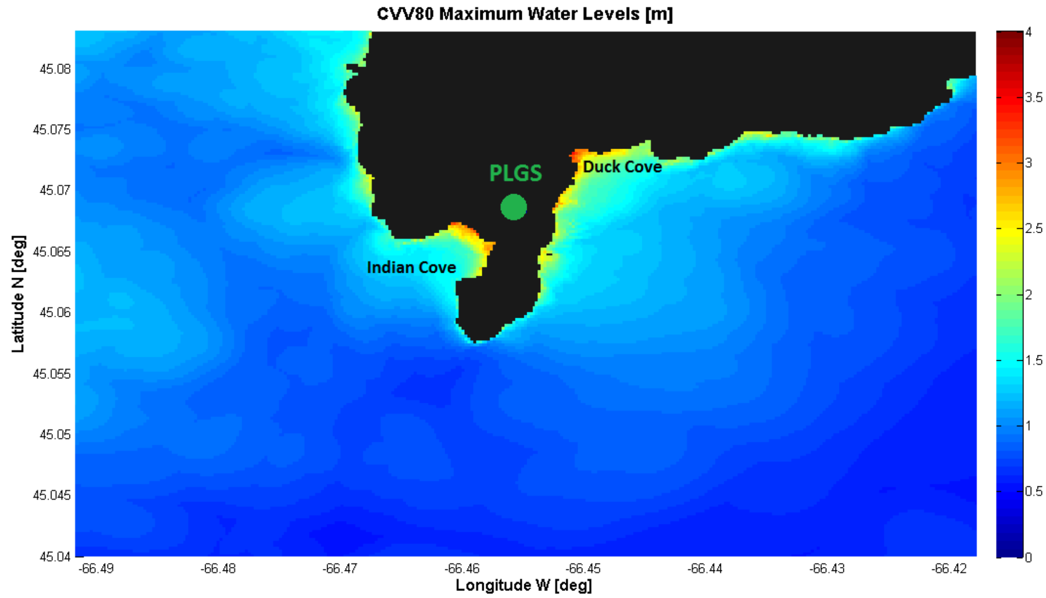

Figure 6 Maximum water levels in the vicinity of Point Lepreau at any time during the simulation of the 80 km^3 CVV flank collapse scenario.

3.2 Continental Slope Landslide

The preliminary screening results indicated that the largest submarine landslide (165 km^3) scenario considered at the location labelled as 6.5 in Figure 3 yields the highest wave runup near the PLGS. This is partly due to the local properties and orientation of the continental slope in this location, and partly due to its position in the immediate vicinity of the relatively deep Northeast Channel, which allows for a relatively efficient pathway for the waves to propagate onto the continental shelf compared to the surrounding shallower areas of the Georges Bank. The initial condition for this scenario (named TS6p5) consists of a relatively large waveform with a depression wave (amplitude ~30 m) on the side of the continental shelf and a positive crest (amplitude ~ 10 m) toward the offshore.

The subsequent propagation of the wave front is greatly controlled by the bathymetry, with the leading front propagating most efficiently toward the northwest along the Northeast Channel, as seen in the water level snapshots at 30 min and 90 min in Figure 7. The first wave front arrives near the PLGS approximately 3 hours after the tsunami generation. The tsunami wave heights are greatly reduced by the time they reach the coastline near the site, with maximum amplitudes of the order of 1 m, which get amplified within Indian Cove to reach a peak runup in the vicinity of the site of 3.2 m (at HAT).

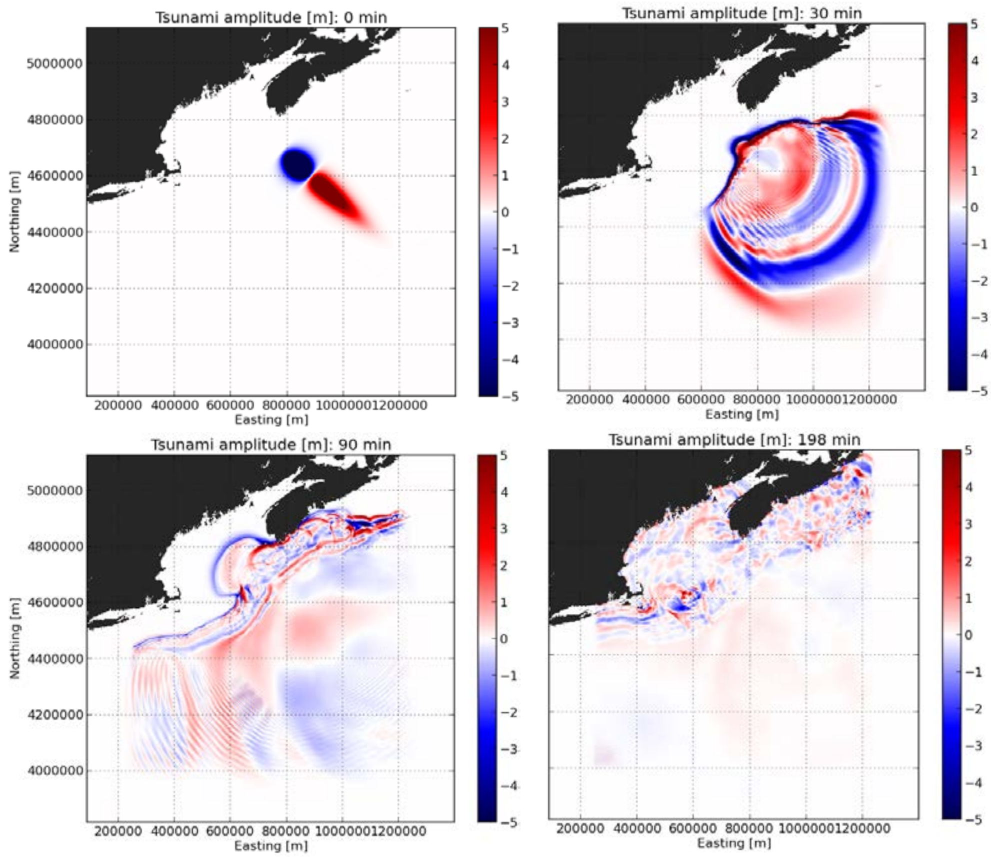

Figure 7 Sequence of tsunami wave propagation for the largest submarine landslide considered for the TS6p5 scenario.

3.3 Puerto Rico Trench Megathrust Earthquake

The largest megathrust earthquake (M 9) considered in the Puerto Rico Trench area (scenario PRT2) yielded the highest earthquake-generated tsunami runup at the PLGS of 2.5 m (at HAT). By comparison, the highest runup values due to the worst-case (M 9) scenarios at the Iberia margin were five times lower at 0.5 m (generated by earthquakes in the Gibraltar Subduction Zone, scenario GSZ1, and the Marques de Pombal-Guadalquivir Fault, scenario MPF1). The Oak Bay Fault (OBF1) M 7 earthquake produced even lower tsunami runup values (0.3 m) despite the close proximity to the PLGS.

The higher runup associated with the Puerto Rico Trench scenarios can be attributed to the fault orientation producing waveforms that propagate northward on a direct course to Atlantic Canada. The propagation of the wave energy is highly dependent on the orientation and configuration of the earthquake fault, therefore the PTHA will consider several variations due to the uncertainties in the initial source parameters, and their effect on coastal runup. Nevertheless, the deterministic results for the worst-case scenario considered for earthquake-generated tsunami indicate that the site would not be inundated even if the highest runup were to occur at the same time as the Highest Astronomical Tide.

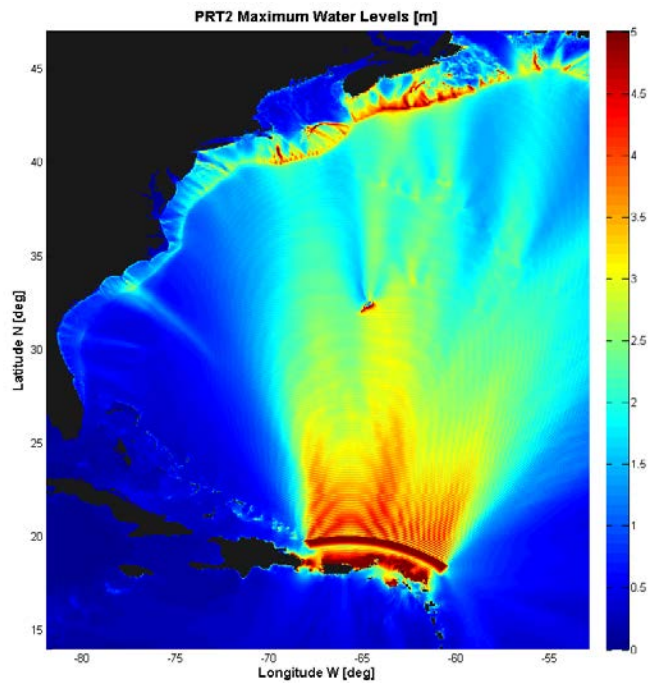

Figure 8 Maximum water levels at any time during the simulation of the worst Puerto Rico Trench earthquake-generated tsunami scenario.

3.4 Summary of Preliminary Deterministic Results

The preliminary results from the deterministic modelling of worst-case tsunami events for all source areas are summarized in Table 1. The highest water level is computed by adding the highest tsunami runup to a tidal level of 3.8 m, corresponding to the Higher High Water Large Tide (HHWLT) tidal level at Pt. Lepreau. This level represents a conservatively high tidal level, based on the average of the annual maximum high tide levels over 19 consecutive years and can be represented as the average annual maximum level with an exceedance likelihood of < 1%. Similarly, the lowest water level is computed by accounting the lowest tsunami drawdown at a tidal level that is approximately 3.8 m below mean sea level, which corresponds to the Lower Low Water Large Tide (LLWLT).

4. Conclusions

The overall methodology for source characterization and deterministic modelling within the site-specific PTHA for PLGS has been presented, along with a subset of preliminary deterministic results illustrating the impact of the plausible worst scenarios from multiple tsunamigenic source areas. Deterministic modelling has been conducted for two tidal stages at the site, at mean sea level and highest tide.

The preliminary results show that highest water level predicted for the CVV80 case of 7.2 m (see Table 1) above mean sea level is significantly lower than grade of the site proper at 13.7 m. The lowest elevation at site is about 7.62 m above mean sea, which corresponds to the Condenser Cooling Water (CCW) pump house, and still would not experience any hydrodynamic forces associated with the worst case plausible tsunami. Drawdown of the Bay of Fundy has also undergone a preliminary assessment to determine if cavitation and consequential damage to low pressure service pumps or interruption of plant cooling is likely. Point Lepreau G.S. was originally designed as a two-unit site with a normal CCW forebay level of -7.32 m with both units operating. The worst case plausible tsunami indicates a slightly higher water level at -7.2 m (per Table 1) and, therefore, it is unlikely that service water operation would be adversely affected by drawdown.

These results indicate the relative impact of the worst plausible cases from each source zone; however, their relative contribution to the hazard at any given return period can be determined only through consideration of the recurrence rates and range of variability of all the sources within a probabilistic framework. The ongoing probabilistic hazard assessment will integrate the outcome of the deterministic simulations for all sources, including less severe but more frequently occurring scenarios, along with their recurrence rates and the effects of aleatory and epistemic uncertainty in the source parameters and deterministic modelling.

Table 1 Deterministic modelling statistics for the worst-case scenarios from each source area.

Source Area	Source ID	Max Initial Amplitude (m)	First Peak Arrival Time (hr)	All Water Levels Are in Metres (m) Referenced to Mean Sea Level (MSL)			
				@ MSL: Max Runup	@ MSL: Max Drawdown	@ HHWLT: Highest Water Level	@LLWLT: Lowest Water Level*
Canary Islands	**CVV80**	52.5	8.9	2.8	-3.4	7.2	-7.2
Continental Shelf	**TS6p5**	27.4	3.0	3.3	-1.9	7.0	-5.7
Puerto Rico Trench	**PRT2**	8.5	6.1	1.8	-2.2	6.3	-6.0
	PRT3_TB	8.5	6.1	1.8	-2.2	6.0	-6.0
Iberia	**GSZ1**	12.2	10.2	0.3	-0.4	4.3	-4.2
	MPF1	10.9	9.7	0.4	-0.5	4.3	-4.3
Bay of Fundy	**OBF1**	0.3	0.5	0.2	-0.2	4.1	-4.0

* Drawdown value for MSL used to calculate lowest water level. Drawdown at low tide should be less, so expect Lowest Water Levels to be less negative in final study

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