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In this report, I evaluate the risk to people and property on Bowen Island from tsunamis. Possible sources of tsunamis that might impact the island include:

1) plate-boundary earthquakes at the Cascadia subduction zone,
2) plate-boundary earthquakes at other subduction zones around the North Pacific Ocean,
3) earthquakes on faults cutting the North America plate.
4) a large subaqueous slide at the front of the Fraser River delta,
5) a large subaqueous slide at the front of the Squamish River delta,
5) a landslide into Howe Sound from an adjacent steep rock slope.

In order to assess the hazard and risk that tsunamis pose to residents of Bowen Island, I examined historical records and simulations of tsunami behavior. A prior study (Clague et al. 2005) sought evidence of tsunami inundation in the near-surface sediments of the Fraser River delta in Richmond, Delta, and Surrey. Sites such as marshes and bogs that are most likely to record and preserve tsunami deposits were cored, providing a record of coastal sedimentation dating back 4000 years. Analysis of the cores indicated that no large tsunami has impacted the shorelines directly south of Vancouver over this period. This type of geological analysis is only able to discern tsunamis with run-ups larger than about 1 m, thus I cannot rule out the possibility than smaller tsunamis have reached Vancouver over the past 4000 years.

Computer simulations indicate that a great earthquake at the local plate boundary (Cascadia subduction zone) would generate tsunami waves 1–2 m high in Boundary Bay south of Delta, but only 0.5-1 m high along the Vancouver waterfront and at Bowen Island. The last great Cascadia earthquake happened in AD 1700. I found no deposits from the tsunami generated by this earthquake nor tsunami deposits generated by earlier plate-boundary earthquakes in low-elevation bogs in Delta and Richmond, or in the tidal marshes of Boundary Bay, Mud Bay, and the Campbell River estuary. The absence of deposits in these areas suggests that the threat to Bowen Island by tsunamis from this source is very low. The only infrastructure that might be impacted is the Snug Cove marine and ferry terminal, and private docks.

Historical records show that earthquakes at plate boundaries elsewhere in the Pacific Ocean (e.g., the giant earthquakes in Alaska in 1964 and Japan in 2011) do not pose a threat to people living along shorelines of the Salish Sea or Howe Sound.

Ruptures of suspected upper-plate faults underlying the Strait of Georgia might generate tsunami waves that propagate into Howe Sound. Again, however, the lack of evidence of tsunami inundation around Boundary Bay and in western Richmond indicates that no significant tsunamis have been generated from this source in the past 4000 years.

Previously published computer models of large subaqueous block slides on the western slope of the Fraser Delta suggest that waves about 2 m high would strike adjacent shorelines shortly after
the landslide. The style of slope failure that was modelled may not be realistic and likely overestimates the hazard from this source. Furthermore, no evidence of such large delta slope failures or of the waves that they would generate has been detected in the geological record. Similarly, high-resolution bathymetric maps of the submarine front of the Squamish Delta, where the Squamish River enters Howe Sound, show no evidence of large submarine slope failures in the recent geological past. The mode of failure at the Squamish Delta front involves small slides and turbidity currents that are incapable of triggering tsunamis. Historic small submarine slope failures at Woodfibre and Britannia Beach similarly did not generate tsunamis. Although high steep rock slopes border some shorelines in Howe Sound (e.g., Anvil Island), these slopes are not known to be unstable and, to my knowledge, none has failed during the historic period spanning the past 200 years. Nevertheless, a rockslide into Howe Sound is the only credible tsunami source among those discussed in this report.

Introduction

Tsunamis are body waves in the ocean or lakes generated by earthquakes, volcanic eruptions, and landslides. Tsunamis can also be produced by asteroid impacts, although these are exceedingly rare and can be ignored for the purpose of this report. Tsunamis generated by earthquakes, which are the most common type, travel at speeds of up to 800 kilometres per hour in deep water. In the open ocean, the waves are generally only a few tens of centimetres high and many tens of kilometres apart, but as they enter shallow water and approach the shore they slow down, bunch up, and may grow to heights of many metres. Near the shoreline, they transform into landward surging masses of turbulent water that, in extreme cases, travel many kilometres inland and reach elevations of several tens of metres. Because of this, tsunamis can cause fatalities and destroy property around the entire margin of the ocean basin. Unlike earthquake-triggered tsunamis, waves created by landslides, whether triggered by earthquakes or not, have only a local impact.

The tsunami hazard at a particular location depends on the potential for a tsunami to happen, the physical character of the shoreline, offshore bathymetry, and inland topography. Risk, which is a measure of both hazard and vulnerability, depends on the number of people and value of property that might be impacted by the tsunami.

In this report, I provide an assessment of the tsunami hazard to Bowen Island by evaluating:

1. the potential threat from tsunamis generated from distant sources (‘teletsunamis’) and local ones, and
2. the recent geology of the Fraser River delta plain, which would be impacted by large tsunamis should they occur, and provides constraints on tsunami magnitude on Bowen Island.

Although more than 30 km from Bowen Island, the Fraser River delta is the only suitable geological archive for tsunamis in the northern Salish Sea and Howe Sound. It lies near sea level and would be inundated by a tsunami exceeding about 2 m in height, and the distinctive deposits of such tsunamis would be preserved in the near-surface sedimentary sequence. As mentioned above, the presence or absence of tsunami deposits on the Fraser Delta plain directly bears on the hazard and risk to Bowen Island.
Documenting Past Tsunamis from The Geological Record

A geological approach to tsunami hazard assessment is based on the observation that tsunamis deposit anomalous, coarse layers of sand or gravel on the surfaces over which they travel. If these layers are subsequently covered by normal river-borne or marine sediments, as is often the case in estuaries and on delta plains, they are preserved in the geological record. The tsunami deposits can be identified and carbon dated, providing a history of events at that location. This approach has been successfully used to determine the number and ages of large tsunamis on the outer coast of Vancouver Island (Clague et al. 2000), in Puget Sound (Atwater and Moore 1992), and Juan de Fuca Strait (Williams et al. 2005).

This geological approach was used on the Fraser River delta and in low-lying wetlands bordering Boundary Bay to determine the tsunami threat to Metro Vancouver (Clague et al. 2005). A total of 33 cores were retrieved from sites where the likelihood of tsunami deposit preservation is greatest, including Richmond Nature Park, Burns Bog, the Campbell River estuary, marshes west of Richmond, and Mud Bay. The cores likely preserve sediments dating as far back as 4000 years. The investigation by Clague et al. (2005) revealed no evidence of tsunami deposits in Richmond, Delta, or other areas of the Fraser Delta. The authors did not completely rule out the possibility that tsunamis have inundated portions of the Fraser Delta in the past. However, their results suggest that if tsunamis have occurred, they had no noticeable impact on the geology of the delta and thus were small. This conclusion is consistent with other evidence, cited above, that the tsunami threat to Vancouver is very small and likely limited to possible damage to marinas and to log booms in the North Arm of the Fraser River.

Potential Sources of Tsunamis That Might Impact Bowen Island

Possible sources of tsunamis that might reach Bowen Island include:

1. plate-boundary earthquakes at the Cascadia subduction zone,
2. plate-boundary earthquakes at other subduction zones around the North Pacific Ocean,
3. a large earthquake on a fault cutting the North America plate
4. a large subaqueous slide at the front of the Fraser River delta
5. a large subaqueous slide at the front of the Squamish River delta,
6. a landslide into Howe Sound from an adjacent steep rock slope.

Plate-Boundary Earthquakes
The tectonic plates that underlie the Pacific Ocean are slowly moving beneath continental margins around the perimeter of the ocean basin along what are termed ‘subduction zones’. At each subduction zone, the interface between the converging oceanic and continental plates is
locked for long periods of time, and the accumulating strain compresses and deforms the continental margin. The accumulated strain is released every few, to many, centuries in great (magnitude (M) ≥8) ‘plate-boundary earthquakes’ (also referred to as ‘subduction zone earthquakes’). During such earthquakes, the sea floor above the locked zone abruptly rises, generating a tsunami that moves away from the source. After the earthquake, the plate interface relocks and the cycle begins again. The giant earthquake that occurred off the coast of Sumatra in 2004 (M 9.1-9.3) and the Tohoku earthquake (M 9.0-9.1) in 2011 exemplify the rupture process.

Plate-Boundary Earthquakes at The Cascadia Subduction Zone

Prior to 1987, assessments of tsunami hazard on the west coast of North America were based on the impact of distant Pacific-wide ‘teletsunamis’. In the past three decades, however, scientists have recognized that the west coast of North America is also vulnerable to tsunamis generated at our local subduction zone (‘Cascadia subduction zone’), where the Juan de Fuca plate is moving beneath the North America plate along an 1100-km long ‘megathrust fault’ that extends from northern California to central Vancouver Island (Figure 1).

Figure 1. Schematic diagram showing subduction of oceanic crust beneath the North American continent at the Cascadia subduction zone. The megathrust fault separating the two lithospheric plates is locked and accumulating elastic strain that will be released in a great earthquake within the next several hundred years. Also shown are epicentres of large historic earthquakes in the region. (Clague and Turner 2003)
Studies of tidal marshes on the Pacific coast of North America show that they suddenly subsided during great (M >8) earthquakes at the Cascadia subduction zone (Atwater and Hemphill-Haley 1997; Clague 1997). Goldfinger et al. (2010) presented evidence for 20 of these events during the past 10,000 years. The average return period for these earthquakes is thus about 500 years, although the intervals between events range from less than one century to more than 1000 years. Sheets of tsunami sand that record these earthquakes are widespread beneath marshes along the Pacific coasts of Oregon, Washington, and British Columbia (Clague 1997), at sites at the east end of the Juan de Fuca Strait (Williams et al. 2005), and in some low-lying coastal lakes along the Pacific coast (Hutchinson et al. 2000; Kelsey et al. 2005).

The question addressed here is: Are tsunami waves triggered by a great plate-boundary earthquake at the Cascadia subduction zone a threat to people and property on Bowen Island? The last great earthquake at this plate boundary happened in AD 1700 (Satake et al. 1996; Atwater et al. 2005), and although there are no written records of the size or impacts of these waves in North America, their devastating impact on coastal settlements on the outer coast of Vancouver Island is recorded in First Nations oral histories (McMillan and Hutchinson 2002; Ludwin et al. 2005). However, as far as I am aware, there are no equivalent oral traditions of a tsunami from this event around the Salish Sea.

Although direct evidence of tsunami impacts is lacking, computer models showing the propagation of the tsunami spawned by a hypothetical great earthquake at the Cascadia subduction zone (M 8.5) has been developed by a group of oceanographers at the Institute of Ocean Sciences in Sidney, British Columbia. The computer model is a useful surrogate for direct evidence. Their “medium resolution” computer simulation indicates wave heights on the outer (west) coast of southern Vancouver Island and adjacent areas of Washington State, Juan de Fuca Strait, and neighboring inland waters (Figure 2).

The model predicts that a great earthquake that ruptures the northern Cascadia plate boundary would generate tsunami waves perhaps more than 10 m high at some sites on the outer (Pacific) coast of Vancouver Island. According to the model, the waves gradually diminish in height as they move through Juan de Fuca Strait and the narrow passages between the southern Gulf Islands. The leading edge of the first wave would reach Boundary Bay on the southern foreshore of the Fraser River delta about 2h 15min after the earthquake. Because Boundary Bay is oriented at right angles to the direction the tsunami would travel, this wave grows to a height of about 1-2 m. The second wave, which is approximately the same size as the first, would arrive about 3h 30min after the earthquake. A third, slightly smaller, wave would arrive at about 5h 30 min. Unlike Boundary Bay, waves at the western foreshore of the Fraser Delta, are forecast to be much smaller (≤0.5 m). Similar small waves would be expected in lower Howe Sound, specifically along Bowen Island shorelines, about 15 minutes after reaching Vancouver.

It must be noted that the magnitudes of the simulated waves generated by the computer model depend on assumptions about the size of the submarine earthquake and the deformation of the seafloor at the boundary between the two lithospheric plates. In addition, because of data limitations, the model does not estimate the extent and depth of tsunami inundation on land.
Assuming that the model predictions are valid, I anticipate that Bowen Island might be affected by a series of small (<0.5 m) waves starting about 2h 45min after a great Cascadia earthquake. Nearly all homes along the coast of Bowen Island lie above the maximum reach of such a tsunami. There are a small number of homes below 5 m above mean sea level, but they too would not likely be affected by a tsunami generated by an earthquake at the Cascadia subduction zone.

Inundation, however, is not the only damaging effect of a tsunami. As it reaches the shore, the surging water of a tsunami has high velocities, up to many metres per second, which can damage docks and release boats from their moorings in marinas. Boats might collide with one another or the shore itself, damaging or potentially overturning them. Poorly secured facilities along the shoreline of Bowen Island might be similarly damaged. The main area where this might be a concern on Bowen Island is the ferry terminal and marina at Snug Cove; the latter has moorage for about 150 boats. In addition, there are a large number of private docks along the coast of Bowen Island that might be damaged or destroyed by a tsunami.

Figure 2. Computer simulation of a great Cascadia subduction zone earthquake, showing wave heights and arrival times 5, 11, 23, 43, 87, 110, and 175 minutes after the earthquake.
Plate-Boundary Earthquakes at Other Subduction Zones Around the North Pacific Ocean

Of the subduction zones that surround the North Pacific (with the important exception of the Cascadia subduction zone), only the Alaska-Aleutian margin represents a significant tsunami threat to the west coast of Canada. Great earthquakes have ruptured the Aleutian subduction zone six times in the past 4000 years. On the last occasion (March 27, 1964; M = 9.2), tsunami waves up to 6 m high damaged several communities on the outer coast of Vancouver Island, most importantly Port Alberni. The island archipelagos at the northern and southern ends of the Salish Sea, however, effectively barred the tsunami from these inland waters. Whereas at the eastern end of Juan de Fuca Strait, the largest wave from the 1964 tsunami was 1 to 2 m high (Williams et al. 2005), it diminished to much less than 0.5 m high in the southern Strait of Georgia (Spaeth and Berkman 1967). Therefore, I conclude that a tsunami triggered by a distant plate-boundary earthquake poses no threat to Bowen Island.

Local crustal earthquakes

Earthquakes on faults within the North America plate represent an additional tsunami hazard to coastal communities in the Pacific Northwest. Faults in central and northern Puget Sound are known to have ruptured in large (M 7) earthquakes several times in the past few millennia (Figure 3). Some low-lying areas around Puget Sound were flooded by the tsunamis generated by these earthquakes. For instance, a sand sheet beneath the coastal marshes of Puget and Possession sounds in northwest Washington State records inundation by a tsunami generated by an earthquake on the Seattle fault in about AD 900–930 (Atwater and Moore 1992; Bourgeois and Johnson 2001). Other crustal faults in northern Puget Sound may have also produced large earthquakes and tsunamis in the past few thousand years (Johnston et al. 2001; Williams et al. 2005). The narrow, winding passages of this inland sea, however, cause rapid loss of tsunami wave energy, and I consider it highly unlikely that tsunamis generated by earthquakes in Puget Sound or Juan de Fuca Strait have ever affected Bowen Island.

What is less certain, however, is the tsunami potential of a fault beneath the Strait of Georgia. Cassidy et al. (2000) identified an active east-west trending fault beneath the southern Strait of Georgia based on a M 4.6 earthquake and its aftershocks in 1997. The fault that generated this earthquake dips to the north. It is unclear whether this fault is large enough to produce an earthquake large enough to produce a significant tsunami, however if it did, the waves would be preferentially directed north and south, perpendicular to the strike of the fault. Numerical modelling of a hypothetical earthquake on this fault is required to determine the potential size of the tsunami that it would generate in the northern Salish Sea and Howe Sound. Again, the lack of evidence for a tsunami larger than 2 m on the Fraser Delta over the past 4000 years provides an upper constraint on such an earthquake and its tsunami.
Figure 3. Known and suspected active faults in the Pacific Northwest (Clague and Turner 2005).
Failure of the Fraser Delta Slope

Ground shaking during a strong earthquake might trigger a submarine landslide at the front of the Fraser Delta, which in turn might generate a tsunami. The unconsolidated sediments forming the delta front might also fail without being shaken by an earthquake.

Landslide-induced tsunamis are particularly dangerous because the waves can be very large near their source and the warning time very short (as little as a few minutes). For example, in November 1994 a submarine slide in Taiya Inlet, perhaps initiated by construction activities in the harbour, created a wave that reached a height of 9-11 m at the shoreline in Skagway, Alaska, causing one fatality and over $20 million of damage (Cornforth and Lowell 1996).

It has long been recognized that the western slope of the Fraser Delta is at risk from submarine landslides (Terzaghi 1956). The Fraser River discharges about 17 million tonnes of sediment into the Strait of Georgia each year (Currie and Mosher 1996), and much of this sediment accumulates on the submarine slope at the front of the delta. Small slides and flows are common at the delta front. For example, between 1970 and 1985, five flow slides are known to have occurred on the western delta foreslope. However, all of them were shallow slides that moved down the delta front over a period of hours and consequently did not produce tsunami waves (McKenna et al. 1992).

Rabinovitch et al. (2003) investigated two potential modes of failure at the Fraser Delta front. They concluded that a large slide could generate tsunami waves up to 18 m high on the eastern shores of Galiano and Mayne islands, but that the tidal flats of the Fraser Delta foreshore would reduce wave energy, and waves at the shoreline in Tsawwassen would likely not exceed 2 m, even if they coincided with a high tide. It should be noted, however, that the deep-seated mass movement envisioned by Rabinovitch et al. (2003) is not the characteristic failure modes of the Fraser Delta front (Christian et al. 1997). Rather, failures appear to be much smaller and to involve shallow sliding. I conclude that any tsunami triggered by the failure of sediment at the Fraser Delta front would be much smaller than suggested by Rabinovitch et al. (2003), likely in the range of a few decimetres at most, and thus would be insignificant at Bowen Island.

Failure of the Squamish Delta Slope

The Squamish River transports large amounts of sand, silt, and clay into upper Howe Sound. The coarser fraction of this sediment load is deposited on the submarine slope at the mouth of the river and is responsible for the gradual seaward advance of the delta over time. As in the case of the Fraser Delta, small slumps and slides occur on the upper part of the Squamish Delta slope and transform into turbidity currents that carry sediment into deep water in upper Howe Sound. High-resolution bathymetric images of the delta front show that much of the sediment is transported into deep water via three submarine channels that cut into the delta front (Figure 4). They also show that no landslide large enough to generate a significant tsunami has happened over the past 100 years and probably longer. Given that the characteristic mode of instability at the delta front is one of small slides and turbidity currents, I conclude that the possibility of a damaging tsunami at Bowen Island from this source is very low.
Landslide into Howe Sound from a Steep Rock Slope

Howe Sound is one of many fiords on the British Columbia coast. Like other fiords, it is deep (maximum depth about 250 m) and bordered by steep mountain slopes (Figure 5). Rockslides, rockfalls, and debris flows in the uplands surrounding Howe Sound have caused damage to infrastructure and loss of life since records were first kept in the early 1900s (Blais-Stevens and Septer 2008). There are records of failures along the shoreline, but they did not produce displacement waves. Among them is the failure of a sand and gravel delta at Woodfibre in 1955 (Terzaghi 1956; Prior et al. 1982; Prior and Bornhold 1984).

In reports published by the Geological Survey of Canada, Jackson et al. (2008, 2014) described deposits of old rock slumps or rockslides in Collingwood Channel west of Bowen Island, Thornbrough Channel near McNab Creek, and along Ramilles Channel off Gambier and Anvil islands based on an interpretation of high-resolution bathymetric imagery and radiocarbon-dated marine sediment cores. They concluded that none of the landslides that entered Howe Sound were large enough to produce a significant tsunami. Furthermore, aside from very slow, creep-like movement of the rock mass on the precipitous west slope of Mount Gardner on Bowen Island (Jackson et al. 2014), no present instability of rock slopes bordering Howe Sound has been reported. In conclusion, a landslide into Howe Sound large enough to produce displacement waves that might cause damage on Bowen Island is unlikely. Nonetheless, this scenario, in my view, is the only one of those discussed in this report that is capable of significant damage to low-lying areas on the island.
Figure 5. Combined swath bathymetry map of Howe Sound and bare-earth Lidar image of the surrounding area. The white zone inside the dark line marking the shoreline is shallow water. Howe Sound is bordered in many places by steep rock slopes, but there are no obvious large rockslide deposits on the seafloor that might provide evidence for prehistoric displacement waves.
References


