ACT Adaptation to Climate Change Team

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Adaptation to Sea Level Rise in Metro Vancouver: A Review of Literature for Historical Sea Level Flooding and Projected Sea Level Rise in Metro Vancouver

Prepared for: The Adaptation to Climate Change Team
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1 Executive Summary

This literature review seeks to establish Metro Vancouver's vulnerability to sea level rise associated with climate change. Vulnerability was investigated in two timeframes: historical vulnerability from the effects of past sea level flooding events and from future vulnerability from projections of sea level rise.

Historical Vulnerability to Sea Level Flooding

Using sea level measurements at the Point Atkinson tide gauge, the literature review investigated the highest recorded levels as potential dates for sea level flooding. The results indicate that 7 sea level flooding events have occurred between 1960 and 2011. Three of these events resulted in significant flooding and damage. Events on December 16th, 1982 and February 4th, 2006 both indicated damages of approximately $2,000,000+ (in 2011 Canadian Dollars). The concurrence of the damage estimates indicates that this may be a fair estimate of the current vulnerability of Metro Vancouver to sea level flooding.

Sea level flooding has affected many parts of Metro Vancouver in the past, including: the District of West Vancouver, the District and City of North Vancouver, the City of Vancouver, the City of Richmond, the Corporation of Delta, and the City of Surrey. Given its low elevation and exposure to the sea, the Corporation of Delta understandably experienced the most flooding The Corporation of Delta incurred the majority of the damages reported above and experienced flooding in 6 of the 8 events to affect Metro Vancouver.

Anecdotal evidence helps portray the context of Metro Vancouver's vulnerability to sea level flooding. The cover photo illustrates historic vulnerability with flooding in Ladner as far back as 1895. Photographs of flooding in 1977 show the Kitsilano Pool inundated with sea water. Records of flooding in 1967 provided descriptions of flooding at Ambleside Beach, Water Street in Downtown Vancouver, and effects in nearly every Metro Vancouver municipality exposed to the sea.

Future Vulnerability to Sea Level Rise

A literature review of studies for sea level rise projections in Metro Vancouver established future vulnerability to sea level flooding. The literature review investigated six studies that ranged in scope from: narrow focus, as in Kerr Wood Leidal's study of vulnerability for the City of Vancouver's sewer system; to broad focus, as in Nixon's study of social vulnerability across 5 Metro Vancouver municipalities.

Although no single piece of literature exists that summarizes all the effects of sea level rise, the findings from each study can piece together a picture of Metro Vancouver's Vulnerability. The National Round Table on the Environment and the Economy predicted sea level rise to cause $2.1 and $7.6 billion in damages by 2050 for British Columbia (primarily Metro Vancouver, based on sea level rise of 0.28 to 0.85 metre sea level rise by 2100). Bing Tom Architects estimates 1 metre of sea level rise to cause $12 billion in damages to the City of Vancouver, with dike mitigation estimated to cost $255 to $510 million. Nixon's study found social vulnerability to sea level rise to be highest in locations corresponding to: Northeast Vancouver, Downtown

Vancouver, Southeast Vancouver, Central Richmond, and the City North Vancouver. Fox's study of social vulnerability to earthquakes used detailed and sophisticated modelling that could be adapted to estimate vulnerability to sea level flooding. Fox found that Strathcona and Grandview were the most socially vulnerable communities. The Collaborative for Advanced Landscape Planning (CALP) performed a study of the effects of sea level rise visualizations on the public's perceptions. Background information in their study indicated that Agricultural Land Reserves face salinization and crop failure; while sea level rise may squeeze high marsh ecosystems against shoreline dikes, causing a 50% reduction in biodiversity. CALP also concluded with a number of findings that indicate visualizations have a significant impact on the public's perceptions of risks associated with sea level rise. Finally, Kerr Wood Leidal's study of the physical vulnerability of the City of Vancouver's sewer system indicated that there will likely be effects on infrastructure and recommended increased monitoring and measurements.

Limitations for each study revolve mainly around methodology. Broad scoped studies were inherently limited in their ability to perform detailed cost estimates associated with physical vulnerability. Furthermore, social vulnerability did not account well for physical vulnerability or adaptive capacity. Finally, projections of future sea levels, which are the basis of most of the studies, have been consistently increasing as more information becomes available. To account for some of these limitations, this literature review makes the following recommendations:

1. Use the most recent projections for sea level rise and attempt to account for uncertainty.
2. Narrow the geographic scope of the study so that a broad and detailed scope of sea level rise impacts can be assessed.
3. Cover aspects of physical vulnerability, societal vulnerability, and adaptive capacity together in one assessment.
    a. Consider detailed risk assessment as a candidate methodology.
    b. Consider the CALP findings for risk reduction strategies.
4. Consider the Corporation of Delta for pilot study given extensive information available and high physical vulnerability.
5. Consider calibration of any study against the documented effects of the February 4th, 2006 sea level flooding event.
6. Consider findings from historic vulnerability for an assessment of the current state of physical and societal vulnerability.

2 Introduction

2.1 Purpose

The purpose of this literature review is to establish the vulnerability of Metro Vancouver to sea level rise from the effects of climate change. The literature review seeks to establish vulnerability in two ways: from the effects of historical sea level flooding events and from projections of future vulnerability to sea level rise.

2.2 Metro Vancouver

Figure 4.3.1.1

The initial scope of the study area included all of Metro Vancouver. Metro Vancouver includes 24 local authorities situated in the southwest corner of mainland British Columbia. Municipalities located along the coastline or on the Fraser Delta may be vulnerable to sea level rise, which includes nearly every local authority. Despite the large scope, the literature review returned information for past and future vulnerability for only the following municipalities, which are illustrated in Figure 2.2.1:

- Vancouver
- Richmond
- Delta
- North Vancouver (City and District)
- West Vancouver
- Surrey

2.3 Structure of the Report

The main content of the report starts with Section 3, which provides information on vulnerability to historical sea level flooding events. Section 4 then provides information on vulnerability to future sea level rise. Section 5 concludes the report.

3 Past Sea Level Flooding Events and Near Misses

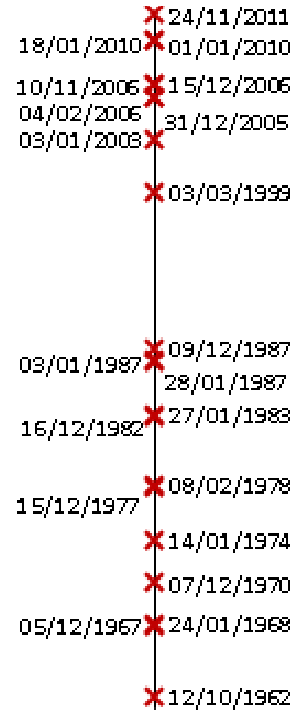
3.1 Methodology

In order to compile a thorough list of dates for sea level flooding events, I employed three strategies: an indirect search of sea level data; a cursory search of well-known severe weather events; and references to past events within known events.

For the indirect search of sea level data, I compiled hourly observations from the Point Atkinson tidal station for the period between 1960 and 2011 using the Canadian Tide and Water Levels

Archive[1] [1]. The search produced 450,383 data points from which I could infer potential flooding events based on the highest measured sea levels. I selected dates for potential sea level flooding events by selecting the dates with the highest levels for one or more hours. With this approach the top 24 observed water levels produced 15 potential dates or periods for further investigation.

Figure 4.3.1.1



Vancouver's history has a few well-known severe weather events that could have produced sea level flooding. Two more famous events are the December 15th, 2006 wind storm that devastated Stanley Park and the October 12th, 1962 landfall of Typhoon Freda. Experts in the BC Ministry of Environment also directed me to a February 4th, 2006 storm surge event that affected the Corporation of Delta. I included each of these in the dates for potential sea level flooding for further investigation.

And finally, as I began my research a number of documents referred to other sea level flooding events. I also included these in the dates for potential sea level flooding events for further investigation.

In total, this indirect approach produced 21 dates to investigate for potential sea level flooding. I performed a targeted search for storms or flooding events on these dates by searching newspaper archives, local government web pages, academic databases, internet search engines, and the meteorological archives. Figure 3.1.1 provides a timeline illustrating the full list of dates for investigation and the proceeding subsections detail the results for each date.

3.2 November 24th – 27th, 2011

Occurrence

Between November 24th and 27th, 2011, Metro Vancouver experienced an extreme tide event that coincided with a storm and resulted in minor flooding. The highest observed water levels for the period (and the year 2011) occurred at 1500 Pacific Daylight Time (PDT) on November 24th, 2011 and measured 5.206 metres[2] [2]. This highest observed hourly average wind speed occurred at 1400 PST on November 24th, 2011 and measured 50 km/h [1]. Tides and winds remained below these peak measurements for the remainder of the period. The wind blew from the southeast for the majority of the period [1].

Effects

The Delta Optimist newspaper reported only minor flooding during this period [3]. They provided no indicators for loss or exposure. No other sources provided detailed information about the effects of the event.

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[1] The concept for this approach was based on a similar approach that the David Suzuki Foundation employed in its 2007 Hot Properties publication.
[2] Note: all tide gauge measurements are measured against the Point Atkinson chart datum.

Preparedness
It appears there was a high level of preparedness for this sea level flooding event. The Corporation of Delta issued a storm surge advisory for Beach Grove and Boundary Bay neighbourhoods (time unknown) on the basis of extreme tides and an Environment Canada wind warning [4]. The Corporation of Delta also activated its Emergency Operations Centre [5]. In total, the Corporation of Delta issued 6 media releases warning of the potential for sea level flooding between November 24th and 27th.

The media also assisted in societal preparedness. In addition to the Delta Optimist, the Province, Surrey Now, South Delta Leader, and Global TV BC all reported the initial warning. The Delta Optimist continued coverage with a total of three articles over the four day period.

Coincidently, representatives from the Corporation of Delta, the Government of British Columbia, and the Government of Canada were in Delta during the sea level flooding event on November 25th, 2011 [6]. The three levels of government were there to mark completion of upgrades to the Oliver Pump Station and four sections of sea dikes along Boundary Bay [6]. In a joint media release on the 25th, they credited the upgrades for improving flood protection. Without further detailed analysis, this literature review cannot ascertain the role of the upgrades in minimizing the impact of this sea level flooding event.

Response
Since only minor flooding occurred during this incident, there were no reports of emergency response.

Summary Analysis of the Event
There is limited information on the effects of the storm on the Corporation of Delta, and no information on effects outside of Delta. The reported minimal effects within Delta may be because there were only minimal effects, or because there was no information publicly available. Likewise, the absence of information on effects outside of Delta may be because there was no information available, or there simply were no effects.

3.3 January 18th, 2010

Occurrence
On January 18th, 2010, Metro Vancouver experienced a high tide event that resulted in no flooding. The peak water level measured 5.393 metres at 800 PDT [2]. Peak water levels coincided with average wind speeds of 32 km/h blowing from the southeast [1]. Rain showers occurred at the time of peak water levels [1]. Earlier at 400 PDT, average wind speeds measured 65 km/h [1], which indicates the peak water levels narrowly missed significant winds.

Effects
Research of archives around this date did not indicate any effects of flooding from the storm and high water levels.

Preparedness

There are no records to indicate that the Corporation of Delta undertook specific preparedness activities in advance of this occurrence. Similarly, no records existed for other municipalities.

Response
The Corporation of Delta issued a storm surge advisory on January 18th, 2010 (time unknown) [7]. The advisory indicated that the mayor activated the Emergency Operations Centre and engineering operations crews were inspecting susceptible locations.

No records exist for other Metro Vancouver municipalities.

Summary of Event / Analysis
Despite being the 20th highest water level recorded over the past fifty years and high winds from the southeast, no flooding occurred. In comparison, February 4th, 2006 experienced water levels only 0.05 metres higher and wind speeds only 5 km/h higher, but it experienced significant flooding (see section 3.5). The research provides no clues as to why one produced significantly worse effects than the other.

3.4 January 1st, 2010

Occurrence
On January 1st, 2010, Metro Vancouver experienced an extreme high tide event that resulted in no flooding. Peak water levels measured 5.151 metres at 700 PDT [2]. Weather conditions at the time of peak water levels were rainy with an average wind speed of 19 km/h from the east [1].

Effects
No flooding occurred as a result of this extreme high tide event.

Preparedness
On December 31st, 2009, the Corporation of Delta issued an extreme water level advisory for the period of January 1st to 4th [7]. The warning identified risk of flooding in low lying areas of Delta that were not protected a dike or seawall. The Corporation of Delta's media archives contained the warning, but there no records to indicate media coverage of the warning. Additionally, there were no other records of warnings from other municipalities.

Response
This extreme tide event resulted in no flooding and required no emergency response.

Summary of Event / Analysis
This date and event were selected because the sea level warning was readily found on the Corporation of Delta's media archives page. The water level was only the 299th highest in the research period. When this water level combined with low wind speeds from the east, the conditions were not sufficient to create wave run-up and sea level inundation.

3.5 December 15th, 2006

On December 15th, 2006, Metro Vancouver experienced a significant wind storm that resulted in no flooding. Peak water levels measured 4.48 metres at 400 PDT [2] and coincided with average wind speeds of 67 km/h winds from the west [1]. The wind storm caused significant damage throughout Metro Vancouver, most notably in Stanley Park. However, the research identified no records of sea level flooding and inundation.

The research methodology identified this date for investigation because it was a recent, significant, and well-known wind storm. The peak average winds did not coincide with high tide or an extreme high tide, which limited the possibility of wave run up and sea level inundation. Furthermore, winds blew from the west and did not directly strike vulnerable areas like Boundary Bay and Beach Grove in Delta.

3.6 November 10th – 15th, 2006

Occurrence
On November 10th, 2006, Metro Vancouver experienced an extreme tide event that resulted in no flooding. Peak water levels measured 5.132 metres at 1000 PDT [2]. Weather conditions at the time of peak water levels were rainy with average wind speed of 26 km/h from the southeast [1].

Effects
No flooding occurred as a result of this extreme tide event.

Preparedness
At 800 PDT on November 10th, the Corporation of Delta issued a storm alert [8]. The alert indicated the Corporation of Delta had activated its emergency operations centre at 600 PDT. City crews locked and blocked beach walkways and prepared vulnerable areas with sandbags, sand berms, and portable pumps.

AT 900 PDT on November 10th, the Corporation of Delta updated its storm alert and indicated that an emergency operations command vehicle was on site and available for response [9]. The alert also identified locations where sand bags were available.

The research did not find evidence that local media carried any of the warnings or alerts. Additionally, the research identified no warnings or preparedness measures from other municipalities.

Response
At 1300 PDT on November 10th, the Corporation of Delta ended its alert after the high tide passed without flooding [10]. The Corporation of Delta kept its Emergency Operations Centre for the remainder of the weekend.

At 1130 PDT on November 15th, the Corporation of Delta issued another media alert indicating it reactivated its Emergency Operations Centre after Environment Canada issued a wind warning [11]. The alert and subsequent updates were primarily concerned with wind and did not address risk of flooding.

The research identified no other response measures from the Corporation of Delta or other municipalities.

Summary of Event / Analysis
The research methodology did not initially identify this date. This event was investigated only after media alerts were found on the Corporation of Delta's media archives website. The peak water levels were the 353rd highest in the research period. When combined with moderate wind speeds, the wave run up was likely not sufficient to flood low lying areas.

The Corporation of Delta displayed a high degree of preparedness. This is likely a result of corrective actions from the February 4th, 2006 flooding event.

3.7 February 4th, 2006

Occurrence
On February 4th, 2006 Metro Vancouver experienced an extreme tide event that coincided with a winter storm. The peak water level measured 5.446 metre at 1000 PDT [2]. The high tide coincided with high winds measuring an average of 50 km/h at 900 PDT and 37 km/h at 1000 PDT, blowing from the southeast [1]. Rain showers occurred during the peak water levels [1]. According to the Corporation of Delta, storm surge caused the 5.5 metre water level to exceed the tide predictions by 3 feet (~ 91 cm) [12]. The Vancouver Sun reported 75 km/h wind gusts [13].

The high tide and storm surge inundated the south Delta communities of Beach Grove and Boundary bay with sea water. Sea water inundation overwhelmed the drainage system and caused localized flooding [14]. Point Roberts, USA, experienced similar sea water inundation and flooding; however, the flood water from Point Roberts proceeded to flow into Boundary Bay village causing flooding to continue for 24 hours past the initial event [14].

The City of Richmond also experienced flooding, which was minor compared to Delta. The high water caused flooding at the Britannia shipyard and a gas station in the Steveston neighbourhood [15]. There were no reports of dike breaches.

Extensive information exists in records that document the February 4th, 2006 occurrence. Romanowski prepared a master's thesis that examined risk perceptions and coping strategies of Boundary Bay and Beach Grove residents during the storm. Her thesis contains qualitative information from interviews with 23 residents [16]. The February 8th, 2006 edition of the Delta Optimist also contained numerous firsthand accounts of the storm [17].

Photographs of the February 4th, 2006 occurrence are also numerous and readily available. Figure 3.6.1 provides a sample of photos of flooding in Delta.

Effects
Sea water inundation affected approximately 150 to 200 homes. According to CBC, approximately 200 people were told to leave their homes and 50 people did so [18]. The report did not indicate whether the evacuation was a mandatory order or voluntary.

Damage costs can be determined from media reports and Disaster Financial Assistance (DFA) payouts. According to the Delta Optimist, 29 homes sought and received Disaster Financial Assistance (DFA) to a value of $218,515 [19]. The BC Ministry of Environment provided figures for DFA claims that indicated $262,104.29 in payouts to private parties and $1,050,688.93 in payouts to public parties (total payouts of $1,312,793.22) [20]. The Ministry of Environment figures did not include the number of applicants, so the previous numbers and figures from the Delta Optimist could not be verified.

Figure 4.3.1.1: February 4th, 2006 flooding in Boundary Bay [45].

Beyond DFA payouts, the Corporation of Delta indicated the following additional expenditures as a result of the flooding event: $100,000 for the East Delta section of the Boundary Bay dike; $300000 for standby power at the 12th avenue sewer pump station; $45,000 for a high volume mobile pump; and $100,000/year for a Municipal Emergency Preparedness Manager [14]. The total cost of these expenditures is $445,000, plus an additional $100,000/year.

Corporation of Delta expenditures and DFA payouts totaled $1,757,793.22 (plus $100,000/year). Since DFA payouts only reimburse a portion of eligible expenses for eligible applicants, the total cost of damages is likely much higher.

Preparedness
The Corporation of Delta deployed city staff as of 600 PDT, prior to peak water levels [21]. Existing seawall and dikes were in place in Delta, although some private structures were below the provincial standard. Where permanent structures do not exist, the Corporation of Delta constructed a temporary sand berm each winter [16].

The City of Richmond indicated city crews patrol dikes and pump stations on a 24 hour/day basis. The crews quickly shut down the flooded road in Steveston [15].

Response
The Corporation of Delta activated its Emergency Operations Centre (EOC) to level 1 [22]. The Southwest PREOC and the PECC activated their EOCs to level 1 in support of the local government [22]. At 1600 PDT, Mayor of the Corporation of Delta declared State of Local Emergency [21]. Areas affected included [21]:

Boundary Bay
- From the Pt. Roberts border near Courbold Road to 4th Avenue up to and including 67th Street
- From 4th Avenue along Centennial Parkway to the Boundary Bay Park Boundary (both sides of road)

Beach Grove
- From 12th Avenue to 17A Avenue up to and including Duncan Drive
- Along 17A Avenue up to Braid Road (both sides of road)

In response to the emergency, the Corporation of Delta deployed 100 police, fire, and engineering staff [21]. As previously noted from a CBC report, approximately 200 people were told to leave their homes and 50 people did so [18]. The report did not indicate whether the evacuation was a mandatory order or voluntary. The Corporation of Delta set up an emergency shelter at a local community center [21].

Romanowski's thesis can provide some indication of societal preparedness. Her thesis analyzed risk perception and coping strategies of Tsawwassen (Boundary Bay and Beach Grove) residents during the storm. Newer residents had a perception of higher risk than long-time residents [16]. Conversely, during the storm the newer residents experienced greater struggles coping with the event than long-time residents [16]. After the flooding event, newer residents were more willing to take steps to prepare against future flooding [16].

The role of the media in societal preparedness is difficult to determine in for this event. No media reports in advance of the event or real-time reporting of the event could be found. It is difficult to determine if this is an accurate assessment, or if such reports exist but could not be found. The media covered the story extensively after the fact.

Summary of Event / Analysis
The February 4th, 2006 sea level flooding event was significant, recent, and well-documented. The recorded water levels are the 10th highest in the research period in Metro Vancouver over the past 50 years. This is one of the more recent sea level flooding events and for that reason there was extensive information available.

The role of wind direction plays an important role in wave run up in the Corporation of Delta. During this event the wind blew from the southeast, which would bring wave run up directly towards Beach Grove and Boundary Bay. It is also important to note that wind speeds at the time of high water levels were high, but higher wind speeds have been recorded. If higher wind speeds had occurred, the flooding would likely have been much worse.

Media and interviewees from the Romanowski thesis appear to have short memories on sea level flooding and high water levels. As documented in a proceeding section, even higher water levels occurred only three years earlier on January 3rd, 2003, which was accompanied by less severe flooding. No reports noted the previous event.

3.8 December 31st, 2005

Occurrence
On December 31st, 2005 Metro Vancouver experienced an extreme high tide event that did not result in flooding. The peak water levels measured 5.461 metres and occurred at 700 PDT [2]. Weather conditions at the time of peak water levels were rainy with an average wind speed of 15 km/h from the east [1].

Effects
No flooding occurred during this high tide event.

Preparedness
There were no records of warnings or preparedness measures specific to this event.

Response
Since no flooding occurred, there are no response measures to report.

Summary of Event / Analysis
This extreme tide event coincided with low winds from the east, which is likely why no flooding occurred.

3.9 January 3rd, 2003

Occurrence
On January 2nd and 3rd, 2003, Metro Vancouver experienced an extreme tide event that resulted in minor flooding. On January 2nd, peak water levels measured 5.368 metres at 700 PDT (30th highest in the research period) [2] and coincided with average wind speeds of 41 km/h from the southeast [1]. On January 3rd, peak water levels measured 5.526 metres at 700 PDT (6th highest in the research period) [2] and coincided with average wind speed of 13 km/h from the southeast; however, earlier in the morning at 100 PDT the average wind speeds measured upwards of 61 km/h from the southwest [1].

The Delta Optimist reported a wind gust of 116 km/h [23], but it is not clear which day these winds occurred. Media reports were also unclear as to which day the flooding occurred, but the Corporation of Delta City Council Report describe flooding on January 2nd, 2003 [24].

Effects
Storm surge and wave-run up accompanied extreme high tides on January 2nd, 2003 and caused localized flooding in three areas of Delta [24]. The Delta Optimist reported flooding of some private residences, but no details as to the magnitude of damage [25]. In Boundary Bay waves breached a private section of sea wall and a temporary sand berm, causing damages and repairs cost of $2500 for the Corporation of Delta $2500 [24]. The section of dike between 96th and 112th avenue suffered minor damages and rip rap required maintenance, all of which cost the Corporation of Delta $5300 [24]. In Beach Grove, a section of dike experienced erosion on the foreshore side, requiring repairs that cost the Corporation of Delta $2000 [24]. At 80th street near the SPCA, drainage and high tide caused localized flooding [24].

In total, the sea level flooding event on January 2nd, 2003, cost the Corporation of Delta $9800 [24]. The Corporation of Delta indicated that it would apply to the Flood Protection Assistance Fund, but the research provided no additional records of compensation. The records also did not detail costs of flooding to private residents. The research did not uncover records of flooding for any other Metro Vancouver municipalities.

Preparedness
Other than the Corporation of Delta's seasonal construction of a temporary sand berm, it appears there were no preparedness measures specific to this sea level flooding event [24].

Response
The Corporation of Delta responded to the flooding by diverting inundated sea water to drainage with sandbags [25]. In the post flooding phase, the Corporation of Delta undertook $9800 in repairs, which were documented in the preceding sections.

Summary of Event / Analysis
Storm surge, wave run up, and extreme high tides combined on January 2nd, 2003 to cause flooding of various parts of South Delta. It appears again that winds were a significant contributor to the flooding, as even higher tides occurred on January 3rd with low winds and no flooding. The extreme tide on January 3rd was the 6th highest in the research period and narrowly missed coinciding with high winds earlier that day.

The research did not provide many details of preparedness measures, damages, and response measures. This may be in part due to lack of actions or due to lack of documentation of these actions. It is not possible to know for certain.

3.10 March 3rd, 1999

Occurrence
On March 3rd, 1999 Metro Vancouver experienced an extreme tide event that resulted in sea level flooding. The peak water level measured 5.292 metres at 700 PDT [2]. Weather conditions at the time of peak water levels were cloudy with average an average wind speed of 56 km/h from the southeast [1]. The Vancouver Sun reported wind gusts of 104 km/h in Tsawwassen [26].

Effects
Flooding occurred when a private section of retaining wall collapsed at Centennial Beach in Delta [26]. The Vancouver Sun reported flooding of half a dozen homes [26] with a conflicting report from the Ministry of Environment of approximately 20 homes [20]. Research provided no data for the exact number of people affected or dollar value of damage.

Preparedness
Records provided no information describing preparedness measures.

Response
On March 3rd, 1999 the Mayor of Delta declared a local state of emergency (time unknown) [20]. The Delta Fire Department, Police, Municipal Engineering Department, and Emergency Social Services responded to the event [20]. The Corporation of Delta installed concrete blocks to shore up the retaining wall [26]. Flooded basements were pumped out, but no residents were forced to leave their homes [20]. At 900 PDT on March 4, 1999 the Mayor cancelled the local state of emergency [20].

Summary of Event / Analysis
This event had the coinciding ingredients for sea level flooding in Delta: extreme high tides and high winds from the southeast. The water levels were high, but only the 74th highest in the research period. This was the lowest water level from the research methodology to coincide with sea level flooding, which indicates that wind plays an important role in wave run up and storm surge.

This occurrence challenged the research methodology because it was not one of the higher recorded water levels and it was not a well-documented event. Traditional methods of searching databases and newspaper archives did not return information for this date; however, data from the Ministry of Environment documented sea level flooding on this date. It is only from this data that a targeted search returned an article from the Vancouver Sun. It is possible that other minor sea level flooding events occurred, particularly further back in time, which the research methodology did not uncover.

3.11 December 9th, 1987

On December 9th, 1987 Metro Vancouver experienced an extreme tide event that resulted in no flooding. The peak water levels measured 5.44 metres at 900 PDT [2]. Weather conditions at the time of peak water levels were rainy with average wind speeds of 20 km/h from the east [1].

This date was examine because the water levels were the 14th highest in the research period. Despite the high water levels, the research returned no evidence of a sea level flooding. The lack of flooding is likely due to relatively low wind speeds and the direction of winds, blowing from the east.

3.12 January 28th, 1987

On January 28th, 1987 Metro Vancouver experienced an extreme tide event that resulted in no flooding. The peak water levels measured 5.4 metres at 600 PDT [2]. Weather conditions at the time of peak water levels were rainy with average wind speeds of 26 km/h from the southeast [1].

This date was examine because the water levels were the 19th highest in the research period. Despite the high water levels, the research returned no evidence of a sea level flooding. The lack of flooding is likely because combined water levels and wind speeds were insufficient to cause sufficient wave run up.

3.13 January 3rd, 1987

Occurrence
On January 3rd, 1987 Metro Vancouver experienced an extreme high tide event that caused minor flooding. The peak water level measured 5.57 metres (highest in the research period) at 900 PDT [2] and coincided with average wind speeds of 24 km/h from the southeast [1]. Weather conditions were cloudy with no rain [1].

Effects
The winds and extreme high tide caused some flooding in Point Roberts and delayed the launch of a new Coast Guard vessel in North Vancouver [27]. The research provided no additional details as to the effects of flooding.

Preparedness
The research provided no details of preparedness measures for this specific event.

Response
The research provided no details of response measures to this specific event.

Summary of Event / Analysis
Relatively low winds and the highest water levels in the research period combined to cause minor flooding on January 3rd, 1987. This event had all the ingredients for a significant sea level flooding events, except for the relatively low wind speeds. Had wind speeds been moderately higher, it is likely a significant flooding event would have occurred.

Information for this specific event was very limited. The Vancouver Sun provided the only reference material and details of flooding constituted one line of text. The effects, costs, and response measures have a great deal of uncertainty for that reason.

3.14 January 27th, 1983

On January 27th, 1983 Metro Vancouver experienced an extreme tide event that resulted in no flooding. The peak water levels measured 5.48 metres at 500 PDT [2]. Weather conditions at the time of peak water levels were rainy with average wind speeds of 7 km/h from the southeast [1].

This date was examine because the water levels were the 8th highest in the research period. Despite the high water levels, the research returned no evidence of a sea level flooding. The lack of flooding is likely because wind speeds were too low to cause sufficient wave run up.

3.15 December 16th, 1982

Occurrence
On December 16th, 1982 Metro Vancouver experienced an extreme tide event that resulted in flooding. Peak water levels measured 5.55 metres at 700 and 800 PDT (3rd and 4th highest in the research period) [2]. Average wind speeds measured 30 km/h from the south at 700 PDT and 41 km/h from the southwest at 800 PDT [1]. Weather conditions were cloudy. The Vancouver Sun reported wind gusts of 100 km/h [28]. The Ministry of Environment noted that storm surge and high tide did not fully coincide [29].

Figure 4.3.1.1: December 16th, 1982 flooding in Boundary Bay (Top) [29]; Flooding in Boundary Bay and Surrey (bottom three photos) [28].

Effects

Flooding occurred throughout many municipalities in Metro Vancouver. Storm surge and wave run up inundated Point Roberts with water, flooding basements and yards [28]. The Vancouver Sun observed a sail boat washed up on a sun porch. Individual residents reported damages to basements in the order of $4000 to $30000 [28]. The storm washed one shoreline cottage off its foundation [28].

Surrey also experienced flooding. Water levels breached dikes along the Serpentine and Nicomeki rivers, flooding mud bay and the King George highway [28]. The Vancouver Sun reported flooding of a 65 hectare dairy farm and flood damage of an estimated $100000 to an Art Knapp's owned by Peter Vander Zalm (brother of then Education Minister, Bill Vander Zalm) [28].

A Ministry of Environment photograph also provided evidence of flooding in Boundary Bay [29], but there are no written observations of the flooding effects. The Vancouver Sun reported that Provincial Emergency Program officials would submit a report on flooding damage to the BC Government, but the research could not locate this report [28].

In total, the Vancouver Sun reported damages from flooding in the millions of dollars [28]. The research provided no other information to verify or ascertain the flooding damage value.

Preparedness

The Vancouver Sun alluded to a storm warning, referring to its cancellation on December 17th [28]. Otherwise, there were no records of other preparedness measures for this specific occurrence.

Response

Provincial Emergency Program officials surveyed the damages in Surrey and Crescent Beach after the flood [28]. The Vancouver Sun also reported that no fixed form of aid was available, but aid was available based on need [28]. In Surrey, crews topped dikes with additional dirt [28].

Summary of Event / Analysis

The extreme tide and high winds combined for significant flooding on December 15th, 1982. Winds from the southwest brought flooding to shorelines and areas that face the west, such as Point Roberts and areas of Surrey. Records for this date were extremely limited with the December 17th, 1982 edition of the Vancouver Sun providing the majority of citations.

3.16 February 9th, 1978

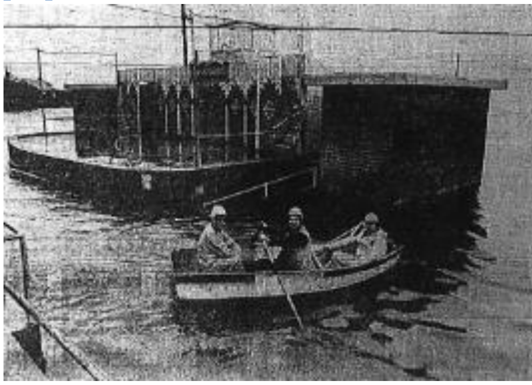
On February 9th, 1978 Metro Vancouver experienced an extreme tide event that resulted in no flooding. The peak water levels measured 5.42 metres at 700 PDT [2]. Weather conditions at the time of peak water levels were rainy with average wind speeds of 7 km/h from the southeast [1].

This date was examine because the water levels were the 16th highest in the research period. Despite the high water levels, the research returned no evidence of a sea level flooding. The lack of flooding is likely because wind speeds were too low to cause sufficient wave run up.

3.17 December 15th, 1977

Occurrence
On December 15, 1977 Metro Vancouver experienced an extreme tide event that resulted in flooding. Peak water levels measured 5.48 metres at 1000 PDT (9th highest in the research period) [2] and were preceded by average wind speeds of 20 km/h from the northwest [1]. Weather conditions at the time of peak water levels were cloudy with no rain [1].

Figure 4.3.1.1: December 15th, 1977 flooding in Kitsilano Pool, Vancouver [30].



Effects
Winds and extreme high tides brought flooding to Richmond and Vancouver. The extreme high tide and debris caused the Fraser River to breach the dikes on the north side of Mitchell Island, flooding the streets with approximately 0.6 metres (2 feet) of water [30]. In Vancouver, westerly winds held back the tide in Burrard Inlet causing water levels to breach the sea wall at Kitsilano beach [30]. Figure 3.17.1 shows the sea water inundation at the Kitsilano Pool.

Preparedness
The research provided no records of preparedness measures for this specific event.

Response
The research provided no records of response measures for this specific event.

Summary of Event / Analysis
Westerly winds and extreme high tide combined to cause sea level flooding on December 15th, 1977. This event is unique in the 50 year sample of this research because it is the only extreme tide that coincided with winds from the west / northwest, which is likely the reason for flooding in the City of Vancouver and Richmond.

3.18 January 14th, 1974

On January 14th, 1974 Metro Vancouver experienced an extreme tide event that resulted in no flooding. The peak water levels measured 5.43 metres at 1000 PDT [2]. Weather conditions at the time of peak water levels were cloudy with average wind speeds of 18 km/h from the south [1].

This date was examine because the water levels were the 15th highest in the research period. Despite the high water levels, the research returned no evidence of a sea level flooding. The lack of flooding is likely because wind speeds were too low to cause sufficient wave run up.

3.19 December 7th, 1970

On December 7th, 1970 Metro Vancouver experienced an extreme tide event that resulted in no flooding. The peak water levels measured 5.39 metres at 1200 PDT [2]. Weather conditions at the time of peak water levels were cloudy with average wind speeds of 37 km/h from the south [1].

This date was examine because the water levels were the 23rd highest in the research period. Despite the high water levels, the research returned no evidence of a sea level flooding. Although wind speeds were moderate and high enough to cause sufficient wave run up (similar to other dates), the lack of flooding is likely because water levels and the wind direction were insufficient to cause wave run up and inundation of vulnerable areas (Boundary Bay, Beach Grove, etc.).

3.20 December 24th, 1968

On December 24th, 1968 Metro Vancouver experienced an extreme tide event that resulted in no flooding. The peak water levels measured 5.49 metres at 1000 PDT [2]. Weather conditions at the time of peak water levels were rainy with average wind speeds of 18 km/h from the east [1]. Records show that snowfall occurred in preceding days, but this appears to have had no effect [1].

This date was examine because the water levels were the 7th highest in the research period. Despite the high water levels, the research returned no evidence of a sea level flooding. The lack of flooding is likely because wind speeds were too low to cause sufficient wave run up.

3.21 December 5th, 1967

Occurrence
On December 5th, 1967 Metro Vancouver experienced an extreme tide event that resulted in significant flooding. Peak water levels measured 5.57 metres at 900 PDT (tied for highest in the research period) [2] and coincided with average wind speeds measured 29 km/h from the southwest [1]. Earlier in the day at 700 PDT, average wind speeds measured 51 km/h from the southwest [1]. Vancouver experienced hurricane force winds in the two days preceding the flooding event [31]. The peak water levels tied for the highest in the research period and the highest record in December 1933 [32].

Effects

The extreme high tides and wind combined to cause significant flooding throughout Metro Vancouver. Areas particularly affected include West Vancouver and Richmond. Figure 3.21.1 illustrates flooding in locations throughout West Vancouver.

In Richmond, the Fraser River breached dikes on the north side of Lulu Island flooding “scores” of homes [31]. The dikes on the south side held [32]. Homes and industrial plants on Mitchell Island also experienced flooding, as did River Road in Richmond [31]. There were no dollar value indications for flooding damage.

In West Vancouver, waves breached a sea wall at Cypress Park flooding 22 homes and washed out a sea wall at Dundarave [33]. Waves inundated Ambleside beach and flooded the Ambleside Park roadway [33].

In Delta, areas around Boundary Bay and Westham Island also experienced flooding [33]. No more specific information was available. In Ladner, most of the main streets were flooded [32]. No more specific information was available.

In Vancouver, flooding occurred at the intersection of Cambie Street and Kent Street, Water Street, and the foot of Burrard Bridge [33].

Throughout all the reports of damage, there were no dollar value estimates of flood damage.

Preparedness
The research provided no records of preparedness measures for this specific event.

Response
In West Vancouver, city crews, civil defence, and volunteers from the Haney Correctional Institution responded to the flooding at Cypress Park [32]. One resident reported that civil defence would not respond and the fire department said it was “not their job.” [34].

The records contained no information about response measures in other municipalities.

Summary of Event / Analysis
The record high water levels and high winds from the southwest caused extensive flooding throughout Metro Vancouver. Of all the flooding events covered in this research, this event affected the greatest number of municipalities. The Vancouver Sun was the single source for citations for this event, but extensive coverage was contained in numerous articles. It

Figure 4.3.1.1: December 5th, 1967 flooding in West Vancouver [34, 33, 32].

is also important to note that the most severe winds preceded high tide. Had they coincided, flooding damage would likely have been much greater.

3.22 October 12th, 1962

On October 12th, 1962 Metro Vancouver experienced a severe wind storm that caused no flooding. Peak water levels measured 5.18 metres at 900 PDT [2] and coincided with average wind speeds of 35 km/h from the southeast [1].

The research methodology selected this date based on historical knowledge. On October 12th, 1962 a sub-tropical storm with hurricane force winds hit Vancouver. This storm, later referred to as Typhoon Freda, carried some of the highest wind speeds measured in Vancouver and is considered one of the worst storms to hit the west coast.

The research methodology found extensive coverage of Typhoon Freda by the Vancouver Sun. Although sources contained no information on flooding, it is possible that flooding occurred during this storm. If flooding had occurred, its effects may have been insignificant in comparison to wind damage.

3.23 Late 1800s

The initial search for sea level flooding events in Metro Vancouver involved a scan of municipal archives, which provided no written description of flooding events but did provide photos. Figure 3.21.1 illustrates flooding in locations around Ladner (Delta) in 1895 and 1899.

Figure 4.3.1.1: January 5th, 1895 flooding in Ladner (top two photos); 1899 flooding in Ladner (bottom photo) [46].

3.24 Synthesis of Observations

Summary

Out of 21 dates examined for sea level flooding from 1960 to 2011, the research identified flooding on 8 dates and no flooding on the remaining 13. Table 3.24.1 summarizes the details surrounding each flooding event and Figure 3.24.2 shows a graphic illustration of flooding on a map of Metro Vancouver.

Table 3.24.1

Occurrence	Affected Municipalities	Sea Level (measured from Chart Datum)	Average Hourly Wind Speed and Direction	Damage (Certainty)
November 24th, 2011	Corporation of Delta	5.206 m	50 km/h from SE	Unknown
February 4th, 2006	Corporation of Delta City of Richmond	5.446 m	37 km/h from SE	Reported: $1,757,793 *2011 eq.: $1,931,323 (High Certainty)
January 3rd, 2003	Corporation of Delta	5.369 m	41 km/h from SE	Reported: ~$9800 *2011eq.: ~$11,000 (Low Certainty)
March 3rd, 1999	Corporation of Delta	5.292 m	56 km/h from SE	Unknown
January 3rd, 1987	Unknown	5.57 m	24 km/h from SE	Unknown
December 16th, 1982	Corporation of Delta City of Surrey	5.55 m	41 km/h from SW	Reported ~$1,000,000+ *2011: eq.: ~$2,100,000+ (Low Certainty)
December 15th, 1977	City of Richmond City of Vancouver	5.48 m	20 km/h from NW	Unknown
December 5th, 1967	West Vancouver Vancouver Richmond Corporation of Delta	5.57 m	29 km/h from SW	Unknown
Total				*2011 eq.: ~$4,000,000

*Note: 2011 equivalent dollars calculated using Bank of Canada Inflation Calculator.

Figure 4.3.1.2

	Date	Affected Areas
A:	November 24th, 2011	Delta (Boundary Bay)
B:	February 4th, 2006	Delta (Boundary Bay)
C:	January 3rd, 2003	Delta (Boundary Bay)
D:	March 3rd, 1999	Delta (Boundary Bay)
E:	December 16th, 1982	Delta (Boundary Bay) Surrey
F:	December 15th, 1977	Richmond (Mitchell Island) Vancouver (Kitsilano)
G:	December 6th, 1967	West Vancouver Vancouver Richmond (Lulu Island and Mitchell Island) Delta (Ladner, Westham Island, Boundary Bay)

Occurrence & Vulnerability

The summary in Table 3.24.1 and Figure 3.24.2 reveal some key observations about sea level flooding in Metro Vancouver. Delta is historically the most vulnerable municipality in Metro Vancouver (6 out of 8 flooding events affected Delta). Delta is historically vulnerable to flooding when extreme tides combine with high winds from the southeast. Delta, West Vancouver, Richmond, and Vancouver are all historically vulnerable when extreme tides combine with high winds from the southwest. Richmond and Vancouver are vulnerable when extreme tides combine with high winds from the northwest. And finally, when extreme tides are near record levels, flooding can occur with winds as low as 24 km/h (e.g. 1987).

Effects

The research informs three main observations about the effects of sea level flooding. When significant sea level flooding occurs in Metro Vancouver, it can cause damages of more than $1,000,000. The costs of the 2006 occurrence have a relatively high degree of certainty and are similar to the cost of the 1982 occurrence. Also, sea level flooding can potentially damage hundreds of homes. This 2006 occurrence demonstrates this observation. Lastly, Metro Vancouver has yet to record a death as a direct result of sea level flooding.

Preparedness

The research informs a number of observations regarding preparedness. Starting with the Corporation of Delta (the organization) has a high degree of preparedness, which is demonstrated by the numerous storm surge advisories, sea level advisories, and media releases throughout most extreme tide and storm events. Review of occurrences that resulted in no flooding shows that the Corporation of Delta usually erred on the side of caution and warned the public regardless. Additionally, the hiring of a full time emergency manager, proactive activation of its emergency operations centre, and implementation during real occurrences demonstrates a high level of preparedness.

Conversely, the citizens of Delta demonstrate varying levels of preparedness. Some have sea walls, but some still resist construction of a sea wall for esthetic reasons.

Little can be inferred about the preparedness of other municipalities in Metro Vancouver because recent sea level flooding occurrences have been isolated to Delta.

The media also plays a varying role in preparedness. The Delta Optimist is not published daily, but covers sea level flooding events closely. However, most other media organizations cover sea level flooding after the occurrence.

Response

The research informs a number of observations regarding emergency response to sea level flooding. First, the level of response has evolved from responders saying it's “not their job,” to sophisticated emergency command structures with city staff, fire departments, and police. The Corporation of Delta is the most tested and response appears well organized. Little can be inferred about other Metro Vancouver municipalities because recent sea level flooding occurrences have been isolated to Delta.

Literature Review Methodology
The literature review methodology for examining potential sea level flooding events provided varying levels of success. Some successful outcomes were the validation with known significant sea level flooding occurrences in 2006 and 1982, and the uncovering of newspaper articles for 4 other less well known occurrences.

Some deficiencies in the methodology include the missing of the March 3rd, 1999 sea level flooding event. The methodology found this event only because it was referenced in the documents for flooding on another date. Additionally, newspaper articles are the most readily available sources, but prior to 2006 they are difficult to find on-line. For that reason, there may be other occurrences that the methodology did not identify.

One strength of the methodology is that it relied on measured water levels at the Point Atkinson station. However, this also a weakness of the methodology because it does not directly account for storm surge and wave-run up. For that reason there may be other sea level flooding events that the methodology did not identify.

Finally, there is an inherent weakness in this or any other methodology because it is searching for information that may not be readily available. Dates identified by the methodology that have no record of flooding cannot lead one to conclude that flooding did not occur; it simply may not have been recorded.

For further studies on historic sea level flooding in Metro Vancouver, I would recommend potential dates to include all listed in this report. I would also recommend subsequent studies to incorporate storm surge and wave run up to help determine potential flooding dates.

4 Future Sea Level Flooding Vulnerability

4.1 Global Sea Level Rise

Global sea levels are rising and climate change will further exacerbate the problem. The Fourth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (UNIPCC) predicts sea levels to rise between 0.18 metres and 0.59 metres by 2100 [35]. The UNIPCC recognized a low probability scenario of extreme melting of Greenland and Antarctic ice sheets, which could raise sea levels by 0.69 metres by 2100. In the years since the Fourth Assessment Report, the Arctic Monitoring and Assessment Programme has observed record warmth and melting in the Arctic, leading to a revised estimate of 0.9 metres to 1.6 metres of sea level rise by 2100 [36]; however, these predictions remain uncertain.

4.2 Local Sea Level Rise

Metro Vancouver will experience a greater effect of sea level rise due to the natural subsidence of the Fraser River Delta. In 2008, the BC Ministry of Environment projected sea levels to increase of 0.89 to 1.03 metres for Vancouver and 1.2 metres for the Fraser River Delta by 2100 [37], based on the extreme high scenario of the UNIPCC Fourth Assessment Report.

4.3 Metro Vancouver Vulnerability to Sea Level Rise

4.3.1 Technical Report on Local Climate Change Visioning for Delta: Findings and Recommendations [38]

In 2008 the Collaborative for Advanced Landscape Planning (CALP) at the University of British Columbia performed a study for the Corporation of Delta to determine how knowledge of sea level rise affects public perceptions. CALP provided information in two forms: traditional forms (graphs, maps, diagrams) and visualizations. CALP depicted the effects of a 0.58 meter sea level rise a number of areas of Delta and conducted surveys on public perceptions. Figure 4.3.1.1. provides an illustrative depiction of CALP's work, showing Boundary Bay before and after sea level rise (2100). The following paragraphs detail their findings.

Figure 4.3.1.1: Boundary Bay at present (top) and after sea level rise (2100).

In Roberts Bank, CALP found that 0.58 m sea level rise with 2 m high tide and a 0.9 m storm surge (3.48 m total) would overtop the 3.5 m dike. Even without storm surge, sea levels may breach the dikes with minimal wave activity. For these reasons, CALP raises longer term concerns for a major dike breach in Roberts Bank.

In Westham Island, CALP found that 2 m high tide and 0.9 m storm surge (2.9 m total) would breach the 2.9 m dikes even without sea level rise. With sea level rise, the dikes would be overtopped by 0.58 m. Without sea level rise or storm surge, sea levels may still breach the dikes with minimal wave activity. Westham Island has particular vulnerability in that salinization would eventually affect crops and change the ecosystem and species composition of the George C Reifel Migratory Bird Sanctuary.

CALP also found that the Agricultural Land Reserves (ALR) would experience salinization as a result of dike breaches and the formation of a salt wedge expanding up the Fraser Delta. By 2020, CALP predicted that salinization may make some crops non-viable. By 2050, CALP predicted that a large portion of the ALR near the coast line would be abandoned.

In shoreline ecosystems, CALP found that rising sea levels will squeeze high marsh lands against the dikes. High marsh would become low marsh or mud plain ecosystems and loose half their biodiversity.

CALP also speculated about the cumulative effects of other aspects of climate change with sea level rise. CALP speculated that climate change displaced populations may find Metro Vancouver an attractive location for emigration. The increased pollution will likely encroach on the agricultural land reserve, stress community infrastructure, and create socio-economic impacts. In Boundary Bay coastline development may continue, but in areas resistance to private sea walls would those areas more vulnerable and eventually causing residents to retreat.

CALP made a number of findings regarding the effect of visualizations on public perceptions. Table 4.3.1 summarizes the findings and the supporting statistics.

Table 4.3.1

Finding	Supporting Information
Finding 1. Visualizations increased awareness and relevance of climate change info in the community.	Participants who thought GHG reductions were a good or very good idea: 49% before visualizations; 81% after. Participants who felt they were quite or very knowledgeable about the effects on the local community: 32% before visualizations; 81% after. Participants who somewhat or strongly agreed that they understood how their family could respond to climate change: 83% before visualization; 98% after.
Finding 2. Visualizations increased concern about impacts of climate change	This finding was not statistically significant.
Finding 3. Visualizations increased empowerment to act on climate change	Participants agreed that they felt empowered to act on climate change: 45% before visualization; 68% after.
Finding 4: Imagery can help build understanding and capacity	Participants who felt they learned a great deal: 29% with visualization; 8% with non-visualizations. Participants who felt they were quite or very knowledgeable about the effects on the local community: 81% with visualizations; 55% with non-visualizations. Participants who somewhat or strongly agreed that they understood how their family could respond to climate change: 98% with visualizations; 76% with non-visualizations. Participants who support local mitigation measures somewhat or a lot: 73% with visualizations; 59% with non-visualizations.
Finding 5: Visualizations inspire the need for action	Participants who felt motivated to do something about climate change: 74% with visualizations; 56% with non-visualizations.

4.3.2 Human Vulnerability and Climate Change: An Assessment of Greater Vancouver's Human Vulnerability to Sea Level Rise in 2100 [39]

Emily Nixon of the BC Ministry of Health performed a study of human vulnerability to 2100 sea level rise in Vancouver. The study area included locations corresponding to the City of Richmond, the City and District of North Vancouver (City and District), and the City of Vancouver. The study further subdivided the geographic areas on the basis of like socio-economic communities. The study modeled a best case scenario of 0.09 m sea level rise, a worst case scenario 0.88 m sea level rise, and a catastrophic case 6 m sea level rise by 2100. The vulnerability indicators assessed include:

- Population density
- Household characteristics (ownership status)
- Family characteristics
- Level of education
- Labour force
- Primary transportation
- Household income
- Family economy (lower income less access to insurance and monetary resource)
- Recently immigrated
- Primary language
- Age

Nixon assigned scores for each vulnerability indicator: 10 for low; 20 for medium; and 30 for high. Vulnerability scores were added and tabulated for each area. The five areas with the highest score were:

- Northeast Vancouver
- Downtown Vancouver
- Southeast Vancouver
- Central / Downtown Richmond
- City North Vancouver

There are limitations to this study. The report provided only a high level summary of results; the data for the vulnerability indicators were not part of the report. Vulnerability scoring ultimately came down to assigning numerical values for some qualitative factors; however the assessment framework was transparent and available in the report.

4.3.3 Vulnerable Populations: A Spatial Assessment of Social Vulnerability to Earthquakes in Vancouver, British Columbia [40]

Fox performed a spatial assessment of social vulnerability of the City of Vancouver to earthquakes. Although this study centers on vulnerability to earthquakes, I reviewed this paper in case there was applicability to sea level rise.

Fox performed her vulnerability study using the Social Vulnerability Index (SoVI) and Pareto modeling methods. Assessment areas followed census tracts and used 2001 census data. Fox chose 15 variables for social vulnerability, mostly socio-economic factors chosen on the applicability and availability of data. Fox catered some variables specifically to earthquake vulnerability, which indicates that the method and models may be applied to sea level rise. Her analysis concluded that with both SoVI and Pareto models that Strathcona and Grandview Woodlands are Vancouver`s the most vulnerable locations.

Fox's report provided a significant amount of detail and used two well established vulnerability models. For these reasons, Fox's report warrants consideration as a framework for future vulnerability studies in Vancouver.

4.3.4 The Local Effects of Global Climate Change in the City of Vancouver: A Community Toolkit and Atlas [41]

Bing Tom Architects (BTA) conducted a study that focused on the effects of sea level rise in the City of Vancouver. The study area extents followed the municipal boundaries. BTA extensively used Vancouver's Open Data Catalogue as the source for much of their information.

BTA projected sea level rise scenarios on topographic maps to estimate the extent of sea level rise affected areas affected. BTA estimated the % of affected land area with sea level rise scenarios ranging from 0 m to 6 metres. BTA conducted parallel estimates that added 2 meters to the affect zone to account for land area that may be required for dikes.

For the basis of cost projections, BTA determined that a 1 metre sea level rise would require a 5.6 m flood construction level. With that logic, BTA then conservatively assessed the loss of land associated with an effective 5 m sea level rise. The result was a loss of 12% of the total land area in the City of Vancouver. Based on the land use breakdown, this loss of land disproportionately affects industrial lands, historic area, and public spaces (including sea walls and waterfront parks). BTA estimated the value of a square metre land in Vancouver by dividing the total value of Vancouver ($212 billion, not including lands and buildings, public space, or city infrastructure) by the lost land area. The result of the analysis was an estimated loss of $25 billion for 1 metre sea level rise.

For the counter scenario of mitigation, BTA also estimated the value of expenditures required to mitigate 1 m of sea level rise. The analysis assumed the need for dikes along 59.5 km of coastline (including the University Endowment Land), $5000 / m for earth dike, and $1000 / m for sea wall. The cost estimate for mitigation by diking totals $255 to $510 million. It is important to note that these costs do not include the land acquisition required for diking, nor do they include mitigation beyond 1 metre sea level rise (or approximately past 2100).

BTA concluded the report with the recommendation to perform more detailed studies following a sea level rise planning area, as in the Ausenco Sandwell guidelines.

This study provided valuable insight for estimating sea level rise impacts in Vancouver. BTA's inclusion of total affected lands for flood construction levels is an important consideration. BTA's analysis also provided reasonable ballpark estimates of the cost of inaction and the cost of mitigation. Both estimates have their gaps that should be accounted for in future analyses. In the estimate of the cost of inaction, more detailed analysis should include the cost of buildings and public infrastructure, as well as land, in the estimates. In the estimate of mitigation by diking, more detailed analysis should the cost of land acquisition. Since both estimates have their limitations, it is reasonable to compare BTA's estimates and conclude that inaction will likely cost upwards of 50 times more than mitigation.

4.3.5 Adapting to Climate Change Canada's First National Engineering Vulnerability Assessment of Public Infrastructure Appendix B.3 Vulnerability of Vancouver Sewerage Area Infrastructure to Climate Change [42]

In 2008, Kerr Wood Leidal assessed the vulnerability of the City of Vancouver Sewer Area infrastructure to climate change on behalf of the Public Infrastructure Engineering Vulnerability Committee (PVIEC). The study area included the City of Vancouver, the University of British Columbia (UBC), the UBC Endowment Lands, and parts of the City of Burnaby and City of Richmond. Specific to sea level rise, the report estimated the impact of sea level rise scenarios for 0.06 m by 2020, 0.14m by 2050, and 0.26 m by 2080. Kerr Wood Leidal then assessed vulnerability using the PVEIC vulnerability assessment for each of the sea level rise scenarios.

Kerr Wood Leidal's vulnerability assessment drew the following conclusions:

- Storm surge has strong probability of a severe effect on Effluent disposal, on-site pipelines (tankage for sea level), and Buildings Tankage and Housed Process Equipment.
- Sea level rise can have a possible major effect on pipelines (tankage for sea level), and Buildings Tankage and Housed Process Equipment.
- Kerr Wood Leidal recommended management action for records with respect to sea level rise and surge. This includes additional measurements, monitoring, and recording of sea level events and impacts.
- Recommended additional study for the impacts of sea level rise and storm surge on on-site pipelines/tankage and buildings tankage and housed process equipment.

4.3.6 National Roundtable on the Environment and the Economy Climate Prosperity Paying the Price: The Economic Impacts of Climate Change [43]

In 2011, the National Roundtable on the Environment and the Economy (NRTEE) assessed the economic impacts of climate change in Canada. The study had a national scale and a scope that included numerous aspects of climate change. The study provided discrete assessment of the impacts of sea level rise down to the local level for Metro Vancouver.

A considerable number of assumptions went into NRTEE's assessment. NRTEE treated sea level rise as a risk for permanent flooding and storm surge as a risk for temporary flooding. Flooding from sea level rise would therefore occur only once, while storm surge flooding would only be repaired once per year. NRTEE assessed four scenarios for climate change ranging from low climate change (0.28 m sea level rise by 2100) with slow growth to high climate change (0.85 m sea level rise by 2100) with rapid growth. NRTEE did not account for subsidence at the local scale and did not account for protection that existing dikes offered.

To assess the economic impact, NRTEE used GIS data to identify affected land areas. NRTEE used 2006 census data for the GIS coordinates of affected areas to determine the value of dwellings. The analysis results estimated that 8900 to 18700 dwellings are at risk for flooding in BC by 2050. As a result, NRTEE estimated that sea level rise and storm surge in British Columbia could cost between $2.1 and $7.6 billion by 2050.

4.3.7 Sierra Club of Canada, BC Chapter, Potential Sea Level Rise [44]

The Sierra Club of Canada, BC Chapter published a computer generated graphic illustrating a 6 metre sea level rise in Metro Vancouver (Figure 4.3.7.1). According to the Sierra Club of Canada, BC Chapter, a 6 metre sea level rise in Metro Vancouver would inundate 91% of Richmond, 76% of Delta, and 32% of New Westminster.

Figure 4.3.6.1: Overlay of 6 metre sea level rise in Metro Vancouver.

4.4 Synthesis

Overall Observations
Taking the available studies at face value, a number of observations can be made about Metro Vancouver`s vulnerability to sea level rise. According to NRTEE, Metro Vancouver could face a cost for sea level rise of $2.1 to $7.6 billion by 2050. BTA estimates a cost of $25 billion for a 1 metre sea level rise for the City of Vancouver alone. PVIEC was the only study that investigated vulnerability of public infrastructure, specifically the City of Vancouver`s sewer system. Although PVIEC does not estimate the costs, it identifies vulnerability and recommends better record keeping and monitoring. Nixon investigated societal vulnerability of Richmond, Vancouver, and the City and District of North Vancouver and her high level analysis found the most vulnerable locations to be Northeast Vancouver, Downtown Vancouver, Southeast Vancouver, Central Richmond, and the City of North Vancouver. Fox investigated the societal vulnerability of the City of Vancouver to sea level rise and found Strathcona and Grandview to be the most vulnerable locations. Finally, CALP`s work with the Corporation of Delta used innovative modelling and made a number of findings for how visualizations affect public perceptions of climate change.

Limitations of the Studies
The strengths and limitations of each study are described in their respective sections earlier in the report; however, there are some common limitations to highlight. None of the studies bridge the gap between physical and societal vulnerability, nor do they account for risk reduction strategies or adaptive capacity. Delta for instance may have high physical vulnerability, but low societal vulnerability due to its high level of preparedness. Vancouver on the other hand may have high societal vulnerability, but the locations are likely much less physically vulnerable than Delta. Additionally, the basic assumptions for sea level rise in each report appear conservative in light of new predictions of higher sea level rise. This means that each report likely underestimates the impact and their conclusions should be taken as conservative. Finally, the scope of each report varied substantially: from all of Metro Vancouver to just the City of Vancouver or the

Corporation of Delta. Generally, the analysis appears to be in greater detail for the more narrow scope studies.

Recommendations for Future Studies

1. Use the most recent projections for sea level rise and attempt to account for uncertainty.
2. Narrow the geographic scope of the study so that a broad and detailed scope of sea level rise impacts can be assessed.
3. Cover aspects of physical vulnerability, societal vulnerability, and adaptive capacity together in one assessment.
    a. Consider detailed risk assessment as a candidate methodology.
    b. Consider the CALP findings for risk reduction strategies.
4. Consider the Corporation of Delta for pilot study given extensive information available and high physical vulnerability.
5. Consider calibration of any study against the documented effects of the February 4th, 2006 sea level flooding event.
6. Consider findings from historic vulnerability for an assessment of the current state of physical and societal vulnerability.

5 Conclusions

This literature review established Metro Vancouver`s vulnerability to sea level flooding in two timeframes: historical vulnerability from the effects of past sea level flooding events and future vulnerability from projections of sea level rise. Eight (8) sea level flooding events between 1960 and 2011 established details of historical vulnerability. Six (6) studies established details of future vulnerability.

Sea level flooding is a part of Metro Vancouver`s history and will continue to be a part of its future. Regardless of the effects of climate change, Metro Vancouver has and would experience sea level flooding. Accounting for the effects of climate change, Metro Vancouver will likely experience a dramatic increase the frequency and damage of sea level flooding.

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