Causes and Effects of the November 2021 Pacific Northwestern Floods in British Columbia

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Abstract. Global warming can result in high frequency in precipitation in some areas, and as a result of high precipitation, floods may occur more frequently and may cause more damage to urban areas. The Pacific Northwestern Flooding event that happened between November 14, 2021, to December 17, 2021, is a series of recent flooding events, and it can reasonably be the most expensive flooding event in British Columbia history. This study used QGIS tools to analyze the topographical characteristics of Vancouver in contribution to the severity of the floods. This study also organized reports on the infrastructure, population, and economic impacts of the floods in British Columbia, where Vancouver settled. Results show that Vancouver is generally low in altitude, with some areas in pot shape, making it easy for floods to invade. There was also an increase in rainfall frequency in Vancouver in the past 50 years, which aided the severity of floods. The flooding event in British Columbia has led to transportation damages, fatalities and injuries, and economic losses. Some suggestions for urban planning and administration in conscious of the presence of more severe flooding events are proposed such as comprehensive emergency management program.

Keywords: British Columbia, Vancouver, Flood, QGIS, Remote Sensing Technology.

1. Introduction

Flood has been the leading cause of yearly damage that brought immense economic loss, fatalities, and injuries to thousands of people in the last decades. With climate change being a more significant issue, more enormous flood damages may be present to threaten urbanization and humanity [1]. Frequent occurrences of severe weather due to global warming may also boost the frequency of floods. Floodplains or low-lying coastal zones with a dense population or trade ports can be hugely impacted due to the frequent floods. Overall, an increase in urban destruction caused by the floods would expect to be the situation for the foreseeable future [2]. To give a few examples of those damages: in 1998, a vast flood rushed over the major watersheds in China, which resulted in the emergency activation of 15,000 dike segments across the country. Nationwide, 186 million people were impacted by the floods, which were responsible for 4,150 fatalities and resulted in a total economic loss of $70 billion [3].

The November 2021 Pacific Northwestern Floods event is an example of the devastating effect brought by the floods. Since November 14, 2021, heavy rainfall in the Pacific Northwest triggered a series of floods and landslides in parts of the Canadian province of British Columbia and the neighboring US state of Washington. The rainfall was caused by an atmospheric river that moved across the Pacific Ocean. The atmospheric river brought strong winds and near-record amounts of precipitation [4]. Several interruptions on the transportation corridor connecting Vancouver to the Fraser Valley were damaged and shut down. According to the Insurance Bureau of Canada, the floods caused at least 450 million CAD in insured damages, making it the costliest natural disaster in British Columbia's history. In the Abbotsford area, more than 600,000 farm animals perished in the floods

[5]. And more damage unreported. Although these huge impacts on people and the economy, there are not many studies concerning this flood event.

Therefore, this study takes the November 2021 floods incident in Vancouver as an example to conclude and discuss its cause and effect and gives a few suggestions on how to prevent mitigating flooding damages.

2. Background of Vancouver

British Columbia, Canada's westernmost province, is surrounded by the Pacific Ocean to the west and the Rocky Mountains to the east, covering an area of 950,000 km², or about 10% of Canada's land area. It is Canada's third-largest province. British Columbia borders the U.S. states of Washington, Idaho and Montana to the south, Alberta to the east, the Yukon Territory and the U.S. state of Alaska to the north, and the Pacific Ocean to the west, rendering it the entry point for Canada into the Asia-Pacific region [6]. British Columbia has a temperate maritime climate influenced by latitude, mountainous terrain and the Pacific Ocean. The diversity of the climate results in considerable differences in average rainfall, snowfall, temperature and sunshine hours, sometimes even in two regions close to each other. However, the south generally has a warmer climate than the north, with the most rainfall on the coast and the least inland in the south [6]. With 600,000 square kilometers of forest, or 63 percent of the province's land area, British Columbia is Canada's environmentally and biologically diversified province. Ninety-four percent of British Columbia's land is designated as Crown land. This allows the province to manage its forest resources sustainably [7]. The province's water resources are also abundant because of its coastal location. Of course, freshwater is also plentiful, being the second most abundant province in Canada at 19,549 square kilometers [8].

Vancouver, a city located in the southwestern part of British Columbia, is the political, cultural, and transportation center of Western Canada [9]. It is also a port city constantly threatened by floods. Geographically speaking, Vancouver is located in the middle of the west coast of the North American continent, surrounded by the sea on many sides, with flat topography, the rolling Rocky Mountains in the east and a direct wedge into the Pacific Ocean in the west. Most of Vancouver is at low elevation, and flooding is almost in the coastal areas (Figure 1). Canada has a mild oceanic climate, bordering the warm-summer Mediterranean climate. A marine environment's general temperature characteristics are extraordinary and infrequent temperature extremes. So, when combined with the topography of Vancouver, the protection of the mountains, the warmth of the Pacific Ocean currents, and the low evaporation from the rivers make Vancouver one of the warmest cities in Canada. Summers in Vancouver are usually very dry. The remainder of the year is wet, especially from October to March. One of the soaking times is early winter, the most crucial reason Vancouver has much flooding in winter [10]. The rise of global temperature corresponds to the increase in sea level, which would make the flood more likely to happen, especially in a region like British Columbia, which is geographically adjacent to the ocean [11].

Vancouver has a long history of flooding. Indeed, due to heavy rainfall, floods occurred more frequently in the fall and the early winter with the advent of warm temperatures from a primary storm system, in which snowmelt at higher elevations contributed significantly to flood runoff along with rainfall. Once the snowpack reached sufficient depth, the snowpack would absorb a substantial amount of precipitation. Sometimes, these storms were strong enough to cross the Coast Range and produce floods in the basins on the east side of the range [12]. Because of the constancy and the devastating effects of the floods, optimizations of the hydraulic wave for alleviating the shortcomings and implementations of defense systems were introduced to protect the locals and to improve the accuracy and effectiveness of the warning forecast.

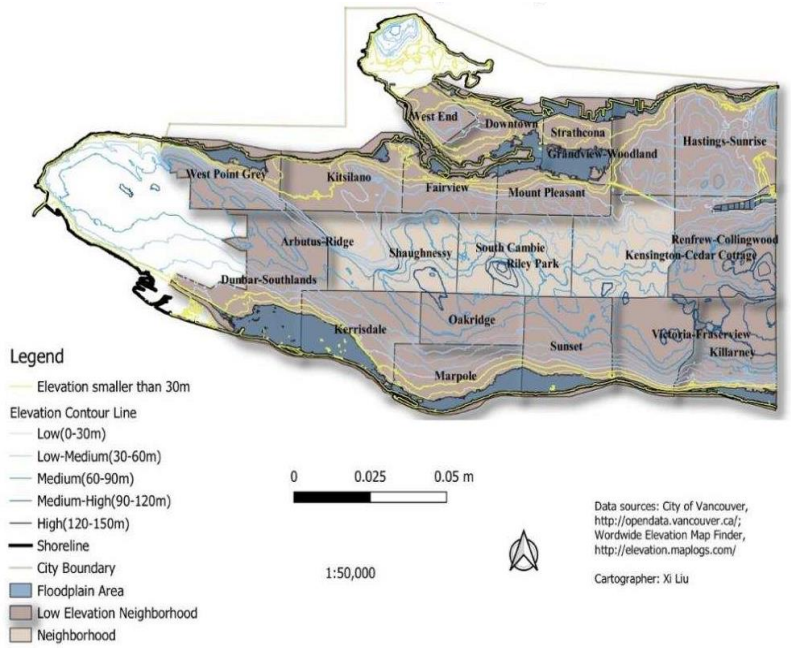


Figure 1. Vancouver floodplain map

3. Methods

3.1. Extraction of NDVI values

Normalized Difference Vegetation Index (NDVI) was used to obtain data on vegetation distribution, coverage, health, or generally the greenness of some objects. For our purposes of examining the effect of the November 2021 flooding event, two Sentinel 2 satellite images (one dated on September 11, 2021, and the other dated on November 16, 2021) had their NDVIs calculated and compared to examine the extend of flood in Vancouver, a city in southern British Columbia. QGIS raster calculator was used with the formula:

$$NDVI = RNIR - RR / RNIR + RR \quad (1)$$

Where RNIR is the reflectance of the infrared wave of the electromagnetic spectrum, in the case of Sentinel 2, it is band 8. RR is the reflectance of the red part, which is band 4. For clarity of the impact of floods on inland and outland Vancouver, the calculated NDVI values were split into four intervals: $-1.000 \leq -0.525$, $-0.525 \leq 0.050$, $0.050 \leq 0.425$, $0.425 \leq 0.900$.

3.2. Extraction of the DEM data

Digital Elevation Model (DEM) was built with an altitude of 30° using QGIS, and the slopes of the east and the west side, the south and the north side of Vancouver were drawn to study the topographical characteristics of this area. Shuttle Radar Terrain Mission (SRTM) data were used to generate the digital elevation data. The possible link between the elevations of certain areas and their ability to drain flood was introduced in the discussion part of this paper.

3.3. Mapping tool

QGIS 3.16 was used to analyze the impacted transportation systems in British Columbia. The characteristics of the study area, such as the locations of populated places, ports, airports, and water bodies, were also mapped by QGIS to draw a relationship between them and the great economic loss. All data were obtained from the Natural Earth website.

3.4. Using python to present British Columbia rainfall days trend

Linear regression is used to analyze the trend of the number of rainfalls in British Columbia, and climate data from January 1970 to December 2021 are retrieved from the official site of the government of Canada, station 100 Mile House 6NE, 70 Mile House, and 150 Mile House 7N. The analysis is based on the rows under the Total Rain (mm) column and is performed using Python sklearn library.

4. Results

4.1. Topography of Vancouver

Contour topographic map of Vancouver shows that the inland part of Vancouver is not that high in elevation since the highest peak is 125 meters above sea level, and the mountains are located on the east side in contrast to the ocean settling on the west side (Figure 2). Zooming into the inland part of Vancouver, the orange central area, with the lowest elevation at 75 meters, is higher than the green areas on the sides, with the highest elevation at 50 meters and the lowest at 0 meters. In addition, there is more than one peak in Vancouver, with its slope lines are not linear. Some of the areas are in the shape of a pot with one low land in the middle and two high peaks on the side, like the Shaughnessy area in the west of the center of Vancouver with an elevation of 50 to 75 meters in the middle and two 100 to 125 meters peaks on the side. Figure 3 shows that the elevation slope lines of Vancouver are wavy, and some areas are in pot shape.

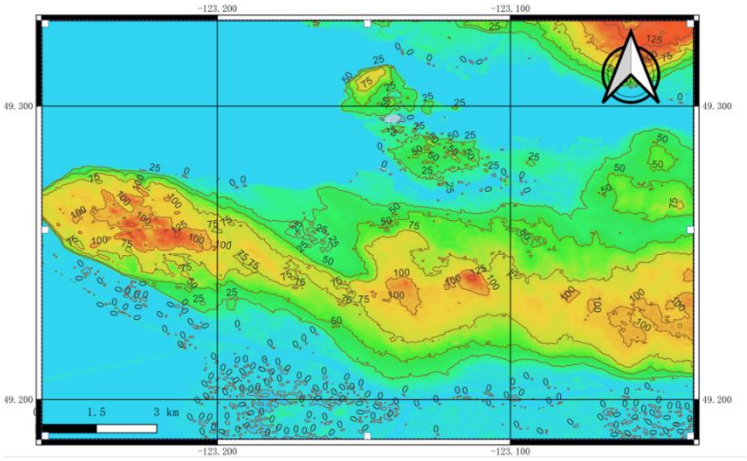
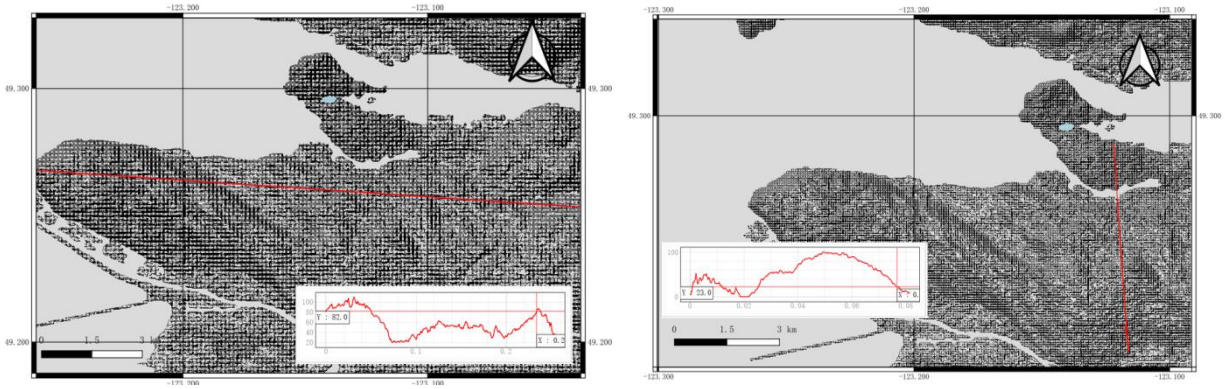


Figure 2. Contour Topographic Map of Vancouver in British Columbia

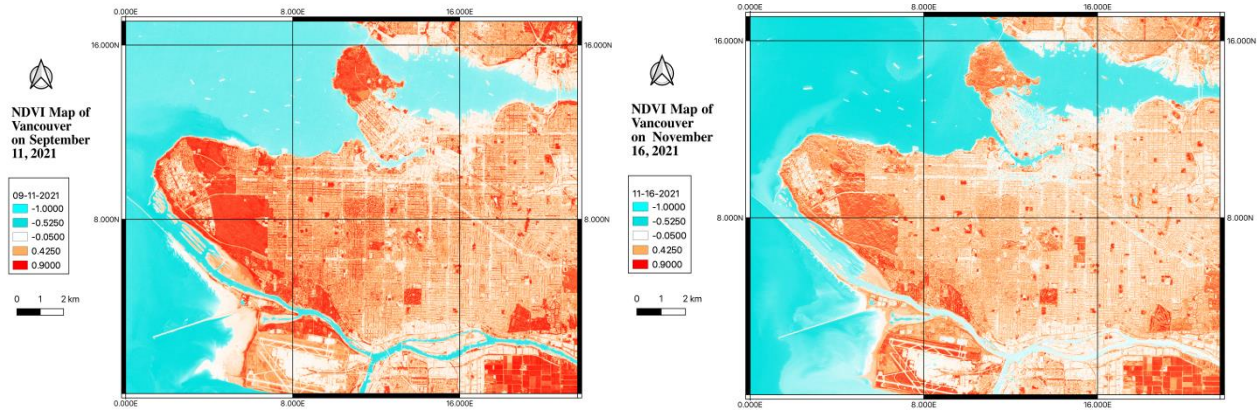


(a) DEM with west to east slope line (b) DEM with north to south slope line

Figure 3. DEM Maps of Vancouver

4.2. Comparison of NDVI values in Vancouver before and after the floods

There was a decrease in NDVI value, or a decrease in the healthiness of vegetation, after the flooding event happened (Figure 4.). Inspecting the two images taken before and after the floods on September 11, the NDVI values were much higher than that there were more reddish color pixels present on the north and the west coast of Vancouver than those present on the satellite image on November 16, two days after the incident happened (Figure 4.). Notice how the dark red color on the north and the west coast of Vancouver was turned into almost the same color as that of the urban plantation, which has much lighter color.



(a) NDVI Map on September 11, 2021 (b) NDVI Map on November 16, 2021

Figure 4. NDVI Maps of Vancouver in British Columbia

5. Discussion

5.1. Rainfalls in Vancouver

The flood incident in Vancouver was related to its geography and the increased rainfall. In fact, there is an increasing number of reports on the linkage between global warming and the growing flood occurrences. The rationale behind those reports is: the rise of global temperature corresponds to the increase of sea level, and the higher the sea level, the easier for ocean water to flood to regions like British Columbia, which is geographically closer to the ocean. The statistics show an increase in rainfall frequency in British Columbia (Figure 5), and thus British Columbia is topographically easily impacted by rainfalls and floods [13]. The November 2021 rainfall was brought mainly by the Pineapple Express, a type of atmospheric river caused by the combination of the earth's jet stream and the warm moisture air moving across the Pacific Ocean from east to west. The Pineapple Express is not a particular weather condition [14]. It happened many times and triggered several flooding events around the Northwest part of the Pacific Ocean in cities like Vancouver [15]. The combination of precipitation brought by the Pineapple Express and the increased rainfall could threaten cities like Vancouver, where there are not many high mountains present to prevent flood spread. A satellite image of the precipitation on November 14, 2021, also indicates that large areas of Vancouver were hit by heavy rainfall (Figure 6).

Combined with the topography of Vancouver near the Pacific Ocean and the total rainfall amount being relatively higher in this area, Vancouver is easily stroked the hardest by the floods, almost no natural barrier protects Vancouver from ocean flood tides. Additionally, the pot shape topography of some areas may indicate that the flood and rainfall water can be trapped mostly there. Also, based on the north to south slope line, since the north side is much lower in elevation, it may be more susceptible to floods, especially during the winter season when snow water melted by the rain may flow into the northern area from the southern peak, which may aid to the severity of the floods (Figure 3). The significant changes in NDVI also prove that the Pacific Ocean's flood tides might be stirred

by the wind and the rainfall, which may strike cities like Vancouver more strongly because they are close to the ocean (Figure 4).

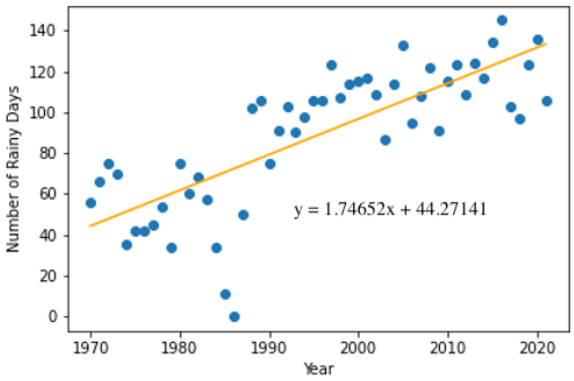


Figure 5. The trend of the number of rainy days with years in Vancouver

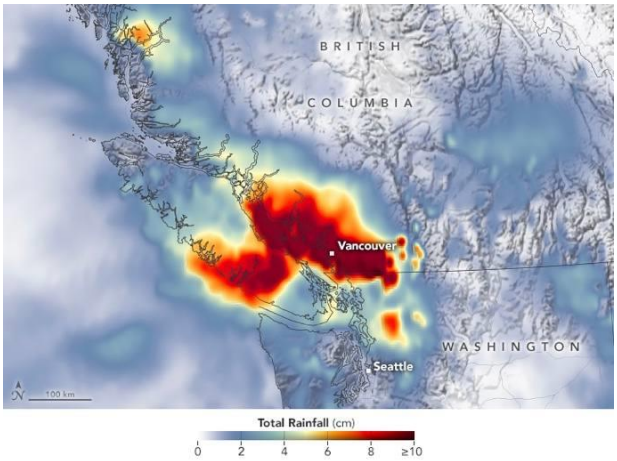


Figure 6. A Satellite Image of the Precipitation on November 14, 2021 [16]

5.2. Impacts on transportation systems

Not only was Vancouver impacted by the heavy rainfall, but more people and trades in southern British Columbia were also impacted due to rainfall damages to transportation systems. On November 15, a section of Highway 1 was first closed due to a flood warning near the Sumas River [17]. Then on November 27, several sections of Highway 3 and 99 were closed [18]. And on December 9, more sections of Highway16, 29, and 97 were closed due to the severe weather condition and pavement cracking [19]. Under the pressure of city evacuation, numerous people were trapped in the impacted sites due to floods and highway closure. At the same time, between November 14 to December 4, the Canadian National Railway (CNR) and the Canadian Pacific (CP) closed their services due to the companies experiencing 58 outrages [20]. More economic burdens were added to restore the impacted highways and neighborhoods.

According to the official website of the British Columbia government, Highway 1, 3, 5, 7, 8, 11, 19, 99, and some side roads were covered in the 2021 B.C. Highway Flood Recovery Project [21]. Until July 14, 2022, only temporary repairs were finished on Highway 8. Figure 7 illustrates all impacted highways and railways mentioned above. Most of them were located in the southern part of British Columbia near the rivers and the lake center lines, which is reasonable since there was a great chance that the rainfall contributed to the rise of water level. The flooding water could have a devastating effect on infrastructures.

Since 75% of British Columbia is covered by mountains, the rainfall might contribute to landslides and mudslides. The populated areas, ports, and airports were primarily located in southern British Columbia, where the rain hit the heaviest. It could cause serious economic loss when trades, tourism,

and local businesses were shut down and damaged by the weather and the natural disasters (Figure 8).

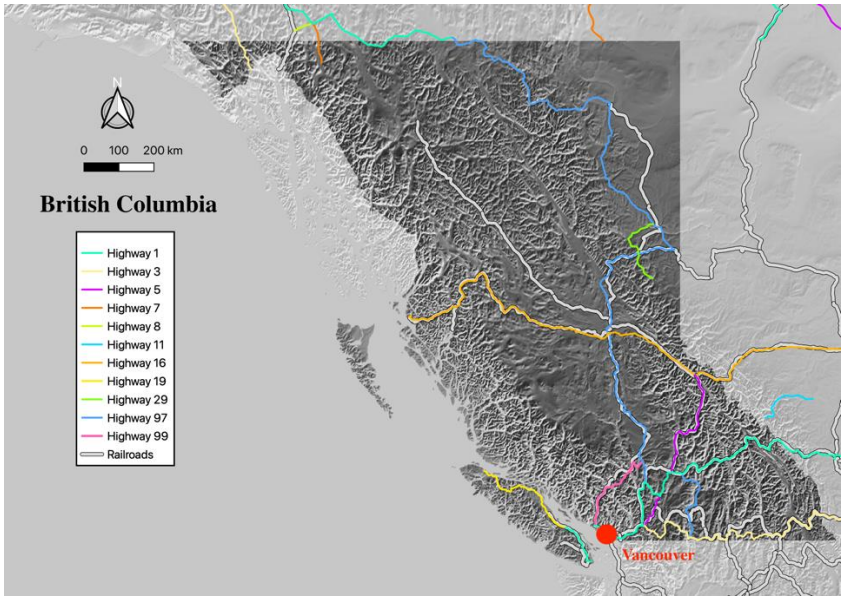


Figure 7. British Columbia Map of Highway 1, 3, 5, 7, 8, 11, 16, 19, 29, 97, 99 and Railways

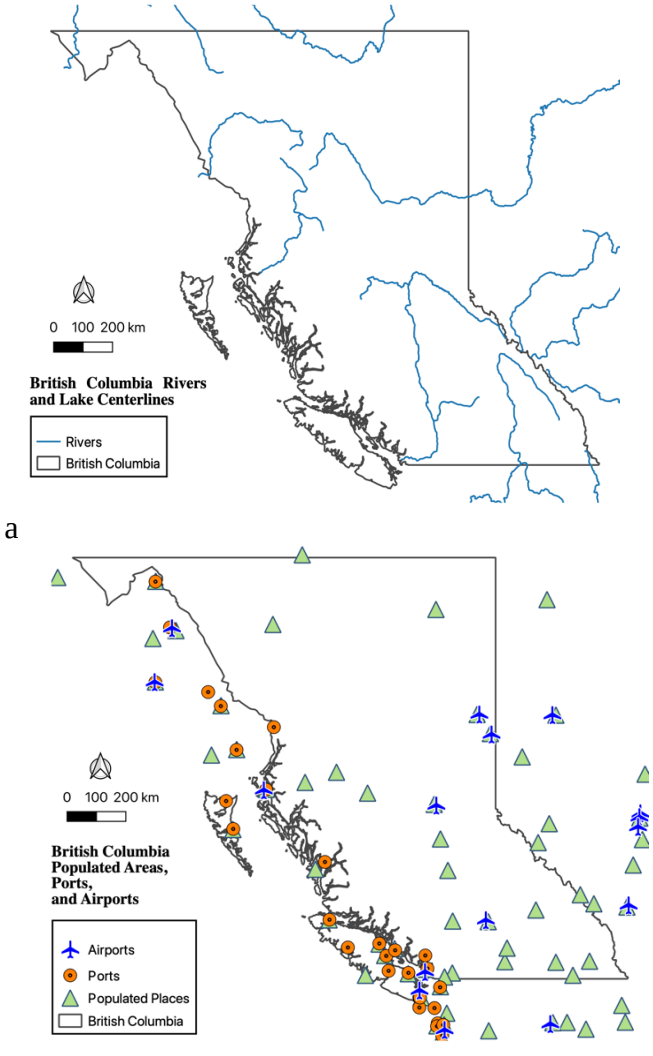


Figure 8. (a) Rivers and Lake Center Lines; (b) Map of Airports, Ports, and Populated Places

5.3. Fatalities, injuries, and impacted people

Most of the published death and injury events happened when people were on their way to leave the impacted sites. Four deaths and one missing were reported on Highway 99 due to a mudslide [22]. One death was reported on Highway 97C — according to her family members (witnesses), they were forced to take Highway 97C because of the closure of Highway 5 [23]. Moreover, B.C. Hydro, a British Columbia electric services company was hit between 3 and 4 p.m. and caused around 126,000 people to be left without power [24]. The hardest hit areas were Victoria, Surrey, Sechelt, and Hope, all located at and near Vancouver Island in lower British Columbia, adjacent to the Pacific Ocean. And between 7 and 8 p.m., around 82,000 people were left without power in southern British Columbia [24]. Meanwhile, in Merritt, a city of 7,100 residents, all residents and tourists were urged by the emergency act to leave the city through Highway 97C and Highway 99 to Lower Mainland or Highway 5 and 5A to Kamloops [25]. Around 1,100 people were stuck on the highway in the district of Hope when leaving [26].

5.4. Economic impacts of British Columbia floods

Figure 9 shows the economic impact data from 1972 to 2016, retrieved from the Canadian Disaster Database. The most recent flood with an estimated total cost of 65,132,000 CAD was the one in June 2016. The flood lasted 3 days, many people experienced power outages, and some roads and bridges were damaged due to floods and mudslides. However, the impacted area of the November 2021 floods was many times larger (southern British Columbia and Northern Washington state were impacted rather than a district) and the lasted days were longer (the November 2021 floods lasted for around a month). The significant differences between the two events might indicate the greater severity of the November 2021 floods and the greater economic loss due to that. Though no official total cost data are posted, there are several deductions: Insurance Insider estimated that at least 450 million CAD was spent besides the money spent on recovery plans, while the NGO Christian Aid proposed more than 7.5 billion USD (around 9.7 billion CAD) was spent. All these estimations suggest that the November 2021 flooding incident may be the costliest flood incident in the history of British Columbia flood disaster. This is reasonable because the heavy rainfall was correlated to, or cause, a series of natural disasters (tides, landslides, mudslides) and the closure of 11 highways, the two major railways, and several ports and airports along the coastlines.

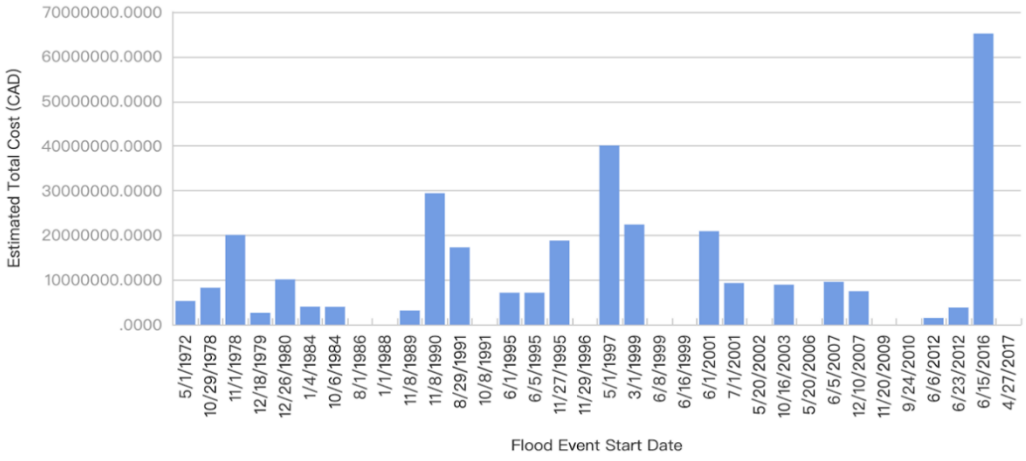


Figure 9. Estimated Total Cost of Each Flooding Event in British Columbia

5.5. Long-term effects

Storm activity could also harm Canada's drinking water sources, as surface pollutants and storm-sewage overflows may flush into water sources [27-29]. It is anticipated that the occurrence and intensity of runoff events would increase due to climate change [30-31]. Therefore, a comprehensive emergency management program is required to lessen floods' negative impacts on plant health. As

natural catastrophes are becoming more frequent and severe, they can easily exceed a community's capacity to deal with the effects, so implementing a comprehensive policy framework may be necessary to lower a community's susceptibility to the impact of floods [32]. The federal Flood Damage Reduction Program (FDRP) carried out in Quebec was an excellent example of a response to flood threats — it aimed to restrict the growth of flood-prone areas [33]. Unfortunately, the program did not last long and was not implemented in the context of global warming, which means that it did not consider the increase in the frequency of rainfalls and floods, which may ruin the built-up barrier implemented by it.

Moreover, due to various funds and tools provided for flood management in each province, the degrees of preparation in each province also vary, meaning that some provinces lack resources to control floods. There is also a lack of up-to-date floodplain maps and regulations provided by the British Columbia government, which might confuse each province's construction work. Even within some projects aided by the government, it usually takes a long step to receive aid and approval for the implementation. Overall, the British Columbian policy on flood control is very decentralized, with different provinces taking a variety of actions and the lack of effective resources to provinces to take action. On the other hand, there is also a lack of social awareness to prevent floods or buy or receive flood insurance [34]. In fact, prior to the actual experience of a severe flood, many people might not have a clear awareness of the flood risks or even the presence of a flood [35]. Therefore, it is necessary to take measures to govern flooding damages.

6. Conclusion

This study analyzes the causes and the effects of the November 2021 Pacific Northwest floods on British Columbia. Vancouver, a populated city neighboring the Pacific Ocean, has areas with two higher lands on the sides and one lower land in the middle (in the shape of a pot), which have a risk of trapping the flood water and damaging the neighborhoods and the plantation there.

There is an increased frequency of rainfall in British Columbia due to global warming. There is also the presence of Pineapple Express which brings more precipitation to British Columbia. The combination of these two events may have a devastating effect especially on cities in the Northwestern part of the Pacific Ocean, where Pineapple Express hit the hardest.

In the November 2021 Pacific Northwest Flooding event, southern British Columbia was hit the hardest with four reported fatalities, thousands of people impacted with power loss, mudslides or highway blockages; several sections of 11 highways and two railway companies were damaged and closed due to floods and mudslides; and 450 million CAD to 9.7 billion CAD were lost for the financial aid program to individualists and local governments and infrastructure rebuilding.

To mitigate the risk caused by the heavy rainfall and the flood, this study suggests implementing or repairing meteorological monitoring systems and pipeline monitoring systems and investigating the topographical characteristics of the routes before they are suggested to people trying to avoid flood strikes. And, to boost the public awareness of the severity and increasing frequency of floods in terms of global warming.

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