Some Factors Associated with the November 13-15, 2021, Catastrophic Flooding in South-West British Columbia[1]

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1. Summary

This brief report documents some of the rainfall and snow melt factors associated with the flooding. In addition, the report examines whether logging and forest fires might have a role in the severity of flooding is some locations, and presents information on rainfall forecasts available in the days before the storm occurred. The purpose is to try understand factors that contributed to the flooding, so as to possibly have better-informed flood forecasts in the future, to provide better protection of lives and infrastructure. A number of observations can be made from the information presented here.

- The Nov 13-15 rainfall that resulted in the catastrophic flooding was large. It was the record 1-day rainfall for some locations (Abbotsford, Agassiz, Hope) but was not the record 2-day rain storm at the Environment Canada climate stations with long records. For the Environment Canada climate stations, Nov 14-15, 2021 was often the second or third largest 2-day rain of record, with an estimated return period of 40-100 years. Other major and similar storms appear in the record in Oct-2003, Nov-1990, and a few other years.
- The storm is notable for producing the heaviest rain in the north and east Fraser valley, pushing north into the Fraser Canyon, as far as Lytton, and for pushing over the crest of the Coast Mountains, well into the Coldwater, Tulameen and Nicola river drainages, as evidenced by the MOTI road weather data and the MOE Snow Pillow data. This penetration of the heavy rain east of the crest of the Coast Mountains was evident in the weather forecast models available 36-hours before the storm began.
- The front stalled over the affected areas, producing sustained and substantial storm rainfall for approximately 48 hours. The significant storm of Oct-2003, as a comparison, was briefer, lasting about 36 hours in these locations, and, although it produced comparable amounts of rain at Hope, Agassiz and Abbotsford, the Oct-2003 storm produced substantially lesser amounts of rain in the Coast Mountains and the Coldwater and Tulameen headwaters, compared to Nov-2021.
- The MM5-NAM and WRF-GFS weather forecast models from the University of Washington were quite accurate in forecasting the record or near-record 24-hour rainfall associated with the storm, 36 hours before the rain began, in the eastern Fraser Valley and adjacent interior (Coldwater, Tulameen, Similkameen, Fraser Canyon). They under-forecast the 48-hr rain, but this may have improved in later model runs. Much more could be done with these forecasts, to enhance warnings to affected populations and communities.
- The freezing elevation rose to greater than 2000 m elevation, caused by the warm and wet frontal storm, triggering aggressive melt of the early-season snow and generating substantial volumes of

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runoff. This snowmelt runoff added to the already high rate of rainfall, augmenting the saturation of hillslopes and runoff into rivers at the valley bottoms. This snowmelt was a significant contributor to the severity of the river flooding (and likely also the slope instability). At some of the Snow Pillow sites and the Road Weather sites, the water contributed by snow melt over the 48-hr period of November 14-15 was as much as 50-100% of the storm rainfall amount. Flood forecasts and warnings from the Ministry of Forests would be significantly improved if spatially explicit quantitative data on SWE were incorporated into flood forecast models and information systems.

- The Water Survey of Canada preliminary records shows the extreme nature of this storm, with peak flows on November 15 in some affected rivers often being the largest of record, with estimated return periods of 300-500 years for many gauges (Tulameen, Nahatlatch, Sumas). Both the gauges on the Coldwater River were damaged during the flooding. However, peak flow magnitudes for them were estimated based on concurrent data from neighbouring headwater gauges (Tulameen and Coquihalla rivers). The peak flow for both the Coldwater River at Brookmere and the Coldwater River at Merritt were beyond extreme, estimated to possibly be a 1000+ year return period. The WSC gauge Nicola River near Spences Bridge is not "real-time" and so has no data for the November 2021 event. However, based on comparison with the Coldwater River estimates, the peak flow on the Nicola River is estimated to possibly be 700-1000 m^3/s, 2+ times larger than the previous record flow in 59 years of record, and also with an estimated 1000+ year return period.
- The WSC data also clearly shows that **<u>all</u>** the floods of record (and so the design floods for flood protection works) in the Coldwater, Tulameen and Similkameen east of the Coast Mountains result from October-January atmospheric river rain storms, and this combination of heavy rain and snowmelt. The November 13-15 storm, although extreme, should not be considered unusual in this regard. It is the standard flood-causing mechanism for these rivers. Flood forecast modeling, intelligence and communication by the Ministry of Forests could be improved by clearly recognizing this.
- The data indicate that the Coldwater and Nicola rivers likely experienced significantly more extreme peak flows than other rivers affected by the November, 2021, storm. Why? Three large wildfires burned large portions of the Coldwater and Nicola basins in summer 2021. The July Mountain Fire burned 26% of the Coldwater River at Brookmere and 16% of the Coldwater River at Merritt. The July Mountain Fire combined with the Lytton Creek Fire and the Tremont Creek fire to burn 13% of the Nicola River at Spences Bridge. It is likely that the hydrologic effects (changes in ground cover and soil properties, vegetation loss and changes in snow accumulation and melt, and changes in runoff mechanisms and pathways, hydrophobicity, etc.) of these fires over such extensive portions of the watersheds enhanced and accelerated rain and snowmelt runoff, converting what would have been large floods into the disastrous behemoths they became.
- Along with the likely fire effects in the Coldwater and Nicola basins, there is a possibility for historic forestry activity to be associated with the extreme peak flows in the Coldwater, Nicola and Tulameen basins. Clear-cutting encompasses 27% of the basin of the Tulameen River at Princeton, 23% of the basin of the Coldwater River at Merritt and 25% of the Nicola River at Spences Bridge. Road densities are high, at 1.85 km/km^2, 1.5 km/km^2 and 1.2 km/km^2, respectively, in the three basins, potentially augmenting the rapid movement of storm rainfall into stream channels, causing peak flows to be increased.
- The significantly elevated flood risk on the Coldwater and Nicola Rivers will persist for a number of years, with implications for Merritt, First Nations communities, the various rural residents, and infrastructure situated along the river corridors.

2. Introduction

An atmospheric river (AR) storm stalled over portions of southern Vancouver Island, the south coast and adjacent portions of the south-west interior of British Columbia during the period of November 13-15, 2021, producing catastrophic flooding and debris slides. At the time of writing, there appears to have been the loss of five lives from debris slides impacting highways, and the loss of one life from flooding on the Nicola River, which likely occurred on the evening of Sunday November 15, 2021. Flood protection dikes along the Coldwater River, Tulameen River and Simkameen River, protecting the communities of Merritt and Princeton, either breached or were overtopped late November 15 or early November 16, resulting in substantial and extensive flood damage in the communities. The Nicola River between Merritt and the Thompson River experienced catastrophic flooding, destroying large pieces of Hwy 8, and damaging many rural residential properties and a First Nation community. A dike along the Sumas River breached, causing floodwater to inundate a large portion of the Sumas Prairie, compounded by overflow into British Columbia of flood water from the Nooksack River in Washington State. The Sumas flooding resulted in the deaths of tens of thousands of cattle, poultry and other animals. Extensive sections of Highway 1 (in the Fraser Canyon and in the Chilliwack-Abbotsford area), and Highway 5 (Coquihalla) and Highway 7 (Agassiz area), Highway 8 and Highway 99 were flooded or damaged significantly. On Vancouver Island, flooding damaged and closed the Malahat section of Highway 1 between Victoria and Cobble Hill. The November 13-15 2021, flood event is one of the largest in Canada's history, with damages estimated at $7.5 US billion (**Wikipedia, 2021**)

In addition to the heavy storm rainfall, it would logically be expected that significant snowmelt occurred during the November 13-15, 2021, storm, contributing to the flooding. Before the term "atmospheric river" came into vogue, these frontal storm systems had been colloquially referred to as "Pineapple Express" or "Tropical Punch" storms. These now-less-used terms are, in some ways, more apt in their description than the term atmospheric river, as they depict the tropical or sub-tropical source of the moisture, and that the storms are warm as well as wet, with a substantial rise in the freezing elevation in coastal mountains, creating snowmelt through latent and convective heat exchange.

An additional flood-enhancing factor associated with the Nov-2021 event may be forest fires. It is well understood that areas of recent forest fires have an elevated risk of debris flows and flash floods during rain events due to fire-induced changes in ground cover, soil properties, and vegetation loss, affecting snow accumulation and melt and runoff mechanisms and pathways (**Touma *et. al*., 2022**; **Kean and Staley, 2021**), and the development of soil hydrophobicity (**Woods *et. al*., 2007**). Hydrological effects within burnt watersheds can linger for up to a decade, but are thought to be most severe within 1-2 years of wildfire, before ground cover, fine roots and water absorption properties have experienced any recovery (**Mcguire *et. al*., 2021**). Forest fires occurred in the flood-affected areas during recent years, very notably including the large Lytton Creek Fire, the Tremont Creek Fire, and the July Mountain Fire in summer 2021.

The potential for historic logging and forest road building to be a flood-contributing factor has to be considered. The Tulameen, Coldwater, and Nicola river basins have all experienced significant clear-cut logging over the past two or three decades, in part to log pine-dominated forests susceptible to insect infestation. To access the forests to enable the logging and log hauling, extensive networks of forest resource roads have been constructed. It is again well understood that clear-cut logging and forest road construction can alter the hydrology of a watershed and, in some situations, can cause peak flow to increase in magnitude. In particular, for flooding associated with rain storms, forest roads are of particular concern, as they intercept subsurface flow and route it into ditches, and their impervious surfaces transport rainfall quickly and directly into streams (**Wemple *et. al*., 1996**). When the density of forest roads is sufficiently high in a watershed, increased peak flows can result (**Wemple and Jones, 2003**).

This brief report documents some of the rainfall and snow melt factors associated with the flooding. In addition, the report examines whether logging and forest fires might have a role in the severity of flooding is some locations, and presents information on rainfall forecasts available in the days before the storm occurred. The purpose is to try understand factors that contributed to the flooding, so as to possibly have better-informed flood forecasts in the future, to provide better protection of lives and infrastructure.

3. Water Survey of Canada Data

To better understand the hydrological effects of the November 2021 floods, discharge records for several rivers of interest were extracted from the Environment Canada's historic hydrometric data archive (**Canada, 2021a**), and real-time hydrometric data website (**Canada 2021b**).

A number of rivers experienced significant, probably record, peak discharges during the November 14-15, 2021 storm. The six largest discharge events in each record is presented for nine rivers in **Table 1**. Because of frequent missing data in the historic record, the Similkameen River at Princeton (08NL007) is not included, despite it experiencing failures of flood protection dikes[3]. The Similkameen, Coldwater and Tulameen rivers are "interior BC", draining eastward from their headwaters in the Coast Mountains. The Nahatlatch River flows eastward into the Fraser River in the Fraser Canyon. The discharge values shown for November 14 or 15, 2021, are preliminary, and are derived from the Water Survey of Canada's "real-time hydrometric" website (**Canada 2021b**). These values will undoubtedly change in a year or two, after the WSC completes their analysis and produces a corrected and final peak discharge value.

The discharge values presented for the two Coldwater River gauges are estimates, as both gauges were damaged during the flooding (Note: the "real-time" data for the Coldwater at Merritt (08JNL010) shown on the WSC "real-time" site are incorrect, as a portion of the flow bypassed the gauge following the dike breach). The estimated peak discharge for the Coldwater River at Brookmere (08NL023) is based on the overlapping record with the Tulameen (08NL071) and Coquihalla (08MF062) gauges. The peak discharge for the Coldwater River at Merritt (08NL010) is based on the comparison of its peak flows with those at 08NL023). The Water Survey of Canada is working on estimates for these gauges, and will undoubtedly produce values different from what is presented here when they are completed their analysis (**Garner, 2022, personal communication**).

The November 14 or 15, 2021, peak is the largest of record for the Coldwater, Nicola, Tulameen, Coquihalla, Nahatlach and Sumas rivers. For the two Tulameen river gauges and the Nahatlatch River, the November 2021 peak appears to be in the 300-500 year return period level, based on log-Pearson III extreme value frequency analysis of data up to 2020) (**Table 2**). The peak discharge for the Coldwater River at Brookmere and the Coldwater River at Merritt are extraordinary, both estimated to be 1000+

[3] It should be noted that the peak flow data record for some WSC gauges are frequently missing some of the largest flows, due to gauge damage or malfunction during the extreme flood event. The Similkameen River at Princeton (08NL007) is a good example of this. The November 15, 2021 discharge of 544 m^3/s appears to be the largest of record, but many years of peak flow record are missing. Caution is necessary when interpreting the historic record.

year return period event. The peak on the Sumas River is estimated as a 300-year return period. For the Chilliwack River, the November 2021 peak was the second largest in the period of record, with approximately a 50 year return period. The peak on the Coquihalla River (above Alexander) was about a 125-year event.

Flooding on the Coldwater, Tulameen and Similkameen rivers overtopped or breached flood protection dikes, causing severe flood damage in Merritt and Princeton. These rivers have a mixed nival-pluvial hydrologic regime, experiencing peak flows both during Oct-Jan “coastal” rain storms and in spring as a result of the freshet snowmelt. For the Tulameen River, 17% of annual peak flows result from “coastal” rain events during October to January, but is important to note that **all** of the six largest peak flows result from fall rains. For the Coldwater River, 12% of the annual peak flows result from “coastal” rain events, but again it is important to note that **all** of the six largest peak flows result from fall rains, from atmospheric river storms.

The WSC gauge Nicola River near Spences Bridge (08LG006) does not operate in “real-time”, so there are no data available at present for the November, 2021, flood. However, from the 59 years of historic record the largest peak flow measured was 406 m^3/s (May 13, 1997). From the historic relationship in peak flows between the Nicola at Spences Bridge and the Coldwater at Merritt, for years when the annual flood of record occurred during fall atmospheric river storms, the peak from for the Nicola River at Spences Bridge from November 15, 2021, is estimated to be 700-1000 m^3/s. This is calculated to be a 1000+ year return period. The historic record indicated that 10% of annual floods on the Nicola River at Spences Bridge result from fall atmospheric river rain storms.

4. Rain and Snow Data

Media reported numerous “rainfall records” and “unprecedented rain” in the days during and immediately following the flood event. To place these statements in context and to better understand the November 13-15 storm in relation to long-term historic weather, Environment Canada (ECCC) climate stations with long, stable and robust records were selected for analysis. Daily rainfall records for 15 climate stations with records of 47 to 131 years were extracted from the Environment Canada historic data archive (**Canada, 2021c**), using the Cygwin application.

Rainfall and snowpack data from eleven Road and Avalanche Weather Stations affected by the November 2021 storm were extracted from the Ministry of Transportation and Infrastructure’s Avalanche and Weather Programs data archive (**British Columbia 2021a**) Because these data are collected at remote locations along highways, they characterize high elevation precipitation and snow conditions not captured by the Environment Canada climate stations.

Further high elevation precipitation and snow water equivalent (SWE) data for eight Automated Snow Pillows (ASP) affected by the November 2021 storm were extracted from the British Columbia Ministry of Environment’s snow data archive (**British Columbia 2021b**). The snow pillows have shorter periods of record (maximum = 30 years), but they provide data on high elevation precipitation, snow depth and snow water equivalent data not captured by the Environment Canada climate stations, and they provide data on the extent of early season snow accumulation and snow melt triggered associated with the AR storm.

4.1. Environment Canada Climate Station Data

Metadata for the 15 Environment Canada climate is provided in **Table 3**. **Table 4** lists hourly rain intensities for those stations that report hourly data, and lists the start and end times of the storm. The hourly data indicate the storm was approximately 50 hours in duration, with rain beginning near 2:00PM Saturday November 13 and ending near 3:00PM on Monday November 15. **Table 5** lists the accumulated daily rainfall for 1-day to 3-day periods associated with the storm. The largest 1-day rainfall occurred consistently on Sunday November 14, 2021.At the Abbotsford A, Agassiz CDA, Hope A and Mission West Abbey stations, November 14 saw the largest 1-day rain in the period of record, with return periods estimated empirically in the 70 to140 year range based on a log-Pearson III extreme value frequency analysis[4]. The highest recurrence interval 1-day rain was the 138 mm measured at Agassiz CDA, which has a 131 year record, and is estimated to have a 150-200 year return period. The previous maximum 1-day rain at Agassiz was 132 mm on October 16, 2003. The November 14 rain event was the 2nd to 7th largest in the period of record at many other ECCC climate stations on the south-west coast. The storm of October 2003 was generally the largest 1-day rainfall for most stations, and was the 2nd largest on record at the Abbotsford A and Agassiz CDA stations. The October 2003 storm produced severe flooding and damage in the Squamish to Pemberton area, and resulted in numerous deaths associated with a bridge failure on Highway 99 near Pemberton. The November 14, 2021, rainfall at the ECCC stations was large, but generally appears to be within typical “design criteria” for engineering works.

The 2-day storm rainfall data shows the November 14-15 storm as generally being the 2nd to 4th largest in the period of record, with the October 2003 generally surpassing November 2021 as the 2-day storm of record. Return period estimates for the 2-day November 14-15 rainfall are generally in the 20-50 year range. Again, Agassiz CDA experienced the highest magnitude 2-day storm, with an estimated return period of about 80-100 years. The 2-day rain of November 14-15, 2021, was large, but, again, generally appears to be within typical “design criteria” for engineering works.

The 3-day storm rainfall data shows November 14-16 as being the 2nd to 4th largest in the period of record, with return periods of 20-50 years. Again, October 2003 is generally the largest 3-day rain of record. For Agassiz CDA, a large storm in February 1951 is the largest of 3-day rain of record, followed by October 2003.

The climate records for Lytton and Princeton are notable. They indicate that the 1-day and 2-day rain of November 14-15, 2021, was large (about a 15-30 year return period), but not unprecedented. Other large rain storms during the October-January “fall flood season” have produced substantial rain in Lytton and Princeton in previous years. For Princeton, the largest October-January rain occurred in December 1945, while for Lytton the largest storms were in October 1963, December 1974 and January 2007.

Table 6 lists the 7-day, 14-day, 21-day and 28-day antecedent rainfall before November 13, 2021. Antecedent wetness conditions can be a significant indicator of flood risk for a number of reasons:

- Substantial rainfall before a storm creates saturated soil conditions, causing the portion of storm rainfall that generates fast runoff to be increased;

[4] Flood Frequency Analysis was conducted using the U.S. Corp of Engineer's HEC-SSP v2.2, with a log-Pearson III extreme value distribution.

- In areas of low relief, wet antecedent conditions can cause the water table to rise, contributing to saturation at the ground surface and local flooding;
- Antecedent precipitation during the October-January "fall flood season" can be related to the amount of early season snow accumulation in low and mid-slope mountainous areas that might be subject to melt from a wet and warm atmospheric river storm. These low and mid-slope mountain areas have commonly been referred to as "rain-on-snow" areas

For Agassiz, Abbotsford and Hope, in the eastern Fraser valley, the antecedent conditions up to November 13, 2021, were marginally wetter than normal, but were not extreme, with return periods in the range of 2-4 years. Southern Vancouver Island (Victoria A, Shawnigan Lake, Nanaimo A) were significantly wetter than normal before November 13, 2021, in the 10-20 year return period range, particularly for the 21-day antecedent period on October 23 – November 12. Also, both Lytton and Princeton had notably wetter than normal conditions in the 21-day antecedent period before November 13, with cumulative rainfall being about 190% of average. This may be an important factor in relation to the severity of flooding that occurred on the Tulameen and Coldwater rivers.

4.2. Trends in Storm Rainfall

The ECCC rainfall data presented here have long periods of record, up to 131 years, and can be useful to look for trends over time that might be demonstrative of climate change. Trends in 2-day storm rainfall are presented in **Table 7** and **Figure 2**. Changes over time range from -0.9 mm/decade to 5.0 mm/decade (-1.3% to 4.4%/decade). The mean of the 15 ECCC climate stations is an increase of 1.6% in 2-day storm rainfall pre decade. None of the trends over time are statistically significant.

4.3. Road and Avalanche Weather Data

Hourly precipitation and snow depth data were extracted for eleven Road and Avalanche weather stations (**British Columbia 2021a**). They range in elevation from 244 m to 1640 m (**Table 8**). A number of the stations are particularly informative with respect to the severe flooding on the Coldwater and Tulameen rivers, and the flooding and landslide activity in the Fraser Canyon:

- Coquihalla Summit (1230 m elevation) represents the headwaters of the Coquihalla, Coldwater and Tulameen rivers, and recorded 241 mm of rain during Nov 14-15. As well, it recorded 240 mm of snow depth loss on those days, clearly showing the very substantial contribution of snowmelt to the flooding. With a snow density of about 30%, this snow depth loss generated about 80 mm of SWE loss.
- Red Bluffs (830 m elevation) is in the mid-lower Tulameen River drainage. It recorded 103 mm of rain and an additional 43 mm of snow depth loss (13 mm of SWE loss). This was the entire snowpack that was on the ground at this location at the time of the storm.
- Larson Hill (1030 m elevation) is in the mid-Coldwater drainage. It recorded 113 mm of rain and an additional 43 mm of snow depth loss (13 mm SWE loss). This was the entire snowpack that was on the ground at this location at the time of the storm.
- In the Fraser Canyon, Hells Gate Roadside (280 m elevation) measured 217 mm of rainfall during Nov 14-15, and Jackass (350 m elevation, 17 km south of Lytton) recorded 151 mm of rain. These are possibly 2-day record rainfall amounts at these sites. The 2-day rainfall record for Lytton is 111 mm, from December 3-4, 2007. Neither Hells Gate nor Jackass had a measurable snowpack at the start of the storm, although higher elevations in the Fraser Canyon would have

had snow on the ground, which would have melted in a manner similar to what was measured at Larson Hills, Red Bluffs and Coquihalla Summit.

- Helmer Lake (1385 m elevation, Nicola Lake area) measured only 33 mm of rainfall on Nov 14-15, but recorded 103 mm of snow depth loss (34 mm SWE loss). This was almost the entire snowpack on the ground at the start of the storm, indicating the significant contribution of snowmelt runoff to the Coldwater River and Nicola River flooding.

As shown in Table 3, the significant AR storm of October 16-17, 2003, was the largest or second largest 2-day rainfall recorded at a number of the ECCC climate stations in the Fraser Valley. In many ways it could be considered comparable to the Nov 14-15, 2021 storm. So why did the Nov-2021 storm cause catastrophic flooding and damage in Coquihalla, Coldwater and Tulameen river basins, and in the Sumas Prairie, while the Oct-2003 event did not? Part of the answer may lie with the duration of the storm rainfall (**Table 9**). For the Coquihalla Summit, and locations east of the summit and in the Fraser Canyon, the Oct-2003 storm had a duration of 24-36 hours, while the Nov-2021 storm stalled, lasting 46-50 hours. In part, because of the longer sustained rainfall at high elevation in the Coast Mountains, east of the mountains in the Coldwater and Tulameen river drainages and in the Fraser Canyon, the total 2-day storm rain at the Road Weather stations and the ASP stations in Nov-2021 was substantially greater than what occurred in Oct-2003 (despite the low elevation ECCC stations being comparable).

4.4. Automated Snow Pillow Data

Hourly precipitation and snow water equivalent (SWE) data were extracted for eight Automated Snow Pillows (ASP) affected by the November 13-15, 2021, storm (**British Columbia 2021b**). They range in elevation from 900 m to 1940 m. Four of the eight are in the Fraser Coast and North Shore areas, one (Spuzzum – 1D19P) is proximal to the Fraser Canyon area. Two of the ASPs are east of the Coast Mountains - Blackwall Peak (2G03P) is in the Similkameen River drainage, while Shovelnose Mountain (1C29P) is in the Coldwater River drainage southwest of Merritt. The total 2-day loss of snow water equivalent (SWE) and 2-day rainfall are listed in **Table 10.**

The snow pillows recorded substantial amounts of rain over the two days of Nov 14 and 15, generally well above the rainfall totals measured at proximal low elevation ECCC climate stations. The 2-day rain at the Spuzzum ASP of 372 mm was the largest rainfall measured (in this analysis). The 2-day rain of 89 mm measured at the Blackwall Peak and 115 mm at Shovelnose Mountain are notable, as they reflect the significant amount of precipitation that occurred in the headwaters of the Tulameen and Coldwater basins. The rain at both Blackwall Peak and Shovelnose Mountain was augmented by the snow water loss.

All the snow pillow records examined show SWE losses, ranging from 106 mm and 108 mm at Chilliwack River and Palisade Lake ASPs, respectively, to more moderate losses of 14 mm at Blackwall Peak and 21 mm at Shovelnose Mountain. Blackwall Peak is the highest elevation of the ASP sites listed, at 1900 m. The Spuzzum ASP experienced 71 mm of SWE loss over the 2 days. In addition, Spuzzum also measured 372 mm of rainfall, creating a total of 443 mm of combined snow melt and rain during November 14-15, 2021. This is very substantial. The SWE loss during November 14-15, 2021 is shown graphically in **Figure 3**. This is not an uncommon situation, and occurs to some extent during every atmospheric river storm event. As noted earlier, these frontal storm systems are also referred to colloquially as “Pineapple Express” or “Tropical Punch” storms, and are warm as well as wet, with a substantial rise in the freezing elevation in coastal mountains. **Figure 4** depicts the air temperature records at some of the ASPs, showing the rapid rise in temperature during November 14-15 as the front hit. Temperatures at the ASP sites rose 7-9°C (from -3°C to approximately +6°C for a 36-hour period.

This "rain-on-snow" augmentation of runoff and flood risk has been recognized in coastal environments for a number of decades, and has been incorporated into assessments of clear-cut logging effects on hydrology (**British Columbia 1999**). The risk of snow melt augmentation of rainfall is greatest in early- and intermediate-season snowpacks, where there is sufficient snow depth to generate meaningful amounts of liquid water when melted, but still shallow enough to melt during atmospheric river storm events. This appears to have been the situation in November 2021, when slightly wetter and cooler than normal weather from mid-October to mid-November allowed a snowpack to develop. The typical rain-on-snow risk window for the south coast of BC is mid-October to mid-January.

5. Forest Fire and Logging Activity

Some of the flood-affected watersheds have been actively clear-cut logged over the past few decades, and have been altered by forest fires. Logging, forest road locations, and forest fire history was extracted from various spatial data layers maintained by the BC Ministry of Forests, Land, and Natural Resource Operations, through the BC Government Data Catalogue (**British Columbia 2022**), including:

- Fire – Perimeters – Current (2021)
- Fire – Perimeters – Historical
- Consolidated Cut blocks
- FTEN – Road Section Lines
- Digital Road Atlas

Analysis of these spatial data was done in QGIS, V.3.10 (QGIS 2022).

The forest fire and clear-cut logging data for some of the flooding-affected Water Survey of Canada watersheds is summarized in **Table 11**. Three large fires in 2021 are notable:

- The July Mountain Fire burnt 26% of the area of the Coldwater River at Brookmere, and 15% of the total area of the Coldwater River at Merritt. It also burnt 6% of the area of the Spius Creek watershed, a tributary to the Nicola River. The July Mountain Fire touched into the headwater area of the Tulameen River, but only to a small degree (6 km^2, 0.3% of basin area).
- The Lytton Creek Fire and the Tremont Creek Fire burnt a total of 591 km^2 in the Nicola River watershed, comprising 14% of the basin area downstream of Merritt.
- In total, 13% of the area of the Nicola River watershed (including the Coldwater and Spius basins) was burnt in 2021.

The extent of forest fire in the Coldwater and Nicola basins in 2021 was very large, and there is a compelling role for these fires in the severity of flooding that occurred along the Coldwater River and in Merritt, and along the Nicola River between Merritt and the Thompson River. It is probable that these fires were major contributing factors, taking what would have been a large rain and snowmelt flood and creating an unprecedented behemoth catastrophic flood with a 1000+-year return period. If it wasn't understood before, it should be understood now that it is imperative that forest fire information be understood and used by the Ministry of Forests in providing flood forecasts and flood warnings.

Moderate levels of clear-cut logging has occurred in all the basins, most heavily in the basins of Tulameen River at Princeton (27% of basin area), the Coldwater River at Merritt (23%), and the Nicola River at Spences Bridge (25%). Most of the cut has been in the past 20 years. In addition to the area logged, the extent of forest road constructed is worth noting, as the impervious surface of logging roads creates fast surface runoff of rain and snowmelt and can significantly affect peak flows in rivers. The road density in the basin of the Tulameen River at Princeton is very high, at 1.85 km of road per km^2 of basin area, and may possibly be a significant factor related to increased peak flows and floods. The road density for the Coldwater River at Brookmere and the Coldwater River at Merritt are lower, at 1.5 and 1.4 km per km^2, respectively, but are still sufficiently high that they need to be considered a flood-enhancing factor.

This brief analysis leads to the conclusion that the July Mountain Fire from summer 2021 was likely a major causative factor for the severity of flooding along the Coldwater River and in Merritt, and that the July Mountain, Lytton Creek and Tremont Creek fires in combination were major factors associated with the severity of flooding along the Nicola River, downstream of Merritt. The historic clear-cut logging and forest road construction very possibly added to the flood risk in the Coldwater, Tulameen and Nicola rivers. This situation lends itself well to a detailed hydrologic modelling investigation, with the two gauges in the Coldwater basin affected by historic logging and roads and the 2021 fire, the two basins in the Tulameen affected by historic logging and roads but not 2021 fire, and the two basins in the Coquihalla less affected by logging and not affected by 2021 fire.

6. Weather Forecasts

In addition to weather forecasts provided by Environment and Climate Change Canada (ECCC), weather forecast model outputs encompassing southern portions of B.C. are available through the Pacific Northwest Environmental Forecasts and Observation, affiliated with the University of Washington's Department of Atmospheric Sciences (**University of Washington, 2021**). They provide 84 hour (3 ½ day) forecasts of hourly weather using the MM5-NAM (12-km domain) and the WRF-GFS (12-km and 4-km domains). In addition, they run an extended WRF-GFS model, producing 168 hour (7 day) forecasts. The MM5 and WRF models have been calibrated for Pacific Northwest terrain and land use, and are particularly applicable to southern BC. .

Hourly precipitation forecasts from the MM5-NAM (12-km domain) and WRF-GFS (12-km and 4-km domains) (**University of Washington, 2021**) for the **12-Nov-2021 12UTC forecast period** were extracted for a few locations, to assist with understanding the accuracy of the rainfall forecasts in relation to observations (Chapman, 2022). The weather models provided 84 hours of hourly forecasts beginning 4AM Friday November 12 and ending 4PM Monday November 15. These forecasts were available 36 hours before the storm began on the south coast of BC, and encompassed the entire storm period. Forecast rainfall for November 14 and for the total storm period (about 48 hrs) for a few locations where significant flooding occurred are compared to observed rainfall amounts in **Table 12.** The following is noted:

- As noted earlier in this report, the 1-day observed rain at Hope and Abbotsford were the largest in their long historic records. The 1-day rain forecasts were presciently accurate for these locations.
- The weather forecasts were clearly producing substantial rainfall at the crest of the Coast Mountains (Coquihalla Summit) and eastward into the headwaters of the Coldwater and Tulameen basins (Larson Hills, Princeton).
- The weather forecasts were clearly producing substantial rainfall in the Fraser Canyon (Jackass), approaching Lytton, and in the mountainous terrain west of Boston Bar (Spuzzum ASP).

- Over 48-hours, the weather forecast models still forecast extremely large rainfall amounts at Hope and Abbotsford, in the Fraser Canyon, and in the headwaters of the Coldwater and Tulameen rivers, but were somewhat less accurate in comparison with observed rain. Spuzzum ASP and Jackass are notable, where the observed 48-hour rain was about 85% larger than the forecast. During the November 13-15 storm, the front stalled over the eastern Fraser valley, the adjacent Coast Mountains and the Fraser Canyon area for a few hours longer than the 12 UTC 12 November 2021 forecast depicted. I do not know if subsequent forecasts (such as the 12 UTC 13 November 2021 run) depicted this stalling.

It is my conclusion that MM5-NAM and WRF-GFS weather models clearly showed the record or near-record rainfall at least 36 hours before the storm began, in the areas where devastating flood and storm damage occurred. Based on these findings, I believe that much more can be done with weather forecast information to provide enhanced storm and flood warning to at-risk populations and communities.

7. Summary

A number of observations can be made from the information presented here.

- The Nov 14-15 rainfall that resulted in the catastrophic flooding was large. It was the record 1-day rainfall for some locations (Abbotsford, Agassiz, Hope) but was not the record 2-day rain storm at the Environment Canada climate stations with long records (except for Mission, where it was tied with the Oct-2003 storm as the largest 2-day rain of record). For the Environment Canada climate stations, Nov 14-15, 2021 was often the second or third largest of record, with an estimated return period of 40-100 years. Other major and similar storms appear in the record in Oct-2003, Nov-1990, and a few other years. The rainfall data suggest that the severity of the November 14-15, 2021, flooding was from a large 2-day rain storm which had embedded a 24-hour or sub-24-hour period of very intense record rain.
- The storm is notable for producing the heaviest rain in the north and east Fraser valley, pushing north into the Fraser Canyon, as far as Lytton, and for pushing over the crest of the Coast Mountains, well into the Coldwater, Tulameen and Nicola river drainages, as evidenced by the MOTI road weather data and the MOE Snow Pillow data. This penetration of the heavy rain east of the crest of the Coast Mountains was evident in the weather forecast models available 36-hours before the storm began.
- The front stalled over the affected areas, producing sustained and substantial storm rainfall for approximately 48 hours. The significant storm of Oct-2003, as a comparison, was briefer, lasting about 24-36 hours in these locations, and, although it produced comparable amounts of rain at Hope, Agassiz and Abbotsford, produced substantially lesser amounts of rain in the Coast Mountains and the Coldwater and Tulameen headwaters, compared to Nov-2021.
- The MM5-NAM and WRF-GFS weather forecast models from the University of Washington were quite accurate in forecasting the record or near-record 24-hour rainfall associated with the storm, 36 hours before the rain began, in the eastern Fraser Valley and adjacent interior (Coldwater, Tulameen, Similkameen, Fraser Canyon). They under-forecast the 48-hr rain, but this may have improved in later model runs. Much more could be done with these forecasts, to enhance warnings to affected populations and communities.
- The Nov 14-15, 2021 storm was a classic “rain-on-snow” event. The freezing elevation rose to greater than 2000 m elevation, caused by the warm and wet frontal storm, triggering aggressive melt of the early-season snow and generating substantial volumes of runoff. This snowmelt runoff

added to the already high rate of rainfall, augmenting the saturation of hillslopes and runoff into rivers at the valley bottoms. This snowmelt was a significant contributor to the severity of the river flooding and the slope instability. At some of the Snow Pillow sites and the Road Weather sites, the water contributed by snow melt over the 48-hr period of November 14-15 was as much as 50-100% of the storm rainfall amount. Flood forecasts and warnings from the Ministry of Forests would be significantly improved if spatially explicit quantitative data on SWE were incorporated into flood forecast models and information systems.

- The Water Survey of Canada preliminary records shows the extreme nature of this storm, with peak flows on November 15 in some rivers often being the largest of record, with estimated return periods of 300-500 years for many gauges (Tulameen, Nahatlatch, Sumas). Both the gauges on the Coldwater River were damaged during the flooding. However, peak flow magnitudes for them were estimated based on concurrent data from neighbouring headwater gauges (Tulameen and Coquihalla rivers). The peak flow for both the Coldwater River at Brookmere and the Coldwater River at Merritt were beyond extreme, estimated to possibly be a 1000+ year return period. The WSC gauge Nicola River near Spences Bridge is not "real-time" and so has no data for the November 2021 event. However, based on comparison with the Coldwater River estimates, the peak flow on the Nicola River is estimated to possibly be 700-1000 m^3/s, 2+ times larger than the previous record flow in 59 years of record, and also with an estimated 1000+ year return period. The Water Survey of Canada is working on producing peak discharge values for the Coldwater and Nicola rivers, which will undoubtedly be different from what is presented here.
- The WSC data also clearly shows that **all** the floods of record (and so the design floods for flood protection works) in the Coldwater, Tulameen and Similkameen east of the Coast Mountains result from October-January atmospheric river rain storms, and this combination of heavy rain and snowmelt. The November 13-15 storm, although extreme, should not be considered unusual in this regard. It is the standard rain and rain-on-snow flood-causing mechanism for these rivers. Flood forecast modeling, intelligence and communication by the Ministry of Forests could be improved by clearly recognizing this.
- The data indicate that the Coldwater and Nicola rivers likely experienced significantly more extreme peak flows than other rivers affected by the November, 2021, storm. Why? Three large wildfires burned large portions of the Coldwater and Nicola basins in summer 2021. The July Mountain Fire burned 26% of the Coldwater River at Brookmere and 16% of the Coldwater River at Merritt. The July Mountain Fire combined with the Lytton Creek Fire and the Tremont Creek fire to burn 13% of the Nicola River at Spences Bridge. It is likely that the hydrologic effects (changes in ground cover and soil properties, vegetation loss and changes in snow accumulation and melt, and changes in runoff mechanisms and pathways, hydrophobicity, etc.) of these fires over such extensive portions of the watersheds enhanced and accelerated rain and snowmelt runoff, converting what would have been large floods into the disastrous behemoths they became.
- Along with the likely fire effects in the Coldwater and Nicola basins, there is a possibility for historic forestry activity to be associated with the extreme peak flows in the Coldwater, Nicola and Tulameen basins. Clear-cutting encompasses 27% of the basin of the Tulameen River at Princeton, 23% of the basin of the Coldwater River at Merritt and 25% of the Nicola River at Spences Bridge. Road densities are high, at 1.85 km/km^2, 1.5 km/km^2 and 1.2 km/km^2, respectively, in the three basins, potentially augmenting the rapid movement of storm rainfall into stream channels, causing peak flows to be increased.

- The significantly elevated flood risk on the Coldwater and Nicola Rivers will persist for a number of years, with implications for Merritt, First Nations communities, the various rural residents, and infrastructure situated along the river corridors.

Table 1. Six largest discharge events at Water Survey of Canada gauges

Coldwater River (Brookmere) - 08NL023			Coquihalla River (below Needle) - 08MF062			Tulameen River (below Vuich) - 08NL071		
Date	Discharge (m^3/s)	Rank	Date	Discharge (m^3/s)	Rank	Date	Discharge (m^3/s)	Rank
15-Nov-21	480	1	14-Nov-21	130	1	15-Nov-21	600	1
29-Nov-95	166	2	06-Nov-06	69.2	2	29-Nov-95	242	2
10-Nov-90	159	3	26-Dec-80	65.3	3	20-Oct-03	222	3
12-Dec-80	152	4	23-Nov-17	48.5	4	06-Nov-06	219	4
23-Nov-17	127	5	13-Apr-02	48.3	5	10-Nov-90	193	5
06-Nov-06	125	6	04-Jan-84	47.7	6	14-May-97	179	6
Coldwater River (Merritt) - 08NL010			**Coquihalla River (above Alexander) - 08MF067**			**Tulameen R. (Princeton) - 08NL023**		
Date	Discharge (m^3/s)	Rank	Date	Discharge (m^3/s)	Rank	Date	Discharge (m^3/s)	Rank
15-Nov-21	520	1	15-Nov-21	686	1	15-Nov-21	918	1
29-Nov-95	177	2	06-Nov-06	650	2	29-Nov-95	708	2
27-Dec-80	163	3	31-Oct-67	556	3	06-Nov-06	502	3
05-May-72	137	4	29-Nov-95	533	4	10-Nov-90	406	4
13-May-71	136	5	27-Dec-80	476	5	20-Oct-03	393	5
07-Nov-06	126	6	03-Dec-75	344	6	26-Dec-80	343	6
Chilliwack River (at Slesse) - 08MH102			**Sumas River - 08MH028**			**Nahatlatch River - 08MF064**		
Date	Discharge (m^3/s)	Rank	Date	Discharge (m^3/s)	Rank	Date	Discharge (m^3/s)	Rank
06-Nov-06	504	1	15-Nov-21	64.6	1	15-Nov-21	587	1
15-Nov-21	488	2	10-Nov-90	55.5	2	23-Nov-17	473	2
10-Nov-89	465	3	15-Feb-82	49.2	3	27-Dec-80	422	3
29-Nov-95	450	4	05-Jan-84	49.1	4	18-Oct-03	411	4
20-Oct-03	429	5	11-Nov-89	47.4	5	11-Dec-14	389	5
04-Jan-84	404	6	03-Dec-75	46.7	6	04-Jan-84	362	6

The Nov 15, 2021, peak discharge values are from the Water Survey of Canada "Real-Time" information, and so are preliminary. They will undoubtedly be adjusted by the WSC

The Nov 14-15, 2021, peaks for the two Coldwater River gauges are estimates, as both gauges were damaged during the flooding. The value of 590 m^3/s for 08NL023 is estimated by comparison with two neighbouring headwater gauges on the Tulameen River (08NL071) and the Coquihalla River (08MF062). The value of 640 m^3/s for 08NL010 is estimated by the historic relationship between instantaneous flood peaks at 08NL023 and 08NL010.

Table 2. Return priod estimates for Water Survey of Canada gauges, for Nov 14 or 15, 2021, flood peak (using log-Pearson III extreme value distribution). (Refer to Notes for Table 1.)

Gauge	Date	Time	Discharge (m^3/s)	Rank	Return Period (years)
Coldwater River (Brookmere) - 08NL023	15-Nov-21	0:15AM	480	1	1000+
Coldwater River (Merritt) - 08NL010	15-Nov-21	6:00AM	520	1	1000+
Nicola River at Spences Bridge	15-Nov-21	??	700-980	1	1000+
Coquihalla River (below Needle) - 08MF062	14-Nov-21	11:30PM	130	1	300+
Coquihalla River (above Alexander) - 08MF067	15-Nov-21	1:15AM	686	1	125
Tulameen River (below Vuich) - 08NL071	15-Nov-21	0:15AM	600	1	500
Tulameen R. (Princeton) - 08NL023	15-Nov-21	3:30AM	918	1	350
Chilliwack River (at Slesse) - 08MH102	15-Nov-21	2:00PM	456	2	50
Sumas River - 08MH028	15-Nov-21	4:35PM	64.6	1	300
Nahatlatch River - 08MF064	15-Nov-21	5:30PM	587	1	400

Table 3. Weather stations

Name	Climate ID	Location	Latitude	Longitude	Elevation (m)	Period of Record	Years of Record
Environment Canada Climate Stations							
Abbotsford A	1100030, 1100031, 1100032	Fraser Valley - central	49.03	-122.36	59	1944-2021	78
Agassiz CDA	1100120	Fraser Valley -east	49.24	-121.76	15	1890-2021	131
Esquimalt Harbour	1012710	Vancouver Island	48.43	-123.44	3	1958-2021	64
Gibsons Gower Point	1043152	Howe Sound	49.39	-123.54	34	1961-2021	61
Hope A	1113540, 1113542, 1113543	Fraser Valley -east	49.37	-121.49	39	1934-2021	88
Lytton	1114740, 1114741, 1114739, 1114738	Fraser Canyon	50.23	-121.58	225	1944-2021	78
Mission West Abbey	1105192	Fraser Valley - central	49.15	-122.27	197	1963-2021	59
Nanaimo A	1025369, 1025370	Vancouver Island	49.05	-123.87	28	1947-2021	75
Pitt Meadows	1106178, 110FAG9	Fraser Valley - central	49.21	-122.69	5	1974-2021	48
Port Moody Glenayre	1106CL2	Fraser Valley - west	49.28	-122.88	130	1970-2010, 2016-2021	47
Princeton A	1126510, 1126511, 1126518	Similkameen	49.47	-120.51	702	1937-2021	85
Saanichton CDA	1016940	Vancouver Island	48.62	-123.42	61	1914-2021	108
Shawnigan	1017230	Vancouver Island	48.65	-123.63	159	1912-2021	110
Vancouver A	1108395, 1108447	Fraser Valley - west	49.19	-123.18	4	1937-2021	85
Victoria A	1018620, 1018621	Vancouver Island	48.65	-123.43	20	1940-2021	82
BC Ministry of Environment Automated Snow Pillows							
Lamont Creek	1D08P	Fraser Coast	49.5819	-122.3143	1200	2021-2021	1
Wahleach Lake	1D09P	Fraser Coast	49.2203	-121.5760	1480	2003-2021	19
Chilliwack River	1D17P	Fraser Coast	49.0169	-121.7117	1600	1991-2021	30
Spuzzum	1D19P	Fraser Canyon	49.6608	-121.6608	1180	2003-2021	19
Heather Mountain	2B24P	Vancouver Island	48.9439	-124.4521	1190	2015-2021	7
Blackwall Peak	2G03P	Similkameen	49.0847	-120.7794	1940	1967-2021	45
Palisade Lake	3A09P	North Shore	49.4544	-123.0319	900	2018-2021	4
Shovelnose Mountain	1C29P	Coldwater	49.8560	-120.8629	1460	2018-2021	4
BC Ministry of Transportation and Infrastructure Road and Avalanche Weather Stations							
Nicolum Creek	15093	Lower Coquihalla	49.3629	-121.3564	244	2002-2021	20
Hells Gate Roadside	15122	Fraser Canyon	49.7570	-121.4180	280	2007-2021	15
Jackass	15124	Fraser Canyon (Lytton)	50.0761	-121.5475	350	1997-2021	25
Foundation Mines	15321	Coast Mtns - mid elev.	49.2300	-121.0842	1650	1988-2021	34
Allison Pass	15392	Upper Similkameen	49.1156	-120.8674	1340	2003-2021	19
Red Bluffs	24225	Tulameen	49.4762	-120.6243	830	1997-2021	25
Helmer Lake	25092	Nicola	50.3208	-120.6366	1385	1998-2021	24
Larson Hill	25093	Coldwater (mid)	49.8311	-120.9350	1060	2000-2021	22
Coquihalla Summit	25221	Upper Coquihalla and Coldwater	49.5941	-121.0995	1230	1995-2021	27
Pothole Lake	29093	Plateau - east of Merritt	49.9395	-120.5464	1045	2017-2021	5
Malahat	62091	Hwy 1, below Malahat Summit	48.5679	-123.5418	340	2012-2021	10

Table 4. Rain Intensity (mm/hour), November 13-15, 2021

Duration	Hope A	Agassiz	Lytton	Pitt Meadows	Princeton	Malahat	Coquihalla Summit	Larson Hill	Jackass	Hells Gate	Red Bluffs
2-hr	12.3	11.6	6.1	6.3	2.5	9.2	7.6	5.5	6.0	7.5	6.4
4-hr	11.1	10.0	5.8	6.0	2.2	8.1	7.4	4.5	6.0	7.3	6.0
6-hr	10.4	9.2	5.7	5.7	2.0	7.5	7.4	4.1	5.4	7.0	5.4
8-hr	10.1	8.7	5.4	5.5	2.0	7.3	7.3	3.7	4.9	6.9	4.6
10-hr	9.8	8.1	4.9	5.2	2.0	7.1	7.2	3.7	5.0	6.7	4.3
12-hr	9.7	7.7	4.6	5.1	1.9	7.1	7.0	3.4	4.8	6.6	4.2
14-hr	9.5	7.4	4.1	5.0	1.8	7.1	6.8	3.4	4.6	6.4	3.9
16-hr	9.1	7.2	3.8	4.8	1.6	7.1	6.7	3.4	4.3	6.3	3.8
18-hr	8.8	7.0	3.5	4.8	1.5	7.0	6.7	3.4	4.0	6.1	3.7
20-hr	8.4	6.8	3.1	4.8	1.5	6.7	6.7	3.3	3.8	6.1	3.6
22-hr	8.2	6.7	2.9	4.8	1.4	6.2	6.8	3.3	3.7	6.1	3.3
24hr	8.0	6.5	2.7	4.8	1.4	5.7	6.8	3.3	3.7	6.0	3.2
Rain Start	13-Nov 14:00	13-Nov 14:00	13-Nov 18:00	13-Nov 13:00	13-Nov 16:00	13-Nov 10:00	13-Nov 17:00	13-Nov 19:00	13-Nov 15:00	13-Nov 16:00	13-Nov 16:00
Rain End	15-Nov 18:00	15-Nov 15:00	15-Nov 15:00	15-Nov 13:00	15-Nov 18:00	15-Nov 12:00	15-Nov 15:00	15-Nov 15:00	15-Nov 17:00	15-Nov 15:00	15-Nov 15:00
Storm Duration (hrs)	53	50	48	49	51	51	46	44	51	48	48

Table 5. Rainfall and Environment Canada Stations, November 13-15, 2021

1-Day Rainfall					
Location	**Years of Record**	**Rain Amount (mm) Nov 14, 2021**	**Rank**	**Return Period (years)**	**Note**
Abbotsford A	78	100	1	79	Second largest 1-day rain was 94 mm Oct 16, 2003
Agassiz CDA	131	158	1	150-200	Second largest 1-day rain was 132 mm Oct 16, 2003
Esquimalt Harbour	64	60.8	20	3	Largest 1-day rain was 114 mm on Oct 16, 2002
Gibsons Gower Point	61	63.2	5	12	Largest 1-day rain was 66.4 mm on Oct 16, 2003
Hope A	88	174	1	89	Second largest 1-day rain was 173 mm on Nov 9, 1990
Lytton	78	62.3	4	20	Largest 1-day rain (Oct-Jan) was 76.7 mm on Oct 21, 1963
Mission West Abbey	59	133	1	60	Second largest 1-day rain was 123 mm Oct 16, 2003
Nanaimo A	75	77.8	6	13	Largest 1-day rain was 97.3 mm on Feb 01, 1991
Pitt Meadows	48	90.7	7	7	Largest 1-day rain was 137 mm on Oct 16, 2003
Port Moody Glenayre	47	116	3	16	Largest 1-day rain was 139 mm on Oct 16, 2003
Princeton A	85	36	7	12	Largest 1-day rain (Oct-Jan) was 57.2 mm on Dec 27, 1945
Saanichton CDA	108	80	4	27	Largest 1-day rain was 120 mm on Oct 16, 2003
Shawnigan	110	114	2	56	Largest 1-day rain was 117 mm on Oct 16, 2003
Vancouver A	85	53.5	24	4	Largest 1-day rain was 91.6 mm on Sep 18, 2004
Victoria A	82	78.5	5	17	Largest 1-day rain was 136 mm on Oct 16, 2003
2-Day Rainfall					
Location	**Years of Record**	**Rain Amount (mm) Nov 14-15, 2021**	**Rank**	**Return Period (years)**	**Note**
Abbotsford A	78	153	2	40	Largest 2-day rain was 167 mm on Oct 16-17, 2003
Agassiz CDA	131	211	2	80-100	Largest 2-day rain was 216 mm on Feb 9-10, 1951
Esquimalt Harbour	64	90.6	15	4	Largest 2-day rain was 160 mm on Nov 9-10, 1990
Gibsons Gower Point	61	98.6	5	12	Largest 2-day rain was 107 mm on Oct 16-17, 2003
Hope A	88	278	2	45	Largest 2-day rain was 304 mm on Nov 9-10, 1990
Lytton	78	91.7	3	26	Largest 2-day rain was 111 mm on Dec 3-4, 2007
Mission West Abbey	59	185	T1	40	Tied with Oct 16-17, 2003
Nanaimo A	75	125	3	25	Largest 2-day rain was 143 mm on Nov 2-3, 1951
Pitt Meadows	48	163	3	16	Largest 2-day rain was 210 mm on Oct 16-17, 2003
Port Moody Glenayre	47	158	4	12	Largest 2-day rain was 220 mm on Jan 17-18, 2005
Princeton A	85	52.3	6	14	Largest 2-day rain (Oct-Jan) was 64 mm on Dec 26-27, 1945
Saanichton CDA	108	114	4	27	Largest 2-day rain was 162 mm on Oct 16-17, 2003
Shawnigan	110	157	3	37	Largest 2-day rain was 174 mm on Jan 17-18, 1986
Vancouver A	85	100	4	22	Largest 2-day rain was 141 mm on Oct 16-17, 2003
Victoria A	82	128	2	42	Largest 2-day rainwas 169 mm on Oct 16-17, 2003
3-Day Rainfall					
Location	**Years of Record**	**Rain Amount (mm) Nov 13-15, 2021**	**Rank**	**Return Period (years)**	**Note**
Abbotsford A	78	173	3	26	Largest 3-day rain was 190 mm on Oct 15-17, 2003
Agassiz CDA	131	233	3	44	Largest 3-day rain was 287 mm on Feb 8-10, 1951
Esquimalt Harbour	64	103	15	4	Largest 3-day rain was 162 mm on Nov 8-10, 1990
Gibsons Gower Point	61	105	7	9	Largest 3-day rain was 145 mm on Oct 15-17, 2003
Hope A	88	295	3	30	Largest 3-day rain was 329 mm on Nov 8-10, 1990
Lytton	78	94.7	3	26	Largest 3-day rain was 140 mm on Jan 14-16, 1974
Mission West Abbey	59	200	2	30	Largest 3-day rain was 217 mm on Oct 15-17, 2003
Nanaimo A	75	142	2	38	Largest 3-day rain was 148 mm on Nov 1-3, 1951
Pitt Meadows	48	184	3	16	Largest 3-day rain was 223 mm on Oct 15-17, 2003
Port Moody Glenayre	47	194	4	12	Largest 3-day rain was 259 mm on Jan 17-19, 2005
Princeton A	85	60.3	3	29	Largest 3-day rain (Oct-Jan) was 64 mm on Dec 25-27, 1945
Saanichton CDA	108	132	3	36	Largest 3-day rain was 183 mm on Oct 15-17, 2003
Shawnigan	110	169	4	28	Largest 3-day rain was 199 mm on Oct 15-17, 2003
Vancouver A	85	120	3	29	Largest 3-day rain was 154 mm on Oct 15-17, 2003
Victoria A	82	154	2	42	Largest 3-day rain was 182 mm on Oct 15-17, 2003

Table 6. Antecedent Rainfall, before November 13, 2021

		Antecedent Rain (Days Before Nov 13, 2021)											
Location	Years of Record	7-day Nov 6-12	% of Average	Return Period (Yrs)	14-day Oct 30-Nov 12	% of Average	Return Period (Yrs)	21-day Oct 23-Nov 12	% of Average	Return Period (Yrs)	28-day Oct 16-Nov 12	% of Average	Return Period (Yrs)
Abbotsford A	78	56.9	119%	3	118	120%	3	181	130%	4	227	126%	3
Agassiz CDA	131	57.2	120%	3	106	103%	2	201	124%	4	264	125%	4
Esquimalt Harbour	64	9.4	30%	2	44.8	76%	2	50.4	64%	2	66	65%	1
Gibsons Gower Point	61	55	118%	3	132	145%	8	188	147%	10	254	152%	16
Hope A	88	72.4	132%	4	114	100%	2	249	151%	6	271	127%	4
Lytton	78	19.4	146%	5	33.1	132%	3	71.8	191%	9	75.3	150%	5
Mission West Abbey	59	59.4	99%	2	130	108%	3	206	125%	4	256	116%	3
Nanaimo A	75	64.8	180%	6	142	199%	10	211	214%	13	242	189%	19
Pitt Meadows	48	54	88%	2	116	96%	2	160	99%	2	223	110%	3
Port Moody Glenayre	47	92.4	135%	3	184	142%	4	227	130%	3	309	135%	4
Princeton A	85	8.1	95%	3	13.2	81%	10	45.7	188%	8	49.2	158%	6
Saanichton CDA	108	35.0	130%	3	69.3	124%	3	121	153%	7	137	133%	4
Shawnigan	110	77.8	211%	9	144	193%	9	217	209%	19	244	180%	14
Vancouver A	85	40.4	113%	3	89.1	125%	4	119	115%	3	307	137%	5
Victoria A	82	39.8	141%	4	83.2	143%	5	129	160%	8	148	139%	6

Table 7. Trends in 2-Day Storm Rainfall at ECCC climate stations

Name	Climate ID	Period of Record	Years of Record	Mean 2-Day Max Rainfall (mm)	Change per Decade (mm)	Change per Decade (%)
Abbotsford A	1100030, 1100031, 1100032	1944-2021	78	87.4	0.9	1.0%
Agassiz CDA	1100120	1890-2021	131	100	1.3	1.3%
Esquimalt Harbour	1012710	1958-2021	64	74.6	-0.9	-1.3%
Gibsons Gower Point	1043152	1961-2021	61	65.7	-0.2	-0.4%
Hope A	1113540, 1113542, 1113543	1934-2021	88	116.0	4.2	3.6%
Lytton	1114740, 1114741, 1114739, 1114738	1944-2021	78	49.9	0.1	0.2%
Mission West Abbey	1105192	1963-2021	59	100	2.7	2.7%
Nanaimo A	1025369, 1025370	1947-2021	75	75.2	0.2	0.3%
Pitt Meadows	1106178, 110FAG9	1974-2021	48	99.9	3.9	3.9%
Port Moody Glenayre	1106CL2	2010, 2016	47	114	5.0	4.4%
Princeton A	1126510, 1126511, 1126518	1937-2021	85	32.5	-0.2	-0.6%
Saanichton CDA	1016940	1914-2021	108	63.9	1.6	2.5%
Shawnigan	1017230	1912-2021	110	85.6	1.7	2.0%
Vancouver A	1108395, 1108447	1937-2021	85	64.2	1.1	1.7%
Victoria A	1018620, 1018621	1940-2021	82	66.2	2.0	3.0%

Table 8. Rainfall and Snow Melt at MOTI Road Weather Stations, November 14-15, 2021

Name	Location	Rain Nov 14 (mm)	Rain Nov 14-15 (mm)	Snow Depth Loss[1] (mm)	Total Rain and Snow Water Loss (mm)
Nicolum Creek	Lower Coquihalla	118	206	no snow	206
Hells Gate Roadside	Fraser Canyon	120	217	no snow	217
Jackass	Fraser Canyon (Lytton)	78.6	151	no snow	151
Foundation Mines	Cascades - mid elevation	87.9	145	210	214
Allison Pass	Upper Similkameen (Manning Park)	65.0	113	157	165
Red Bluffs	Tulameen	75.7	103	43	117
Helmer Lake	Nicola	11.2	33.3	103	67
Larson Hill	Coldwater (mid)	63.0	113	43	127
Coquihalla Summit	Upper Coquihalla and Coldwater	138	241	240	320
Pothole Lake	Plateau - east of Merritt	22.2	45.0	not measured	45+
Malahat	Hwy 1, below Malahat Summit	65	154	no snow	154

Notes: 1. Snow Depth Loss (mm) refers to the reduction in snowpack depth from melt during Nov 14-15. Not all of this depth necessarily became runoff. A portion of the melt water may have stayed in the snowpack, creating a denser snowpack.

2. For Red Bluffs and Larson Hill, the 43 mm of snow depth loss is the entire snowpack that was measured at these sites at the start of Nov 14.

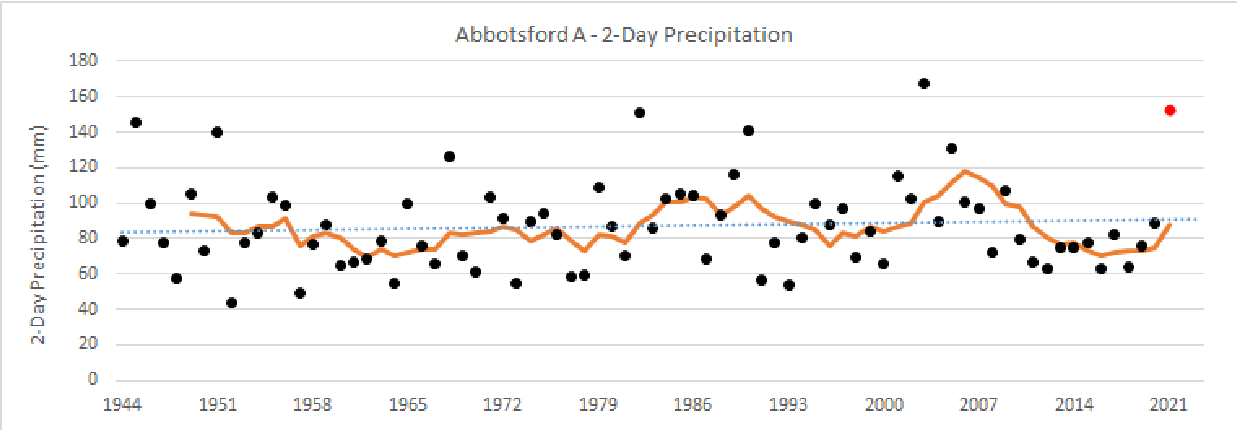
Table 9. Comparison of Oct 16-17, 2003 and Nov 14-15, 2021 Rainfall at MOTI Road Weather Stations

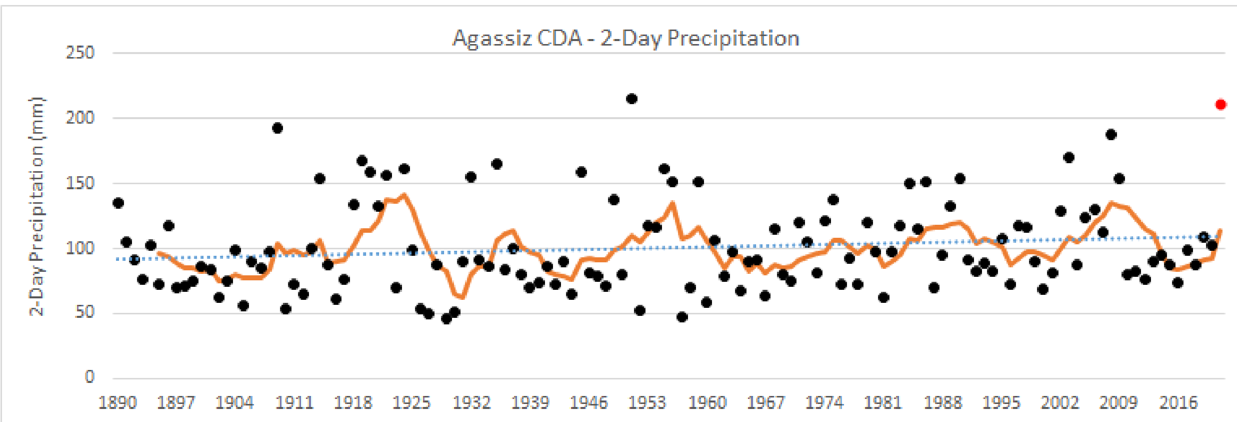
	Coquihalla Summit		Larson Hill		Red Bluffs		Foundation Mines		Jackass	
	Nov 14-15, 2021	Oct 16-17, 2003	Nov 14-15, 2021	Oct 16-17, 2003	Nov 14-15, 2021	Oct 16-17, 2003	Nov 14-15, 2021	Oct 16-17, 2003	Nov 14-15, 2021	Oct 16-17, 2003
2-Day Rain (mm)	241	157	113	59	103	25	145	115	151	103
Largest 6 hr (mm)	45	43	25	24	32	9	28	28	32	36
Largest 12 hr (mm)	84	77	41	38	50	13	52	56	58	56
Largest 24 hr (mm)	162	123	80	53	78	21	92	90	88	79
Largest 48 hr (mm)	253	157	119	60	114	28	165	116	161	103
Duration (hrs)	46	38	46	22	46	25	49	35	50	37

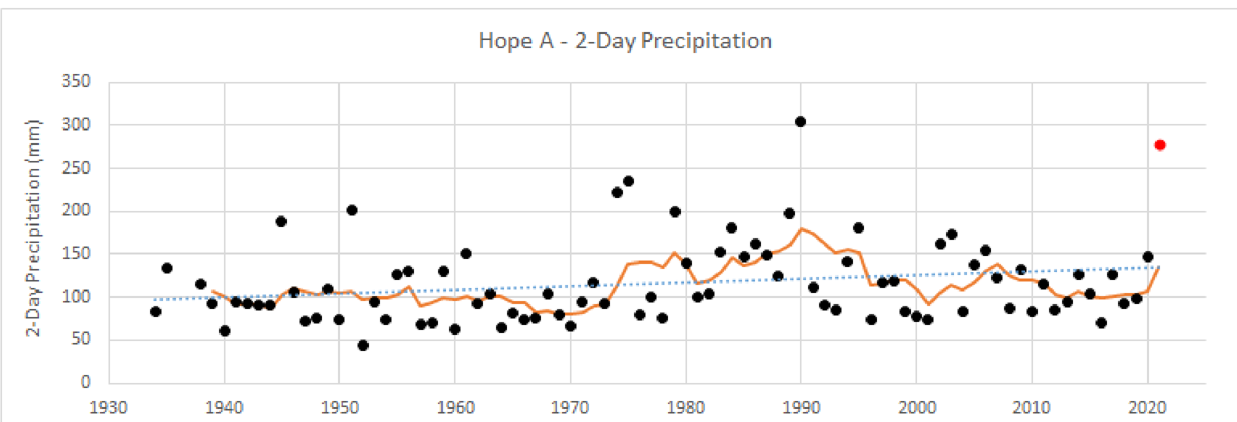
Table 10. Rainfall and Snow Water Loss at Automated Snow Pillows, November 14-15, 2021

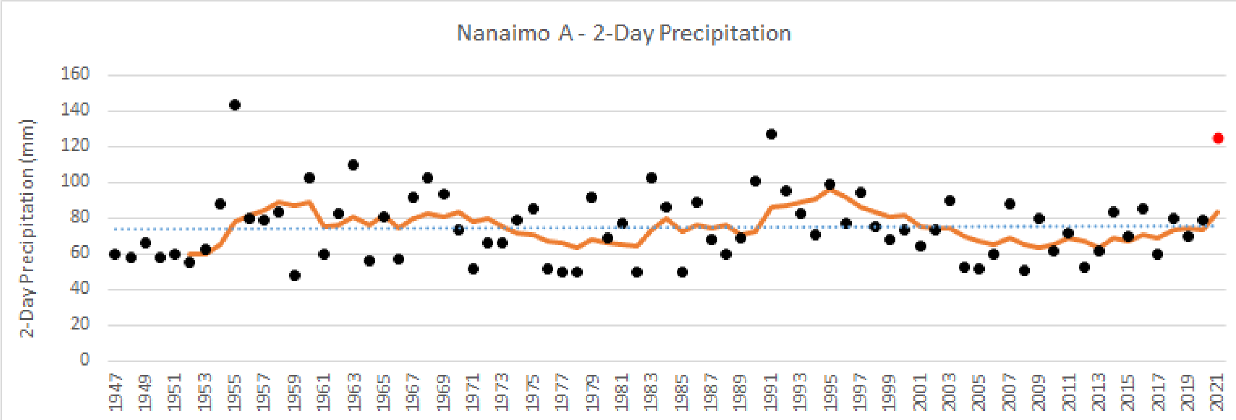
				Nov 14-15, 2021		
Name	ID	Location	Elevation (m)	Snow Water Loss (mm)	Rain (mm)	Total Rain + Snow (mm)
Lamont Creek	1D08P	Fraser Coast	1200	71	n/a	-
Wahleach Lake	1D09P	Fraser Coast	1480	38	n/a	-
Chilliwack River	1D17P	Fraser Coast	1600	106	198	304
Spuzzum	1D19P	Fraser Canyon	1180	71	372	443
Heather Mountain	2B24P	Vancouver Island	1190	68	224	292
Blackwall Peak	2G03P	Similkameen	1940	14	89	103
Palisade Lake	3A09P	North Shore	900	108	131	239
Shovelnose Mountain	1C29P	Coldwater	1460	21	115	136

Figure 2. Trends in 2-Day Storm Precipitation at ECCC climate stations, showing trend line and 5-year moving average. The Nov 14-15, 2021, measurement shown in red.

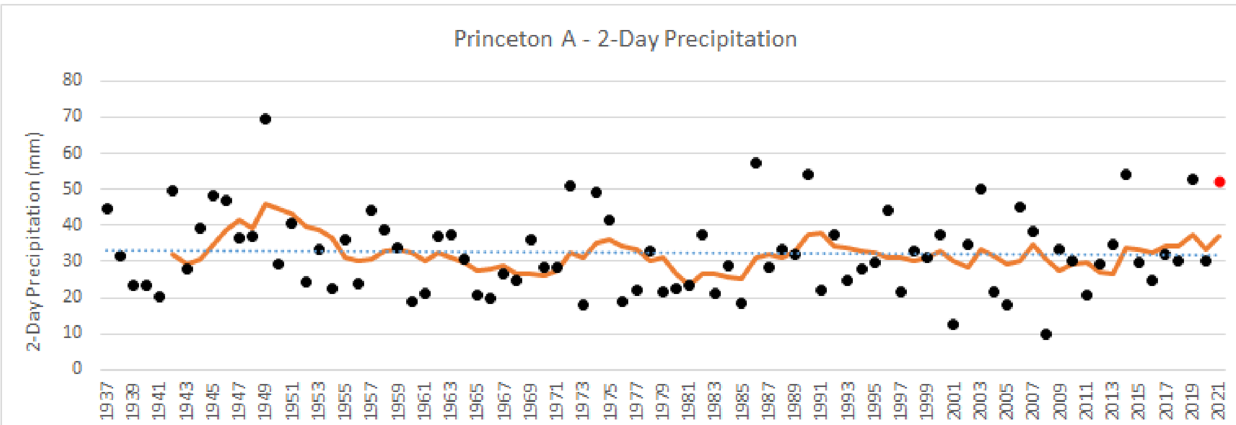




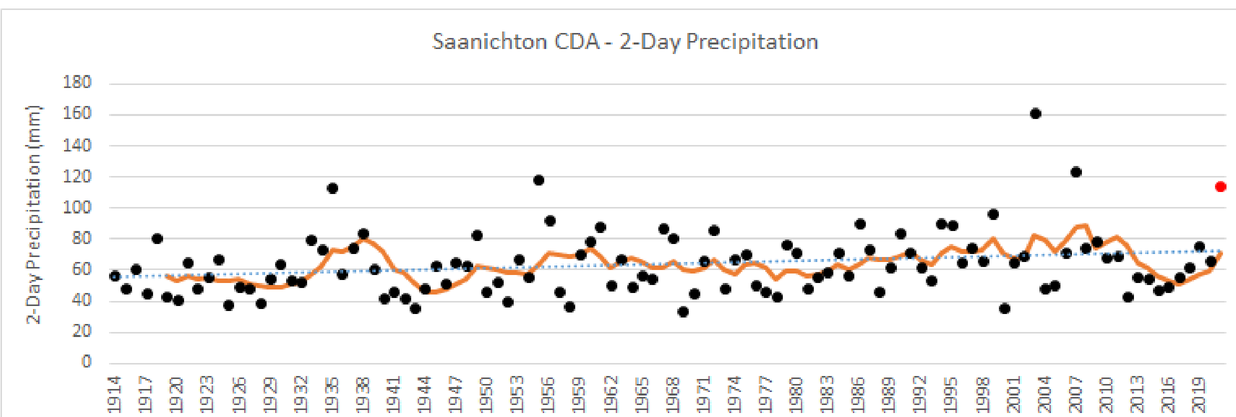




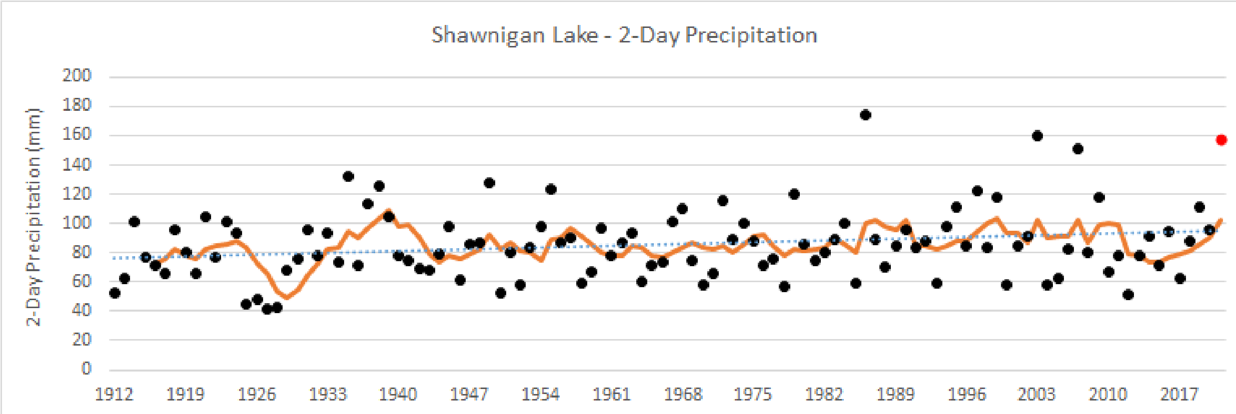
Nanaimo A - 2-Day Precipitation
2-Day Precipitation (mm)
0
20
40
60
80
100
120
140
160
1947
1949
1951
1953
1955
1957
1959
1961
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021

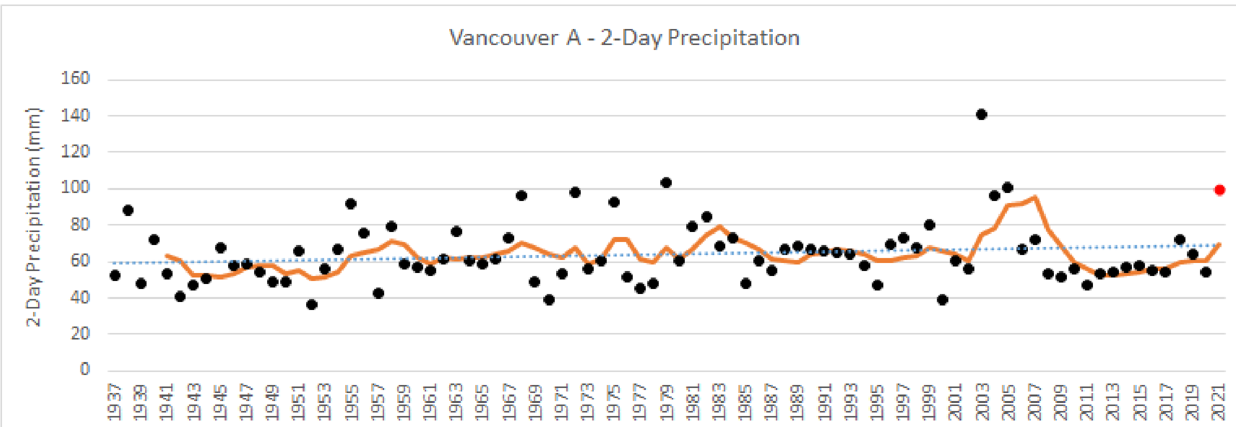


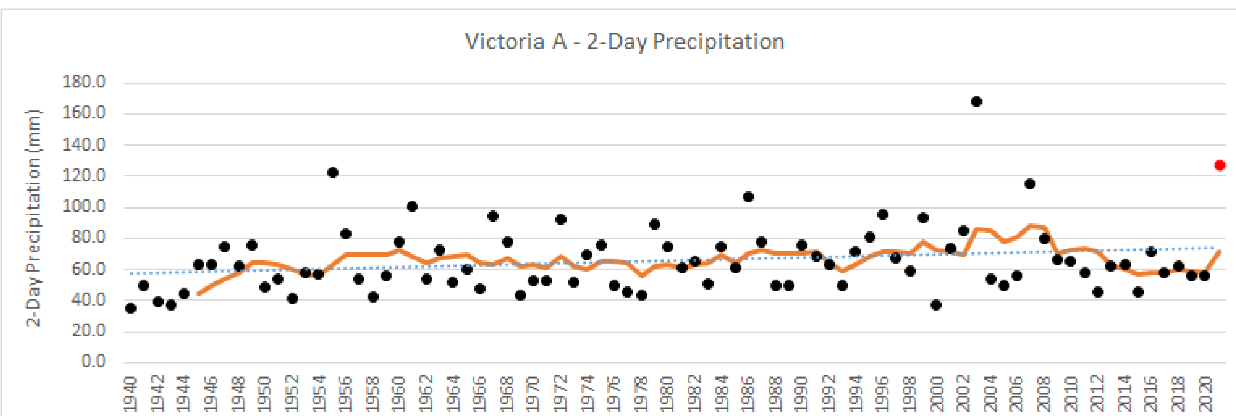
Princeton A - 2-Day Precipitation
2-Day Precipitation (mm)
0
10
20
30
40
50
60
70
80
1937
1939
1941
1943
1945
1947
1949
1951
1953
1955
1957
1959
1961
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021



Saanichton CDA - 2-Day Precipitation
2-Day Precipitation (mm)
0
20
40
60
80
100
120
140
160
180
1914
1917
1920
1923
1926
1929
1932
1935
1938
1941
1944
1947
1950
1953
1956
1959
1962
1965
1968
1971
1974
1977
1980
1983
1986
1989
1992
1995
1998
2001
2004
2007
2010
2013
2016
2019


Shawnigan Lake - 2-Day Precipitation
2-Day Precipitation (mm)
200
180
160
140
120
100
80
60
40
20
0
1912
1919
1926
1933
1940
1947
1954
1961
1968
1975
1982
1989
1996
2003
2010
2017


Vancouver A - 2-Day Precipitation
2-Day Precipitation (mm)
160
140
120
100
80
60
40
20
0
1937
1939
1941
1943
1945
1947
1949
1951
1953
1955
1957
1959
1961
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
2015
2017
2019
2021


Victoria A - 2-Day Precipitation
2-Day Precipitation (mm)
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
1940
1942
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
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1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020

Figure 3. Snow Water Loss at Automated Snow Pillows, Nov 14-15, 2021

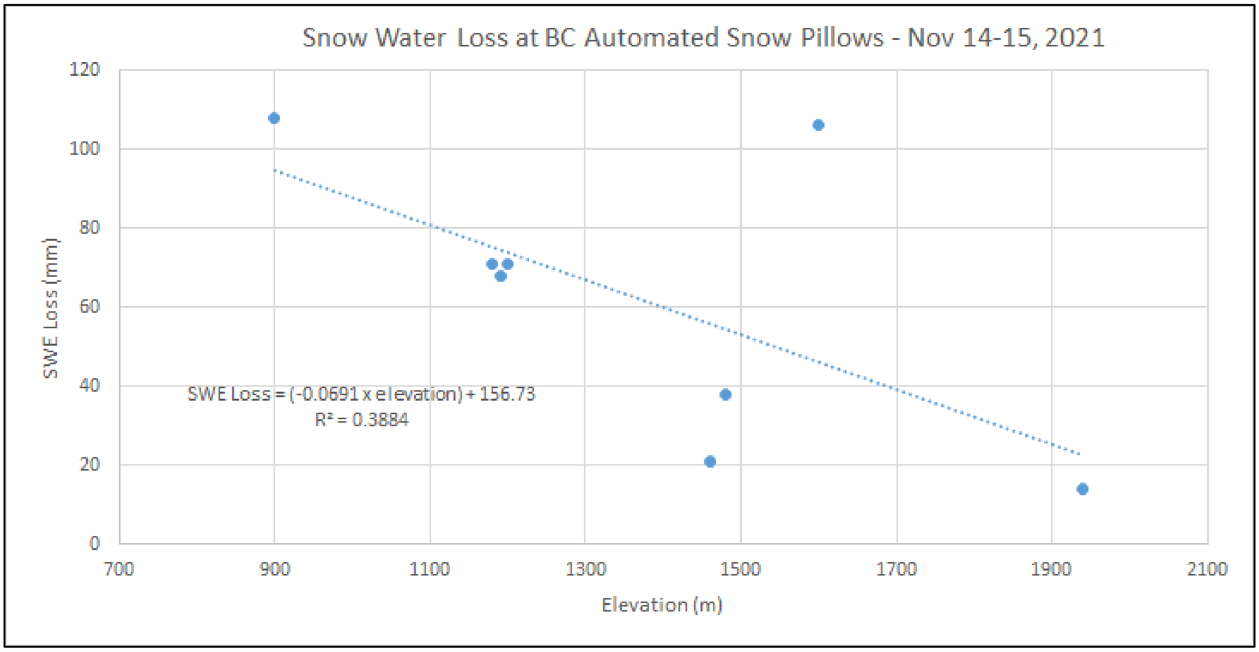

Figure 4. Temperature at Automated Snow Pillows, November 12-16, 2021

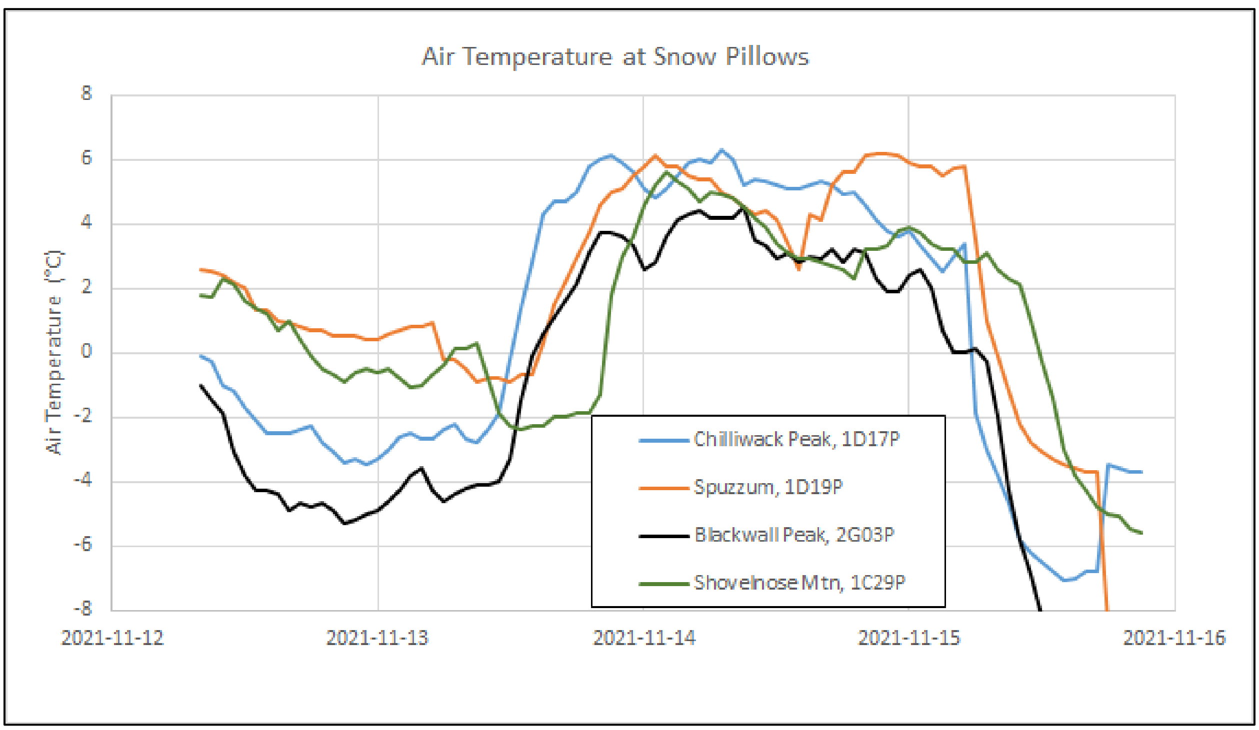

Table 11. Fire, logging and forest road density for various Water Survey of Canada basins that experienced record peak levels on Nov 14-15, 2021.

Watershed	Basin Area (km2)	Fire - 2021 (km^2)	% of Basin	Historic Fire: 1970-2020 (km^2)	% of Basin	Clearcut (km^2)	% of Basin	Clearcut + Fire (km^2)	% of Basin	Roads (km)	Density (km/km^2)
Coldwater River at Brookmere (08NL024)	314	81	25.8%	16	5.1%	48	15%	128	41%	472	1.50
Coldwater River at Merritt (08NL010)	917	140	15.2%	30	3.3%	209	23%	347	38%	1,286	1.40
Tulameen River below Vuich (08NL071)	254	0	0.0%	0	0.1%	18	7%	18	7%	228	0.90
Tulameen River at Princeton (08NL024)	1,780	6	0.3%	128	7.2%	477	27%	608	34%	3,297	1.85
Coquihalla River at Needles	53	0	0.0%	0	0.0%	8	15%	8	15%	55	1.04
Coquihalla River at Alexander (08MF067)	746	1	0.1%	4	0.5%	128	17%	129	17%	1,076	1.44
Spius Creek near Canford (08LG008)	777	51	6.5%	75	9.6%	157	20%	267.9	34%	804	1.03
Nicola River near Spences Bridge (08LG006) (excluding basin above Nicola Lake)	5,884	782	13.3%	168	2.9%	1,467	25%	2,242	38%	7,250	1.23

Note: For the calculation of the "Clearcut + Fire", overlapping areas are excluded so as to not double count.

Table 12. Forecast vs. Observed Rainfall, November 13-15, 2021

	Rain Forecast, November 14, 2021				Rain, Novembr 14, 2021	
Location	**MM5 - 12km**	**WRF - 12 km**	**WRF - 4km**	**Average**	**Observed**	**% of Forecast Average**
Hope A	143	147	192	161	174	108%
Abbotsford A	104	93	80	92	100	108%
Princeton	60	28	36	41	36	87%
Merritt	31	14	10	18	14	76%
Spuzzum ASP	134	126	182	147	162	110%
Coquihalla Summit	139	91	168	132	138	104%
Larson Hills	112	64	44	73	79	108%
Jackass	81	64	46	64	63	99%
	48-Hour Rain Forecast, November 13-15, 2021				**Rain, 48-Hr Total**	
Location	**MM5 - 12km**	**WRF - 12 km**	**WRF - 4km**	**Average**	**Observed**	**% of Forecast Average**
Hope	177	212	259	216	293	136%
Abbotsford	134	160	144	146	173	118%
Princeton	81	46	59	62	55	89%
Merritt	39	36	27	34	31	91%
Spuzzum ASP	170	181	248	200	375	188%
Coquihalla Summit	175	149	231	185	254	137%
Larson Hills	134	98	73	102	119	117%
Jackass	93	98	69	87	161	185%

Note: The weather forecasts refer to the 12 UTC 12-Nov-2021 model runs from the Pacific Northwest Environmental Forecasts and Observations, at the University of Washington, Dept of Atmospheric Sciences. https://a.atmos.washington.edu/mm5rt/

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