BRITISH COLUMBIA **River Forecast Centre**

# Review of Early July 2019 Chilcotin River Flood from Perspective of Hydrologic Modeling Efforts


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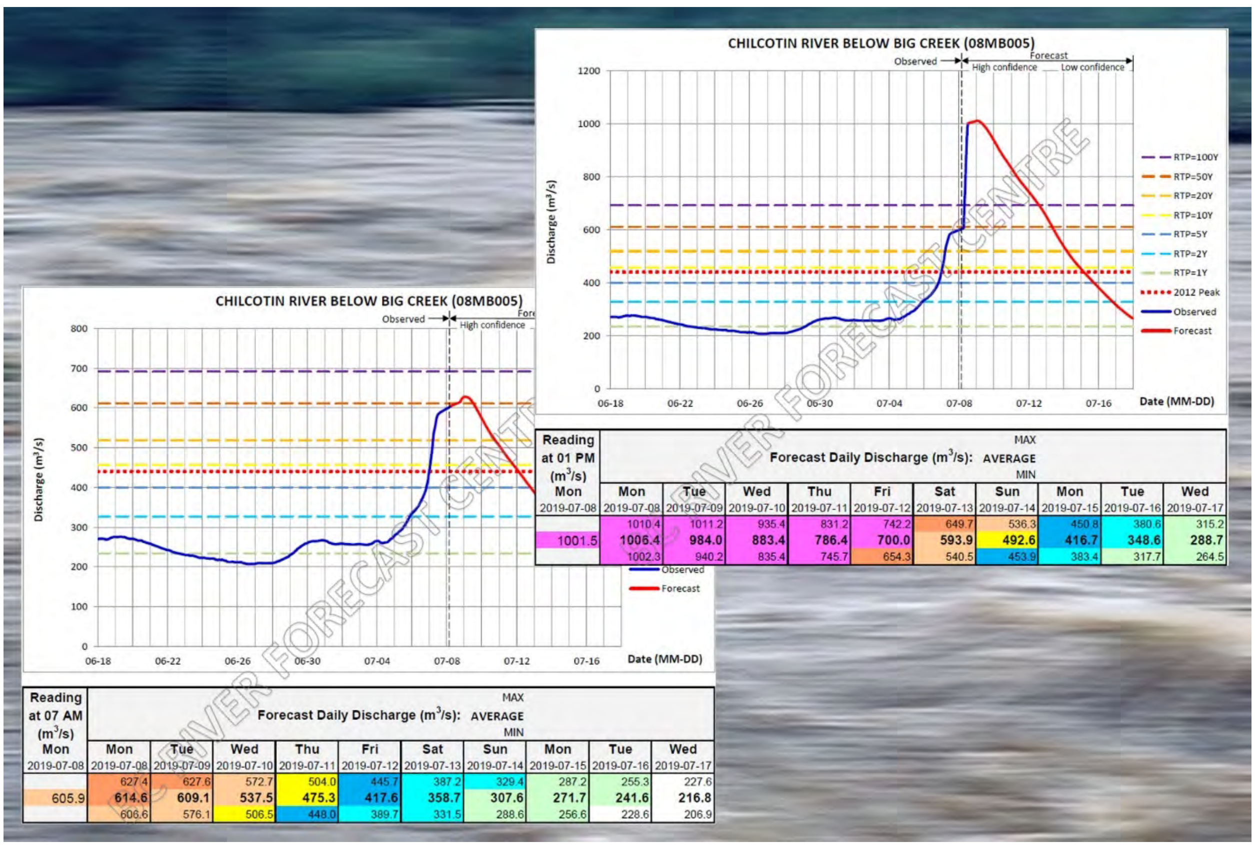
River Forecast Centre, May 2020



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# Abstract

Climate change plays a more and more important role in many flooding events. The early July 2019 Chilcotin River flood is one of these but more complex because that (1) the maximum 24-hour rainfall for this flooding event (38 mm) is not even the maximum historical record, and (2) the Water Survey of Canada (WSC) hydrometric station CHILCOTIN RIVER BELOW BIG CREEK (08MB005), the only modeled station for the Chilcotin River watershed, was not functioning properly.

A long-duration (1- to 4-day) rainfall IDF analysis for the 11 climate stations located in and close to the Chilcotin River watershed was carried out after the flooding event. Comparing with the IDF analysis results, it was found that the maximum 24-hour rainfall (38 mm) recorded at the Fire Weather station NMI – NEMIAH (216) is only at the 10-year return period level. However, the maximum 4-day total rainfall (94.6 mm) recorded at this station is at the 50-year return period level and is the maximum historical record. This reflects the climate change impacts and the severity of this flooding event.

A flood frequency analysis was carried out for all the WSC hydrometric stations located in the Chilcotin River watershed. Comparing with the results, it was found that no flood was recorded at the three upstream stations located in the west of the watershed. However, the downstream station CHILKO RIVER NEAR REDSTONE (08MA001) recorded a flood between the 20- to 50-year return periods. The BIG CREEK ABOVE GROUNDHOG CREEK (08MB006) located in the east of the watershed also recorded a flood between the 50- and 100-year return periods. The latest WSC provisional discharge data (as of December 7, 2019) for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) had a peak of 803 $m^3/s$, which is a flood between the 200- and 500-year return periods.

The malfunction and significant artificial adjustments to the provisional discharge data for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) had posed incredible uncertainties and difficulties to the operational flood forecasting during the flooding event. Faced with these challenges, the River Forecast Centre, by using their best professional judgements and making tremendous efforts including changing the model calibration strategy and immediate model improvements, had managed to produce reasonable and timely flood forecasts throughout the entire flooding event.

After the flooding event, the CLEVER Model was used to reconstruct a most-close-real hydrograph for the flooding event. The estimated peak of the flooding event is 713.5 $m^3/s$, which is a flow slightly over the 100-year return period flow (691.8 $m^3/s$), and which surpasses the historical maximum (699.8 $m^3/s$) recorded in 1991.

After the flooding event, the CLEVER Model has been upgraded for the 2020 freshet. The number of the modeled WSC hydrometric stations has been massively increased, from 110 to 247 or by 134%, leaving no large gaps in most of the watersheds in the province. The new WSC station list for the model also includes four new stations for the Chilcotin River watershed. A new tool has also been built in the upgraded model to allow users to export the forecast for a single station or several related stations.

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# 1. Introduction

The Chilcotin River is a tributary of the Middle Fraser River. The river has a length of about 250 km and the watershed area is approximately 19,500 km$^2$. The Chilcotin River has two major tributaries, the Chilko River and the Big Creek. The Chilcotin River watershed had experienced severe flooding in early July 2019, from July 6, when the Big Creek was reported flooding, to July 16, when the River Forecast Centre ended the High Streamflow Advisory for the Chilcotin River. Figure 1 (a) shows a photo of the inundated site of the Water Survey of Canada (WSC) hydrometric station, the CHILCOTIN RIVER BELOW BIG CREEK (08MB005), taken by the landlord of the station site on July 9, 2019, and Figure 1 (b) shows an aerial photo of the confluence of the Chilcotin River and the tributary Big Creek, taken by a WSC technician on July 12, 2019.


(a) Inundated WSC station (08MB005) (July 9, 2019)   (b) Aerial photo of Chilcotin River (July 12, 2019)

Figure 1. Flooding in Chilcotin River and tributary Big Creek

(Background photos copyright by Water Survey of Canada)

It has been observed that climate change has been playing a more and more important role in many flooding events. The early July 2019 Chilcotin River flood is one of these climate change impacted flooding events. However, this event is more complex because that the 24-hour rainfall is not large, and that the most downstream WSC hydrometric station, the CHILCOTIN RIVER BELOW BIG CREEK (08MB005), was encountering a technical difficulty, which prevented the station from reporting correct provisional discharge data during the flood event.

One of the five climate stations which are located in the Chilcotin River watershed, the Fire Weather station NMI – NEMIAH (216), recorded the heaviest rainfall among the five climate stations. The station recorded a 24-hour rainfall amount of 38 mm on July 7, 2019, which is the maximum single-day rainfall recorded during the flooding event. Rainfall amounts recorded at the other climate stations located in the Chilcotin River watershed were much less, some were event much less than the annual maximum in 2019. Due to lack of rainfall intensity-duration-frequency (IDF) analysis for these climate stations, it was difficult to determine the relative intensities of these rainfall amounts when the flooding event was occurring.

Meanwhile, it was found that the most important WSC hydrometric station for the Chilcotin River, the CHILCOTIN RIVER BELOW BIG CREEK (08MB005), was not functioning properly on and after July 8, 2019 and onsite measurements were also difficult due to the inaccessibility to the station site during the flooding event. This station was the only WSC hydrometric station located in the Chilcotin River watershed which was modeled by the CLEVER Model on and before July 9, 2019. As a consequence of the station's malfunction, the observed provisional discharge data for this station was significantly manually adjusted. This treatment to the observation had posed incredible uncertainties and difficulties to the operational flood forecasting during the flooding event.

Due to the complexity of the flooding event, this document only attempts to review the flooding event from the perspective of hydrologic modeling efforts in the River Forecast Centre. After presenting the analysis of the precipitation and the hydrometric natures of the flooding event, this document reviews the real-time modeling efforts in the River Forecast Centre from July 5 to 16, 2019 day by day, detailing the model calibration, model responses each day, a change of calibration strategy and immediate model improvements. After that, the methodology and results of the CLEVER Model estimated hydrograph for the flooding event are also given. The long-term improvements for the CLEVER Model are introduced briefly at the end of this document.

# 2. Precipitation natures

## 2.1 ECCC Rainfall forecast on July 3, 2019

On Wednesday July 3, 2019, Environment and Climate Change Canada (ECCC) issued a "Weather Notification: Heavy Showers and Thunderstorms for the Southern Interior July 4-6, 2019" with the following key points about the rainfall intensity:

- An upper cold low will bring relatively heavy rainfall and thunderstorms to the Southern Interior from the Coast Range to the Rockies between Thursday morning and Saturday evening.
- Cumulative rainfall amounts of 40-60mm are possible. For the relatively dry Southwestern Interior, this would exceed average monthly precipitation totals (~35mm for July).
- The heaviest amounts are expected over the Fraser Canyon and Rockies.
- The heaviest rainfall period should occur on Thursday with 20-40mm.
- Isolated thunderstorm cells could produce heavy rainfall rates of 10-20 mm/hour.
- An unsettled weather pattern continues with showers and risks of thunderstorms on Sunday and beyond; however, amounts should be less.

The figure attached with this Weather Notification (Figure 1) shows that the Chilcotin River watershed was included in the forecast heavy rainfall region.

The CLEVER Model updated on July 3, 2019 indicated that the flow for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005), which was the only WSC station located in the Chilcotin River watershed that was modeled by the CLEVER Model on and before July 9, 2019, was expected to rise to a flow between the 1- and 2-year return periods only. On July 5, 2019, the ECCC forecast 24-hour rainfall amount increased. The CLEVER Model updated on the same day showed a response between the 10- to 20-year return periods at the above WSC station. Details of the CLEVER Model responses will be given in Section 4.

The above ECCC's Weather Notification and the CLEVER Model responses provide a primitive image of this flooding event.

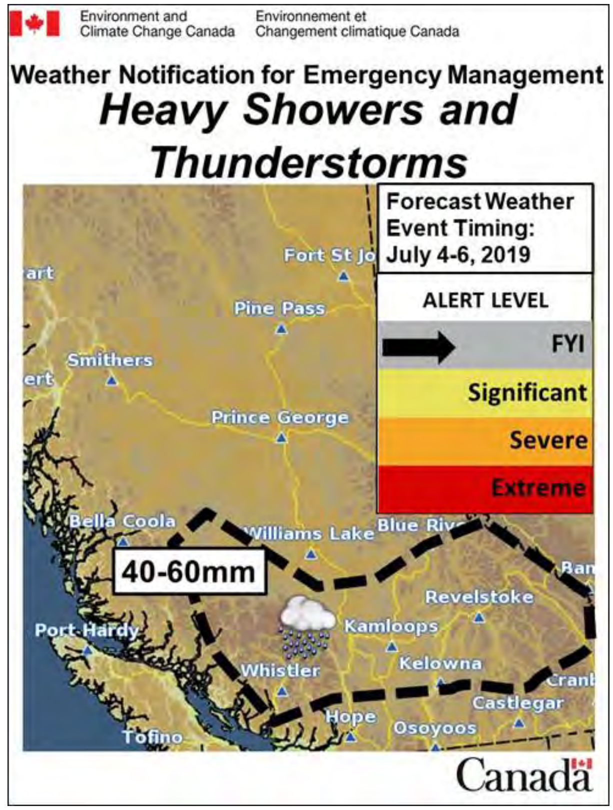



Figure 2. ECCC forecast heavy rainfall Region issued on July 3, 2019 (Copyright by ECCC)

## 2.2 Observed rainfall distributions

There were five climate stations, four Fire Weather stations and one ECCC climate station, located in the Chilcotin River Watershed. In order to obtain a better rainfall distribution over the watershed, six additional climate stations located adjacent to the watershed were also included in this study. Table 1 is the list of these 11 climate stations, which include nine Fire Weather stations and two ECCC climate stations. Table 2 shows the 24-hour rainfall and the 4-day total rainfall amounts observed at these 11 climate stations from July 4 to July 7, 2019. From Table 2, it can be seen that the absolute amounts of the 24-hour rainfall amounts (maximum 38 mm) and the 4-day total rainfall (maximum 94.6 mm) were relatively moderate.

Figure 3 shows the geographic locations of the above 11 climate stations, and WSC hydrometric (flow) stations as well, for the Chilcotin River watershed.

The rainfall amounts recorded at the 11 climate stations were used to produce isohyet maps of the precipitation depth (contours) distribution for the Chilcotin River watersheds during the flooding event. Figures 4 to 8 show the GIS generated isohyet maps of the distribution (contours) for the 24-hour and 4-

day total precipitation depths in the Chilcotin River watershed from July 4 to July 7, 2019. The contours were produced with the ArcMap by using the inverse distance weighted interpolation method, in which 8 points (climate stations) with a power of 1 were adopted to interpolate the rainfall data for the 11 climate stations to a rectangular extend.

Figures 4 to 8 show that the heaviest rainfall was distributed in the south or southeast of the Chilcotin River watershed. However, the relative intensities of the rainfall were left unknow due to lack of statistical (IDF) analysis for the historical rainfall data.

Table 1. List of climate stations inside and adjacent to Chilcotin River watershed

| MD/TC ID | TYPE | ID | Name | Latitude | Longitude | ELEV (m) | CLEVER WT |
|---|---|---|---|---|---|---|---|
| BLF | FW | 221 | BALDFACE | 52.710 | -124.482 | 1666 | 0.2 |
| ACH | FW | 209 | ALEXIS CREEK HUB | 52.084 | -123.273 | 791 | 0.2 |
| TAT | FW | 208 | TATLA LAKE HUB | 51.907 | -124.605 | 945 | NOT USED |
| NMI | FW | 216 | NEMIAH | 51.480 | -123.818 | 1220 | 0.4 |
| TAU | FW | 206 | TAUTRI | 52.535 | -123.250 | 1085 | NOT USED |
| GPD | FW | 222 | GASPARD | 51.452 | -122.662 | 1675 | NOT USED |
| RIS | FW | 210 | RISKE CREEK | 51.959 | -122.504 | 929 | NOT USED |
| SCC | FW | 82 | SCAR CREEK | 51.189 | -125.028 | 126 | NOT USED |
| GWY | FW | 309 | GWYNETH LAKE | 50.796 | -122.880 | 1205 | NOT USED |
| WPU | ECCC | 1086558 | Puntzi Mountain | 52.114 | -124.136 | 910 | 0.2 |
| XTL | ECCC | 1088015 | Tatlayoko Lake | 51.675 | -124.403 | 875 | NOT USED |

Note: MD ID – Model ID for Fire Weather (FW) stations, TC ID – Transportation Canada ID for ECCC stations, CLEVER WT – Weight in the CLEVER Model on and before July 9, 2019

Table 2. 24-hour and 4-day total precipitation for the 11 climate stations from July 4 to July 7, 2019

| MD/TC ID | TYPE | ID | Name | P_JUL4 (mm) | P_JUL5 (mm) | P_JUL6 (mm) | P_JUL7 (mm) | P_TOTAL (mm) |
|---|---|---|---|---|---|---|---|---|
| BLF | FW | 221 | BALDFACE | 8.2 | 3.8 | 5.4 | 3.2 | 20.6 |
| ACH | FW | 209 | ALEXIS CREEK HUB | 15.4 | 12.2 | 8.6 | 9.2 | 45.4 |
| TAT | FW | 208 | TATLA LAKE HUB | 4.8 | 7.4 | 6.2 | 6.2 | 24.6 |
| NMI | FW | 216 | NEMIAH | 9 | 24 | 23.6 | 38 | 94.6 |
| TAU | FW | 206 | TAUTRI | 8 | 0.6 | 2.4 | 8.4 | 19.4 |
| GPD | FW | 222 | GASPARD | 8.6 | 19.2 | 30.2 | 17 | 75 |
| RIS | FW | 210 | RISKE CREEK | 10 | 9.6 | 28 | 1.4 | 49 |
| SCC | FW | 82 | SCAR CREEK | 0 | 3.2 | 0 | 1.6 | 4.8 |
| GWY | FW | 309 | GWYNETH LAKE | 8.2 | 15.2 | 23.4 | 11.8 | 58.6 |
| WPU | ECCC | 1086558 | Puntzi Mountain | 17.5 | 1.8 | 13.1 | 1 | 33.4 |
| XTL | ECCC | 1088015 | Tatlayoko Lake | 3.3 | 12 | 4.8 | 11.2 | 31.3 |

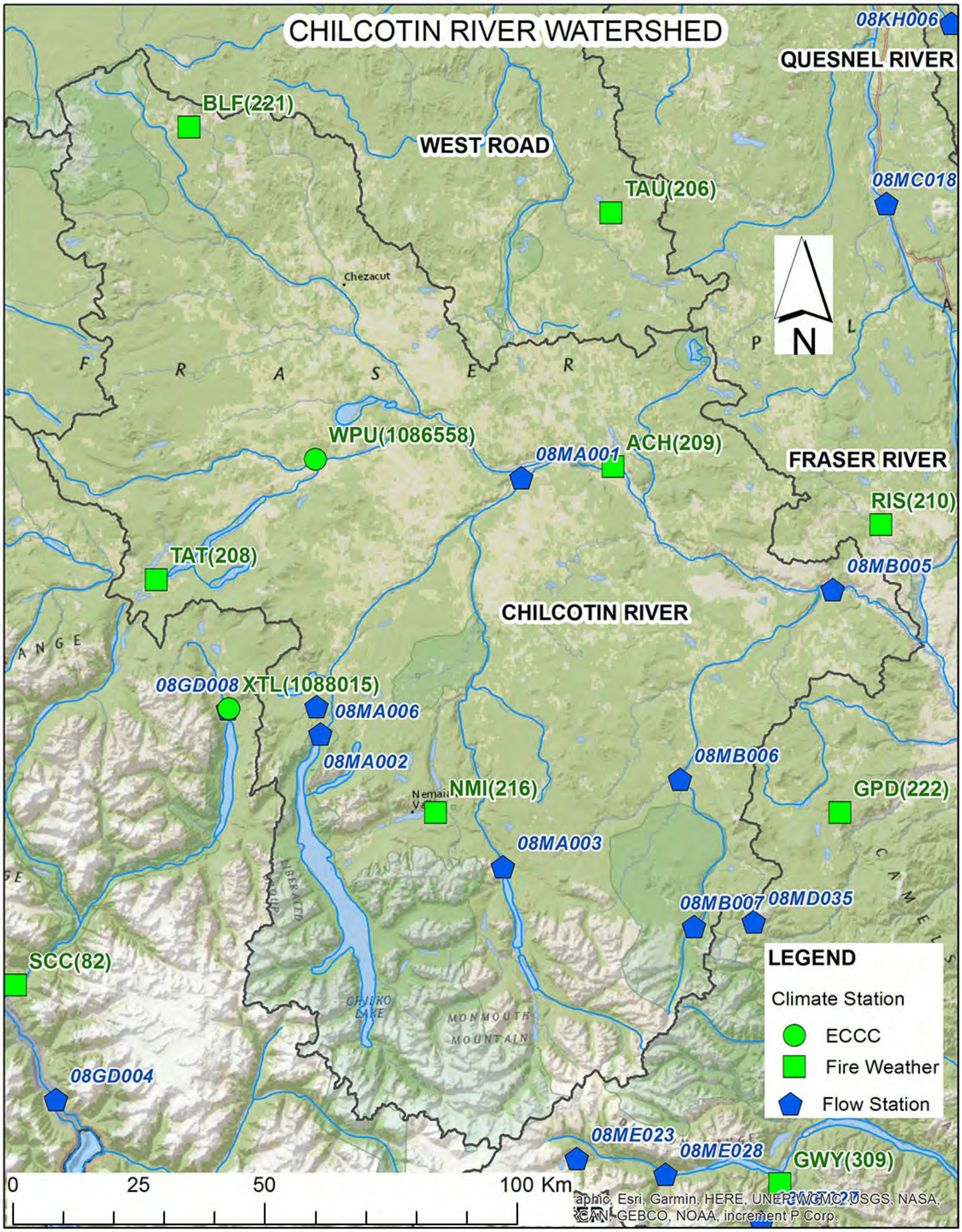



Figure 3. Geographic locations of climate stations and WSC hydrometric (flow) stations for Chilcotin River watershed

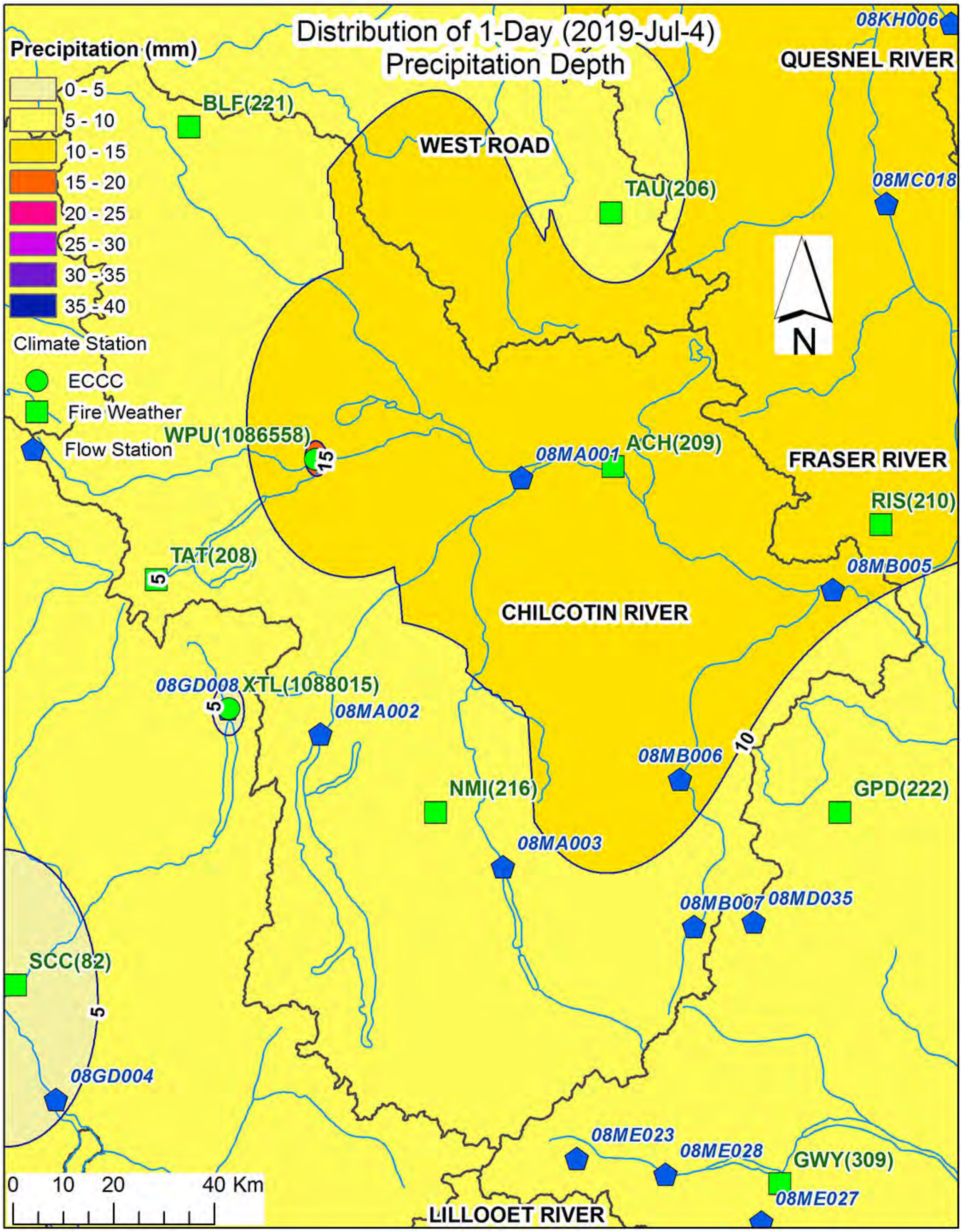



Figure 4. Isohyet map of 24-hour precipitation depth in Chilcotin River watershed, July 4, 2019

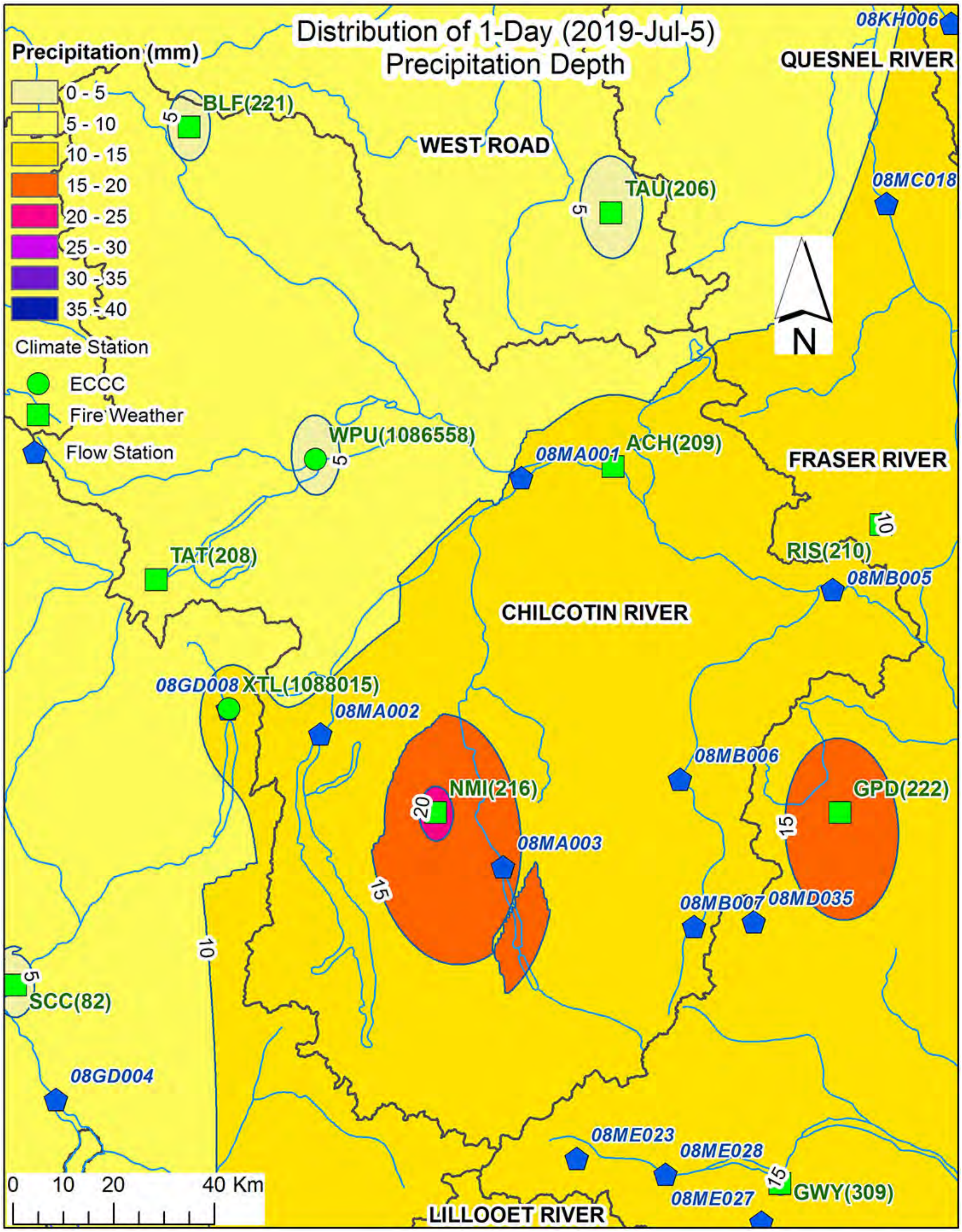



Figure 5. Isohyet map of 24-hour precipitation depth in Chilcotin River watershed, July 5, 2019

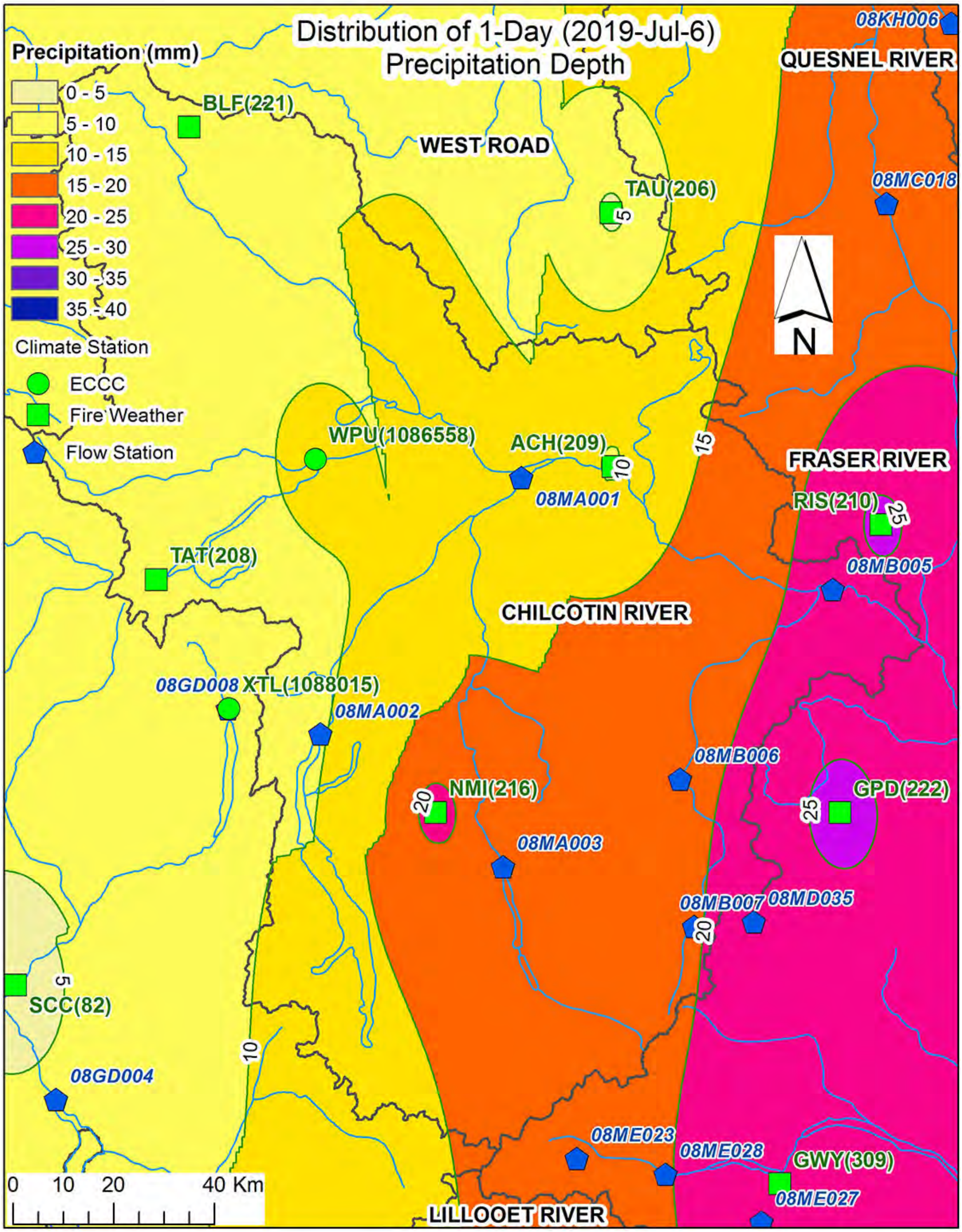



Figure 6. Isohyet map of 24-hour precipitation depth in Chilcotin River watershed, July 6, 2019

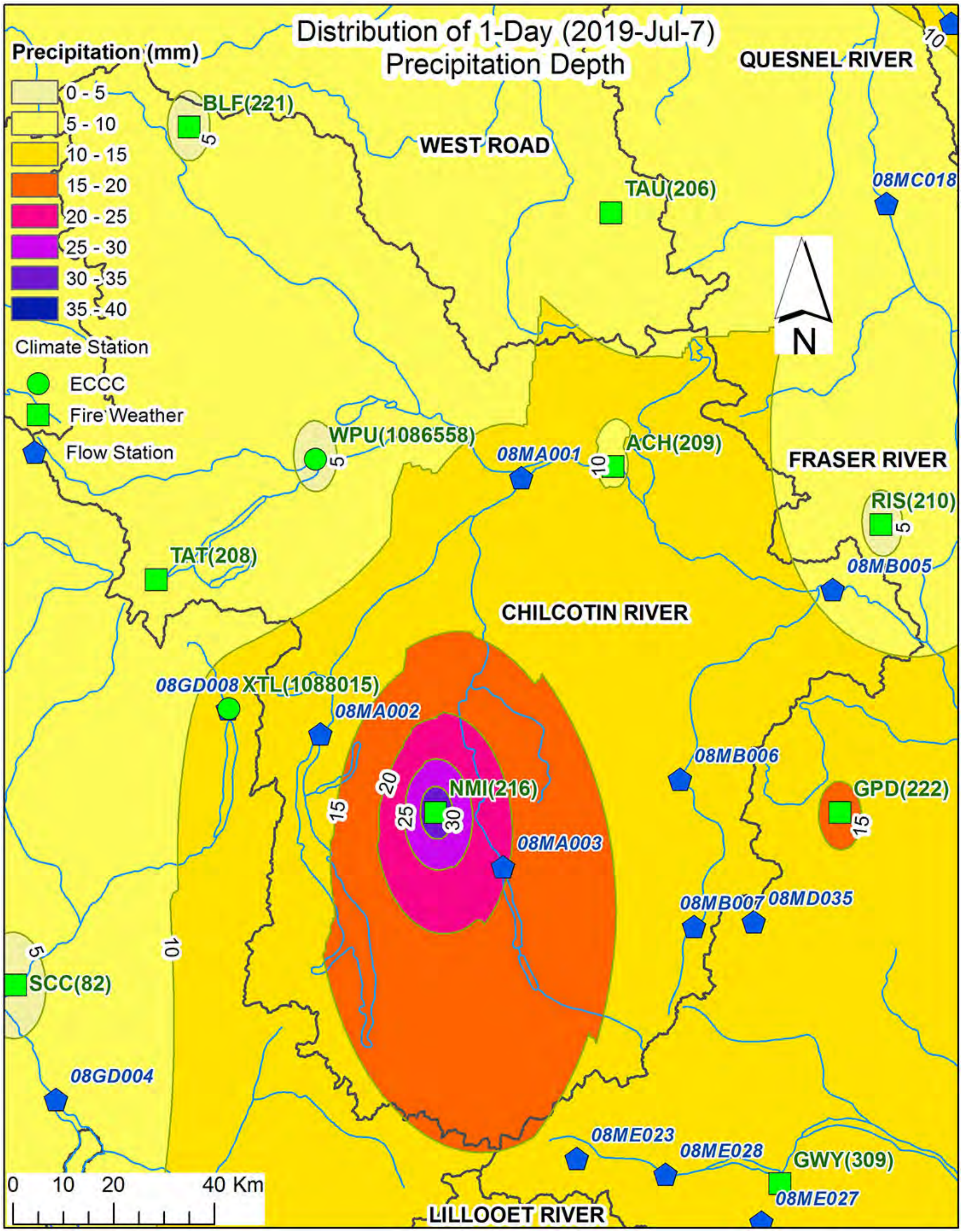



Figure 7. Isohyet map of 24-hour precipitation depth in Chilcotin River watershed, July 7, 2019

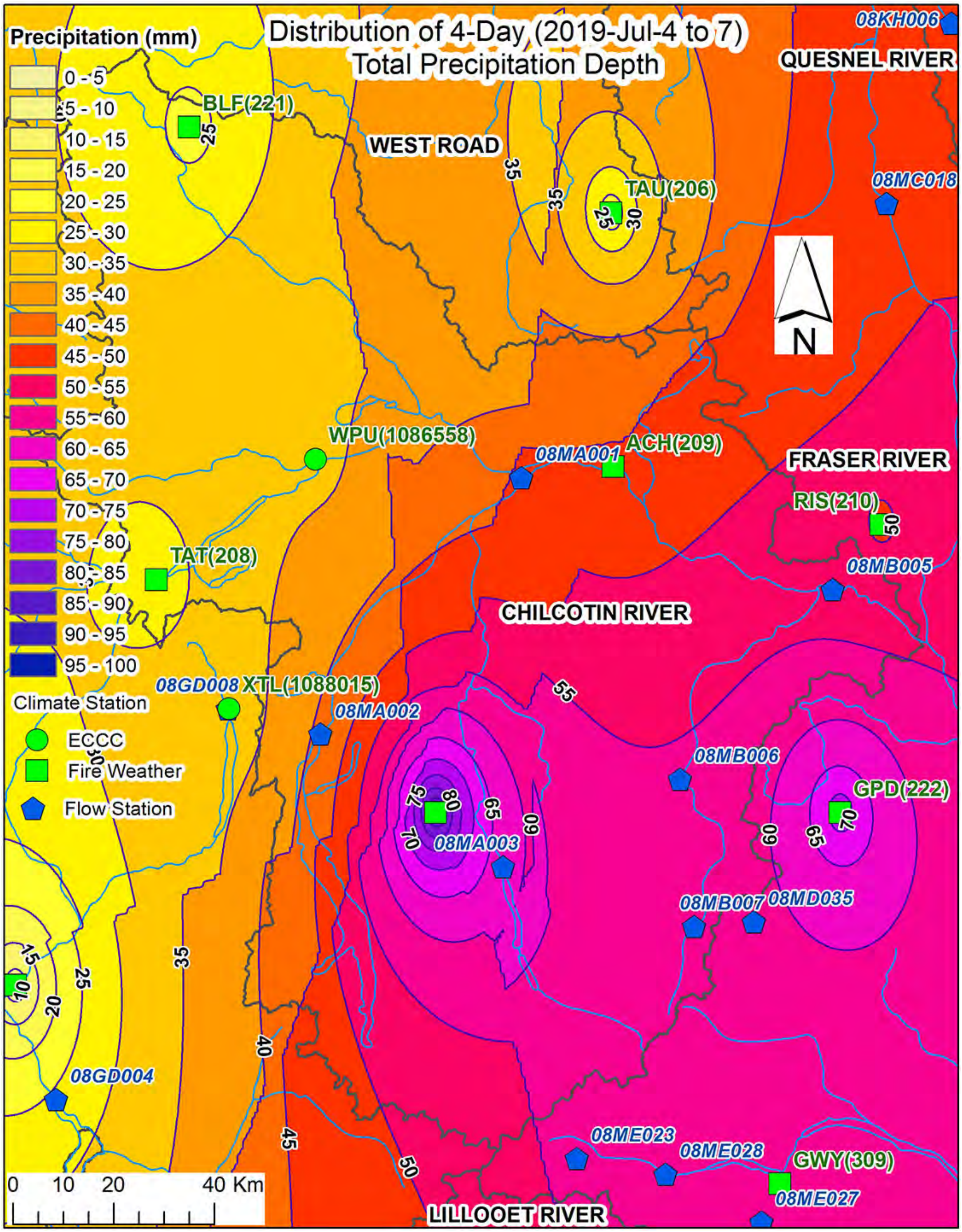



Figure 8. Isohyet map of 4-day (July 4 to 7, 2019) total precipitation depth in Chilcotin River watershed

## 2.3 Long-duration (1- to 4-day) rainfall intensity-duration-frequency (IDF) analysis

In order to evaluate the relative intensities of the rainfall, which were responsible for the early July 2019 Chilcotin River flood, a rainfall intensity-duration-frequency (IDF) analysis is necessary. For a large-scale watershed like the Chilcotin River which has a watershed area of 19,200 $km^2$, floods are always caused by multi-day rainfall events. Therefore, a long-duration (1- to 4-day) rainfall IDF analysis was carried out for the 11 climate stations listed in Table 1. To facilitate the rainfall IDF analysis, the historical rainfall data must be downloaded. For the nine Fire Weather stations, the historical rainfall data were download from:
https://bcfireweatherp1.nrs.gov.bc.ca/Scripts/Public/Common/Report.asp?Report=Daily,
and for the two ECCC climate stations, the historical rainfall data were downloaded from:
https://climate.weather.gc.ca/historical_data/search_historic_data_e.html

For the ECCC climate station WPU – Puntzi Mountain (1086558), there were 26 year of data from 1994 to 2019. This station had been moved from an old location (the old station) to the current location. Although the old station had a different ID (1086556), the elevations of the two stations are similar (905.5 m for the old station - 1086556, and 909.8 m for the new station – 1086558). The old station had 12 years of data from 1968 to 1979. In this study, the data from the old station was also included in the frequency analysis. A similar situation happened to the other ECCC climate station XTL – Tatlayoko Lake (1088015) – the station had experienced moving. The old station (ID: 1088010, elevation 870 m) had 77 years of data from 1928 to 2004, and the current station (ID: 1088015, elevation 875 m) has 15 years of data from 2005 to 2019. Data from both the old and current stations were included in the IDF analysis.

In this long-duration (1- to 4-day) rainfall intensity-duration-frequency analysis, 8 probability distributions were selected to fit the observation rainfall data: (1) Normal, (2) Lognormal, (3) Gumbel (Extreme Value, EV I), (4) Log-Gumbel (EV II), (5) GEV (Generalized Extreme Value), (6) Log-GEV, (7) Pearson III, and (8) Log-Pearson III. Multiple criteria were set up to select the best distribution for each of the stations: (a) Goodness-of-fit test (R_GFT), which is calculated with Equation 18.3.10 in the Handbook of Hydrology, (page 18.27) (Stedinger et al., 1992), (b) plotting the design flood on a straight line against the return period, the plot positions of the observation data along the straight line and the upper and lower limits of the 90% confidence level on the same figure, and counting the data points which are outside the limits (PT_OUT), (c) visually comparing the figures of the above plots for the 8 distributions, (d) producing designed floods which have reasonable intervals or do not crowd together, especially for stations with a small sample, and (e) giving the Gumbel and GEV distributions a priority over the other distributions when the distributions have the same/similar coefficient of Goodness-of-fit (R_GFT) and/or number of points of observation outside the confidence limits (PT_OUT) (Stedinger et al., 1992).

Table 3 shows the results of the long-duration (1- to 4-day) rainfall IDF analysis. Details of the frequency analysis are given in Appendix A.

Table 3. Results of long-duration (1- to 4-day) rainfall intensity-duration-frequency analysis

| MD-ID (TYPE) | No of Sample | DURA-TION | RETURN PERIOD (YEAR)/DESIGN EXTREME PRECIPITATATION (mm) | | | | | | | HIST. MAX | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1.01 | 2 | 5 | 10 | 20 | 50 | 100 | P(mm) | YEAR |
| BLF (FW) | 28 | 1 D | 8.6 | 18.2 | 23.9 | 27.7 | 31.3 | 36.0 | 39.6 | 34.0 | 2019 |
| | | 2 D | 11.7 | 23.4 | 30.0 | 34.2 | 38.1 | 43.0 | 46.6 | 42.4 | 1994 |
| | | 3 D | 12.5 | 25.8 | 33.7 | 38.9 | 44.0 | 50.5 | 55.4 | 52.4 | 2019 |
| | | 4 D | 13.8 | 29.0 | 38.2 | 44.2 | 50.0 | 57.6 | 63.2 | 55.1 | 1994 |
| ACH (FW) | 39 | 1 D | 6.7 | 19.8 | 27.5 | 32.5 | 37.3 | 43.4 | 48.0 | 44.6 | 2009 |
| | | 2 D | 10.6 | 26.6 | 35.3 | 40.7 | 45.7 | 51.9 | 56.3 | 53.2 | 1982 |
| | | 3 D | 12.8 | 29.7 | 39.3 | 45.4 | 51.0 | 58.1 | 63.2 | 53.5 | 1982 |
| | | 4 D | 14.4 | 32.3 | 42.1 | 48.2 | 53.8 | 60.8 | 65.7 | 53.6 | 1982 |
| TAT (FW) | 39 | 1 D | 5.7 | 21.4 | 28.9 | 33.2 | 36.8 | 41.0 | 43.8 | 37.8 | 2011 |
| | | 2 D | 10.0 | 28.2 | 36.9 | 42.0 | 46.4 | 51.4 | 54.8 | 52.4 | 1996 |
| | | 3 D | 14.2 | 30.9 | 40.3 | 46.2 | 51.7 | 58.6 | 63.5 | 54.8 | 2019 |
| | | 4 D | 14.9 | 33.3 | 43.4 | 49.7 | 55.5 | 62.5 | 67.6 | 58.8 | 2019 |
| NMI (FW) | 36 | 1 D | 9.9 | 23.8 | 32.1 | 37.5 | 42.8 | 49.6 | 54.7 | 44.2 | 1995 |
| | | 2 D | 10.4 | 32.0 | 45.0 | 53.5 | 61.7 | 72.4 | 80.4 | 67.5 | 2002 |
| | | 3 D | 13.6 | 35.4 | 50.4 | 61.3 | 72.4 | 87.9 | 100.4 | 85.6 | 2019 |
| | | 4 D | 14.3 | 38.0 | 54.4 | 66.3 | 78.6 | 95.8 | 109.7 | 94.6 | 2019 |
| TAU (FW) | 30 | 1 D | 9.9 | 19.7 | 25.3 | 28.9 | 32.2 | 36.4 | 39.5 | 28.8 | 2009 |
| | | 2 D | 14.1 | 26.5 | 33.3 | 37.5 | 41.4 | 46.4 | 49.9 | 40.1 | 2000 |
| | | 3 D | 19.5 | 29.7 | 35.8 | 39.9 | 43.7 | 48.8 | 52.5 | 47.2 | 2000 |
| | | 4 D | 20.0 | 32.4 | 39.9 | 44.8 | 49.5 | 55.6 | 60.2 | 54.9 | 2000 |
| GPD (FW) | 28 | 1 D | 8.0 | 21.2 | 29.2 | 34.5 | 39.5 | 46.0 | 50.9 | 40.6 | 2004 |
| | | 2 D | 10.8 | 27.7 | 37.8 | 44.4 | 50.9 | 59.1 | 65.3 | 49.4 | 2019 |
| | | 3 D | 11.5 | 31.6 | 43.7 | 51.6 | 59.3 | 69.2 | 76.6 | 66.4 | 2019 |
| | | 4 D | 12.6 | 34.1 | 47.0 | 55.6 | 63.8 | 74.4 | 82.3 | 75.0 | 2019 |
| RIS (FW) | 40 | 1 D | 9.3 | 20.3 | 27.1 | 31.6 | 36.0 | 41.8 | 46.1 | 40.2 | 2014 |
| | | 2 D | 12.6 | 25.3 | 33.5 | 39.2 | 44.9 | 52.7 | 58.7 | 57.8 | 1987 |
| | | 3 D | 13.6 | 28.0 | 37.2 | 43.5 | 49.7 | 58.1 | 64.5 | 57.8 | 1987 |
| | | 4 D | 14.7 | 31.7 | 41.8 | 48.4 | 54.7 | 62.7 | 68.7 | 58.5 | 2001 |
| SCC (FW) | 25 | 1 D | 35.6 | 65.0 | 85.6 | 99.9 | 113.7 | 131.5 | 144.5 | 152.4 | 1999 |
| | | 2 D | 51.5 | 94.3 | 117.2 | 131.3 | 144.4 | 160.6 | 172.3 | 154.7 | 1999 |
| | | 3 D | 63.7 | 117.8 | 145.8 | 162.9 | 178.4 | 197.5 | 211.1 | 194.1 | 2003 |
| | | 4 D | 68.2 | 136.7 | 174.0 | 197.2 | 218.6 | 245.1 | 264.3 | 235.5 | 2003 |
| GWY (FW) | 30 | 1 D | 12.3 | 33.2 | 49.4 | 62.1 | 75.9 | 96.6 | 114.5 | 91.6 | 2011 |
| | | 2 D | 12.4 | 43.6 | 66.7 | 84.1 | 102.7 | 129.7 | 152.5 | 137.9 | 2003 |
| | | 3 D | 13.3 | 52.3 | 79.3 | 99.0 | 119.3 | 147.8 | 170.9 | 162.8 | 2003 |
| | | 4 D | 16.4 | 55.7 | 86.5 | 109.1 | 132.3 | 164.4 | 189.8 | 179.1 | 2003 |

Table 3. (Continued)

| MD/TC-ID (TYPE) | No of Sample | DURA-TION | RETURN PERIOD (YEAR)/DESIGN EXTREME PRECIPITATATION (mm) 1.01 | 2 | 5 | 10 | 20 | 50 | 100 | HIST. MAX P(mm) | YEAR |
|---|---|---|---|---|---|---|---|---|---|---|---|
| WPU (ECCC) | 38 | 1 D | 6.9 | 18.7 | 25.3 | 29.4 | 33.2 | 37.9 | 41.3 | 38.6 | 1998 |
| | | 2 D | 8.9 | 24.8 | 32.9 | 37.7 | 42.0 | 47.0 | 50.5 | 47.5 | 1975 |
| | | 3 D | 10.1 | 27.3 | 37.5 | 44.3 | 50.8 | 59.2 | 65.5 | 68.8 | 1975 |
| | | 4 D | 10.5 | 29.6 | 40.9 | 48.5 | 55.7 | 65.1 | 72.1 | 68.8 | 1975 |
| XTL (ECCC) | 92 | 1 D | 15.9 | 31.8 | 41.3 | 47.6 | 53.7 | 61.5 | 67.4 | 68.1 | 1975 |
| | | 2 D | 17.8 | 40.8 | 54.6 | 63.7 | 72.4 | 83.8 | 92.2 | 112.3 | 1975 |
| | | 3 D | 19.1 | 45.2 | 61.5 | 72.7 | 83.6 | 98.1 | 109.3 | 152.9 | 1975 |
| | | 4 D | 19.8 | 49.1 | 66.9 | 78.7 | 90.2 | 105.1 | 116.3 | 164.8 | 1975 |

Note: MD/TC ID – Modelling or Transportation Canada ID, Hist. Max – Historical Maximum

## 2.4 Return periods of rainfall responsible for flooding event

With the results of the long-duration (1- to4-day) rainfall IDF analysis in the above subsection, it becomes possible to evaluate the rainfall intensity in terms of return periods. Table 4 shows the return periods of the rainfall for the 11 climate stations from July 4 to 7, 2019 and the 4-day total rainfall.

Table 4. Return periods of rainfall for the 11 climate stations from July 4 to 7, 2019 and 4-day total

| MD/ TC ID | TYPE | JULY-4 P (mm) | JULY-4 RTP | JULY-5 P (mm) | JULY-5 RTP | JULY-6 P (mm) | JULY-6 RTP | JULY-7 P (mm) | JULY-7 RTP | 4D TOTAL P (mm) | 4D TOTAL RTP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| BLF | FW | 8.2 | 1Y | 3.8 | <1Y | 5.4 | <1Y | 3.2 | <1Y | 20.6 | 1Y-2Y |
| ACH | FW | 15.4 | 1Y-2Y | 12.2 | 1Y-2Y | 8.6 | 1Y-2Y | 9.2 | 1Y-2Y | 45.4 | 5Y-10Y |
| TAT | FW | 4.8 | <1Y | 7.4 | 1Y-2Y | 6.2 | 1Y-2Y | 6.2 | 1Y-2Y | 24.6 | 1Y-2Y |
| NMI | FW | 9.0 | <1Y | 24.0 | 2Y | 23.6 | 2Y | 38.0 | 10Y | 94.6 | 50Y |
| TAU | FW | 8.0 | <1Y | 0.6 | <1Y | 2.4 | <1Y | 8.4 | <1Y | 19.4 | <1Y |
| GPD | FW | 8.6 | 1Y | 19.2 | 1Y-2Y | 30.2 | 5Y | 17.0 | 1Y-2Y | 75.0 | 50Y |
| RIS | FW | 10.0 | 1Y | 9.6 | 1Y | 28.0 | 5Y-10Y | 1.4 | <1Y | 49.0 | 10Y |
| SCC | FW | 0.0 | <1Y | 3.2 | <1Y | 0.0 | <1Y | 1.6 | <1Y | 4.8 | <1Y |
| GWY | FW | 8.2 | <1Y | 15.2 | 1Y-2Y | 23.4 | 1Y-2Y | 11.8 | <1Y | 58.6 | 2Y |
| WPU | ECCC | 17.5 | 2Y | 1.8 | <1Y | 13.1 | 1Y-2Y | 1.0 | <1Y | 33.4 | 2Y-5Y |
| XTL | ECCC | 3.3 | <1Y | 12.0 | <1Y | 4.8 | <1Y | 11.2 | <1Y | 31.3 | 1Y-2Y |

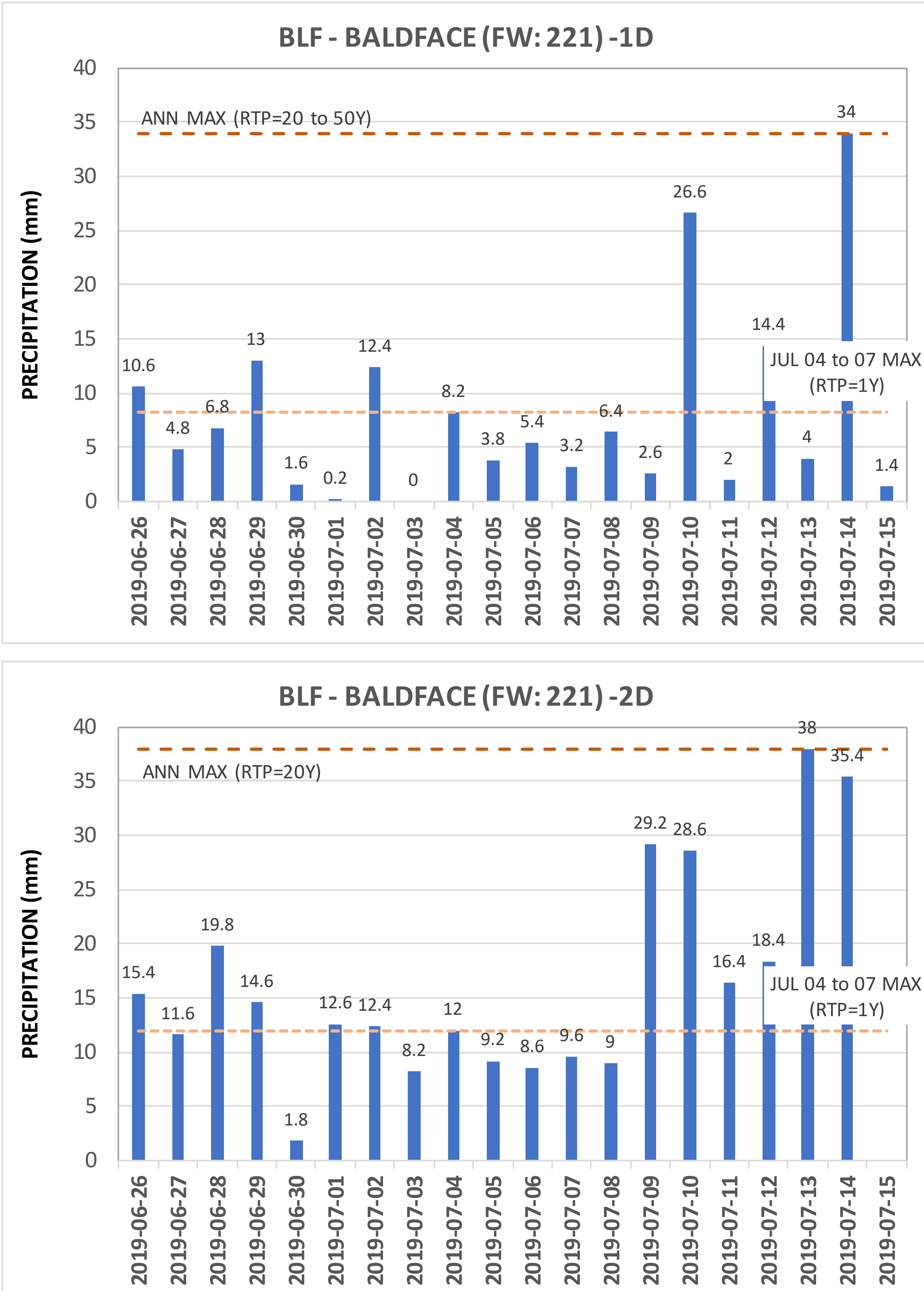
| | <1Y | 1Y-2Y | 2Y-5Y | 5Y-10Y | 10Y-20Y | 20Y-50Y | 50Y-100Y |
|---|---|---|---|---|---|---|---|
| Color scheme: | (white) | (green) | (cyan) | (yellow) | (light orange) | (orange) | (pink) |

From Table 4, it can be seen that, out of the five climate stations which were located in the Chilcotin River watershed, the Fire Weather station NMI – NEMIAH (216) recorded the largest single day (24-hour) rainfall (38 mm) on July 7, 2019, which is at the 10-year return period level. This single-day rainfall is only the fourth largest in the historical records and 6.2 mm smaller than the historical maximum (44.2 mm), which was recorded on August 7, 1995. This station also recorded a 2-year return period single day rainfall on July 5 and July 6, 2019. Meanwhile, two other Fire Weather stations located outside but close to the east of the Chilcotin River watershed, the GPD – GASPARD (222) and RIS – RISKE CREEK (210), recorded the second and third largest single day rainfall on July 6, 2019, which were 30.2 mm and 28 mm, respectively. The largest single day rainfall recorded at the GPD – GASPARD (222) (30.2 mm) on July 6, 2019 is at the 5-year return period level, and that recorded at the RIS – RISKE CREEK (210) (28 mm) on the same day is at a level between the 5- and 10-year return periods. The single day (24-hour) rainfall amounts which were recorded at the above stations on the other days or recorded at the other stations on all days from July 4 to 7, 2019 are at or below the 2-year return period level. The above 24-hour rainfall amounts recorded at the 11 climate stations, which are at or below the 10-year return period level only, do not reflect much of climate change impacts or the severity of this flooding event.

However, the 4-day total rainfall amounts in Table 4 reveal a completely different story. The NMI – NEMIAH (216) recorded the largest amount of 4-day rainfall (94.6 mm), which is at the 50-year return period level. This is the maximum historical record of 4-day rainfall, which is 8.5 mm larger than the second largest historical record (86.1 mm) that was recorded in a four-day period from August 2 to 5, 2002. The GPD – GASPARD (222) recorded the second largest amount of 4-day rainfall (75 mm), which is also at the 50-year return period level and the maximum historical record for this station. These 4-day total rainfall amounts reflect climate change impacts and the severity of this flooding event.

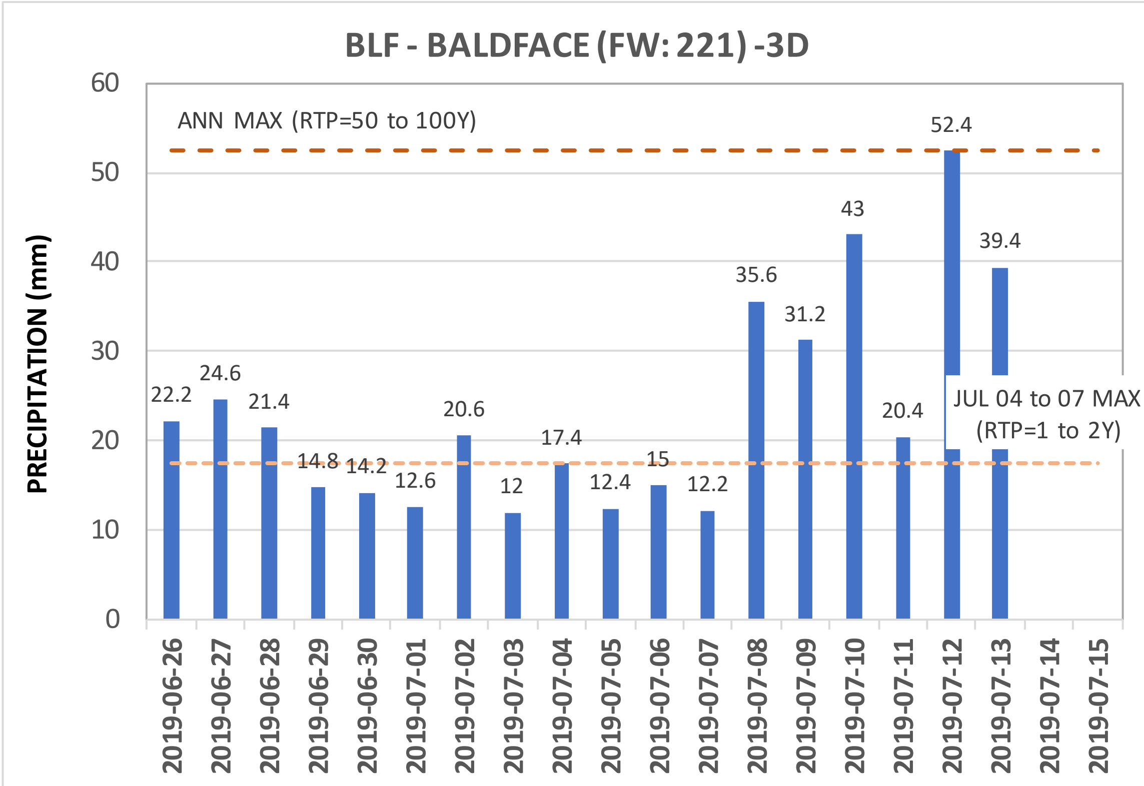
Besides, the RIS – RISKE CREEK (210) recorded the third largest amount of 4-day rainfall (49 mm), which is at the 10-year return period level. The fourth largest amount of 4-day rainfall was recorded by the other Fire Weather station located in the Chilcotin River watershed, the ACH - ALEXIS CREEK HUB (209) (45.4 mm), which is at a level between the 5- and 10-year return periods.

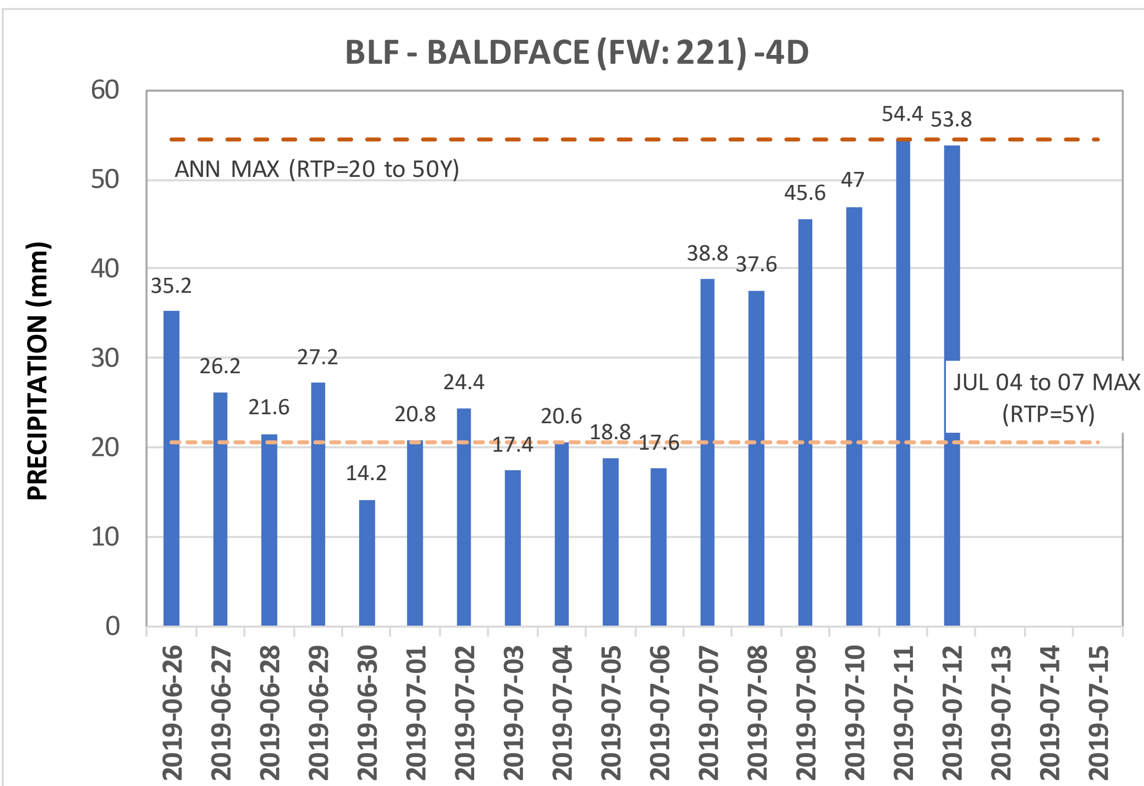
In order to understand better the precipitation natures of the flooding event, bar charts of 1-day (24-hour), 2-day, 3-day and 4-day rainfall with return periods for 8 of the 11 climate stations for 15 days from June 26 to July 15, 2019 were plotted and are shown in Figures 9 to 16. It can be seen from Figures 9 to 11 and Figure 16 that the single-day and multi-day rainfall amounts during the flooding event were even not the 2019 annual maximums. Only three stations shown in Figures 12, 13 and 14 recorded single-day and multi-day rainfall amounts during the flooding event which were the annual maximums or close to the annual maximums. This reflects the complexity of this flooding event.




(a) 1-day (upper) and 2-day (lower) rainfall

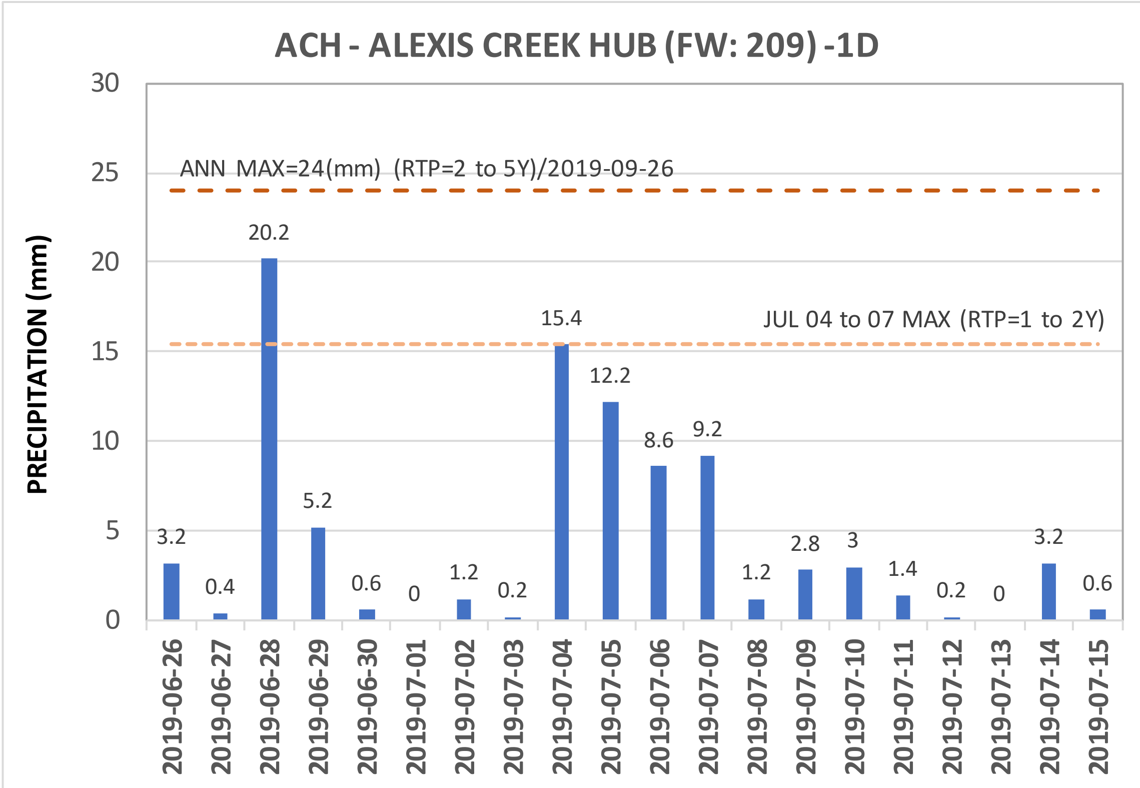
Figure 9. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (BLF)

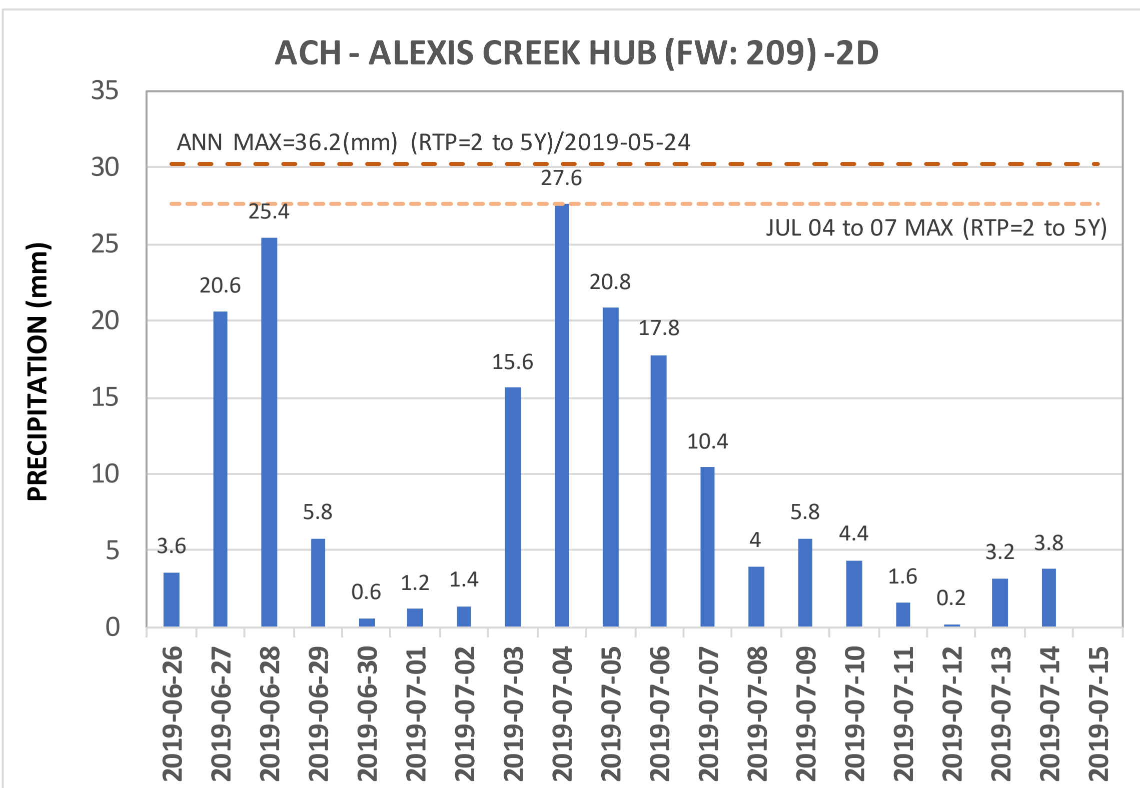



(b) 3-day (upper) and 4-day (lower) rainfall

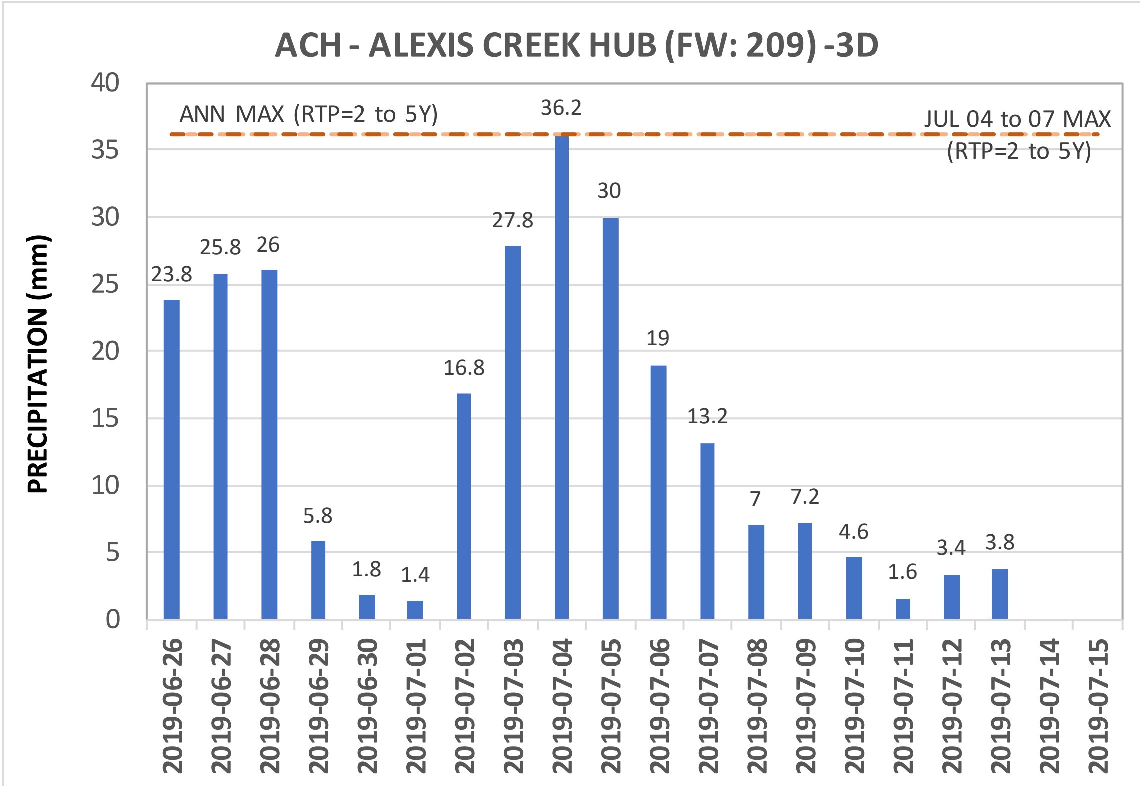
Figure 9. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (BLF) (continued)

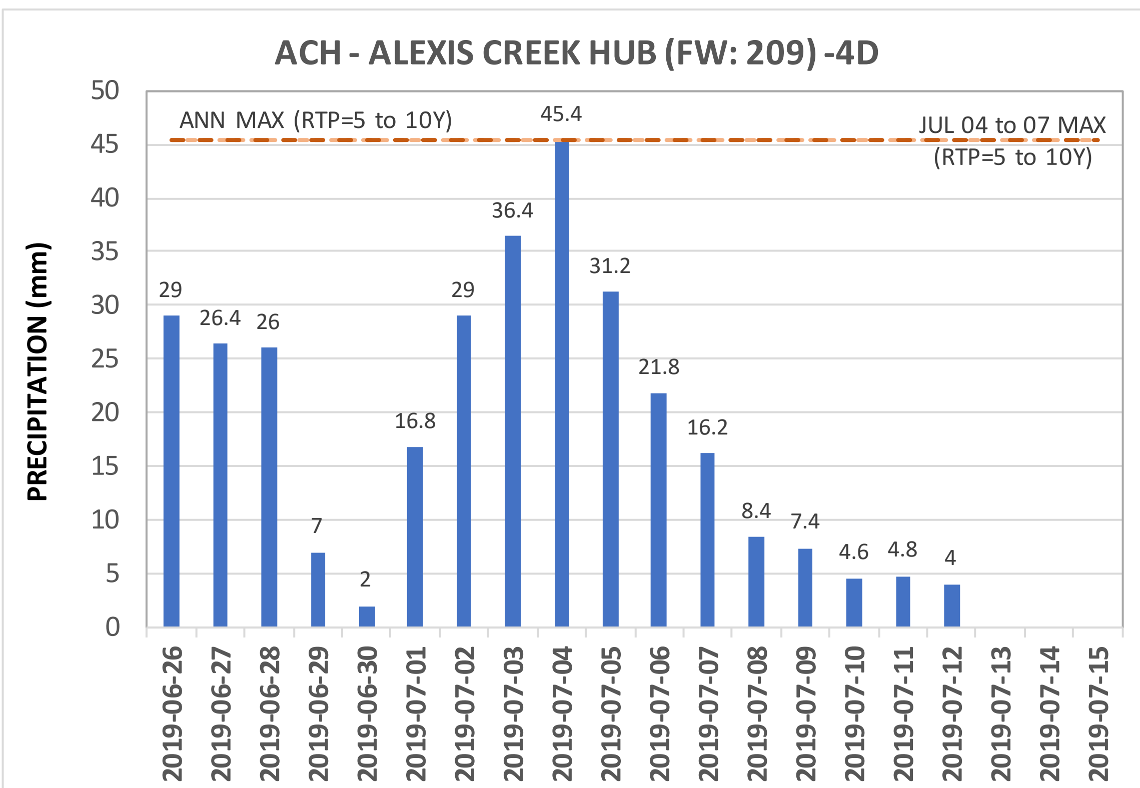



(a) 1-day (upper) and 2-day (lower) rainfall

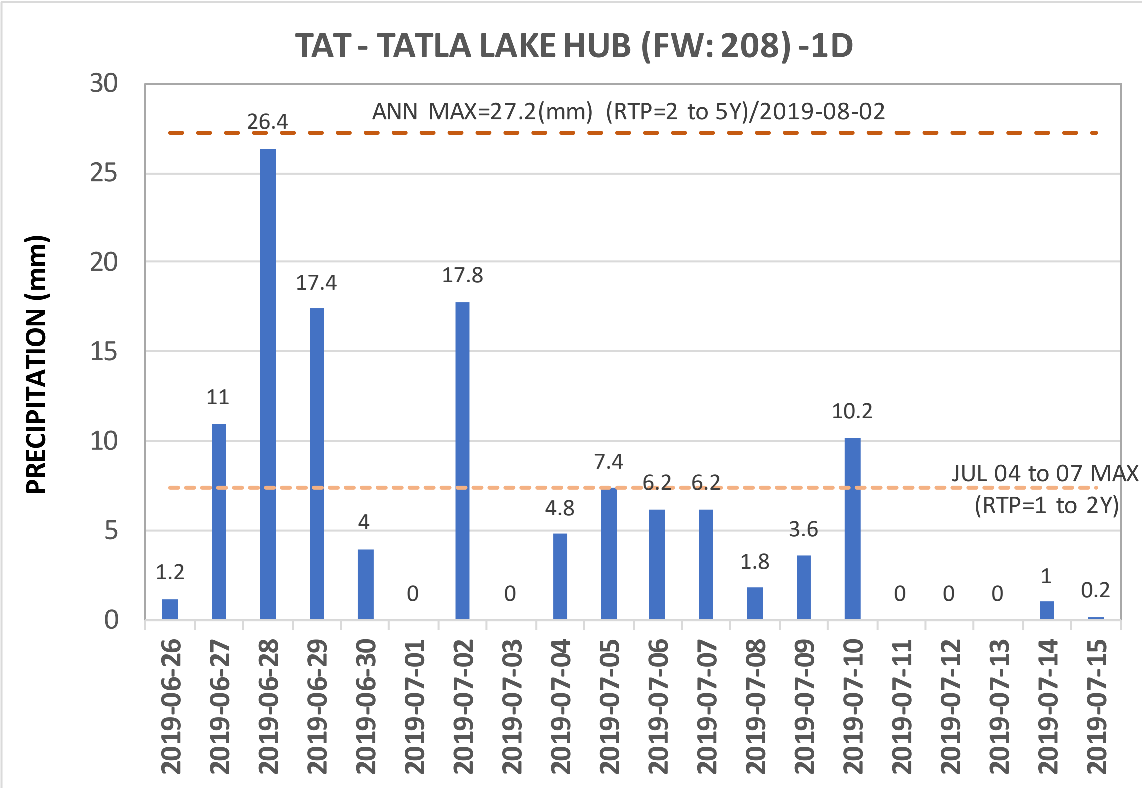
Figure 10. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (ACH)

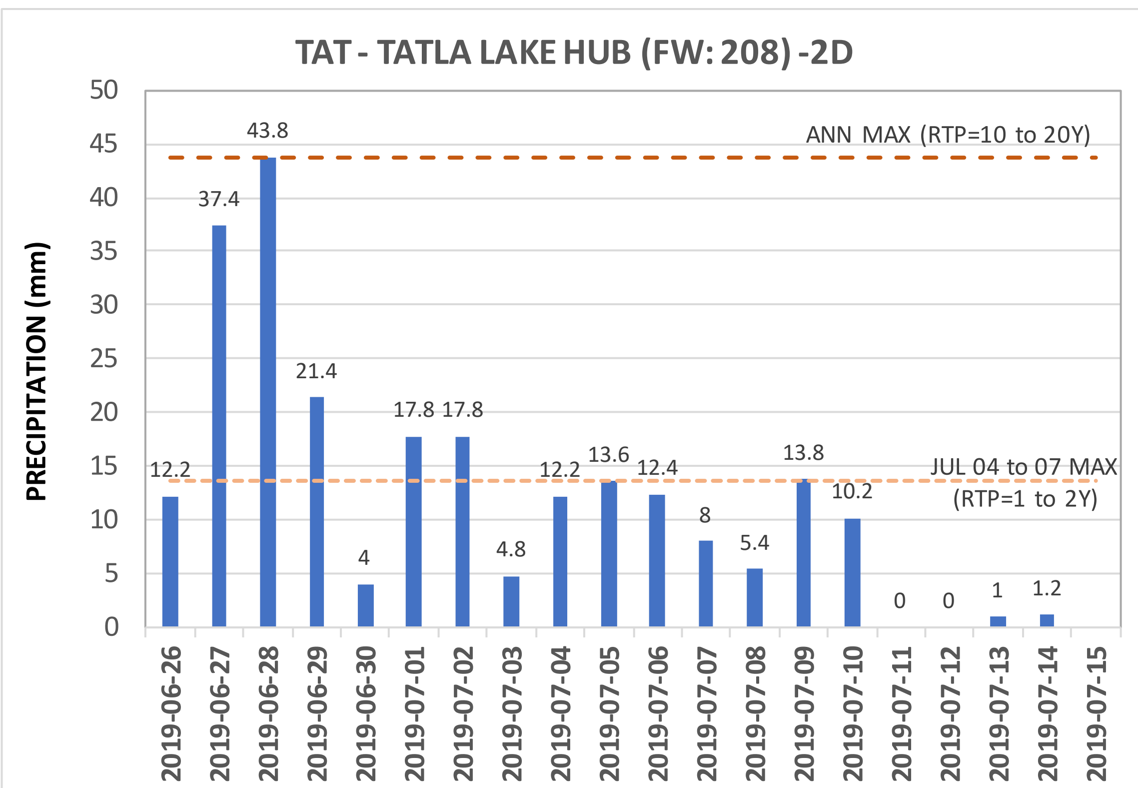



(b) 3-day (upper) and 4-day (lower) rainfall

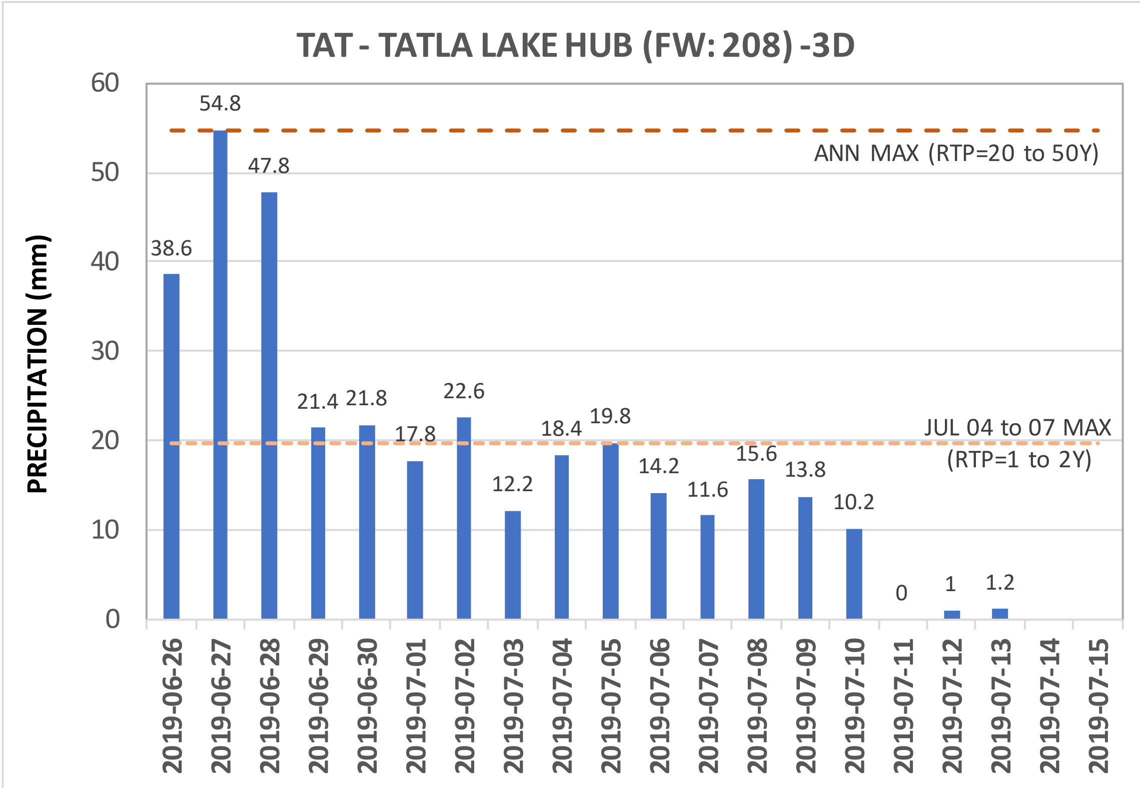
Figure 10. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (ACH) (continued)

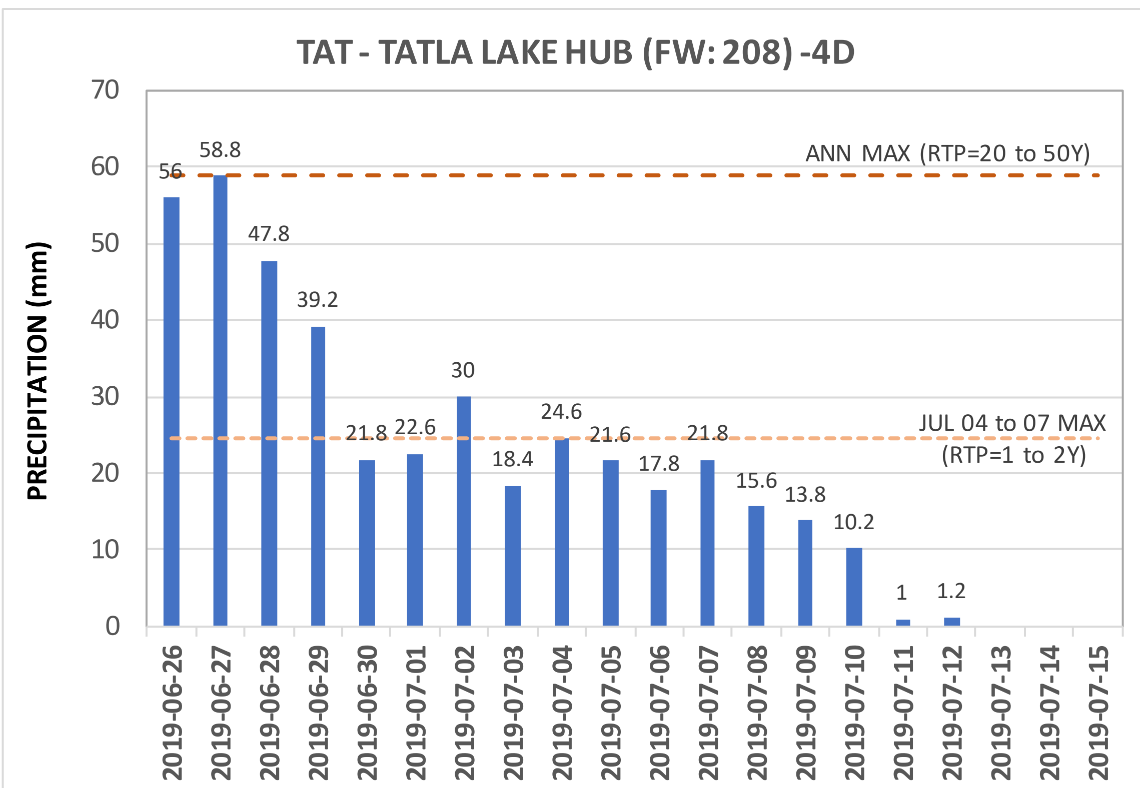



(a) 1-day (upper) and 2-day (lower) rainfall

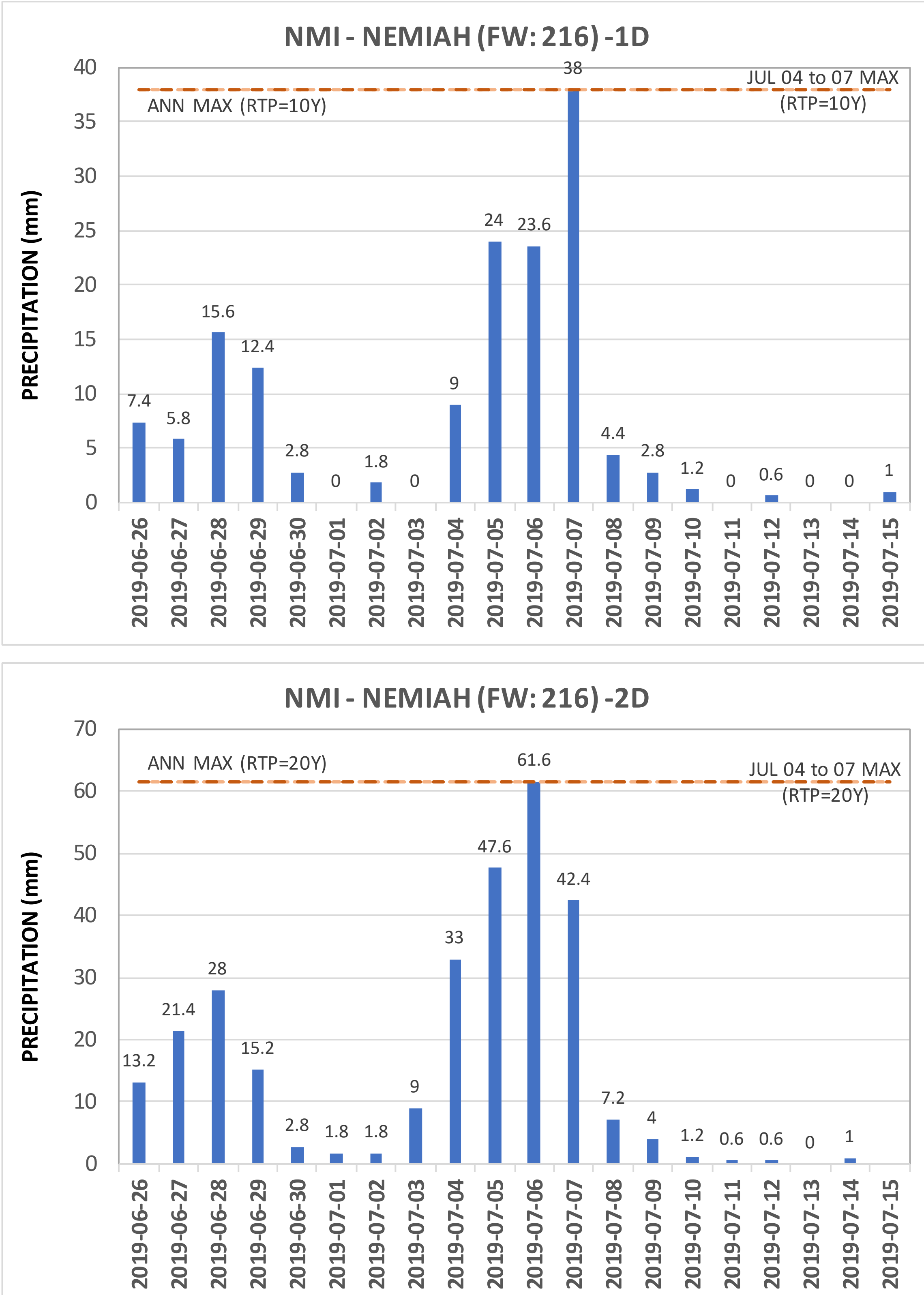
Figure 11. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (TAT)



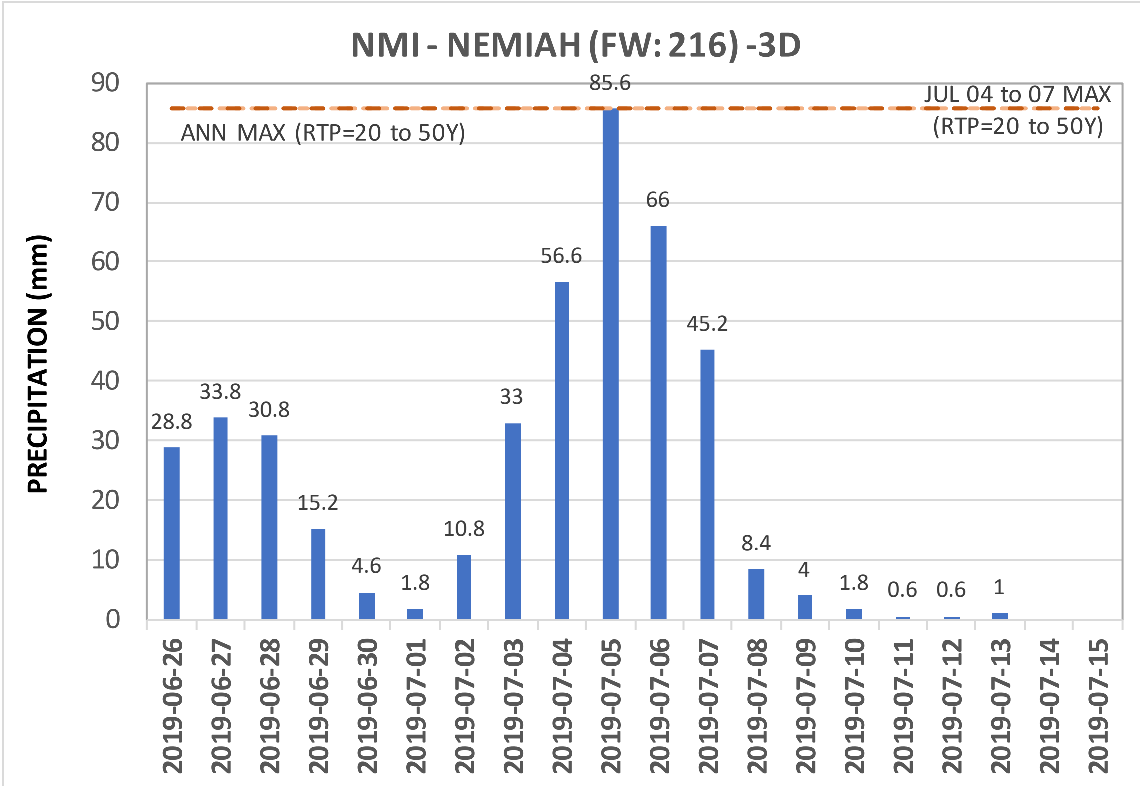

(b) 3-day (upper) and 4-day (lower) rainfall

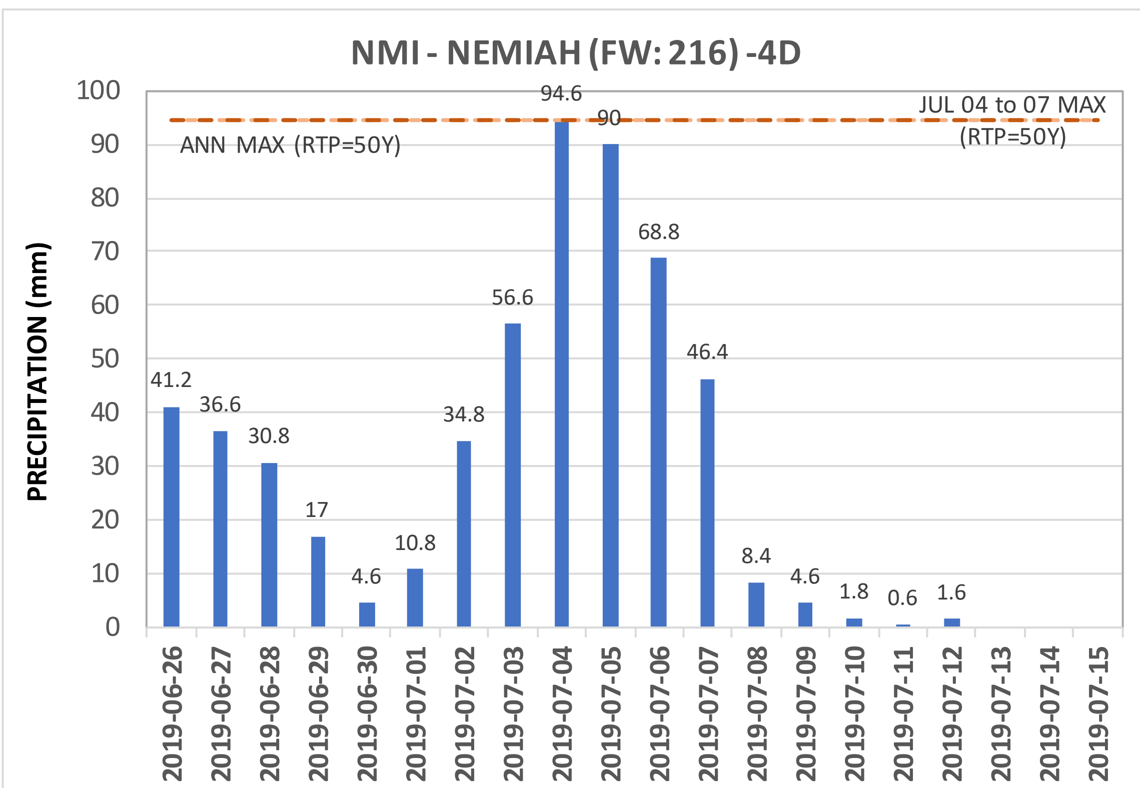
Figure 11. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (TAT) (continued)




(a) 1-day (upper) and 2-day (lower) rainfall

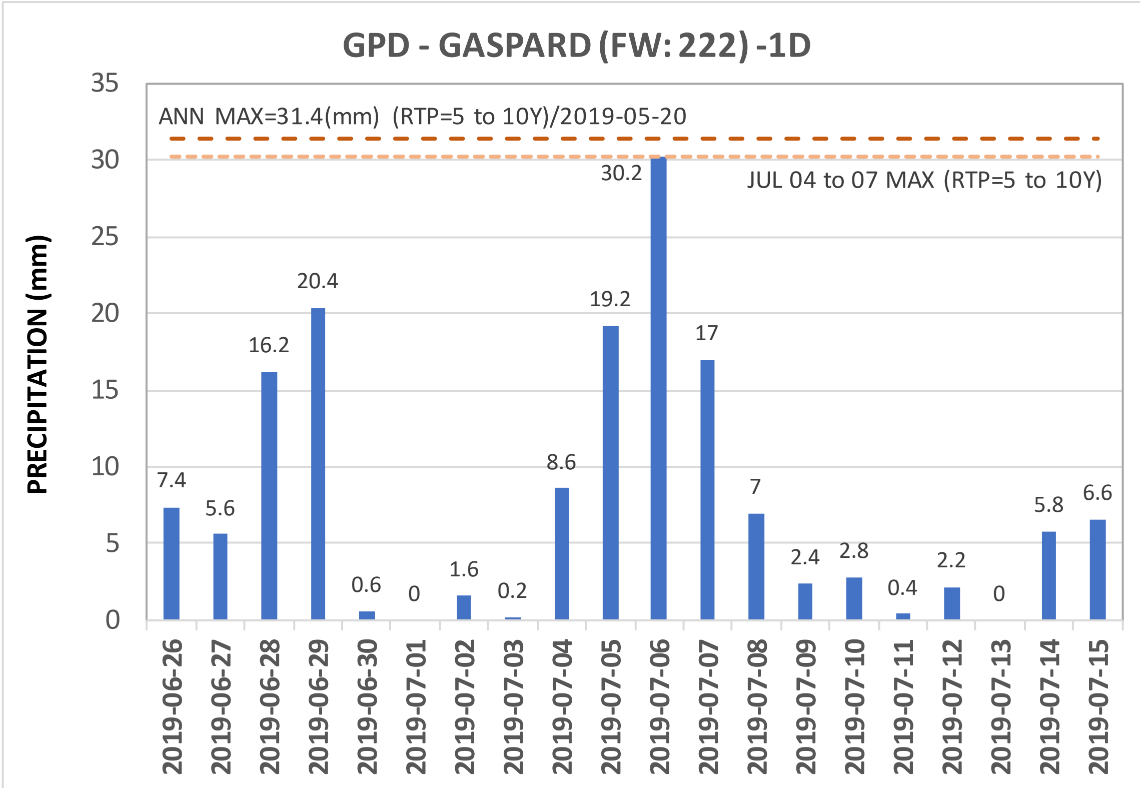
Figure 12. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (NMI)

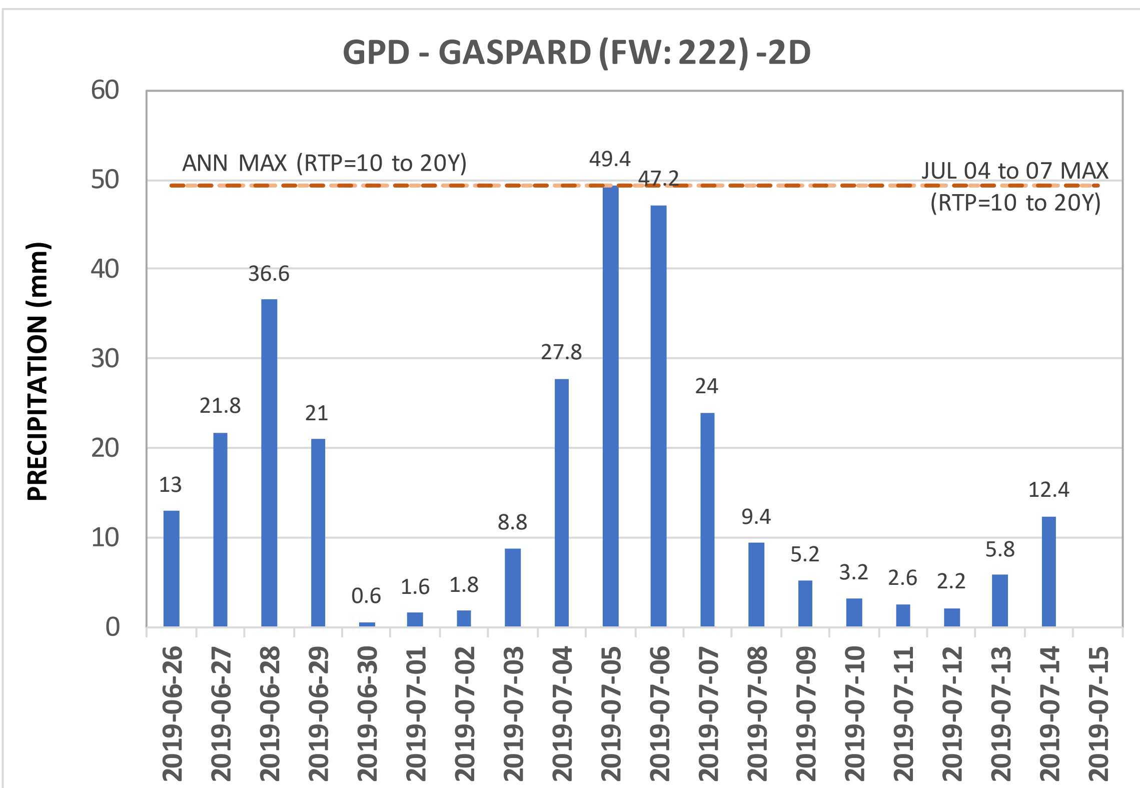



(b) 3-day (upper) and 4-day (lower) rainfall

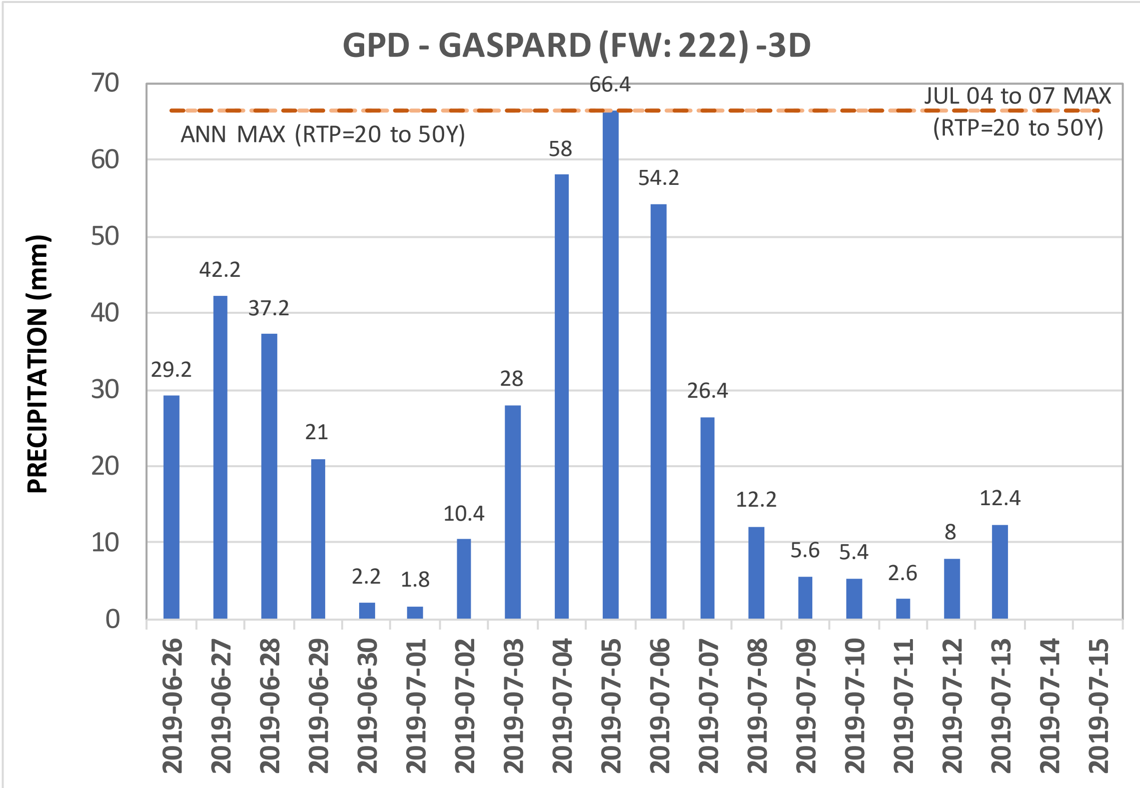
Figure 12. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (NMI) (continued)

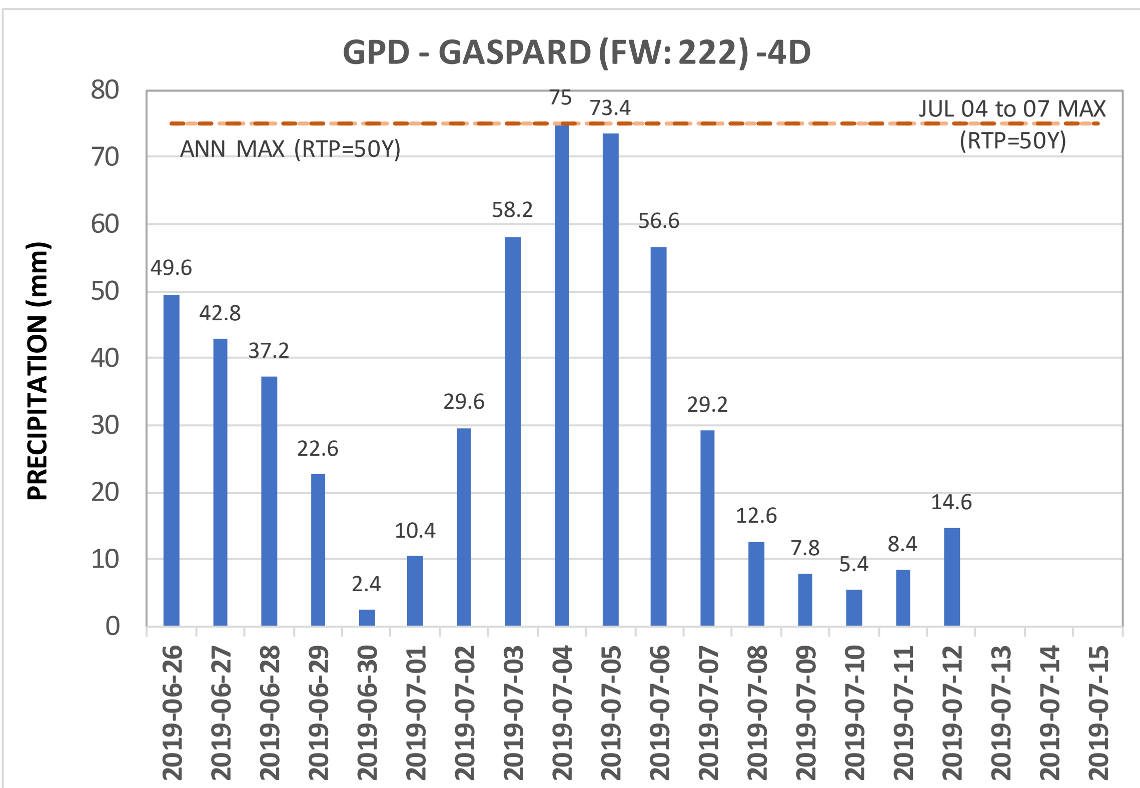



(a) 1-day (upper) and 2-day (lower) rainfall

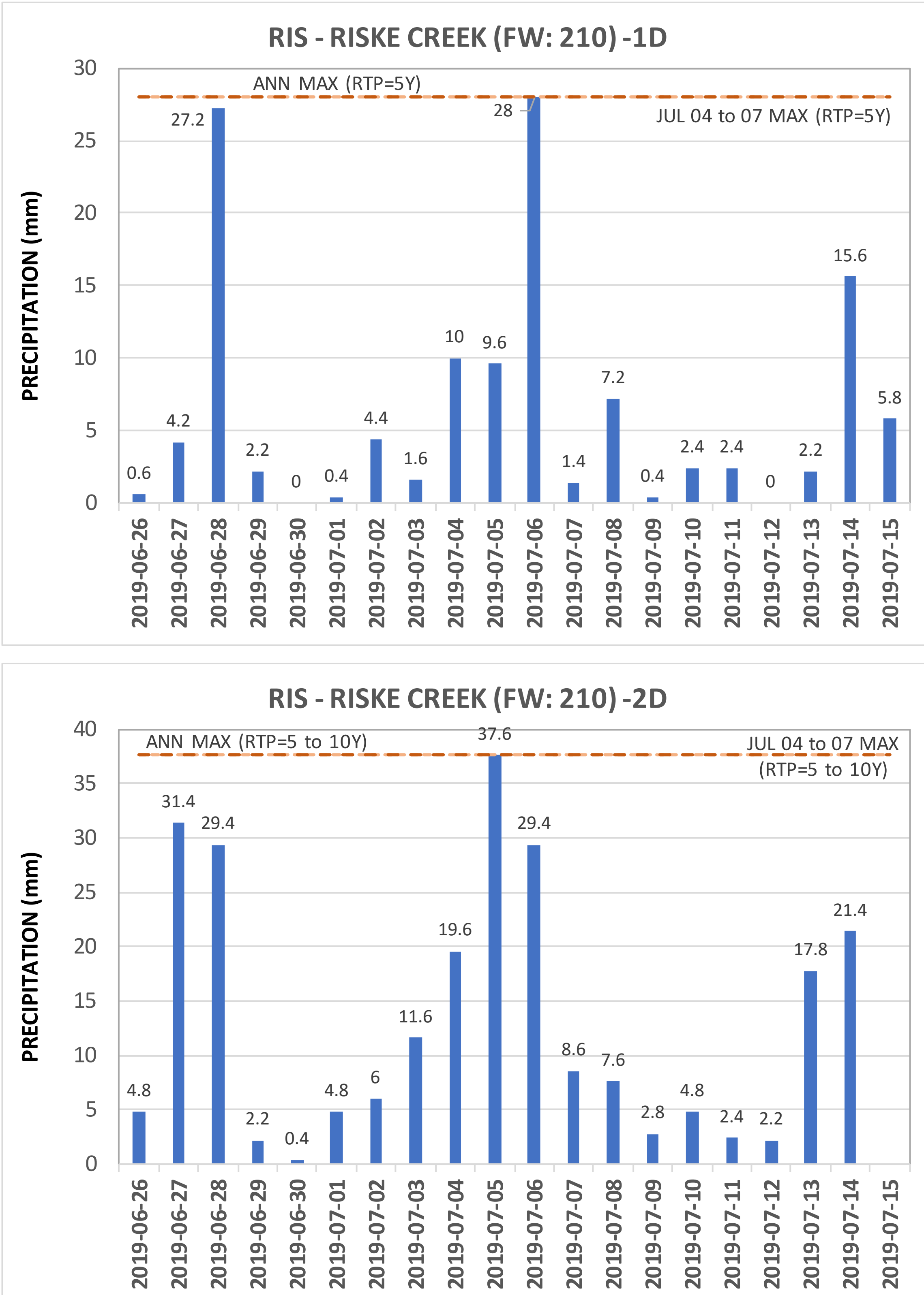
Figure 13. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (GPD)



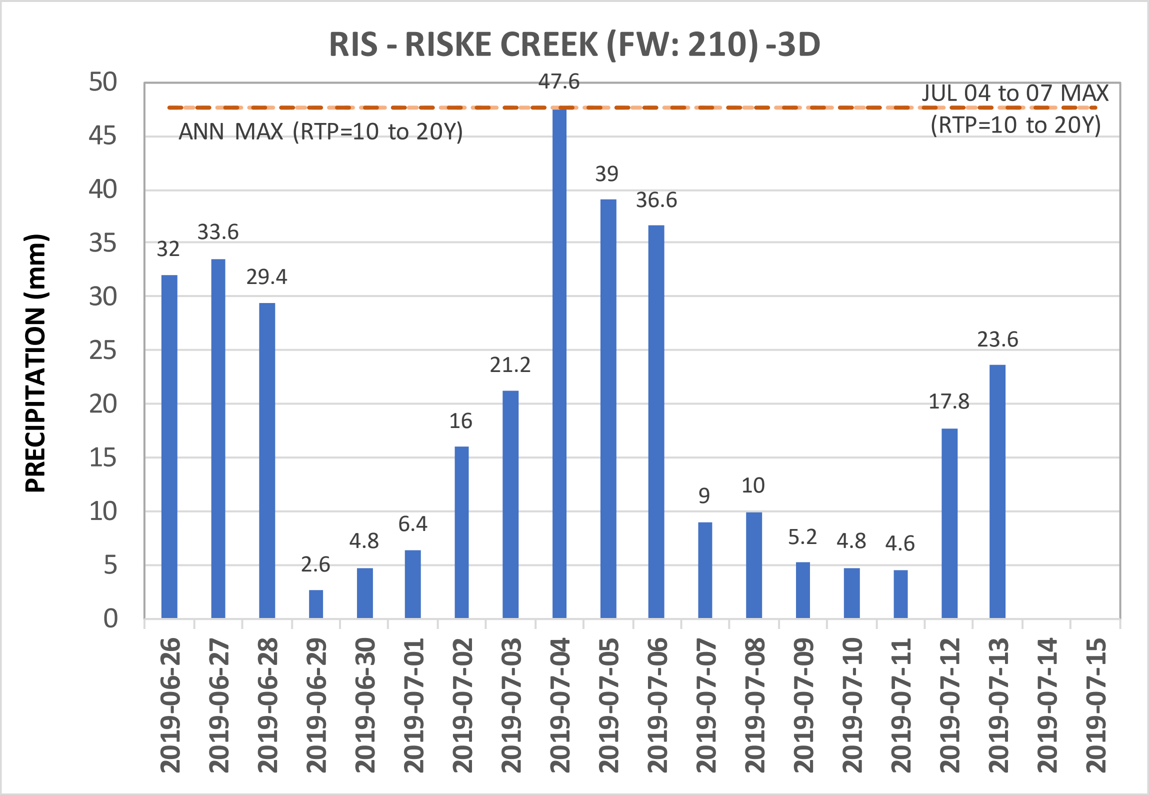

(b) 3-day (upper) and 4-day (lower) rainfall

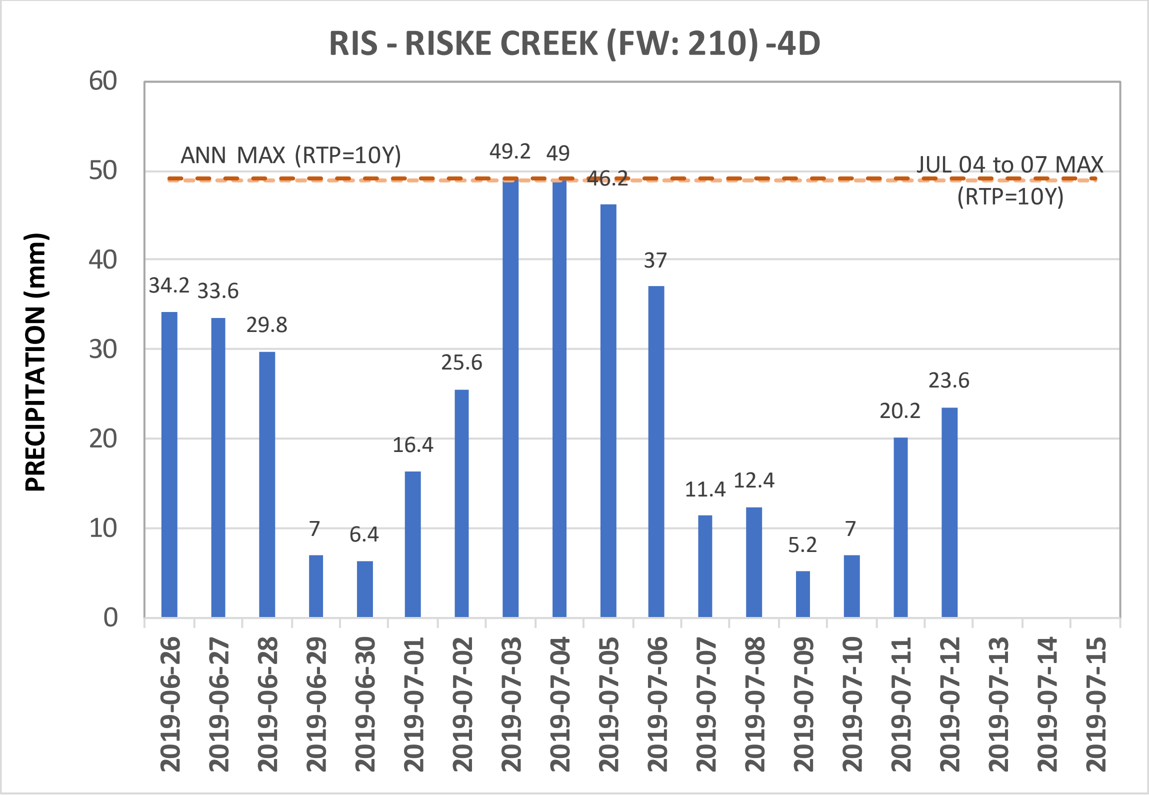
Figure 13. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (GPD) (continued)




(a) 1-day (upper) and 2-day (lower) rainfall

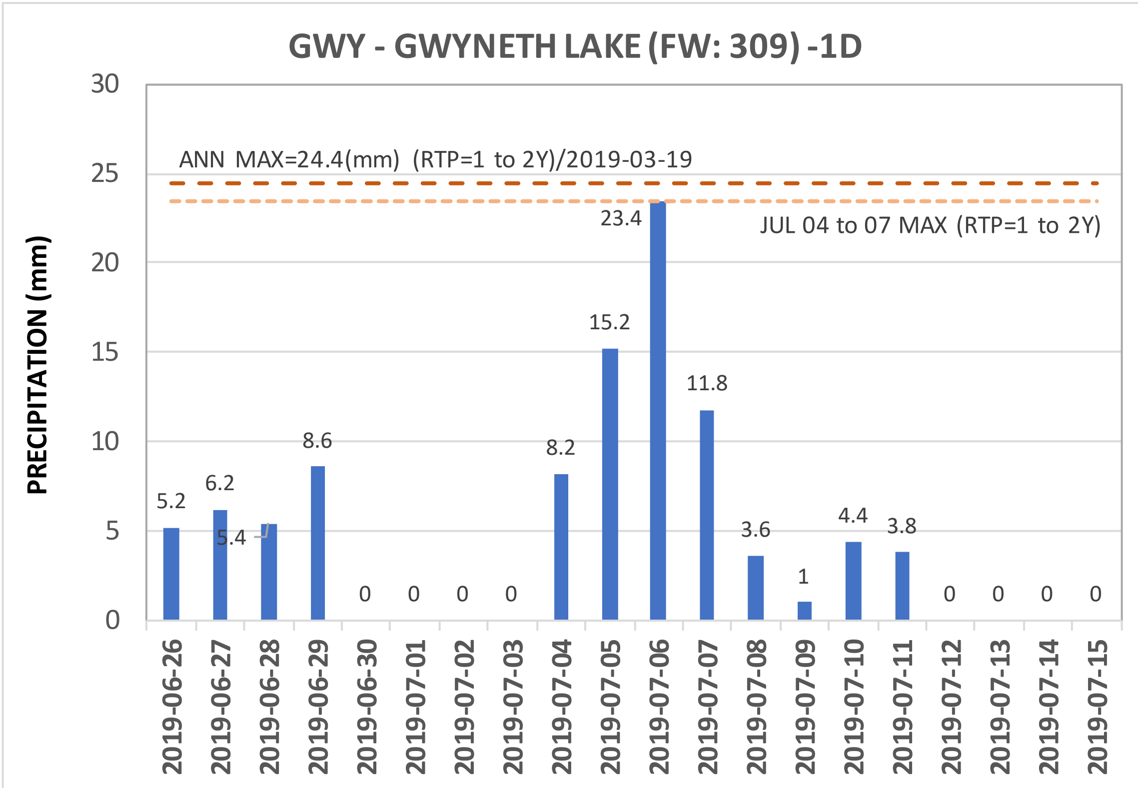
Figure 14. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (RIS)

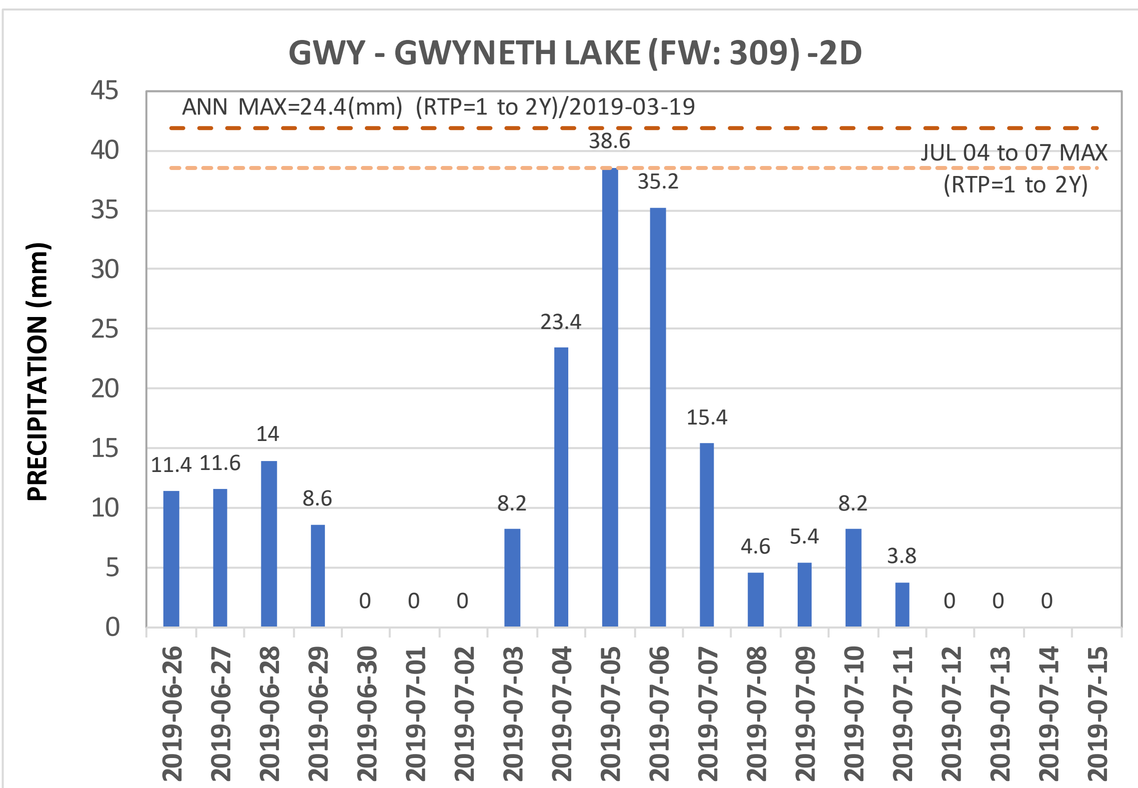



(b) 3-day (upper) and 4-day (lower) rainfall

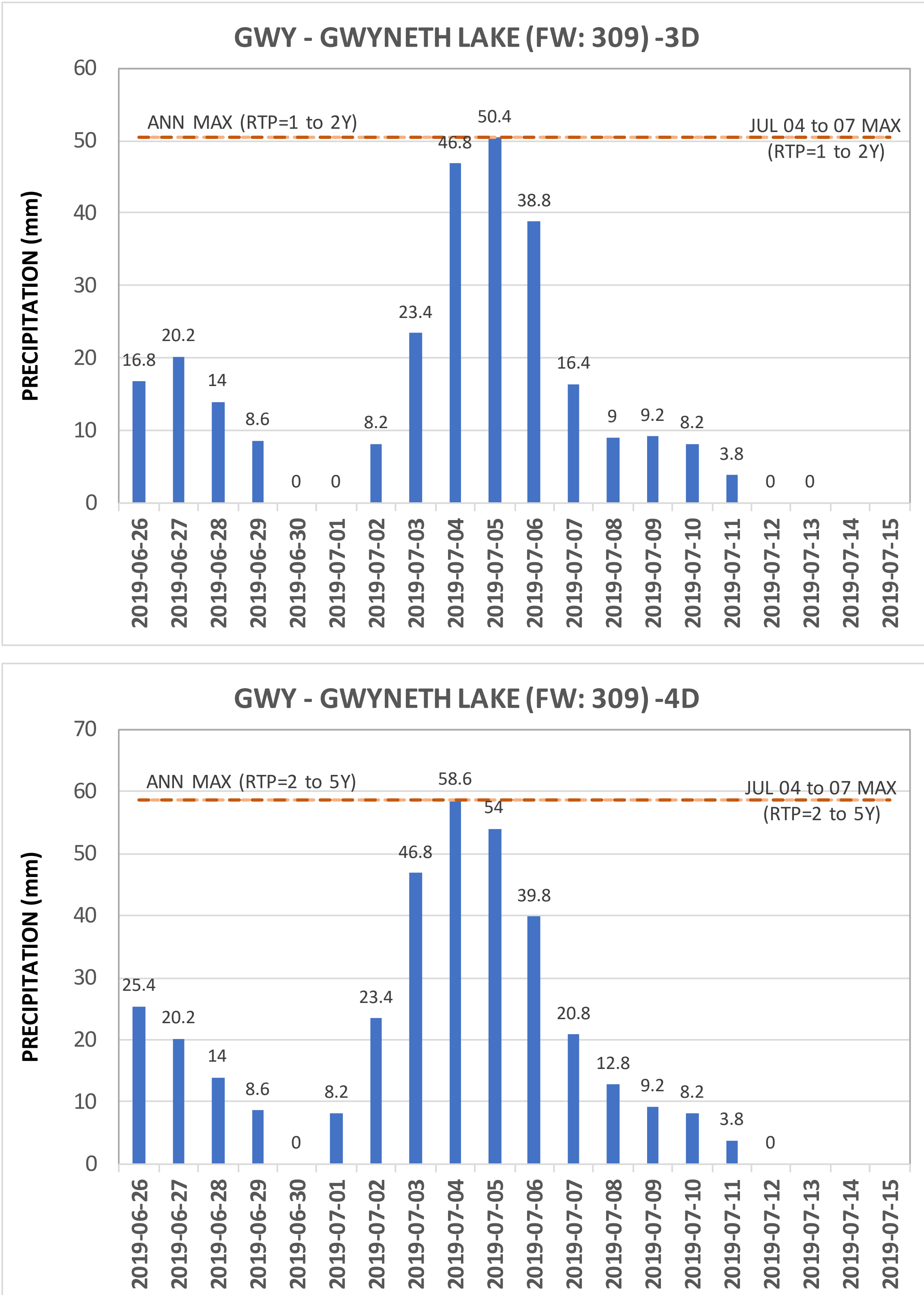
Figure 14. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (RIS) (continued)



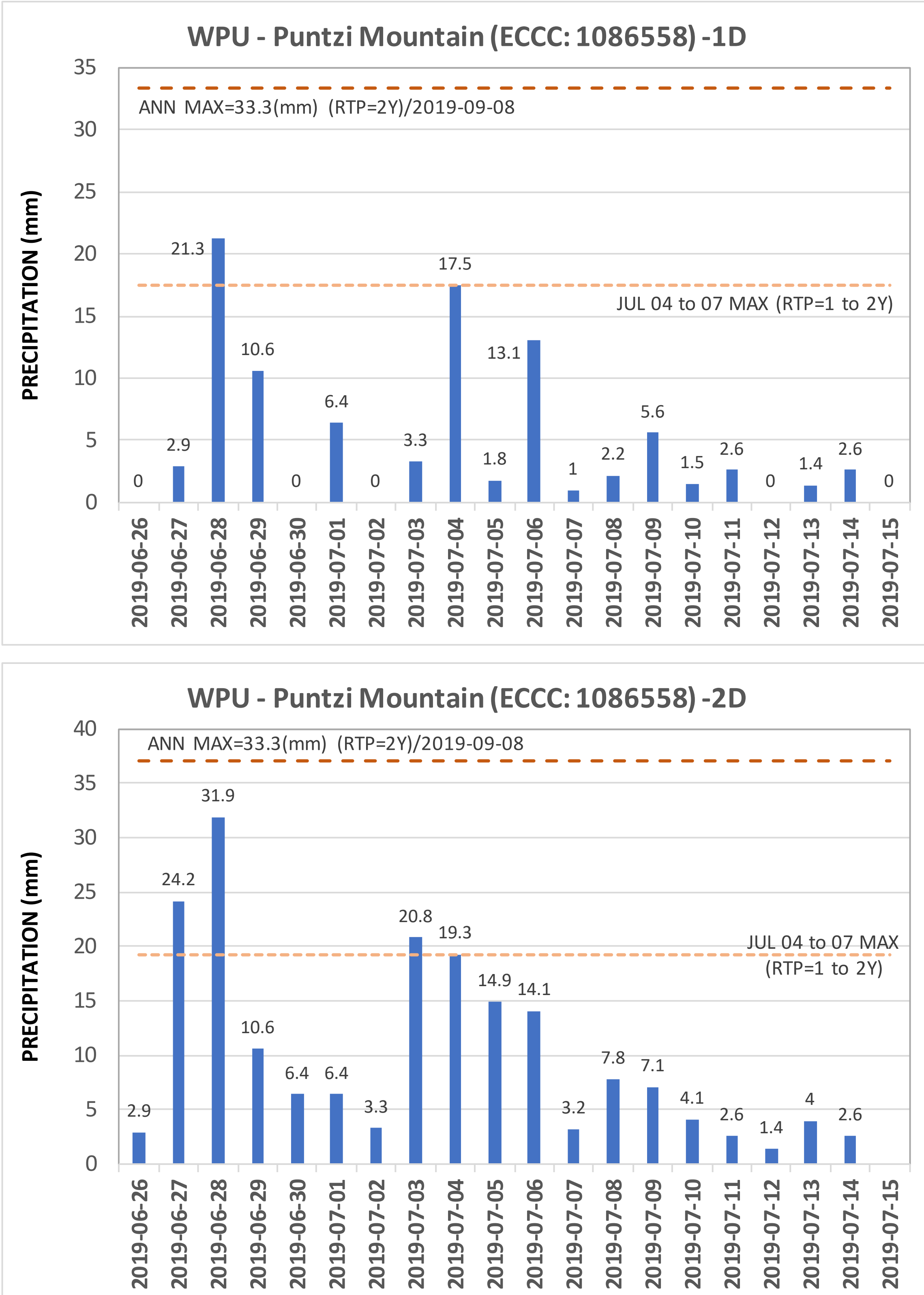

(a) 1-day (upper) and 2-day (lower) rainfall

Figure 15. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (GWY)



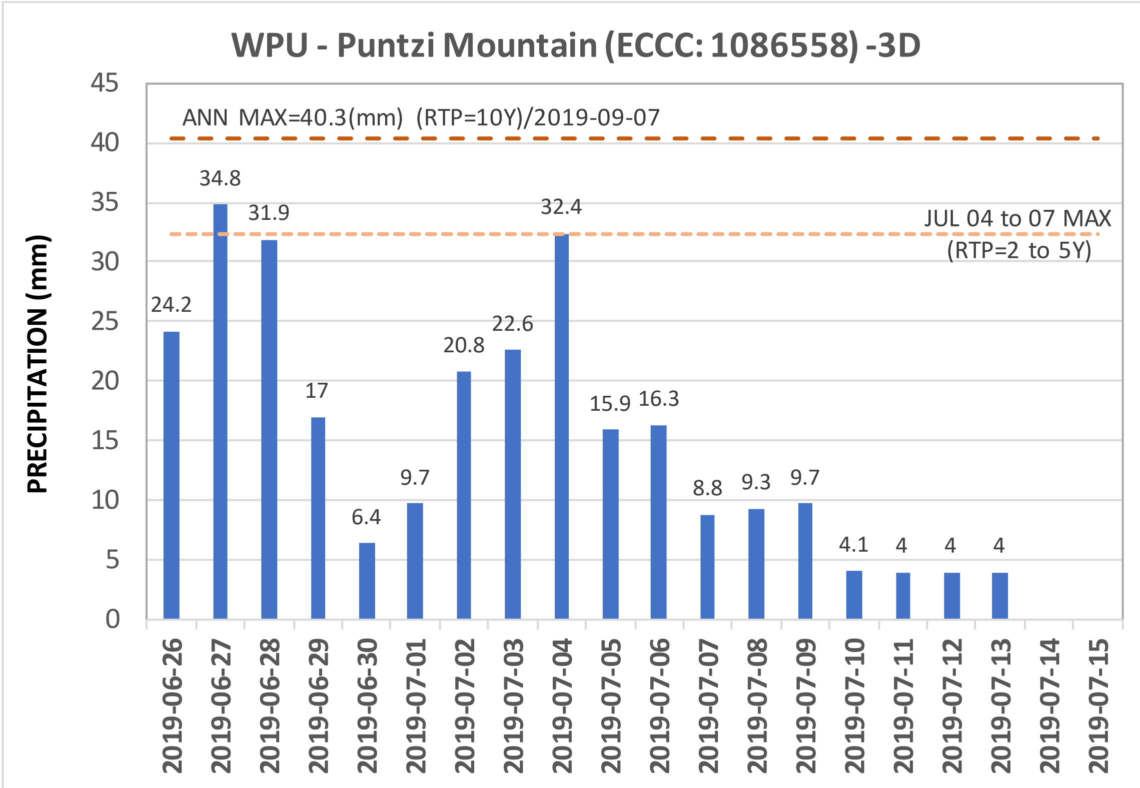

(b) 3-day (upper) and 4-day (lower) rainfall

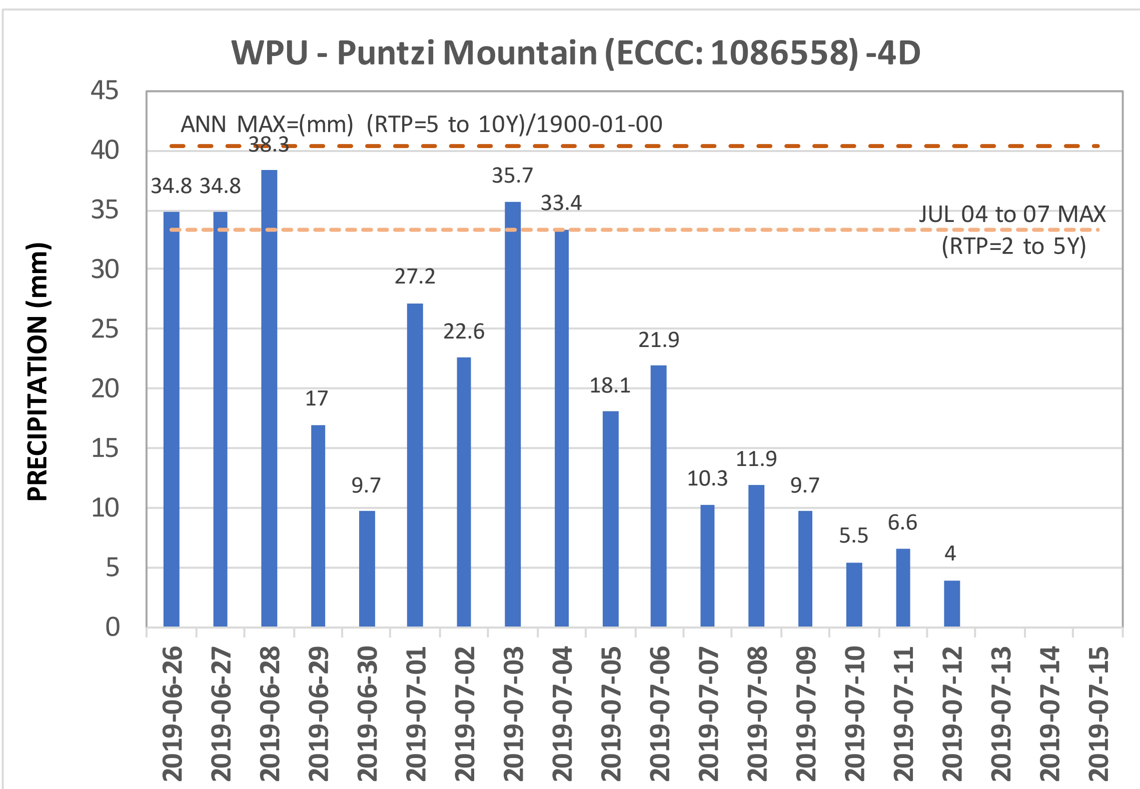
Figure 15. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (GWY) (continued)




(a) 1-day (upper) and 2-day (lower) rainfall

Figure 16. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (WPU)




(b) 3-day (upper) and 4-day (lower) rainfall

Figure 16. Bar charts of rainfall with return periods from June 26 to July 15, 2019 (WPU) (continued)

# 3. Hydrometric natures

## 3.1 WSC hydrometric stations located in Chilcotin River watershed

There were seven WSC hydrometric stations which were located in the Chilcotin River watersheds during the flooding event in early July 2019. But only one station was modeled by the CLEVER Model, the CHILCOTIN RIVER BELOW BIG CREEK (08MB005), and three of these stations had no return periods available before July 9, 2019. Table 5 is a list of the seven WSC hydrometric stations located in the Chilcotin River watershed, which also can be found in Figure 3.

Table 5. WSC hydrometric stations in Chilcotin River watershed during the flooding event

| ID | NAME | LATITUDE | LONGITUDE | AREA ($km^2$) | RTP | CLEVER MD |
|---|---|---|---|---|---|---|
| 08MA002 | CHILKO RIVER AT OUTLET OF CHILKO LAKE | 51.62486 | -124.14336 | 2130 | AV | NO |
| 08MA006 | LINGFIELD CREEK NEAR THE MOUTH | 51.67386 | -124.14531 | 98.8 | N/A | NO |
| 08MA003 | TASEKO RIVER AT OUTLET OF TASEKO LAKES | 51.379 | -123.63122 | 1520 | AV | NO |
| 08MA001 | CHILKO RIVER NEAR REDSTONE | 52.06975 | -123.5395 | 6880 | N/A | NO |
| 08MB007 | BIG CREEK BELOW GRAVEYARD CREEK | 51.25397 | -123.1045 | 232 | AV | NO |
| 08MB006 | BIG CREEK ABOVE GROUNDHOG CREEK | 51.52369 | -123.11589 | 1010 | N/A | NO |
| 08MB005 | CHILCOTIN RIVER BELOW BIG CREEK | 51.84794 | -122.65478 | 19200 | AV | YES |

Note: RTP – Return Period, AV – available, N/A – not available, CLEVER MD – Modeled in CLEVER Model on and before July 9, 2019.

## 3.2 Flood frequency analysis for all WSC stations located in Chilcotin River watershed

Three out of the seven stations which were located in the Chilcotin River watersheds did not have flood frequencies (return periods) available during the flooding event. The available flood frequencies for the three stations except for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005), which was the only WSC station in the Chilcotin River watershed modeled by the CLEVER Model, were also out of date. In order to evaluate the flooding magnitudes by using the most up to date flood return periods for all the stations listed in Table 6, it is necessary to carry out a or redo the flood frequency analysis for all the stations. The flood frequency analysis was conducted with the following special efforts:

A. Exhausting all available observation data: (a) the annual maximum instantaneous peaks, (b) the treated annual maximum peaks of daily average, which were converted to instantaneous peaks by applying an average ratio of the instantaneous peaks to the peaks of daily average, in years when maximum instantaneous peaks were not available but maximum peaks of daily average were, and (c) the instantaneous peaks from the provisional data up to 2018.

B. Selecting eight (8) probability distributions to fit the observation data: (1) Normal, (2) Lognormal, (3) Gumbel (Extreme Value, EV I), (4) Log-Gumbel (EV II), (5) GEV (Generalized Extreme Value), (6) Log-GEV, (7) Pearson III, and (8) Log-Pearson III.

C. Using multiple criteria to selection the best distribution for each station: (a) Goodness-of-fit test (R_GFT) using Equation 18.3.10 in the Handbook of Hydrology (page18.27) (Stedinger et al., 1992), (b) plotting the design flood on a straight line against the return period, the plot positions of the observation data along the straight line and the upper and lower limits of the 90% confidence level on the same figure so that it is easy to count the data points outside the limits (P_OUT), (c) visual comparing of the figures of the above plots for the 8 distributions, (d) producing designed floods which have reasonable intervals or do not crowd together, especially for stations with a small sample, and (e) Gumbel and GEV distributions have priority over the other distributions when the distributions have the same/similar coefficient of Goodness-of-fit (R_GFT) and/or number of points of observation outside the confidence limits (P_OUT) (Stedinger et al., 1992).

The flood frequency analysis results (return periods) for the seven WSC hydrometric stations are give in Table 6. Details of the flood frequency analysis are given in Appendix B.

Table 6. Return periods for WSC stations located in Chilcotin River watershed

| ID | NAME | No of Samp | Return Period (Year) / Design Flood ($m^3$/S) | | | | | | | Hist. Max | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | **1.01** | **2** | **5** | **10** | **20** | **50** | **100** | **($m^3$/s)** | **Year** |
| 08MA002 | Chilko River at Outlet of Chilko Lake | 90 | 94.6 | 136.7 | 160.2 | 175.1 | 188.9 | 206.1 | 218.6 | 210.0 | 1969 |
| 08MA006 | Lingfield Creek near the Mouth | 40 | 3.8 | 9.4 | 14.5 | 18.8 | 23.5 | 30.5 | 36.4 | 29.3 | 2007 |
| 08MA003 | Taseko River at Outlet of Taseko Lakes | 38 | 108.6 | 162.1 | 194.0 | 215.1 | 235.4 | 261.6 | 281.3 | 259.0 | 1991 |
| 08MA001 | Chilko River near Redstone | 92 | 213.8 | 298.4 | 351.5 | 387.8 | 423.4 | 470.8 | 507.2 | 510.0 | 1991 |
| 08MB007 | Big Creek below Graveyard Creek | 43 | 11.1 | 19.9 | 28.4 | 35.8 | 44.8 | 59.8 | 74.3 | 68.1 | 1991 |
| 08MB006 | Big Creek above Groundhog Creek | 43 | 21.9 | 44.0 | 66.7 | 87.9 | 114.4 | 161.1 | 208.1 | 169.0 | 1999 |
| 08MB005 | Chilcotin River below Big Creek | 48 | 233.9 | 327.1 | 399.8 | 456.5 | 518.5 | 611.4 | 691.8 | 699.0 | 1991 |
| 08MB005 | Chilcotin River below Big Creek (water level in metre) (RC#32) | | 2.878 | 3.248 | 3.464 | 3.606 | 3.743 | 3.921 | 4.055 | | |

Note: No of Samp – Number of Samples, Hist. Max – Historical Maximum, RC#32 – Rating Curve No.32.

## 3.3 Hydrographs except for CHILCOTIN RIVER BELOW BIG CREEK (08MB005)

Records of the real-time provisional discharge data recorded at the stations except for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) have not been modified significantly. Therefore, the provisional discharge data for those stations were relatively simpler to evaluate. Figures 17 to 22 show the hydrographs of real-time provisional discharges, downloaded from WSC real-time hydrometric data site as of December 7, 2019. In each of the figures, return periods are also plotted together with the hydrograph for convenience of comparison.

Figures 17 to 19 show that the three upstream stations located in the southwest of the Chilcotin River watershed, the CHILKO RIVER AT OUTLET OF CHILKO LAKE (08MA002), LINGFIELD CREEK NEAR THE MOUTH (08MA006) and TASEKO RIVER AT OUTLET OF TASEKO LAKES (08MA003), only recorded minor rises at or below the 2-year return period although these sub-basins were close to the Fire Weather station NMI – NEMIAH (216) which recorded the largest 24-hour and 4-day total rainfall amounts. From the perspective of return periods, the hydrologic responses at these three WSC stations did not really reflect the magnitudes of the 24-hour or 4-day total rainfall recorded at the above Fire Weather station. The lake effects might play a role in these insignificant responses in the latter two stations.

Figure 20 shows that the CHILKO RIVER NEAR REDSTONE (08MA001) recorded a peak of 451 $m^3/s$, which is a flow between the 20- to 50-year return periods, on late July 7 or early July 8, 2019. The sub-basin of this station enclosed the Fire Weather station NMI – NEMIAH (216) which recorded a 4-day total rainfall amount at a level between the 50- and 100-year return periods. From the perspective of return periods, the hydrologic response at this WSC station roughly reflected the magnitude of rainfall recorded at the above Fire Weather station.

Figure 21 shows that the BIG CREEK BELOW GRAVEYARD CREEK (08MB007) recorded a peak of 36.4 $m^3/s$, which is about the 10-year return period flow, on July 6, 2019. Figure 22 shows that the BIG CREEK ABOVE GROUNDHOG CREEK (08MB006) recorded a peak of 174 $m^3/s$ on July 6 and early July 7, 2019, which is a flow between the 50- and 100-year return periods. This peak (174 $m^3/s$) surpassed the historical maximum (169 $m^3/s$) recorded on July 15, 1999, which was a flow slightly over the 50-year return period. The sub-basin of the Big Creek is located in between the two Fire Weather stations, the NMI – NEMIAH (216) and the GPD – GASPARD (222), which recorded the largest and second largest 24-hour and 4-day rainfall amounts at levels between the 50- to 100-year return periods. From the perspective of return periods, the magnitude of the hydrologic response at the BIG CREEK BELOW GRAVEYARD CREEK (08MB007) reflected the magnitude of the 4-day total rainfall recorded at the above two Fire Weather stations.

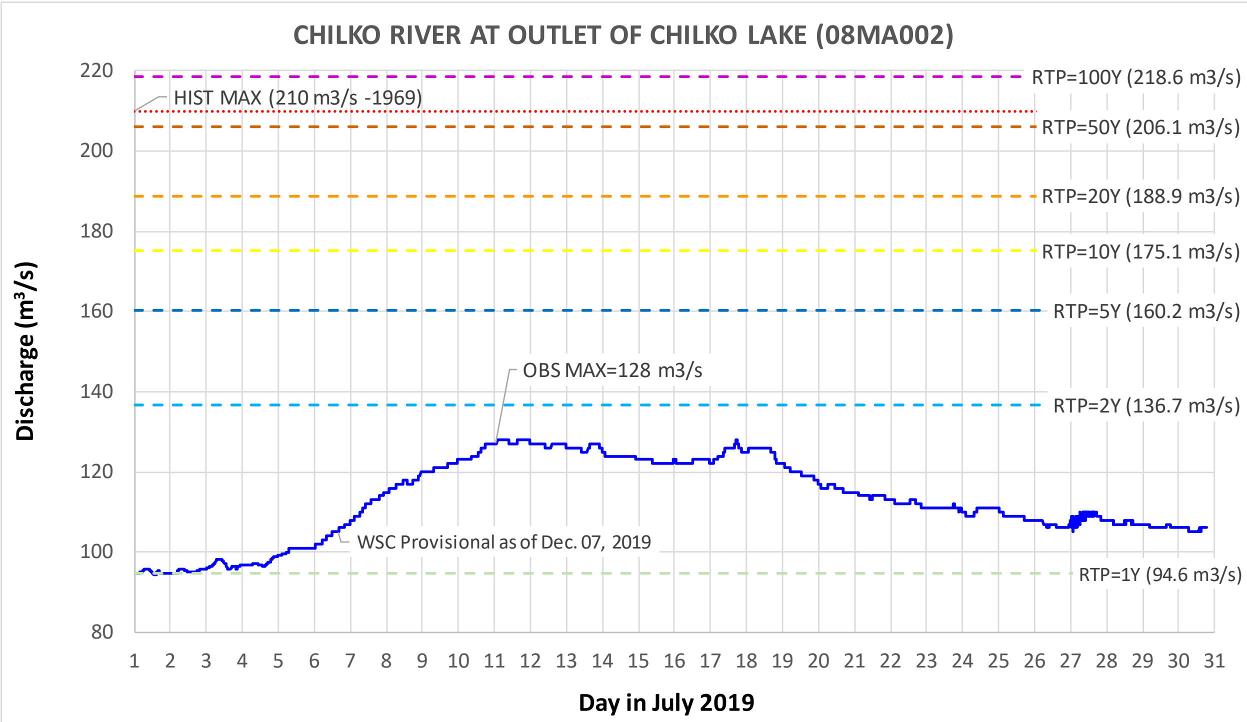



Figure 17. Hydrograph of real-time provisional discharge with return periods for CHILKO RIVER AT OUTLET OF CHILKO LAKE (08MA002) (WSC real-time provisional discharge data as of December 7, 2019)

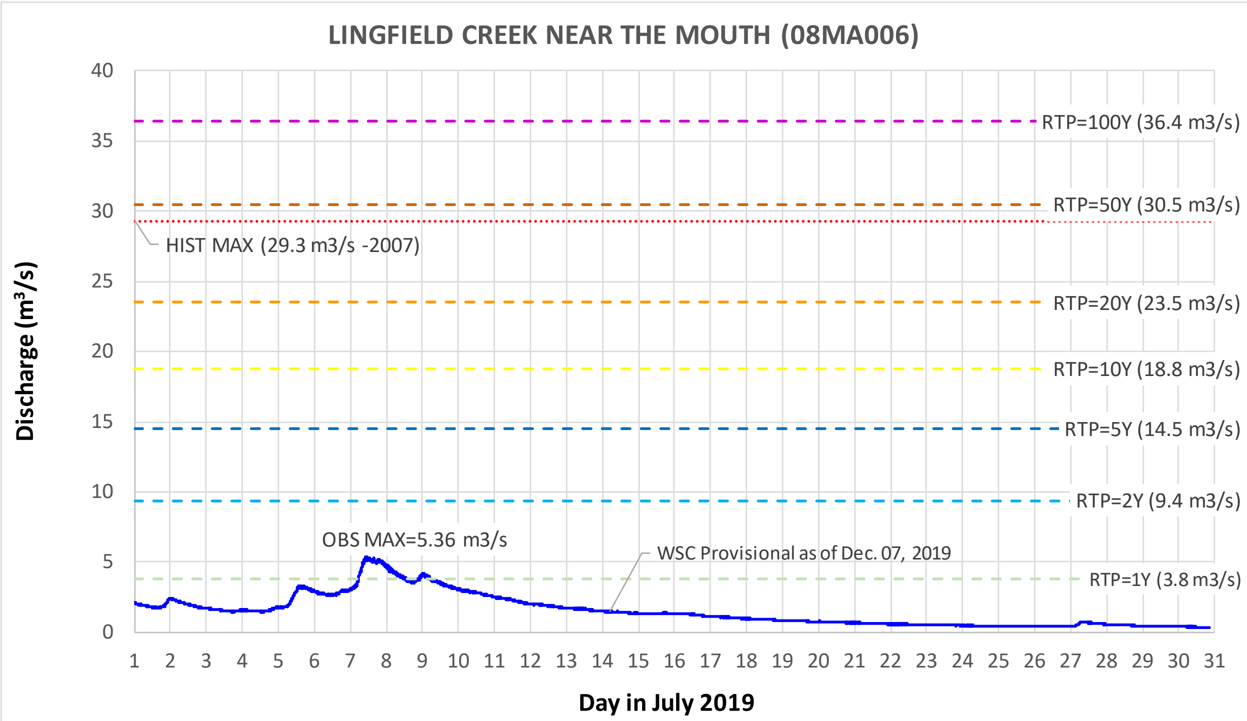



Figure 18. Hydrograph of real-time provisional discharge with return periods for LINGFIELD CREEK NEAR THE MOUTH (08MA006) (WSC real-time provisional discharge data as of December 7, 2019)

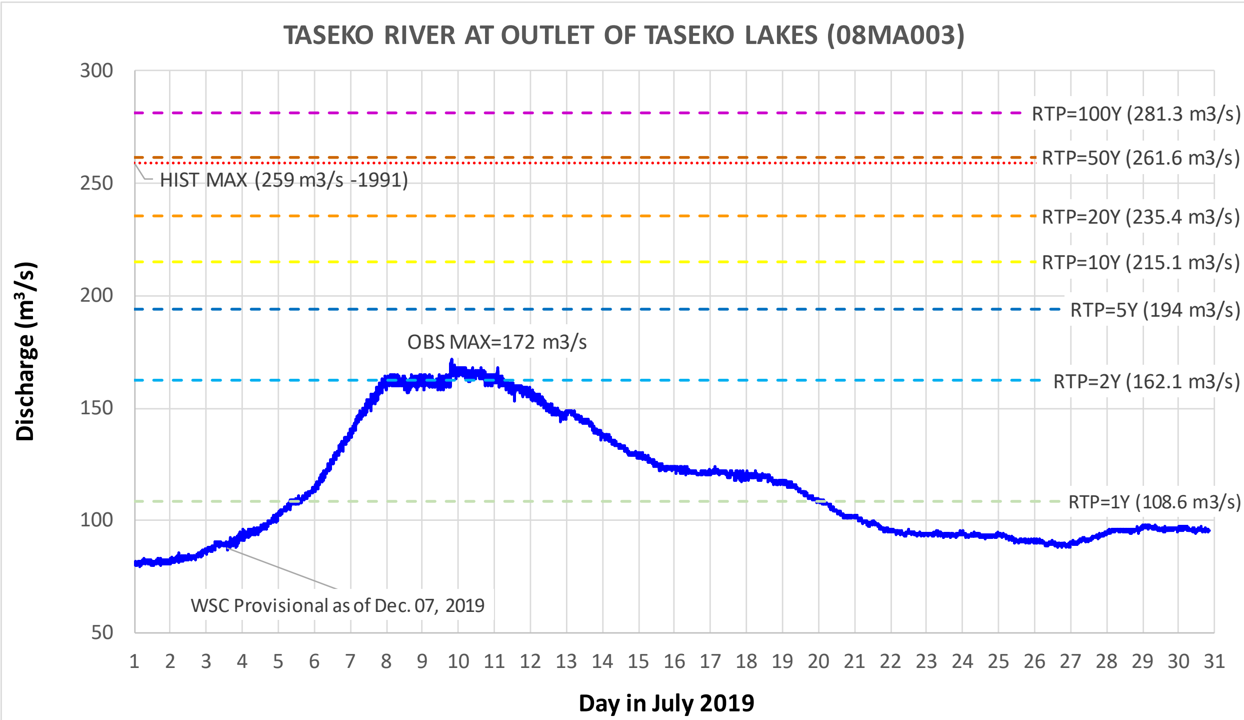



Figure 19. Hydrograph of real-time provisional discharge with return periods for TASEKO RIVER AT OUTLET OF TASEKO LAKES (08MA003) (WSC real-time provisional discharge data as of Dec. 7, 2019)

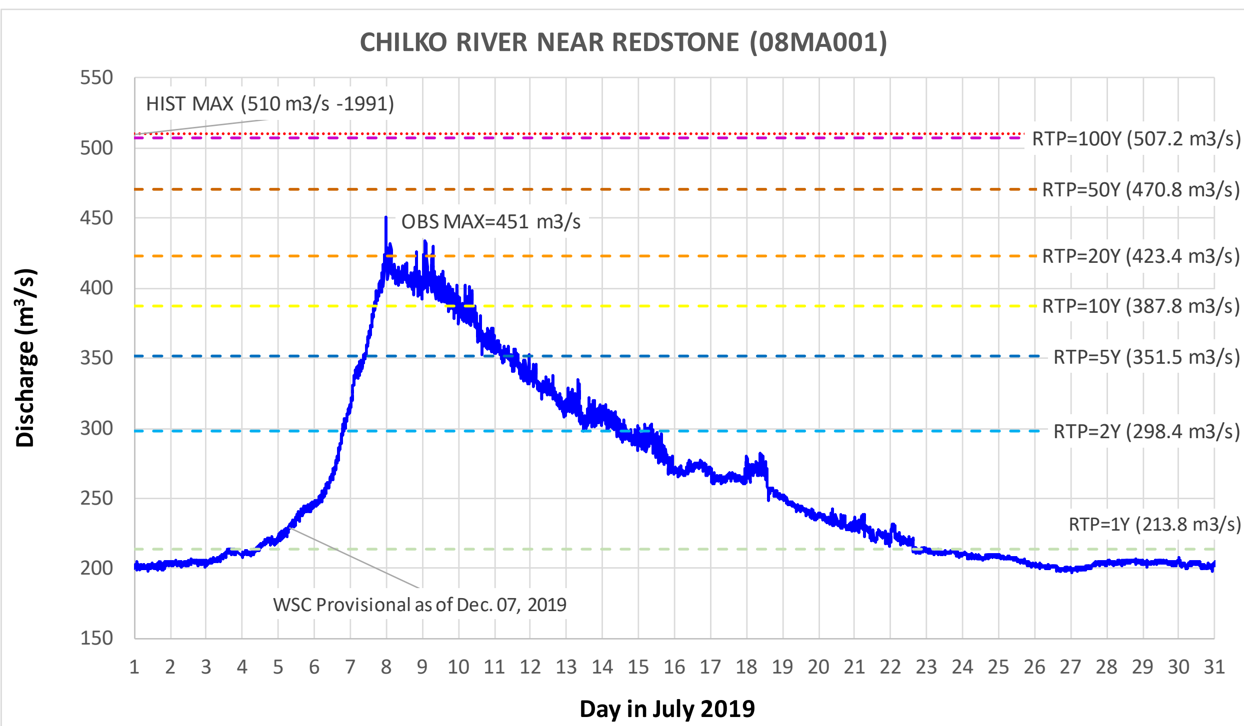



Figure 20. Hydrograph of real-time provisional discharge with return periods for CHILKO RIVER NEAR REDSTONE (08MA001) (WSC real-time provisional discharge data as of December 7, 2019)

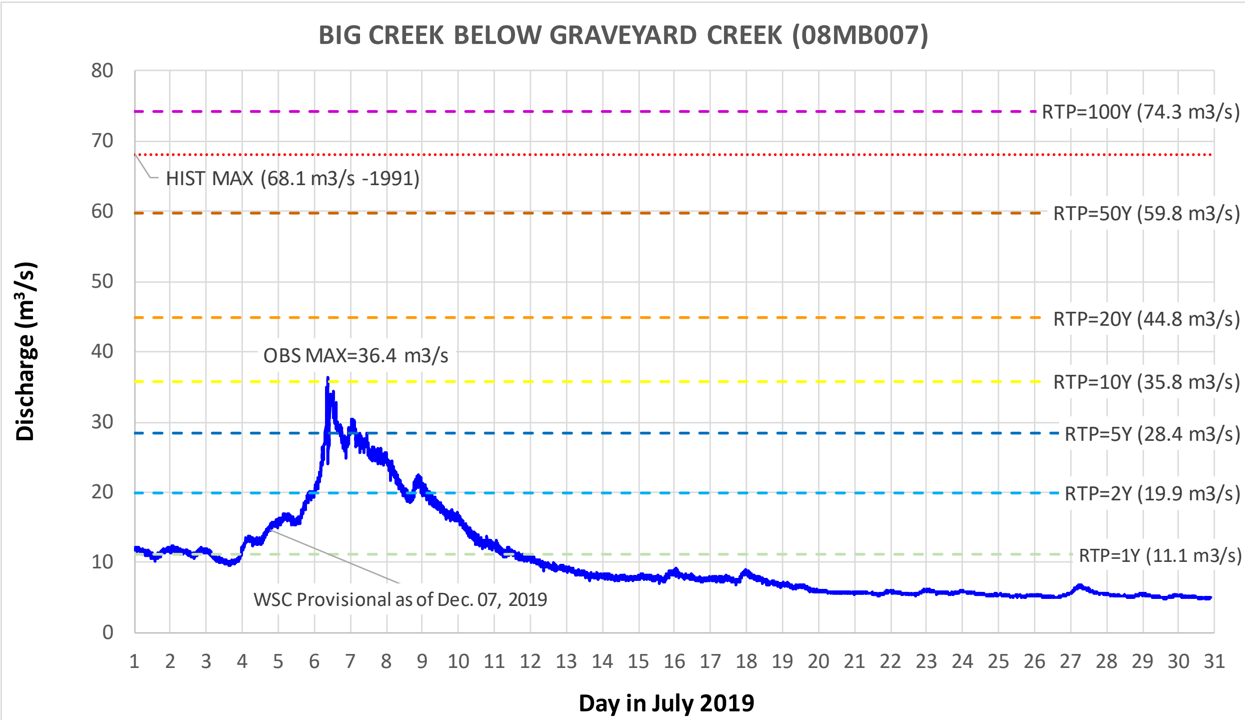



Figure 21. Hydrograph of real-time provisional discharge with return periods for BIG CREEK BELOW GRAVEYARD CREEK (08MB007) (WSC real-time provisional discharge data as of December 7, 2019)

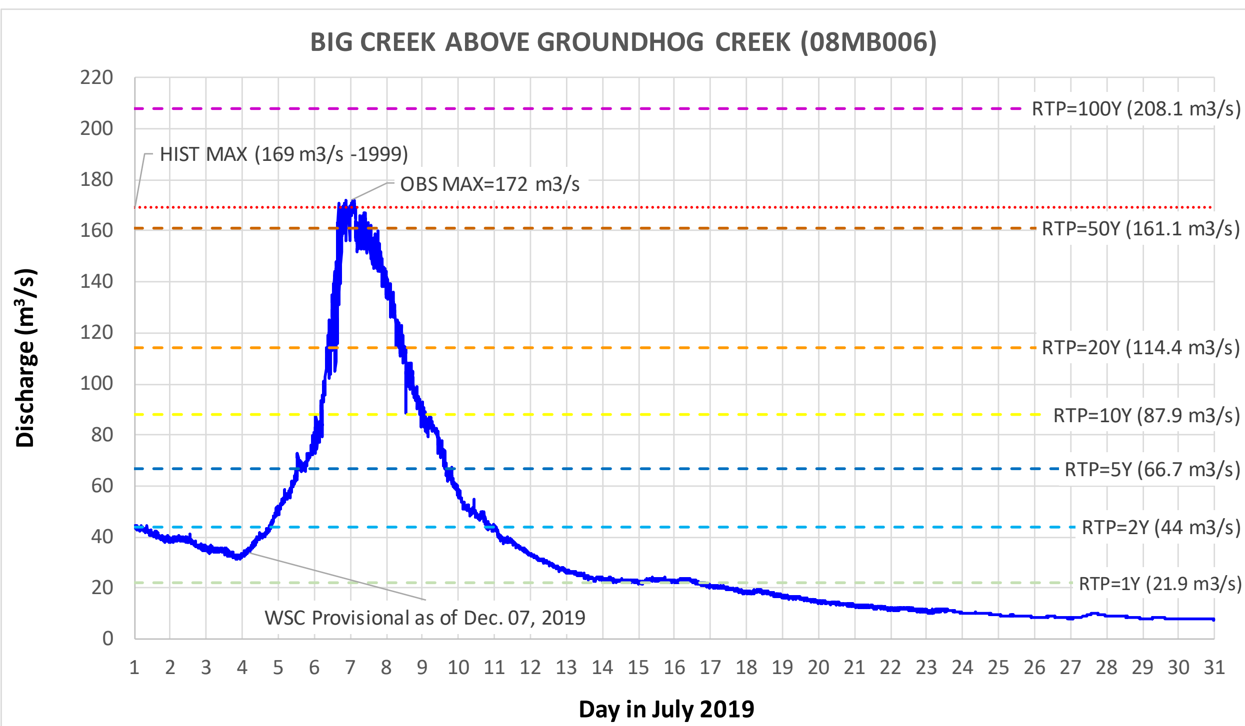



Figure 22. Hydrograph of real-time provisional discharge with return periods for BIG CREEK ABOVE GROUNDHOG CREEK (08MB006) (WSC real-time provisional discharge data as of December 7, 2019)

## 3.4 Hydrographs for CHILCOTIN RIVER BELOW BIG CREEK (08MB005)

The WSC station CHILCOTIN RIVER BELOW BIG CREEK (08MB005) was not functioning properly during the flooding event. However, it might report the water level correctly and the provisional data of the water level was not modified much during and after the flooding event. Figure 23 shows the provisional water levels for this station from July 1 to 27, 2019, which was downloaded from the WSC real-time hydrometric data site as of December 7, 2019. The return periods for water levels, which were converted from the return periods for discharges by using the WSC latest rating curve No. 32, were also plotted in Figure 23 for comparison.

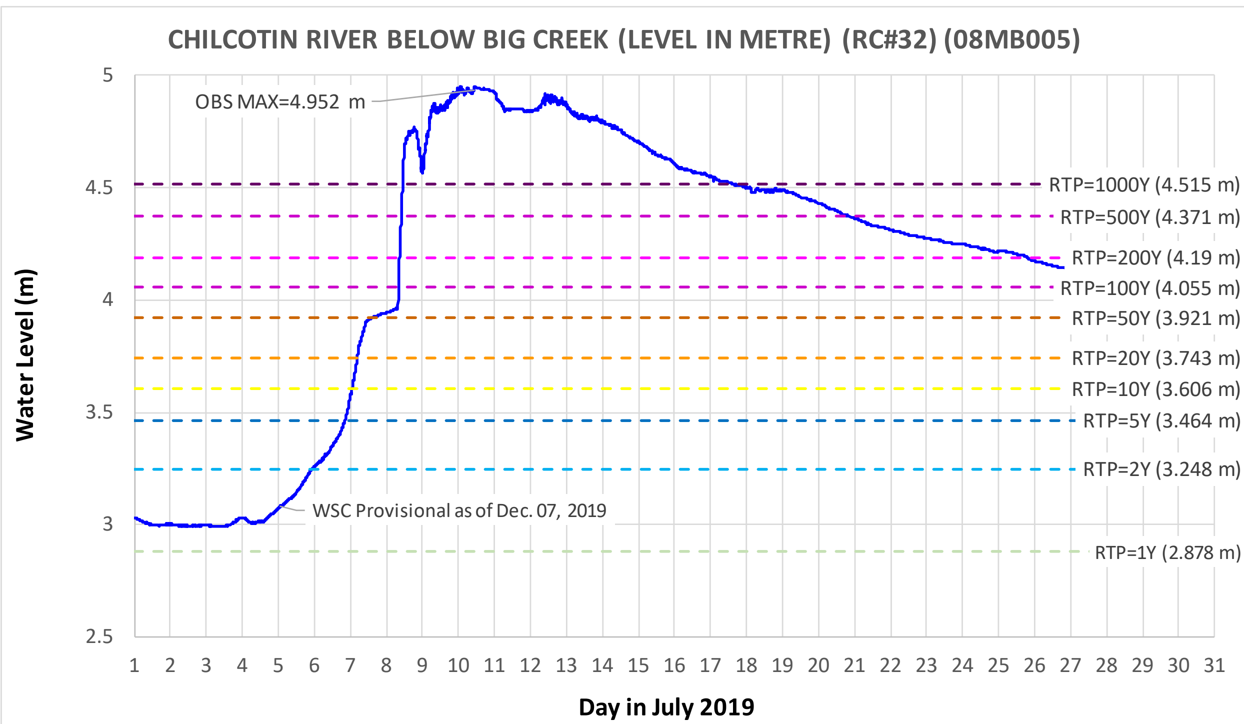
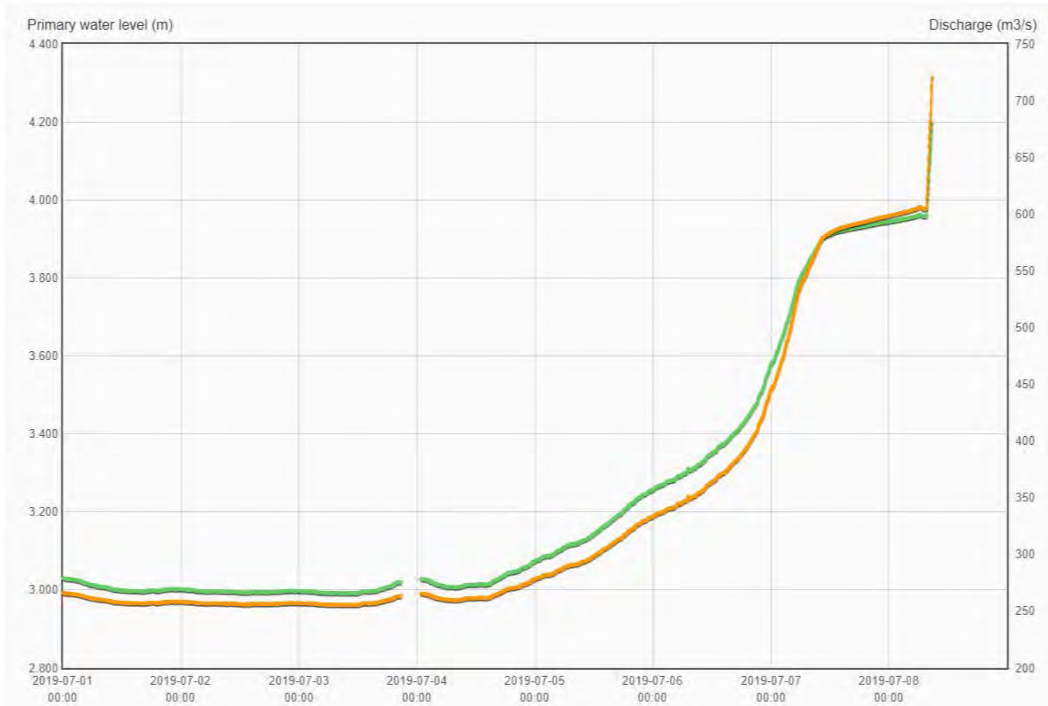


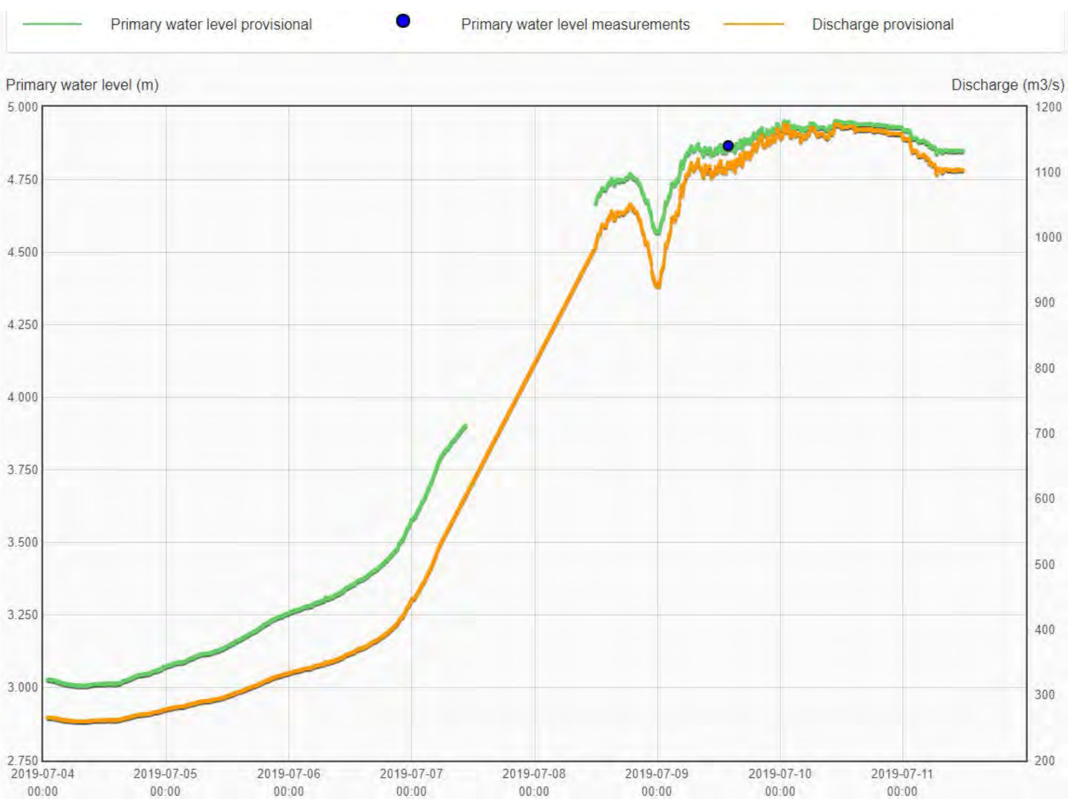

Figure 23. Water levels recorded at CHILCOTIN RIVER BELOW BIG CREEK (08MB005) and return periods (WSC provisional data as of December 7, 2019. Return periods converted with rating curve No. 32)

From Figure 23, it can be seen that the water level surpasses the 1000-year return period level from July 8 to July 17, 2019. This might suggest that the rating curve might be invalid during the flooding event. If so (rating curve invalid), a very complex situation could be present in obtaining discharge estimations with the rating curve.

Figure 24 shows charts of the provisional hydrographs of discharge for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) downloaded from the WSC real-time hydrometric data site on different days. It can be seen that these hydrographs had undergone significant artificial modifications from time to time.

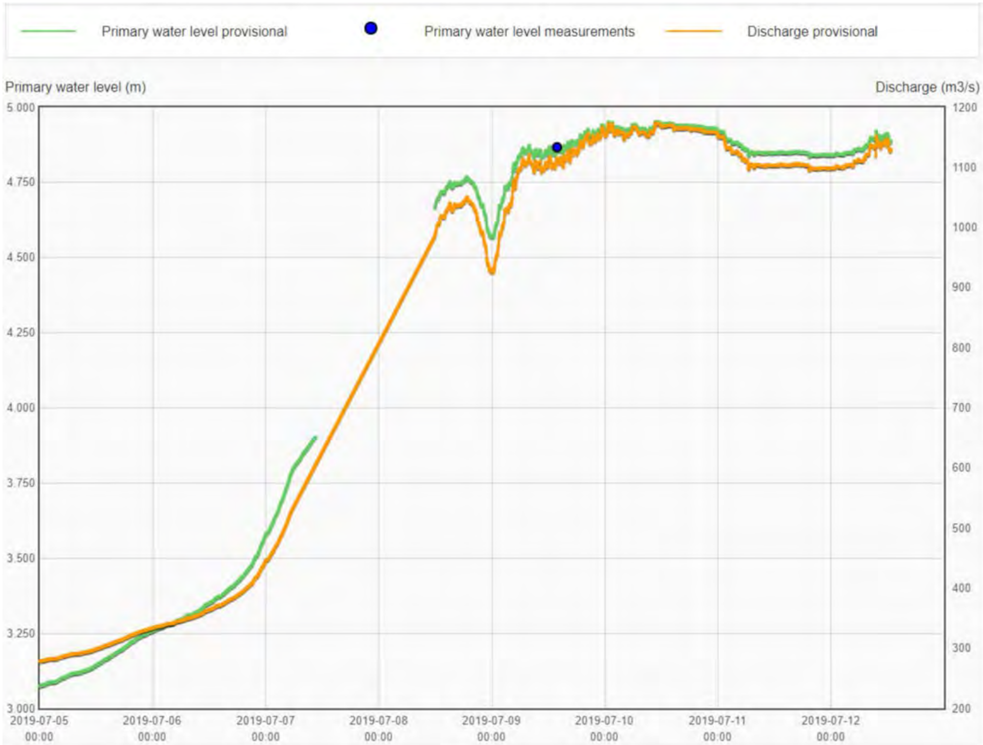



(a) Downloaded at 11:30 am July 8, 2019

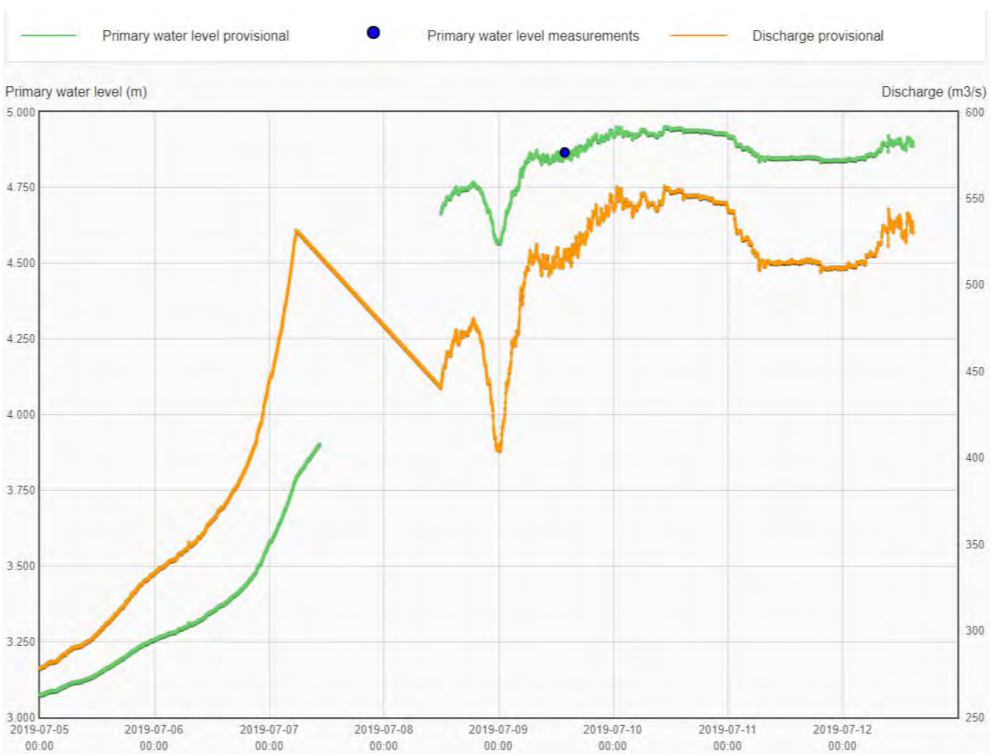



(b) Downloaded at 3:20 pm July 11, 2019

Figure 24. Charts of provisional hydrographs for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) (Downloaded from WSC real-time hydrometric data site. Copyright by WSC)

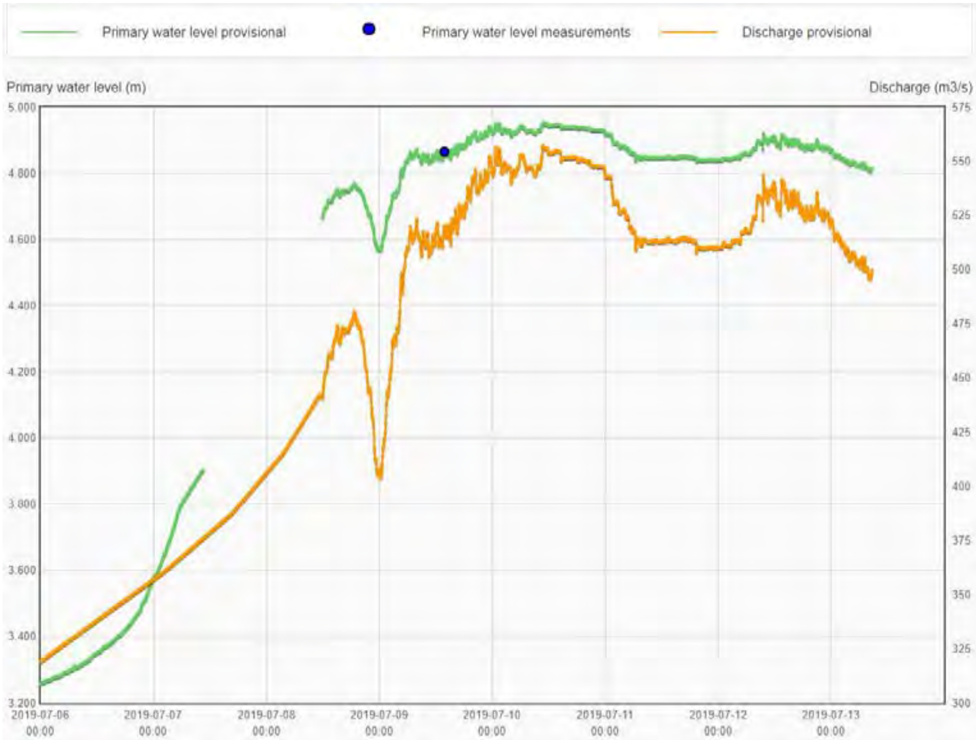



(c) Downloaded at 4:00 pm July 12, 2019

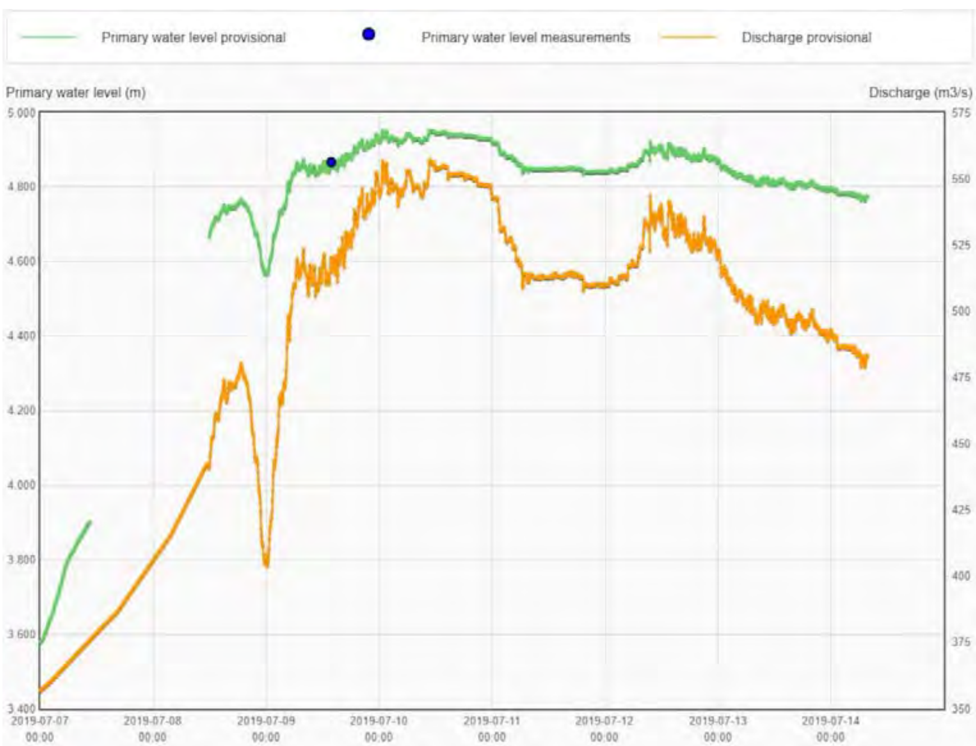



(d) Downloaded at 4:40 pm July 12, 2019

Figure 24. Charts of provisional hydrographs for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) (Downloaded from WSC real-time hydrometric data site. Copyright by WSC) (continued)

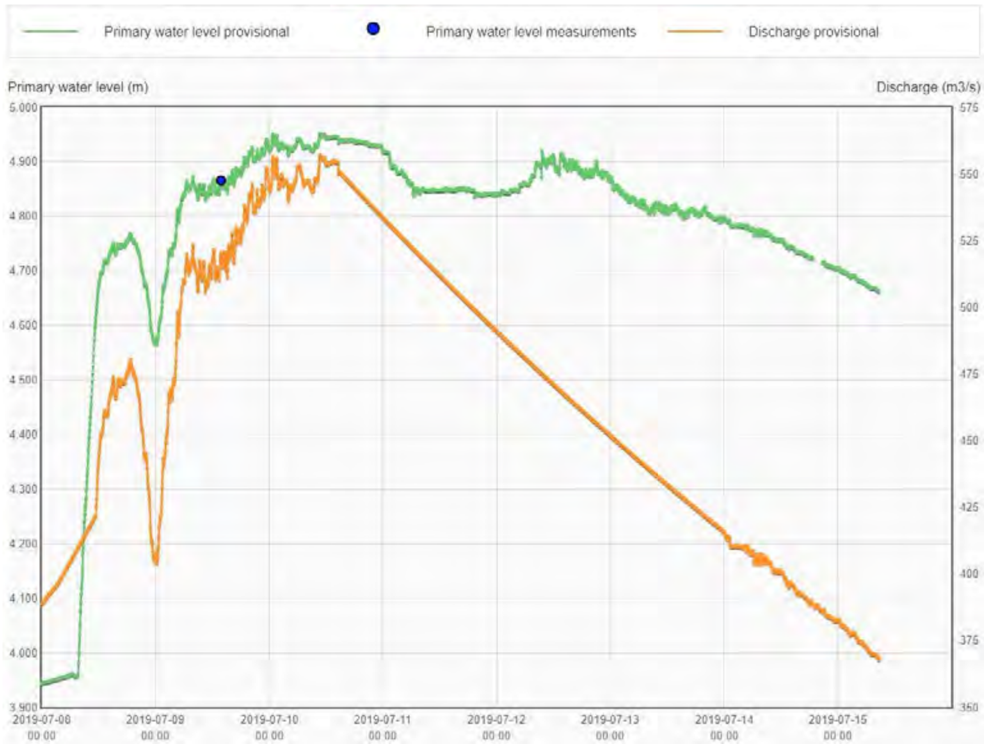



(e) Downloaded at 11:30 am July 13, 2019




(f) Downloaded at 11:30 am July 14, 2019

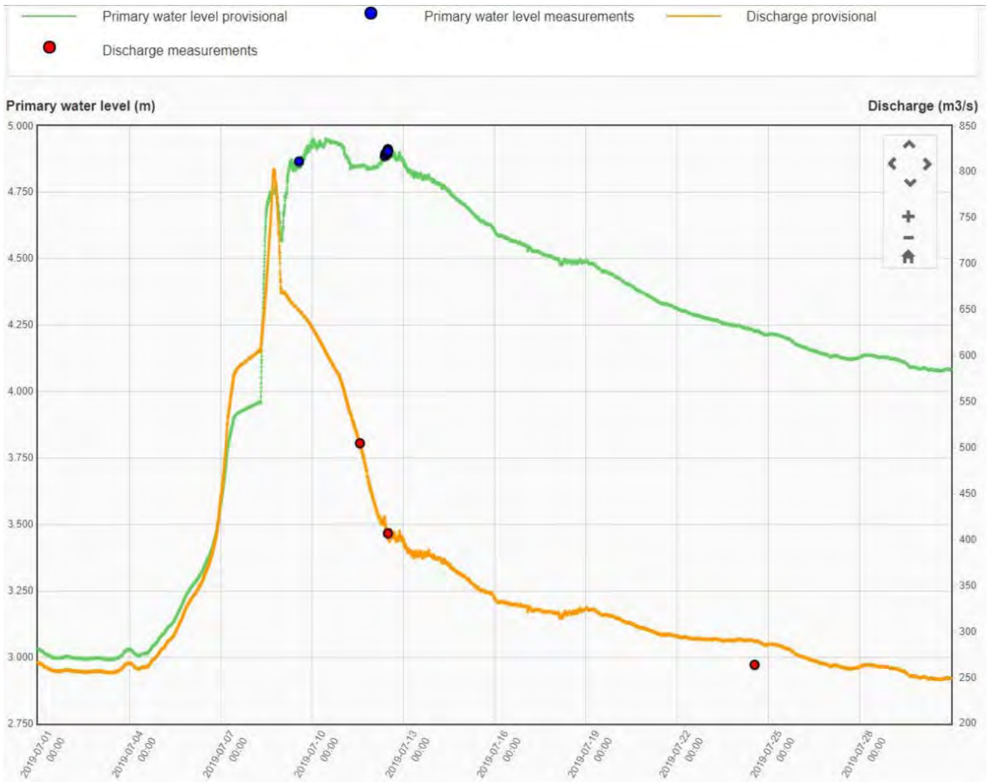
Figure 24. Charts of provisional hydrographs for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) (Downloaded from WSC real-time hydrometric data site. Copyright by WSC) (continued)




(g) Downloaded at 11:15 am July 15, 2019


(h) Downloaded at 9:18 am July 16, 2019

Figure 24. Charts of provisional hydrographs for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) (Downloaded from WSC real-time hydrometric data site. Copyright by WSC) (continued)

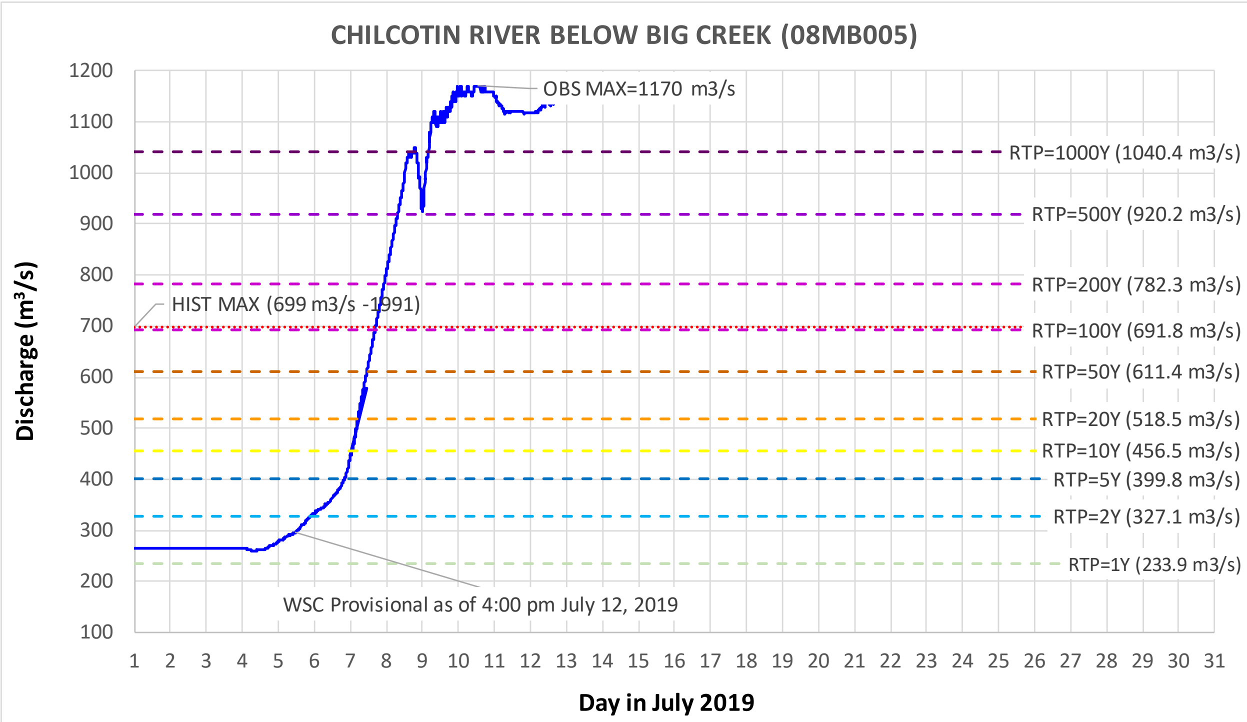



(i) Downloaded at 9:58 am November 7, 2019

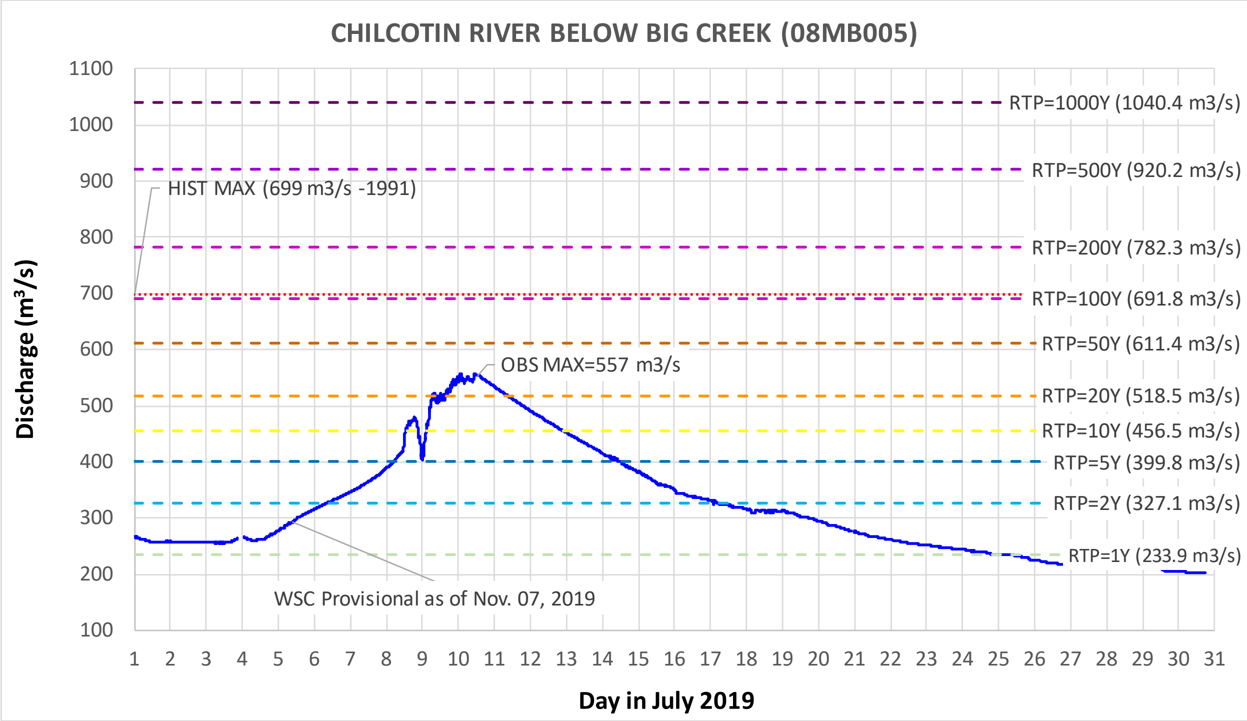
Figure 24. Charts of provisional hydrographs for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) (Downloaded from WSC's real-time hydrometric data site. Copyright by WSC) (continued)

From Figure 24 (a) to (i), it can be seen that the provisional hydrographs for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) had taken three major forms, (i) before 4 pm July 12, 2019, (ii) from 4:40 pm July 12 to November 7, 2019, and (iii) on and after December 7, 2019. Figure 25 (a), (b) and (c) shows the plots of these different forms of hydrograph together with the return periods for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005).

The first form, Figure 25 (a), has a peak flow of 1170 $m^3/s$, which was marked on July 10, 2019, and which is a flow greater than the 1000-year return period flow (1040.4 $m^3/s$). The second form, Figure 25 (b), has a peak of 557 $m^3/s$, which was also marked on July 10, 2019, and which is a flow between the 20- and 50-year return periods. The third form, Figure 25 (c), has a peak of 803 $m^3/s$, which was marked on July 8, 2019, and which is a flow slightly over the 200-year return period flow (782.3 $m^3/s$). These significant adjustments to the provisional discharge data might be justified. However, these significant artificial lifting and lowering the real-time provisional data practically posed incredible uncertainties and difficulties to the operational real-time flood forecasting during the flooding event.

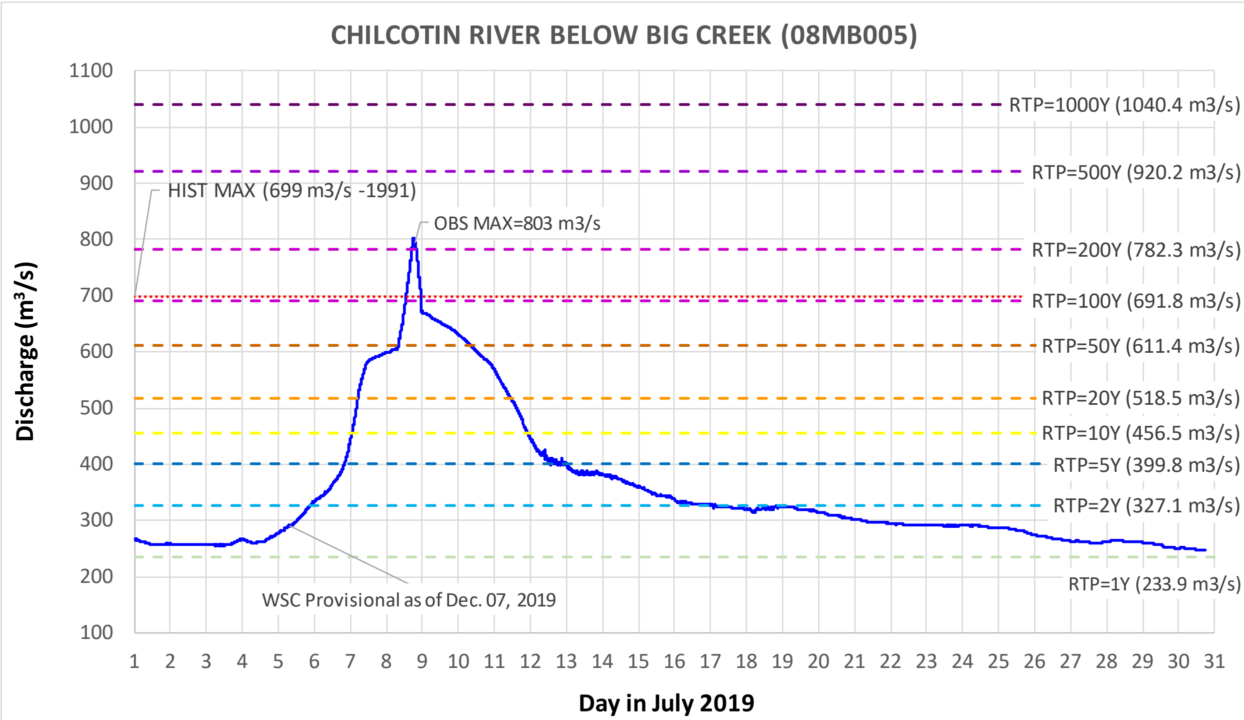



(a) Provisional data downloaded at 4 pm July 12, 2019




(b) Provisional data downloaded on November 7, 2019

Figure 25. Three major forms of provisional hydrographs for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) for the flooding event




(c) Provisional data downloaded on December 7, 2019

Figure 25. Three major forms of provisional hydrographs for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) for the flooding event (continued)

# 4. Hydrologic modeling efforts in River Forecast Centre

The core hydrologic model for freshet real-time flood forecasting in British Columbia (BC) is the CLEVER Model. The accuracy of the model forecasts depends on the accuracy of the input climate data and the model calibration. The provisional discharge data recorded at the WSC hydrometric stations are used for the model calibration. On and before July 9, 2019, the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) was the only WSC hydrometric station located in the Chilcotin River watershed that was modeled by the CLEVER Model. As pointed out in Section 3, the significant artificial adjustments to the provisional discharge data from the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) during the flooding event practically posed incredible uncertainties and difficulties to the operational real-time flood forecasting for the flooding event.

Figure 26 is a Google map updated at 10:43 am July 5, 2019, which shows that 08MB005 was the only WSC hydrometric station in the Chilcotin River watershed which was included in the CLEVER Model. As shown in Table 5, there was no return period available for two important upstream WSC hydrometric stations in the Chilcotin Rive watershed, the CHILKO RIVER NEAR REDSTONE (08MA001) and BIG CREEK ABOVE GROUNDHOG CREEK (08MB006). Without necessary return periods, it was impossible to evaluate the flooding levels of the upstream tributaries. These also posed additional difficulties to the modeling.

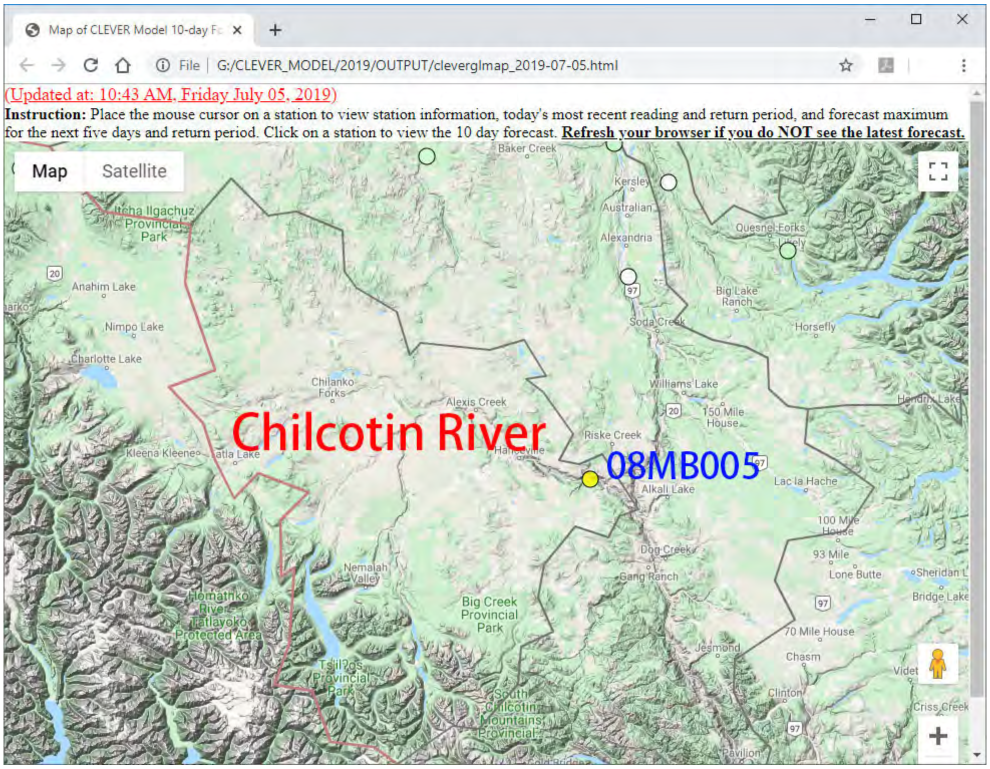



Figure 26. Map showing the only WSC station CHILCOTIN RIVER BELOW BIG CREEK (08MB005) in Chilcotin River watershed modeled by CLEVER Model on and before July 9, 2019

In this section, the hydrologic modeling efforts in the River Forecast Centre are addressed day by day regarding, (1) the model calibration, (2) model responses to the observed and forecast climate data input (numerical weather prediction, NWP), mainly the rainfall data, and (3) when necessary, immediate adjustments to the model calibration strategy and prompt improvements to the model to adapt to the significant artificial lifting and lowering of the WSC provisional observed discharge data.

## 4.1 Forecast rainfall for four climate stations in Chilcotin River watershed

The climate data driving the CLEVER Model include observed and forecast climate data. The 10-day forecast climate data are obtained by downscaling the NWP GRIB2 data from the regional and global models of the Canadian Meteorological Centre (CMC) of ECCC.

There was no snow weather station located in the Chilcotin River watershed, however there were two located to the west of the watershed, 3A22P and 3A24P. These two snow weather stations indicated that all the snowpack had been melted by the end of May 2019. This means that rainfall could be the only cause of flooding in the early July 2019 Chilcotin River flood.

As shown in Table 1, four climate stations were used for the Chilcotin River watershed in the CLEVER Model, three Fire Weather stations: NMI – NEMIAH (216) weight = 0.4, BLF – BALDFACE (221) weight = 0.2, and ACH – ALEXIS CREEK HUB (209) weight = 0.2, and an ECCC climate station: WPU – Puntzi Mountain (1086558) weight = 0.2. According to the records of the model's data flow, Table 7 lists the forecast 24-hour rainfall for seven days from July 4 to 10, 2019 and 4-day total rainfall from July 4 to 7, 2019. In the table, these forecast rainfall amounts are compared with the observed rainfall amounts for these four climate stations.

Table 7. Forecast 24-hour rainfall from July 4 to 10, 2019 and 4-day total rainfall from July 4 to 7, 2019 for four climate stations in Chilcotin River watershed forecast

| FOR Date | MD ID | Date/Forecast Rainfall (mm) | | | | | | | 4D Total | WT AVE (mm) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | JUL4 | JUL5 | JUL6 | JUL7 | JUL8 | JUL9 | JUL10 | | JUL6 | JUL7 | 2D |
| JUL3 | NMI | 28.1 | 6.0 | 1.3 | 1.1 | 15.2 | 15.7 | 1.6 | 36.5 | 1.8 | 2 | 1.9 |
| | WPU | 11.3 | 0.0 | 6.2 | 0.0 | 14.8 | 3.5 | 0.1 | 17.5 | | | |
| | BLF | 1.4 | 0.6 | 0.0 | 2.4 | 9.2 | 0.0 | 3.2 | 4.4 | | | |
| | ACH | 3.6 | 0.0 | 0.3 | 5.6 | 15.2 | 2.6 | 0.5 | 9.5 | | | |
| JUL4 | NMI | 10.3 | 16.6 | 19.1 | 22.5 | 7.6 | 1.4 | 0.0 | 68.5 | 10.6 | 11.1 | 10.9 |
| | WPU | 3.8 | 6.2 | 2.1 | 1.7 | 1.0 | 0.0 | 0.0 | 13.8 | | | |
| | BLF | 14.3 | 3.0 | 0.3 | 1.5 | 1.0 | 11.0 | 1.5 | 19.1 | | | |
| | ACH | 11.1 | 0.9 | 12.2 | 7.2 | 13.5 | 3.3 | 0.1 | 31.4 | | | |
| JUL5 | NMI | | 16.1 | **56.3** | 19.7 | 2.4 | 0.1 | 0.1 | 101.1 | **28.2** | 9.4 | 18.8 |
| | WPU | | 1.4 | 17.6 | 5.0 | 2.9 | 0.8 | 4.1 | 41.5 | | | |
| | BLF | | 1.0 | 0.8 | 0.0 | 1.6 | 3.8 | 12.7 | 10.0 | | | |
| | ACH | | 3.3 | 9.9 | 2.4 | 1.2 | 0.1 | 2.8 | 31.0 | | | |
| JUL6 | NMI | | | 14.3 | 6.6 | 0.2 | 0.3 | 0.1 | 53.9 | 14.8 | 3 | 8.9 |
| | WPU | | | 36.4 | 1.1 | 0.0 | 0.0 | 4.4 | 56.8 | | | |
| | BLF | | | 2.4 | 0.5 | 0.8 | 6.2 | 4.8 | 14.9 | | | |
| | ACH | | | 6.8 | 0.3 | 1.9 | 0.0 | 2.4 | 34.7 | | | |
| JUL7 | NMI | | | | 10.8 | 1.1 | 1.2 | 0.0 | 67.4 | 14.9 | 6.9 | 10.9 |
| | WPU | | | | 5.3 | 1.1 | 0.1 | 3.0 | 37.7 | | | |
| | BLF | | | | 6.8 | 0.0 | 1.2 | 9.7 | 24.2 | | | |
| | ACH | | | | 0.7 | 8.4 | 1.6 | 1.3 | 36.9 | | | |
| **OBS** | **NMI** | **9.0** | **24.0** | **23.6** | **38.0** | 4.4 | 2.8 | 1.2 | **94.6** | 14.9 | 17.9 | **16.4** |
| | **WPU** | **17.5** | **1.8** | **13.1** | **1.0** | 2.2 | 5.6 | 1.5 | **33.4** | | | |
| | **BLF** | **8.2** | **3.8** | **5.4** | **3.2** | 6.4 | 2.6 | 26.6 | **20.6** | | | |
| | **ACH** | **15.4** | **12.2** | **8.6** | **9.2** | 1.2 | 2.8 | 3.0 | **45.4** | | | |

Note: FOR Date – the day on which the rainfall forecast was issued, MD ID – model ID, 4D Total – 4-day total rainfall from July 4 to 7, 2019, WT AVE – weighted average.

From Table 7, it can be seen that July 5's forecast rainfall for NMI for July 6, 2019 is 2.4 times the observation and the weight average of the 4 stations for the same day is about twice the observation. On a forecasting day when the CLEVER Model was run, the observed climate data (rainfall/precipitation and daily maximum and minimum temperatures) did not exist for the next 10 future days. The CLEVER Model estimated hydrograph is the combined response to both the observed climate data for the immediate 20 preceding days and the forecast climate data for the immediate next 10 future days

## 4.2 CLEVER Model response before July 5, 2019

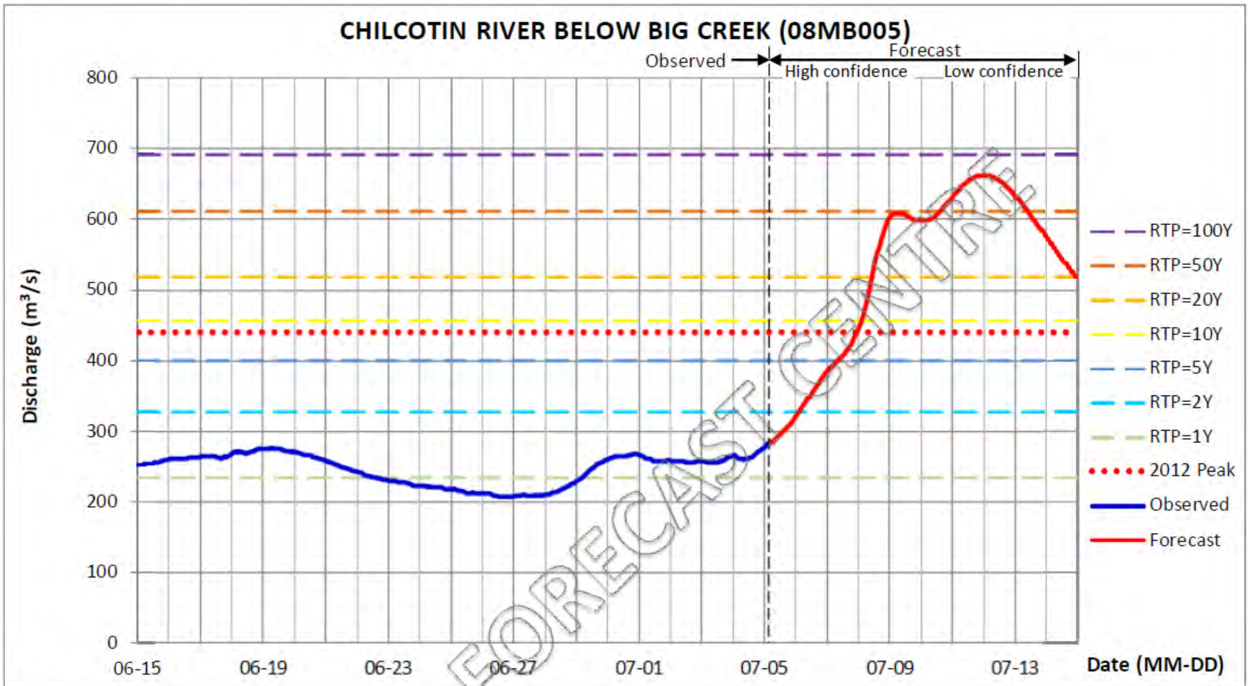
In the CLEVER Model two parameters, dP and P_factor, are used to modify the input precipitations, and dP is the increment, which is added to the original precipitation, and P_factor is a factor, by which the original precipitation is multiplied. In the Chilcotin River watershed, dP and P_factor were the same for all the four climate stations, -2 mm and 0.4, respectively. These parameters were pre-set when the model was developed in 2013 and had not really been calibrated for the Chilcotin River watershed because that there had never been any rainfall-triggered flood since the model was put into operational function in 2015. With all these pre-set parameters, the CLEVER Model did not respond to the forecast rainfall at all on July 3, July 4, 2019.

## 4.3 CLEVER Model response on July 5, 2019

On Friday July 5, 2019, the CLEVER Model responded to the about doubly overestimated rainfall for July 6, 2019. Figure 27 was the model forecast at the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) output from the first run of the CLEVER Model in the morning of July 5, 2019. This forecast hydrograph was reconstructed because that the real-time output from the first run of the model was overwritten by the second run of the model in the same morning.

It can be seen from Figure 27 that, even though the forecast peaking time was a few days away, the forecast peak (662.8 $m^3/s$), which is a flow between the 50- and 100-year return periods, was quite scary. This forecast peak surpasses the recent snowmelt-triggered peak recorded in 2012 (440 $m^3/s$) and the peak recorded in 1999 (636 $m^3/s$), and is only slightly smaller than the historical maximum (699 $m^3/s$) recorded in 1991.

Since the CLEVER Model was developed and tested in 2013, the recorded largest annual peak was 347 $m^3/s$ (2015), which is a flow between the 2- and 5-year return periods. This means that the model had not experienced such a high streamflow in the Chilcotin River ever since. Considering modeling uncertainties, a criterion for model calibration is that the first forecast of a very high or unprecedented high streamflow should not be too "scary." Therefore, after the first run of the model on Friday morning, the precipitation parameters were adjusted to reduce the forecast peak so that it looked less "scary." The increment dP was reduced from -2 mm to -4 mm, and P_factor was increased slightly from 0.4 to 0.45. The model was rerun with these new parameters for the Chilcotin River.




| Reading at 08 AM ($m^3$/s) | Forecast Daily Discharge ($m^3$/s): MAX / AVERAGE / MIN | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Fri 2019-07-05 | Fri 2019-07-05 | Sat 2019-07-06 | Sun 2019-07-07 | Mon 2019-07-08 | Tue 2019-07-09 | Wed 2019-07-10 | Thu 2019-07-11 | Fri 2019-07-12 | Sat 2019-07-13 | Sun 2019-07-14 |
| | 317.2 | 380.9 | 439.1 | 599.4 | 608.6 | 628.9 | 662.8 | 662.8 | 634.9 | 576.0 |
| 284.9 | **298.5** | **350.5** | **407.1** | **522.6** | **604.5** | **608.6** | **650.9** | **653.8** | **607.5** | **546.7** |
| | 284.4 | 319.6 | 383.1 | 444.5 | 598.5 | 598.5 | 631.2 | 636.9 | 578.6 | 518.2 |

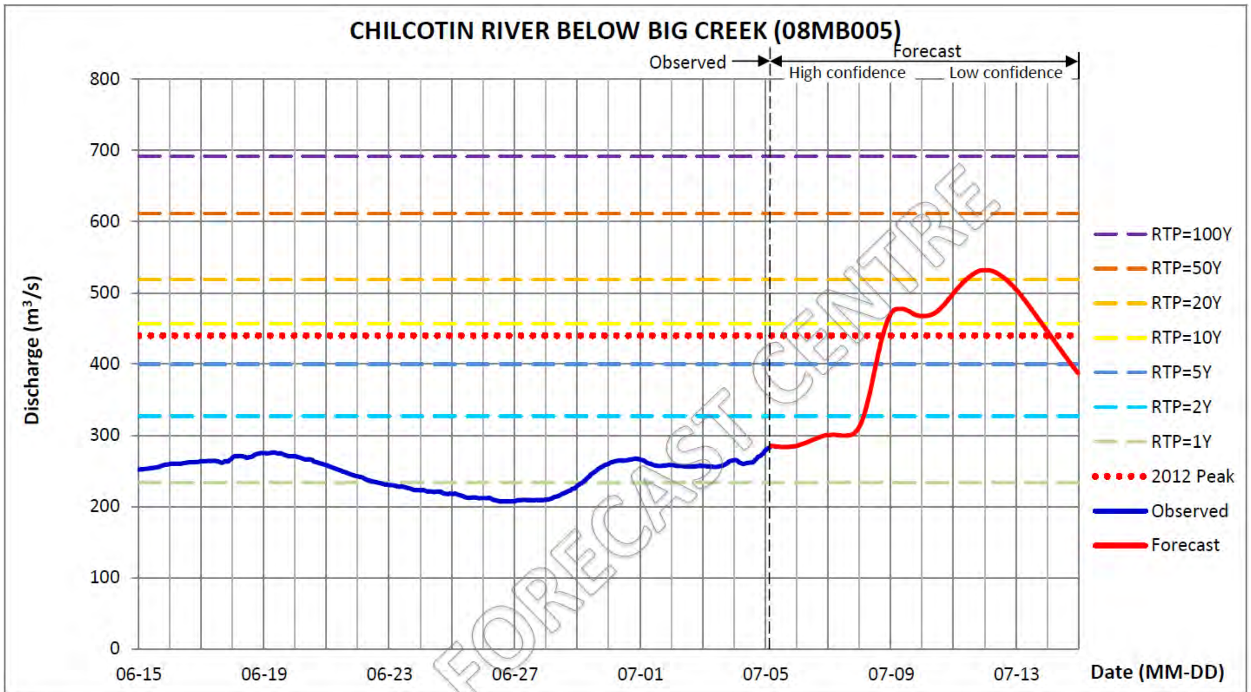
| | RTP=1Y | RTP=2Y | RTP=5Y | RTP=10Y | RTP=20Y | RTP=50Y | RTP=100Y | 2012 Peak |
|---|---|---|---|---|---|---|---|---|
| Color Scheme for Return Periods: | 233.9 | 327.1 | 399.8 | 456.5 | 518.5 | 611.4 | 691.8 | 440.0 ($m^3$/s) |



Figure 27. Reconstructed model forecast for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) from the first run of CLEVER Model on July 5, 2019

Figure 28 is a clip from the real-time model output for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005), which was actually issued for the public on July 5, 2019. It can be seen from Figure 28 that the forecast peak (531.9 $m^3$/s), which was a response to the forecast rainfall for July 6, 2019, is slightly over the 20-year return period and surpasses the recent peak in 2012 (440 $m^3$/s), though the forecast peaking day was a few days later than the actual peaking day (July 8 or 10, 2019).

The about doubly overestimated forecast rainfall for July 6, 2019 bumped up the CLEVER Model response significantly if the model rainfall parameters had not been calibrated after the first run. As a matter of fact, the CLEVER Model might have produced no response on July 5, 2019 if the forecast rainfall for July 6, 2019 had not been overestimated.




| Reading at 07 AM ($m^3/s$) | Forecast Daily Discharge ($m^3/s$): MAX / AVERAGE / MIN | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Fri 2019-07-05 | Fri 2019-07-05 | Sat 2019-07-06 | Sun 2019-07-07 | Mon 2019-07-08 | Tue 2019-07-09 | Wed 2019-07-10 | Thu 2019-07-11 | Fri 2019-07-12 | Sat 2019-07-13 | Sun 2019-07-14 |
| | 284.9 | 300.3 | 310.1 | 468.4 | 477.6 | 498.0 | 531.9 | 531.9 | 503.9 | 445.1 |
| 285.1 | **284.0** | **293.0** | **301.3** | **391.6** | **473.6** | **477.7** | **520.0** | **522.8** | **476.5** | **415.8** |
| | 283.6 | 285.4 | 299.7 | 313.5 | 467.5 | 467.5 | 500.2 | 506.0 | 447.6 | 387.3 |

| Color Scheme for Return Periods: | RTP=1Y | RTP=2Y | RTP=5Y | RTP=10Y | RTP=20Y | RTP=50Y | RTP=100Y | 2012 Peak |
|---|---|---|---|---|---|---|---|---|
| | 233.9 | 327.1 | 399.8 | 456.5 | 518.5 | 611.4 | 691.8 | 440.0 ($m^3/s$) |

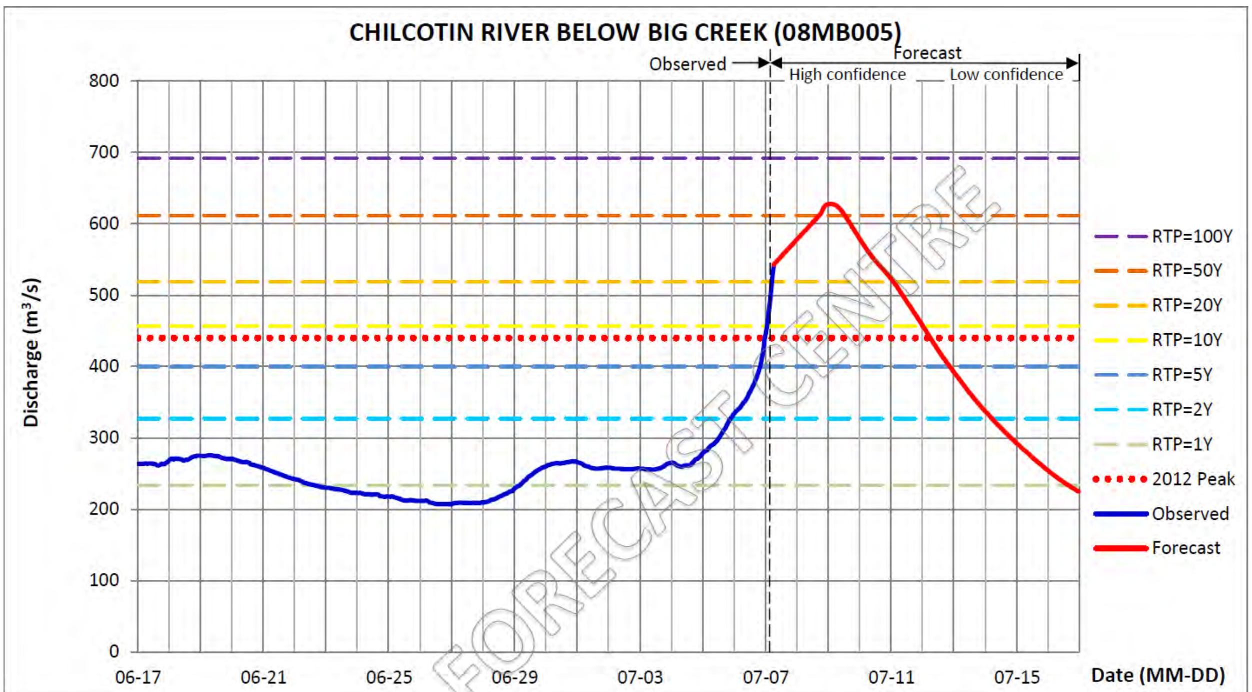
Figure 28. Published model forecast for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) from second run of CLEVER Model on July 5, 2019

## 4.4 CLEVER Model response on July 7, 2019

The flow in the Chilcotin River was monitored but the model was not run on Saturday July 6, 2019 for the following reasons, (1) on the River Forecast Centre's "Map of Current Streamflow Conditions," no flooding color was shown for the upstream WSC station, the BIG CREEK ABOVE GROUNDHOG CREEK (08MB006), because that there was no return period available for this station, and that this station was not modeled by the CLEVER Model, (2) the flow at the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) was at about the 2-year return period level only in the afternoon of July 6, 2019 due to the time lag in the real-time hydrometric data, (3) Friday's forecast showed the peaking time was on the early weekdays of the coming week.

The model was run on Sunday morning July 7, 2019, when the flow recorded at the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) had reached 543 $m^3/s$, which was higher than the 20-year return period flow. In order to match the estimated discharge to the provisional observation, the rainfall parameters had to be increased. The increment dP was increased from -4 mm to -3 mm, and P_factor was increased from 0.45 to 0.54. The model calibration was faced with difficulties, struggling to estimate a correct peaking time, which was delayed due to the huge single-piece watershed area. Figure 29 is a clip from the published real-time model forecast on July 7, 2019. The forecast peak was 627.5 m$^3$/s and the estimated peaking time was at late night of July 8 or in the early morning of July 9, 2019.

After the model forecast was published, a Flood Watch for the Chilcotin River watershed was issued, circulated via email and posted on the River Forecast Centre's website by 10:30 am.




| Reading at 07 AM (m$^3$/s) | Forecast Daily Discharge (m$^3$/s): MAX / AVERAGE / MIN | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sun 2019-07-07 | Sun 2019-07-07 | Mon 2019-07-08 | Tue 2019-07-09 | Wed 2019-07-10 | Thu 2019-07-11 | Fri 2019-07-12 | Sat 2019-07-13 | Sun 2019-07-14 | Mon 2019-07-15 | Tue 2019-07-16 |
| | 576.7 | 627.2 | 627.5 | 577.8 | 522.1 | 456.6 | 391.4 | 336.6 | 291.9 | 253.7 |
| 543.0 | **560.9** | **602.3** | **610.3** | **549.7** | **491.3** | **424.1** | **364.1** | **314.5** | **273.2** | **238.5** |
| | 545.0 | 578.7 | 580.7 | 524.4 | 459.4 | 393.8 | 338.6 | 293.6 | 255.2 | 224.8 |

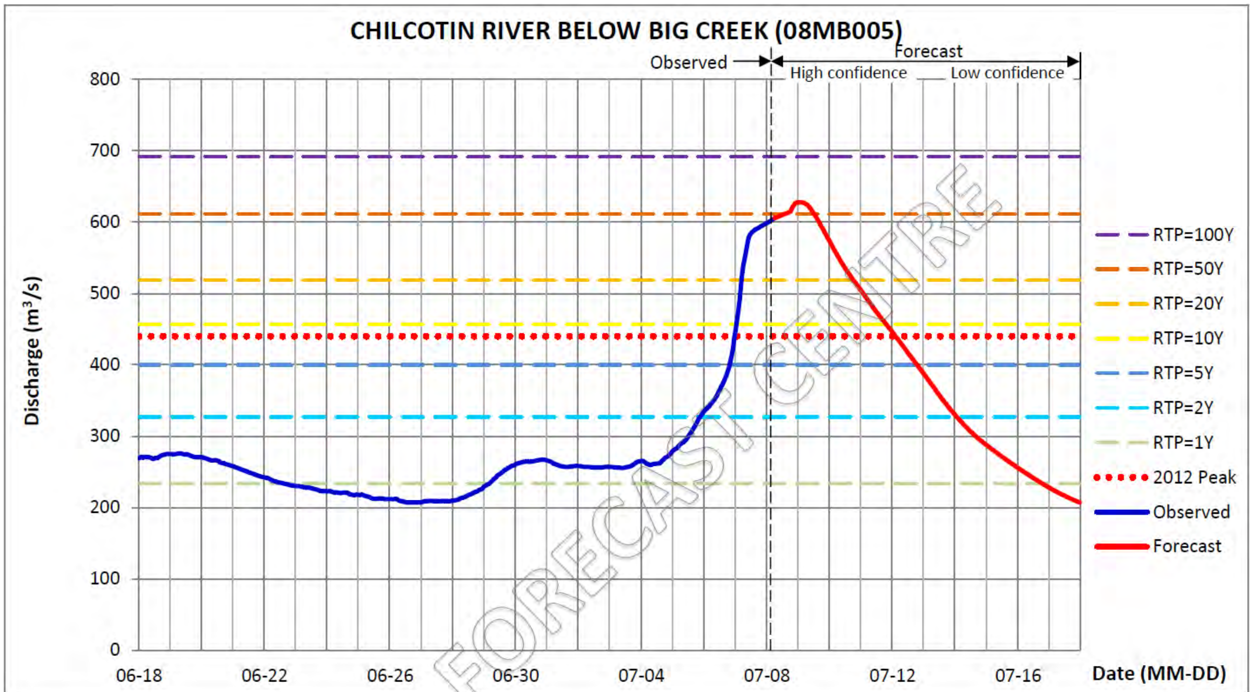
| | RTP=1Y | RTP=2Y | RTP=5Y | RTP=10Y | RTP=20Y | RTP=50Y | RTP=100Y | 2012 Peak |
|---|---|---|---|---|---|---|---|---|
| Color Scheme for Return Periods: | 233.9 | 327.1 | 399.8 | 456.5 | 518.5 | 611.4 | 691.8 | 440.0 (m$^3$/s) |

Figure 29. Published model forecast for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) on July 7, 2019

## 4.5 Model recalibration to reflect hike in provisional discharge data on July 8, 2019

The precipitation parameters for the first run of the model in the morning were kept the same as those used on July 7, 2019. Figure 30 shows the model forecast for the first run. Both the forecast peak and peaking time were almost the same as those from the forecast issued a day ago.

The Flood Watch for the Chilcotin River watershed was maintained, circulated via email and posted on the River Forecast Centre's website by 10:40 am.




| Reading at 07 AM ($m^3/s$) | Forecast Daily Discharge ($m^3/s$): MAX / AVERAGE / MIN | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Mon 2019-07-08 | Mon 2019-07-08 | Tue 2019-07-09 | Wed 2019-07-10 | Thu 2019-07-11 | Fri 2019-07-12 | Sat 2019-07-13 | Sun 2019-07-14 | Mon 2019-07-15 | Tue 2019-07-16 | Wed 2019-07-17 |
| | 627.4 | 627.6 | 572.7 | 504.0 | 445.7 | 387.2 | 329.4 | 287.2 | 255.3 | 227.6 |
| 605.9 | **614.6** | **609.1** | **537.5** | **475.3** | **417.6** | **358.7** | **307.6** | **271.7** | **241.6** | **216.8** |
| | 606.6 | 576.1 | 506.5 | 448.0 | 389.7 | 331.5 | 288.6 | 256.6 | 228.6 | 206.9 |

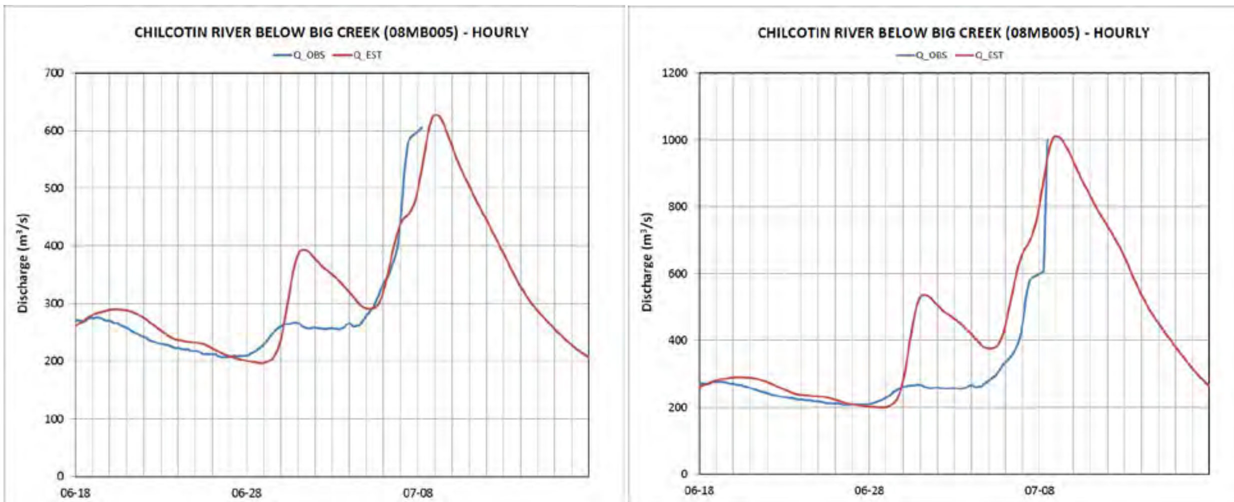
| Color Scheme for Return Periods: | RTP=1Y | RTP=2Y | RTP=5Y | RTP=10Y | RTP=20Y | RTP=50Y | RTP=100Y | 2012 Peak |
|---|---|---|---|---|---|---|---|---|
| | 233.9 | 327.1 | 399.8 | 456.5 | 518.5 | 611.4 | 691.8 | 440.0 |
| | | | | | | | | ($m^3/s$) |

Figure 30. Published model forecast for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) from first run of CLEVER Model on July 8, 2019

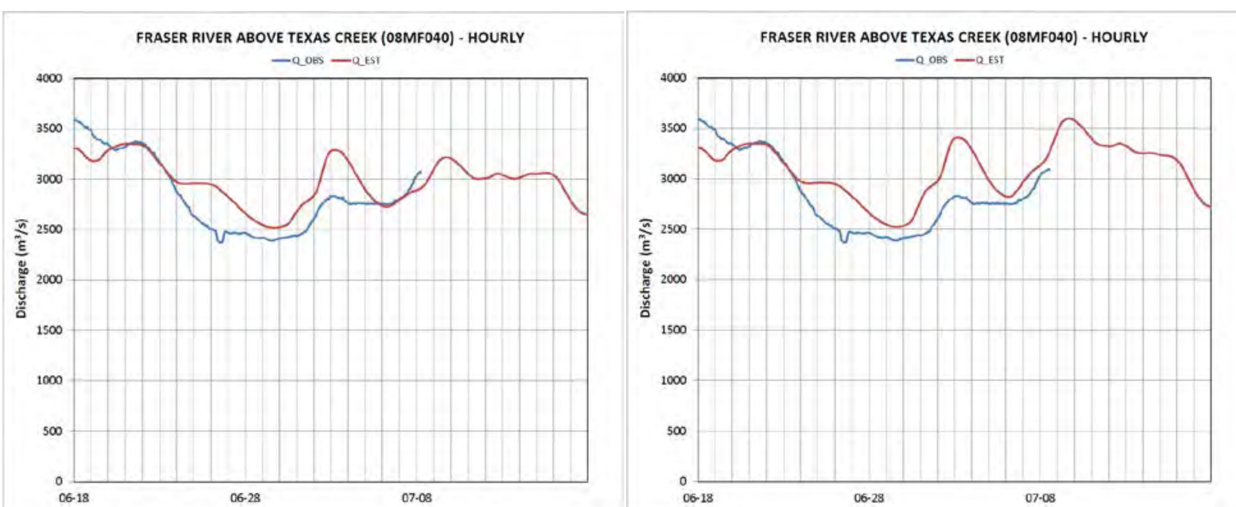
However, the situation became much more complex at about 11:30 am, when it was noticed that an almost vertical hike was present in the observed provisional discharge data for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) (see Figure 24(a)) on the WSC real-time hydrometric data website. In order to reflect this new change of the observation data, the CLEVER Model had to be rerun and recalibrated in the afternoon.

In order to achieve such a hike in the estimated hydrograph so that it fitted the significantly adjusted observation, one of the precipitation parameters, P_factor, was twisted and increased from 0.54 to 0.68.

By doing so, the model skewed the estimated hydrograph and caused an overestimation of about 300 $m^3/s$ at the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) and the downstream station, the FRASER RIVER ABOVE TEXAS CREEK (08MF040) comparing with the morning calibration. Figure 31 shows the model calibration in the morning (left) and recalibration (right) in the afternoon for these two stations.




(a) CHILCOTIN RIVER BELOW BIG CREEK (08MB005) (Left – morning calibration, Right – afternoon recalibration)

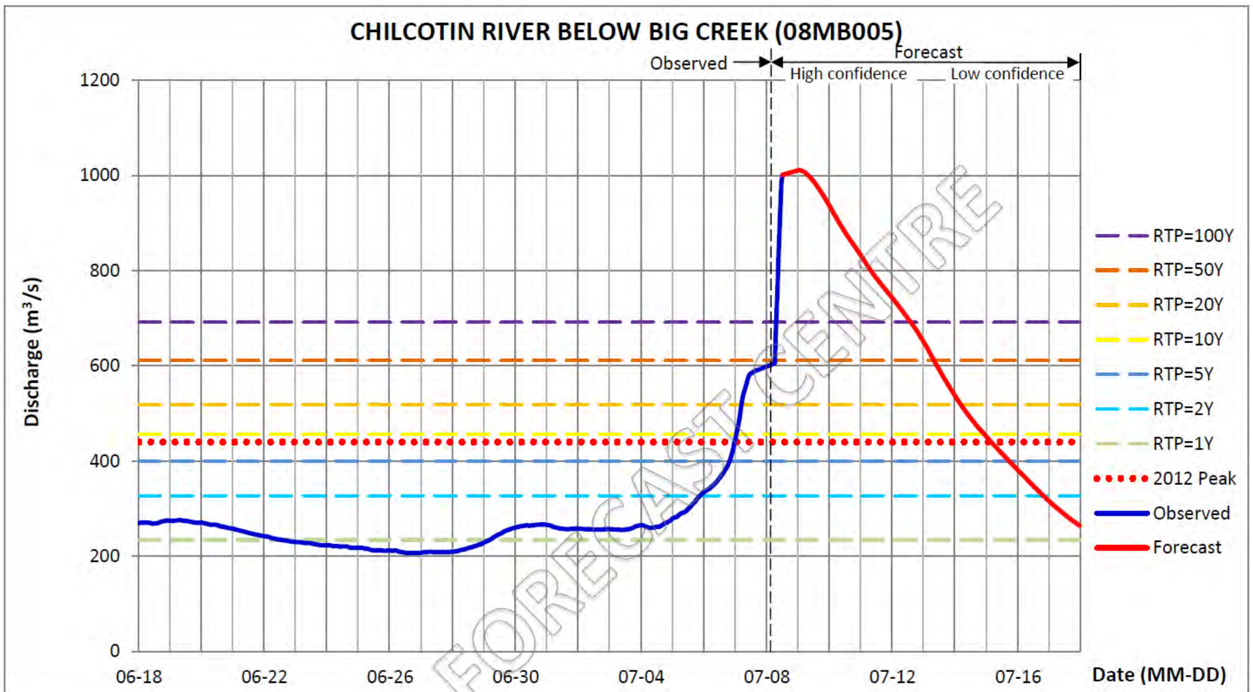



(b) FRASER RIVER ABOVE TEXAS CREEK (08MF040) (Left – morning calibration, Right – afternoon recalibration)

Figure 31. Model calibration in the morning and recalibration in the afternoon for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) and FRASER RIVER ABOVE TEXAS CREEK (08MF040)

Figure 32 shows the model forecast of the second run, which is a clip from the real-time output from the model that was re-published at 4:50 pm July 8, 2019. From the second run, the forecast peak was 1011.2 $m^3/s$, which is a flow about the 1000-year return period flow (1040 $m^3/s$). The forecast peaking time was unchanged.

The Flood Watch for the Chilcotin River was upgraded to a Flood Warning at 4:30 pm, circulated via email and posted on the River Forecast Centre's website at 4:52 pm.




| Reading at 01 PM ($m^3$/s) | Forecast Daily Discharge ($m^3$/s): MAX / AVERAGE / MIN | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Mon | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed |
| 2019-07-08 | 2019-07-08 | 2019-07-09 | 2019-07-10 | 2019-07-11 | 2019-07-12 | 2019-07-13 | 2019-07-14 | 2019-07-15 | 2019-07-16 | 2019-07-17 |
| | 1010.4 | 1011.2 | 935.4 | 831.2 | 742.2 | 649.7 | 536.3 | 450.8 | 380.6 | 315.2 |
| 1001.5 | **1006.4** | **984.0** | **883.4** | **786.4** | **700.0** | **593.9** | **492.6** | **416.7** | **348.6** | **288.7** |
| | 1002.3 | 940.2 | 835.4 | 745.7 | 654.3 | 540.5 | 453.9 | 383.4 | 317.7 | 264.5 |

| | RTP=1Y | RTP=2Y | RTP=5Y | RTP=10Y | RTP=20Y | RTP=50Y | RTP=100Y | 2012 Peak |
|---|---|---|---|---|---|---|---|---|
| Color Scheme for Return Periods: | 233.9 | 327.1 | 399.8 | 456.5 | 518.5 | 611.4 | 691.8 | 440.0 |

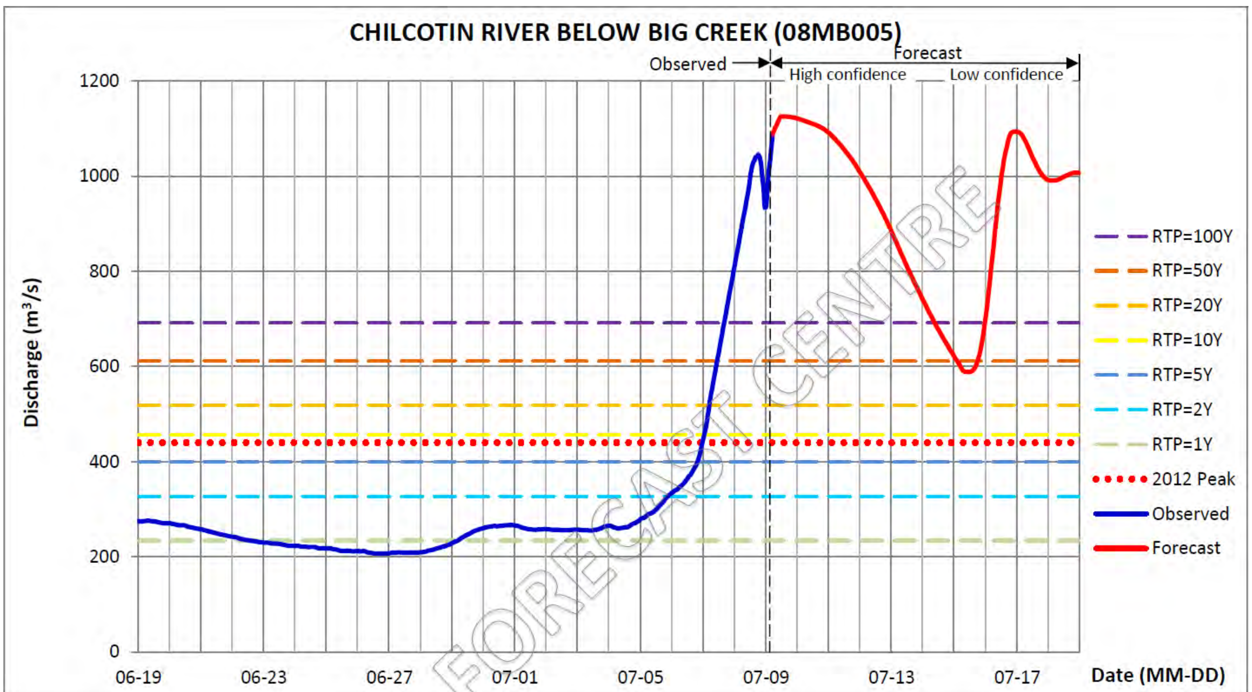
($m^3$/s)

Figure 32. Re-published model forecast for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) from second run of CLEVER Model in afternoon of July 8, 2019

## 4.6 CLEVER Model response on July 9, 2019

On July 9, 2019, the precipitation parameters were further increased, dP increased from -3 mm to -2 mm, and P_factor increased from 0.68 to 0.71, to achieve the “best” model calibration. The goal of this “best” model calibration was to bump up the rise in the estimated hydrograph as much as possible so that it fitted best the hike in the observed provisional discharge data. Figure 33 shows the model forecast on July 9, 2019, which is a clip from the real-time output from the model. The forecast peak was 1125 $m^3/s$, which is a flow over the 1000-year return period (1040 $m^3/s$). The forecast peaking time was in the morning of the same day.

The Flood Warning was maintained and updated at about 10 am after the model was run.




| Reading at 06 AM ($m^3/s$) | Forecast Daily Discharge ($m^3/s$): MAX / AVERAGE / MIN | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Tue 2019-07-09 | Tue 2019-07-09 | Wed 2019-07-10 | Thu 2019-07-11 | Fri 2019-07-12 | Sat 2019-07-13 | Sun 2019-07-14 | Mon 2019-07-15 | Tue 2019-07-16 | Wed 2019-07-17 | Thu 2019-07-18 |
| | 1125.4 | 1121.2 | 1090.7 | 1007.4 | 883.0 | 739.7 | 685.2 | 1093.8 | 1093.6 | 1007.3 |
| 1090.0 | **1119.8** | **1109.3** | **1054.9** | **951.3** | **812.6** | **680.1** | **610.0** | **954.2** | **1043.0** | **998.8** |
| | 1095.9 | 1093.1 | 1011.8 | 889.1 | 745.3 | 625.1 | 588.5 | 705.7 | 992.7 | 991.1 |

| | RTP=1Y | RTP=2Y | RTP=5Y | RTP=10Y | RTP=20Y | RTP=50Y | RTP=100Y | 2012 Peak |
|---|---|---|---|---|---|---|---|---|
| Color Scheme for Return Periods: | 233.9 | 327.1 | 399.8 | 456.5 | 518.5 | 611.4 | 691.8 | 440.0 ($m^3/s$) |

Figure 33. Published model forecast for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) on July 9, 2019

## 4.7 Model improvements on July 10, 2019

In order to resolve the delay in the forecast peaking time, the huge watershed was slit into four sub-basins and two more/new WSC hydrometric stations, the CHILKO RIVER NEAR REDSTONE (08MA001) and BIG CREEK ABOVE GROUNDHOG CREEK (08MB006), and a fake station located immediately upstream of the confluence of the Chilko River and the Chilcotin River, were incorporated in the Model. To do so, intensive work was necessary, including (i) flood frequency analysis for the two newly added WSC hydrometric stations, which was not done before the day, (ii) a series of modifications to the model including adding new watersheds and channel links to the model, (iii) calibration the two newly added stations from the beginning of the year, and (iv) various input and output setting. The improvement work was started from the afternoon of July 9, 2019. Figure 34 shows a Google map of the Chilcotin River watershed with the newly added stations, which was updated at 10 am July 10, 2019.

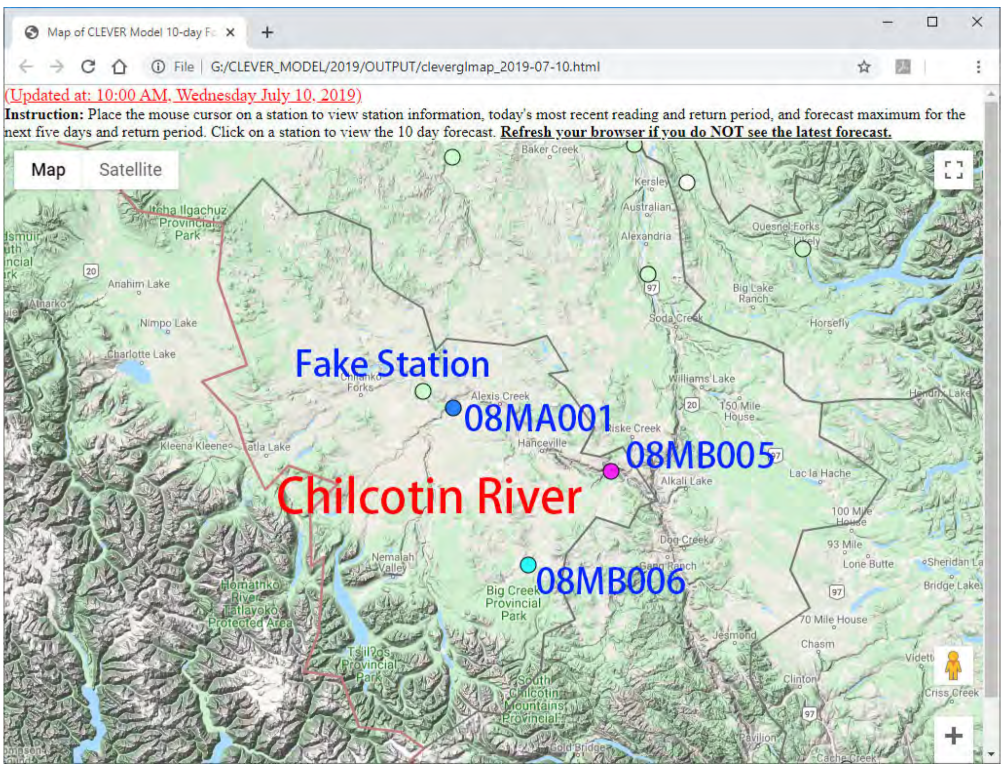
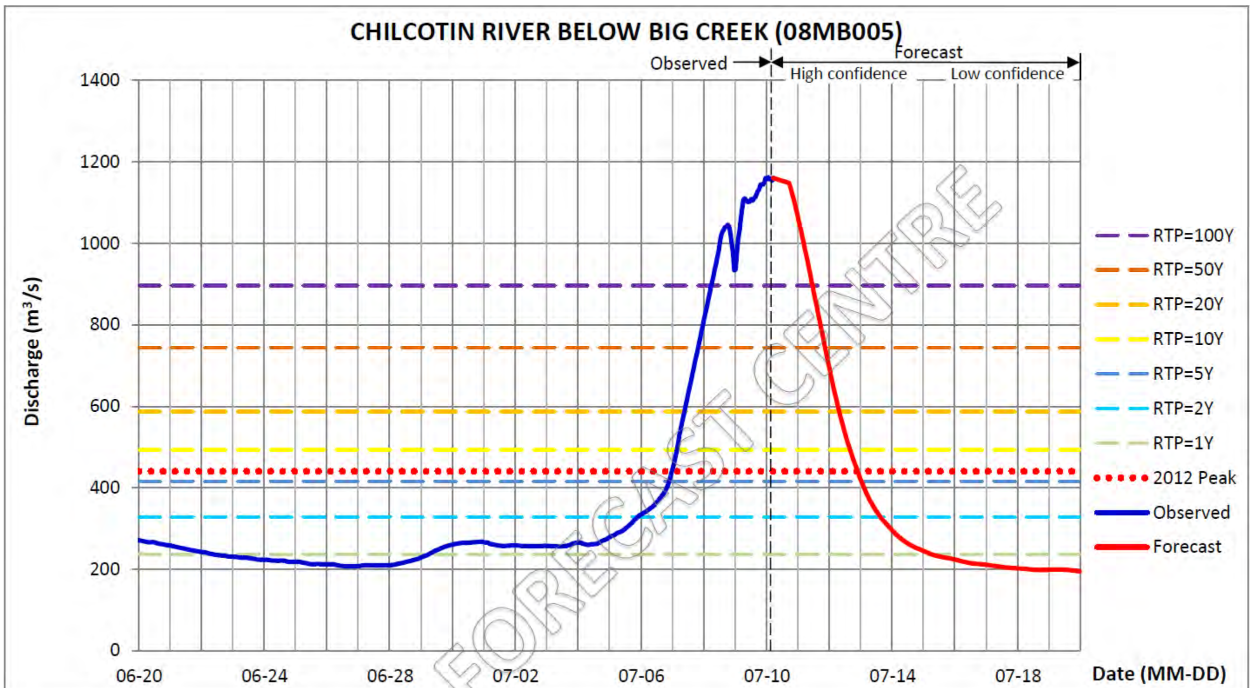



Figure 34. Map of Chilcotin River watershed with two newly added WSC hydrometric stations and a fake station for the improved CLEVER Model on and after July 10, 2019

The two precipitation parameters are not commented hereinafter because that there are four sets of these parameters now, one set for each of the four sub-basins.

Figure 35 shows the model forecast on July 10, 2019, which is a clip from the real-time output from the improved CLEVER Model. The forecast hydrograph shows that the flow had peaked and was expected to drop quickly back to the normal in four days. The return periods in Figure 35 were also different from those in the previous figures before the model was improved because that the flood frequency analysis was redone for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005). The provisional peak (1170 $m^3/s$) was included in the sample of the redone flood frequency analysis. However, the new return periods were abandoned after July 12, 2019 when the provisional discharge peak for this station was artificially lowered (reduced) significantly.

The Flood Warning was maintained for the Chilcotin River, but it was downgraded to a High Streamflow Advisory for the CHILKO RIVER NEAR REDSTONE (08MA001) and BIG CREEK ABOVE GROUNDHOG CREEK (08MB006) because that these two sub-basins were modeled separately on and after the day and the forecast flows for these two stations were relatively low. The Flood Warning and High Streamflow Advisory were update at 10:31 am.




| Reading at 06 AM ($m^3/s$) | Forecast Daily Discharge ($m^3/s$): MAX / AVERAGE / MIN | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wed | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri |
| 2019-07-10 | 2019-07-10 | 2019-07-11 | 2019-07-12 | 2019-07-13 | 2019-07-14 | 2019-07-15 | 2019-07-16 | 2019-07-17 | 2019-07-18 | 2019-07-19 |
| | 1159.0 | 1059.8 | 688.9 | 417.0 | 294.2 | 244.3 | 223.4 | 210.4 | 201.8 | 198.9 |
| 1160.0 | **1137.7** | **884.3** | **543.6** | **348.2** | **265.8** | **232.3** | **215.8** | **205.7** | **199.2** | **197.7** |
| | 1073.7 | 704.2 | 425.2 | 297.7 | 245.8 | 224.1 | 210.8 | 202.0 | 197.8 | 194.4 |

| | RTP=1Y | RTP=2Y | RTP=5Y | RTP=10Y | RTP=20Y | RTP=50Y | RTP=100Y | 2012 Peak |
|---|---|---|---|---|---|---|---|---|
| Color Scheme for Return Periods: | 236.5 | 328.1 | 415.5 | 493.1 | 586.7 | 744.1 | 896.3 | 440.0 ($m^3/s$) |

Figure 35. Published model forecast for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) from improved CLEVER Model on July 10, 2019

## 4.8 Change of model calibration strategy on July 11, 2019

Model improvements on July 10, 2019 resolved the timing issue. However, the overestimation about 300 $m^3/s$ in the estimated hydrographs for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) and FRASER RIVER ABOVE TEXAS CREEK (08MF040) continued. This caused severe problems for the downstream stations in the Fraser River. In order to obtain correct calibration for the downstream stations in the Fraser River, the calibration strategy was changed. The new calibration strategy was that, instead of fitting the estimated hydrograph for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) to the significantly artificially adjusted provisional discharge data, the estimated hydrograph for this station was so calibrated that the estimated hydrograph for the downstream station, the FRASER RIVER ABOVE TEXAS CREEK (08MF040), fitted best the provisional discharge data recorded at this downstream station.

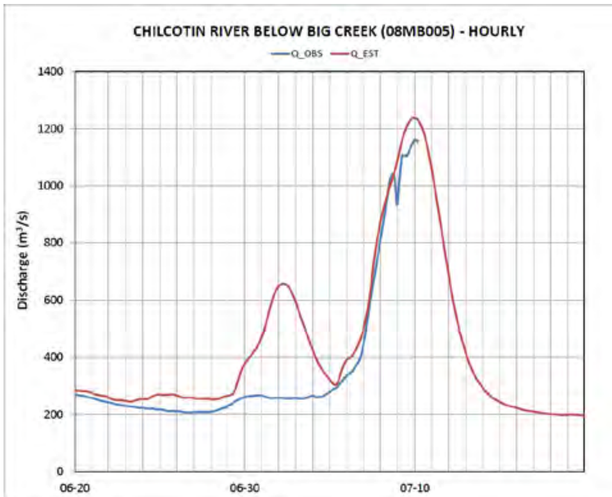
Figure 36 shows the comparison of model calibrations for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) and FRASER RIVER ABOVE TEXAS CREEK (08MF040), before (July 10, 2019) and after (July 11, 2019) the change of model calibration strategy. It can be seen from this figure that, after the change of calibration strategy, the model had a better calibration for the previous peak at the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) (Figure 36 (b)), and the estimated hydrograph fitted the observed one better for the FRASER RIVER ABOVE TEXAS CREEK (08MF040) (Figure 36 (d)).

After the change of model calibration strategy, how to produce a forecast hydrograph for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) became a little tricky because that the gap between the model estimated hydrograph and observed provisional hydrograph was so large.

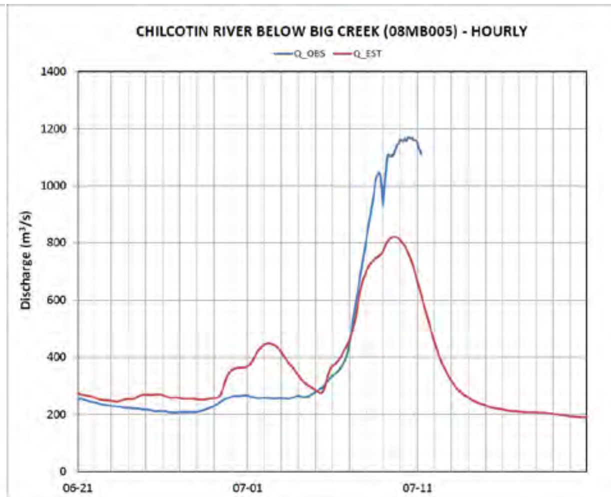
If no bias correction was applied to the estimated hydrograph and simply connect it and the observed hydrograph with a straight line to produce a forecast hydrograph, the forecast discharge might drop too fast. If 100% bias correction was applied to the estimated hydrograph by lifting it up by a uniform increment to produce a forecast hydrograph, the forecast discharge would drop very slowly and stay high for a long time. After balancing, it was decided that the latter was adopted to produce the forecast hydrograph.

Figure 37 shows the model forecast for July 11, 2019 which was a clip from the real-time output from the model. Looking at Figure 37, the forecast discharge was expected to recede from over the 1000-year return period level to the 50-year return period level in three days but maintained above the 20-year return period level for the rest of the next 10 days.

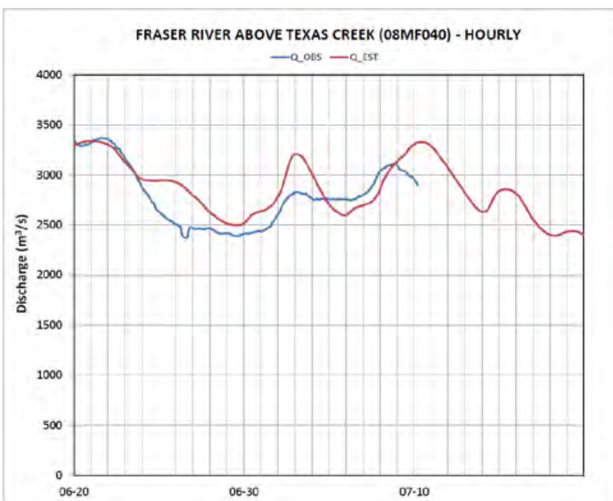
Based on the model forecasts for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) and the upstream tributaries, the Flood Warning for the Chilcotin River and the High Streamflow Advisory for the Chilko River and Big Creek were maintained and updated at 10 am July 11, 2019.



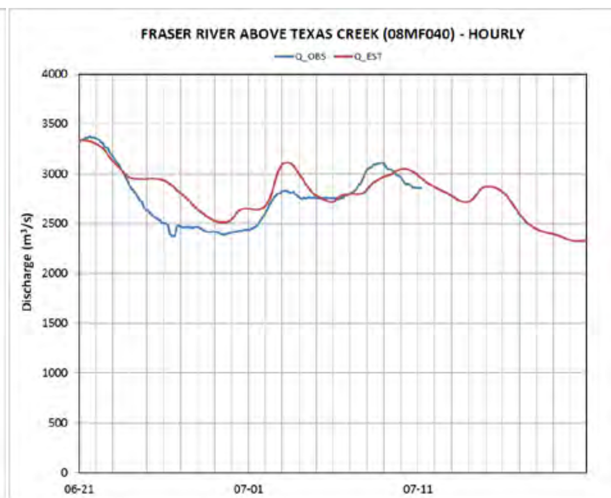

(a) 08MB005 – July 10, 2019 (before change)




(b) 08MB005 – July 11, 2019 (after change)

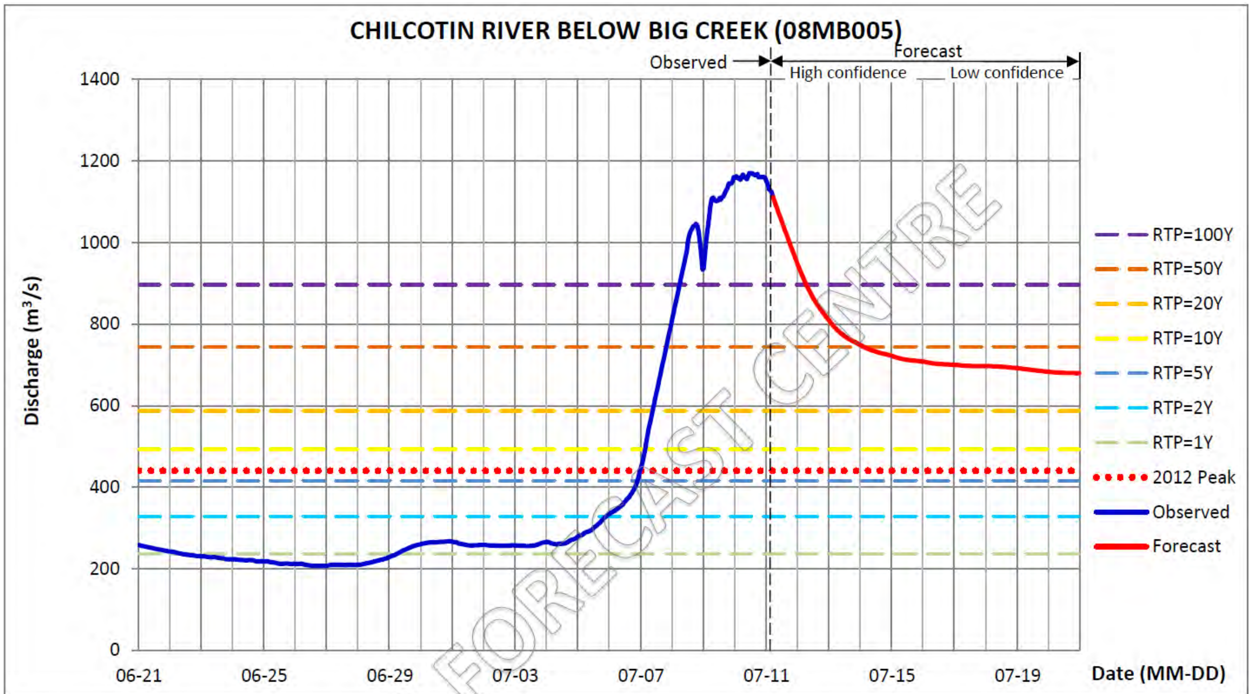



(c) 08MF040 – July 10, 2019 (before change)




(d) 08MF040 – July 11, 2019 (after change)

Figure 36. Comparison of model calibrations for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) and FRASER RIVER ABOVE TEXAS CREEK (08MF040) before and after change of calibration strategy






| Reading at 06 AM ($m^3/s$) | Forecast Daily Discharge ($m^3/s$): MAX / AVERAGE / MIN | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Thu 2019-07-11 | Thu 2019-07-11 | Fri 2019-07-12 | Sat 2019-07-13 | Sun 2019-07-14 | Mon 2019-07-15 | Tue 2019-07-16 | Wed 2019-07-17 | Thu 2019-07-18 | Fri 2019-07-19 | Sat 2019-07-20 |
| | 1101.9 | 944.9 | 807.5 | 748.2 | 721.6 | 707.6 | 699.8 | 696.8 | 691.5 | 682.7 |
| 1111.0 | **1026.8** | **870.1** | **773.7** | **733.4** | **713.1** | **702.8** | **697.7** | **694.9** | **687.1** | **680.6** |
| | 953.2 | 811.6 | 749.9 | 722.6 | 708.1 | 700.0 | 696.8 | 691.9 | 682.9 | 679.4 |

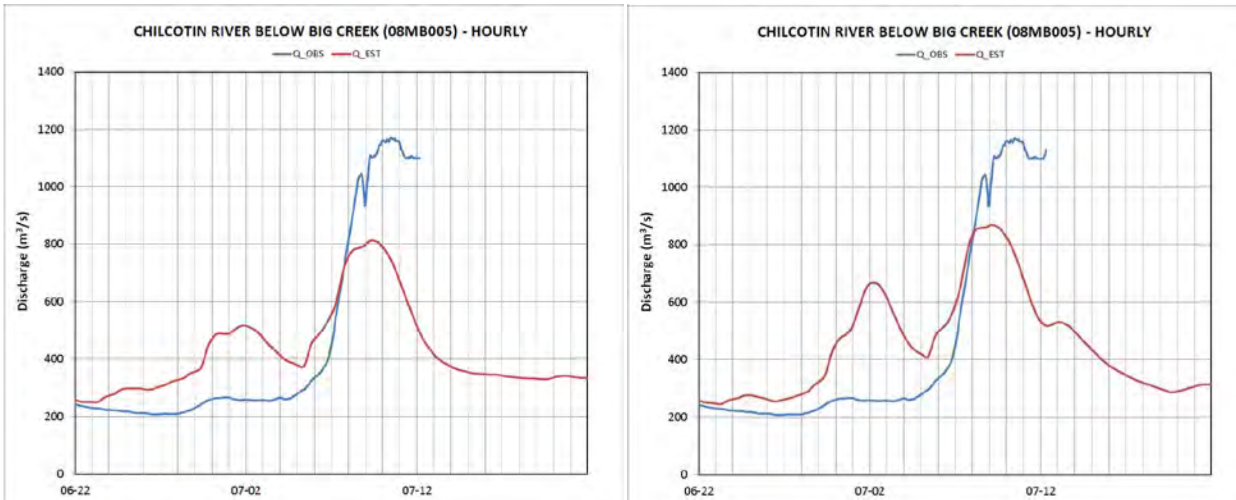
| Color Scheme for Return Periods: | RTP=1Y | RTP=2Y | RTP=5Y | RTP=10Y | RTP=20Y | RTP=50Y | RTP=100Y | 2012 Peak |
|---|---|---|---|---|---|---|---|---|
| | 236.5 | 328.1 | 415.5 | 493.1 | 586.7 | 744.1 | 896.3 | 440.0 ($m^3/s$) |

Figure 37. Model forecast for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) on July 11, 2019

## 4.9 Model forecast on July 12, 2019

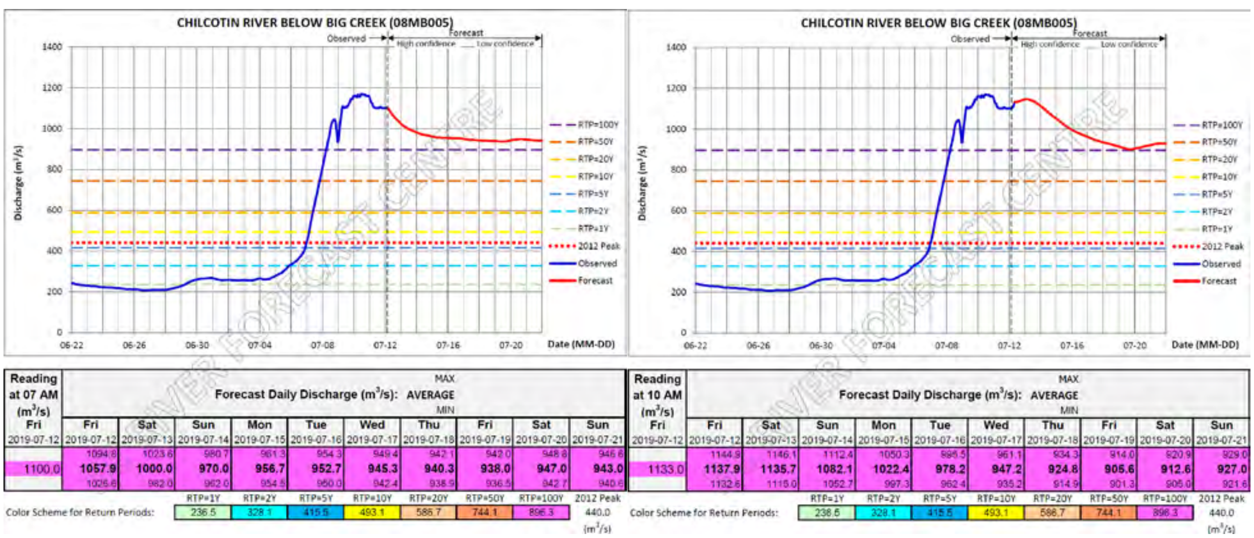
On July 12, 2019, the provisional discharge data for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) maintained at an extremely high level (greater than 1100 $m^3/s$). In stead of showing a trend of dropping, the provisional discharge even rose slightly after the rainfall event ended. It was very difficult to calibrate the model so that the estimated hydrograph followed this trend. Figure 38 (a) and (b) shows the model calibration in the morning and afternoon. In the afternoon calibration (Figure 38 (b)), the early peak (July 2) was overestimated considerably so that the estimated hydrograph showed a the slightly rising trend in the provisional discharge data.

Figure 39 (a) and (b) shows the forecast hydrographs which were published in the morning and afternoon. The Flood Warning was maintained for the Chilcotin River and updated at 10 am July 12, 2019.




(a) Morning calibration (b) Afternoon calibration

Figure 38. Model calibrations in morning and afternoon July 12, 2019



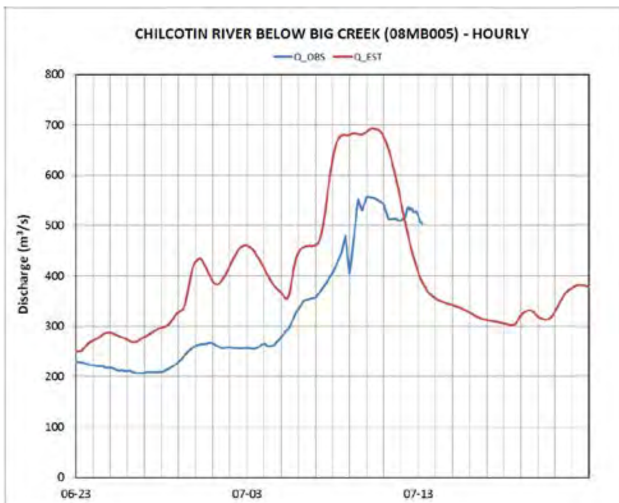

(a) Morning forecast (b) Afternoon forecast

Figure 39. Forecast hydrographs published in morning and afternoon July 12, 2019

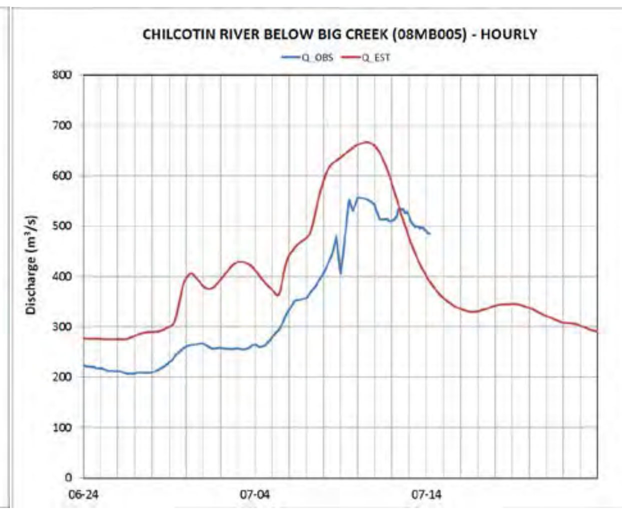
Looking back at Figure 24 (d), it can be seen that at about 4:40 pm July 12, 2019, the peak of the provisional discharge data for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) was artificially plunged from 1170 $m^3/s$ to about 530 $m^3/s$. However, the CLEVER Model was not recalibrated on the same day because that the time was late. The Flood Warning was also maintained.

## 4.10 Model recalibration from July 13 to 16, 2019 after artificial plunge in provisional discharge data

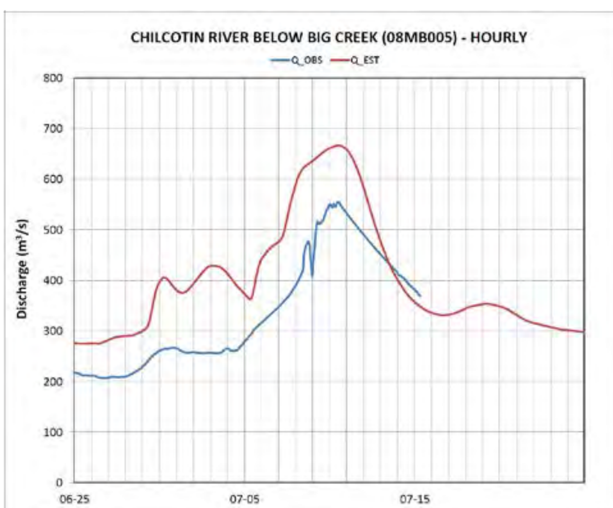
Figure 40 shows the model calibration results for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) from July 13 to 16, 2019 after the artificial plunge from 1170 $m^3/s$ to about 530 $m^3/s$ in the provisional discharge data in the afternoon of July 12, 2019. From this figure, it can be seen that the estimated peaks were about 200 $m^3/s$ higher than the observed provisional ones, even though these were the best calibrated estimations.



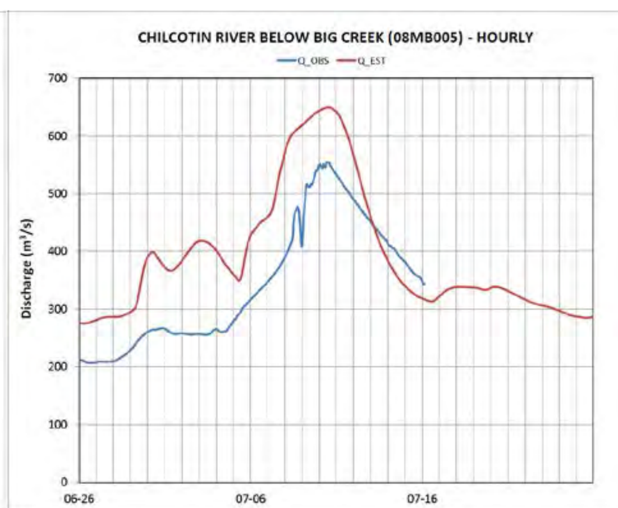

(a) July 13, 2019




(a) July 14, 2019



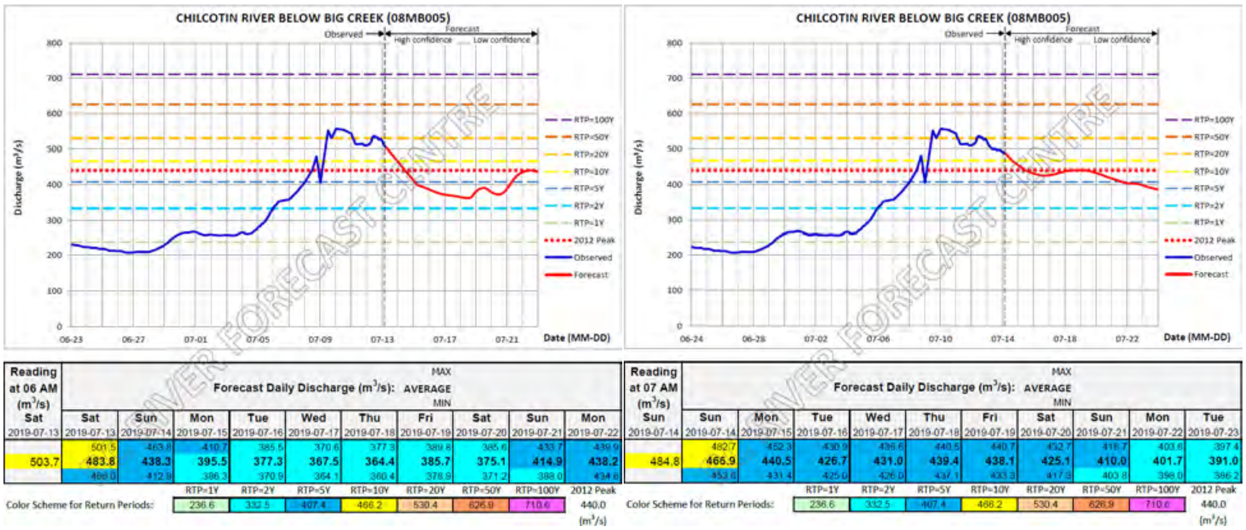

(c) July 15, 2019



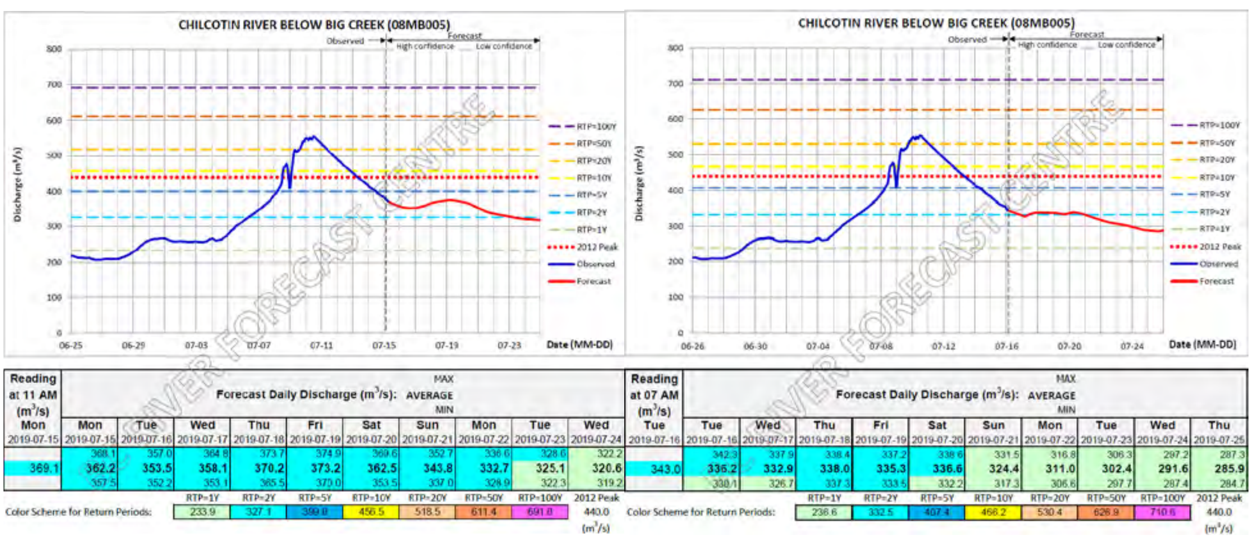

(d) July 16, 2019

Figure 40. Model calibration results for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) from July 13 to 16, 2019 after the artificial plunge in the provisional discharge data

Figure 41 shows the published model forecasts for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) from July 13 to 16, 2019, which are clips from the real-time model outputs. The return periods in Figure 41 (a) to (d) are slightly different. This is the result of a recalculation of the return periods after the flood frequency analysis carried out on July 10, 2019 was abandoned.




(a) July 13 2019 (b) July 14 2019




(c) July 15 2019 (d) July 16 2019

Figure 41. Published model forecasts for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) from July 13 to 16, 2019

In order to reflect the changes in the provisional discharge data and the model calibration results, as of July 13, 2019, the Flood Warning for the Chilcotin River was downgraded to a High Streamflow Advisory, which was maintained for two more days and then ended on July 16, 2019.

# 5. CLEVER Model estimated flooding hydrograph for CHILCOTIN RIVER BELOW BIG CREEK (08MB005)

## 5.1 Concerns of overestimation and underestimation in provisional discharge for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) during the flooding event

In the CLEVER Model, there is a sophisticated, physically based open channel routing sub-model using the kinematic wave (Luo, 2015). The Chilcotin River is one of the tributaries of the Middle Fraser River. The flow at the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) is routed down to the downstream station, the FRASER RIVER ABOVE TEXAS CREEK (08MF040). Assuming that the observed provisional discharges at the FRASER RIVER ABOVE TEXAS CREEK (08MF040) and its upstream station, the FRASER RIVER NEAR MARGUERITE (08MC018), are correct, any errors present in the discharge at the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) will propagate downstream to and be shown at the FRASER RIVER ABOVE TEXAS CREEK (08MF040).

During the flooding event, the CLEVER Model calibration at the FRASER RIVER ABOVE TEXAS CREEK (08MF040) suggested that the WSC provisional discharge peak at the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) might include a large overestimation (about 350 $m^3/s$ or 40%) when the provisional discharge peak was artificially bumped up to 1170 $m^3/s$ from July 9 to July 12, 2019, and a large underestimation (about 250 $m^3/s$ or 30%) when the provisional peak was artificially cut to 530 $m^3/s$ from 1170 $m^3/s$ in the afternoon of July 12, 2019.

These concerns of overestimation and underestimation at the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) in the provisional discharge data were communicated and discussed back and forth between the River Forecast Centre and WSC from July 10 to 12, 2019.

## 5.2 Stations and channel links involved in open channel routing for estimation

From the previous section (Section 4), it was difficult to obtain the real flooding hydrograph at the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) and it was also difficult to find out the real peak and peaking time for this flooding event in early July 2019. In this section, the CLEVER Model was used to reconstruct the most-close-to-real hydrograph for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) from July 1 to July 30, 2019, which covers the entire period of the flooding event.

Figure 42 shows a Google map of the relative locations of the flow stations and channel links that were involved in the open channel routing to estimate a flooding hydrograph for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005). These stations include the fake station, CHILKO RIVER NEAR REDSTONE (08MA001), BIG CREEK ABOVE GROUNDHOG CREEK (08MB006), CHILCOTIN RIVER BELOW BIG CREEK (08MB005), FRASER RIVER NEAR MARGUERITE (08MC018), FRASER RIVER AT BIG BAR CREEK (08MD013), which was added on August 19, 2019 for the purpose of the Big Bar landslide management, and FRASER RIVER ABOVE TEXAS CREEK (08MF040).

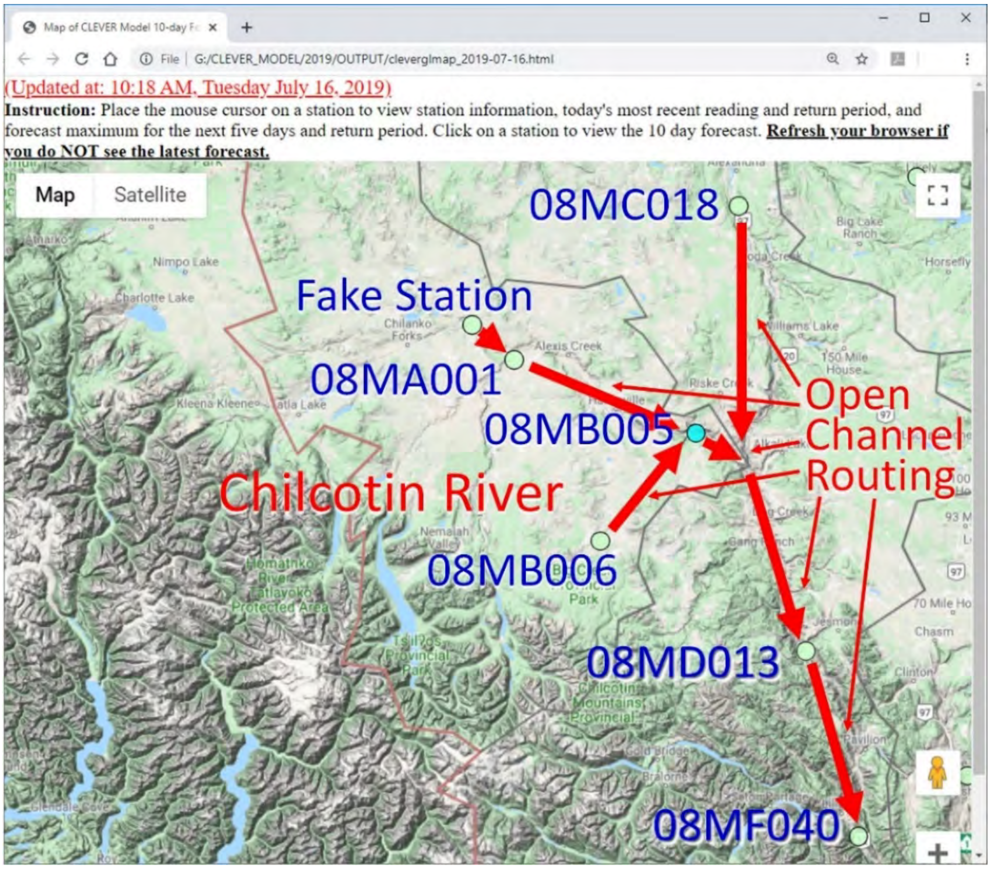



Figure 42. Locations of flow stations and channel links (thick red arrows) involved in open channel routing for estimation of flooding hydrograph for CHILCOTIN RIVER BELOW BIG CREEK (08MB005)

## 5.3 Methodology

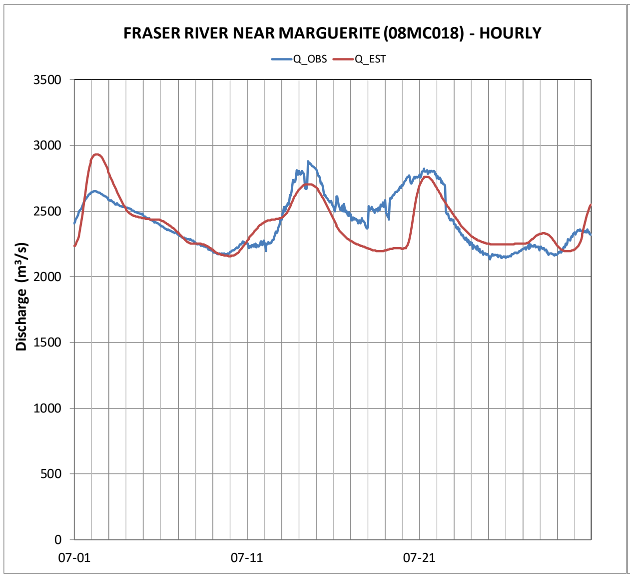
This estimation includes two steps.

Step 1: Estimate a flooding hydrograph for the fake station.

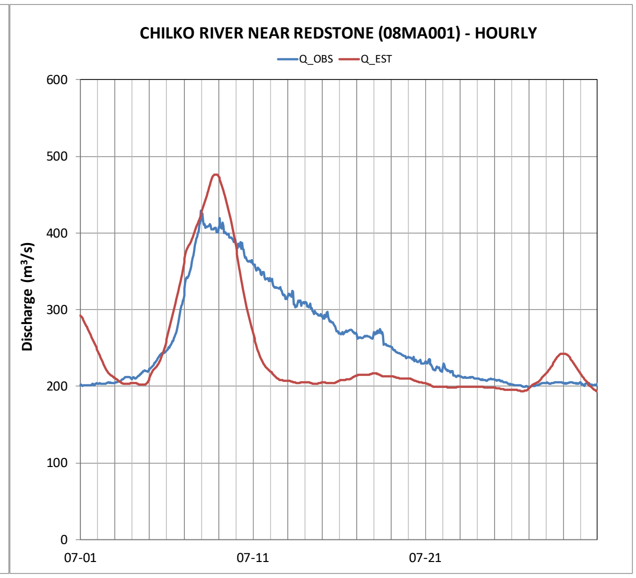
In the CLEVER Model, there was a fake station, the CHILCOTIN RIVER ABOVE CHILKO RIVER, for the Chilcotin River watershed, which had no observed discharge data. In order to estimate the flooding hydrograph for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005), a flooding hydrograph must be first estimated for the fake station.

In this step, the CLEVER Model was run and calibrated for the following related WSC stations, the CHILKO RIVER NEAR REDSTONE (08MA001), BIG CREEK ABOVE GROUNDHOG CREEK (08MB006), FRASER RIVER NEAR MARGUERITE (08MC018), FRASER RIVER AT BIG BAR CREEK (08MD013) and FRASER RIVER ABOVE TEXAS CREEK (08MF040), but did not calibrated for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) because that the provisional discharged data for this station was assumed incorrect.

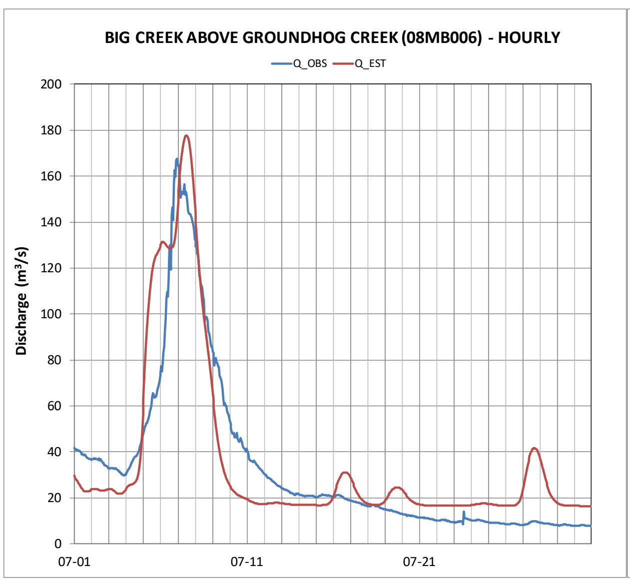
Figure 43 (a) to (f) shows the model calibrations for the above WSC stations and the estimated hydrograph for the fake station CHILCOTIN RIVER ABOVE CHILKO RIVER.



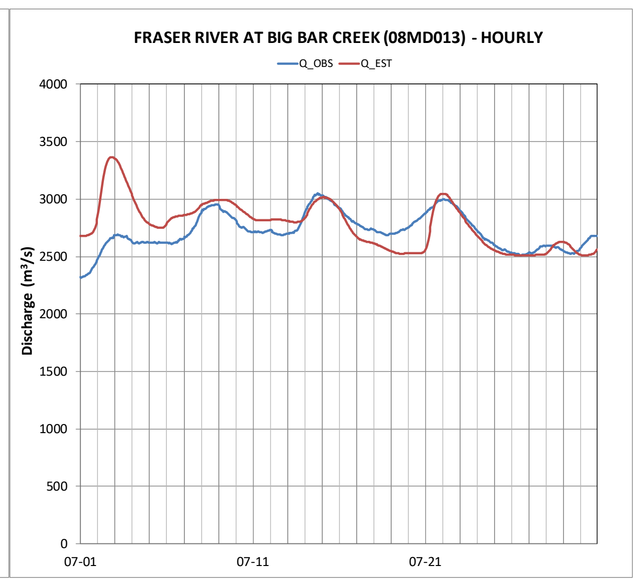

(a) FRASER RIVER NEAR MARGUERITE (08MC018)




(b) CHILKO RIVER NEAR REDSTONE (08MA001)

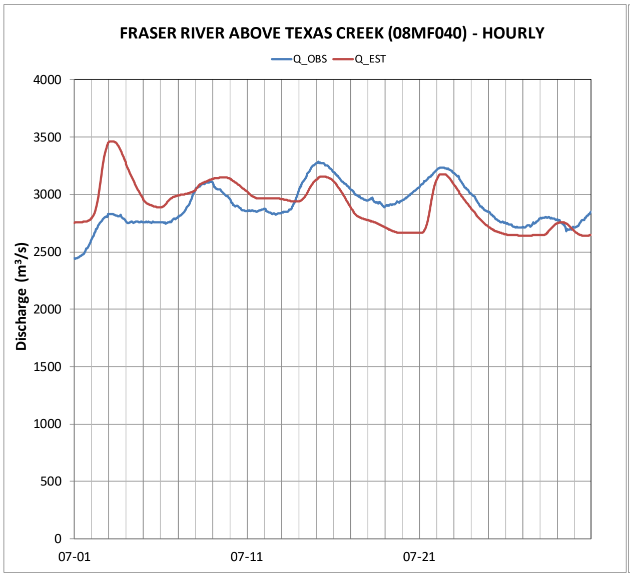


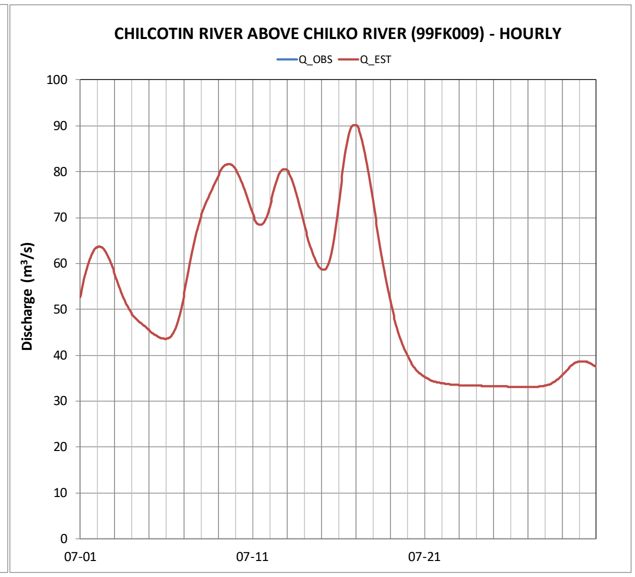

(c) BIG CREEK ABOVE GROUNDHOG CREEK (08MB006)




(d) FRASER RIVER AT BIG BAR CREEK (08MD013)

Figure 43. Model calibrations for related WSC stations and estimated hydrograph for the fake station (to be continued on next page) (Note: Observed provisional discharge data as of July 30, 2019)




(e) FRASER RIVER ABOVE TEXAS CREEK (08MF040) (f) FAKE STN - CHILCOTIN RIVER ABOVE CHILKO RIVER

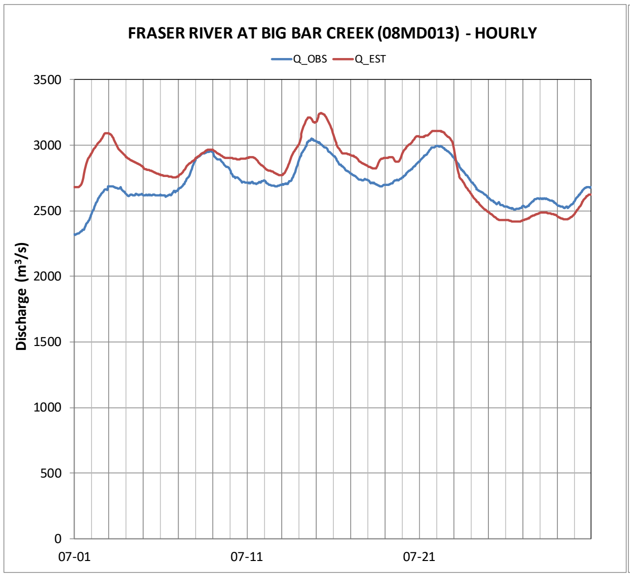
Figure 43. Model calibrations for related WSC stations and estimated hydrograph for the fake station (continued) (Note: Observed provisional discharge data as of July 30, 2019)

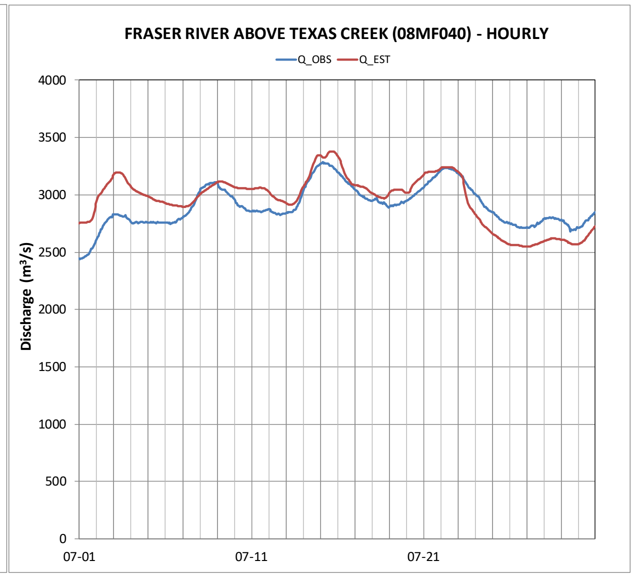
Step 2: Estimate the flooding hydrograph for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005).

In this step, the model estimated discharges were replaced by the observed provisional discharges for the following three stations, the FRASER RIVER NEAR MARGUERITE (08MC018), CHILKO RIVER NEAR REDSTONE (08MA001), and BIG CREEK ABOVE GROUNDHOG CREEK (08MB006). The observed provisional discharges for the above three stations were assumed correct. The model estimated discharge for the fake station CHILCOTIN RIVER ABOVE CHILKO RIVER was maintained because that there was no observation for the fake station.

With the above change to the discharge data, the watershed routing sub-model of the CLEVER Model was rerun for the sub-basin of the CHILCOTIN RIVER BELOW BIG CREEK (08MB005). The drainage area of this sub-basin excludes the drainage areas of the two upstream stations, the CHILKO RIVER NEAR REDSTONE (08MA001) and BIG CREEK ABOVE GROUNDHOG CREEK (08MB006). And the open channel routing sub-model for the channel links shown in Figure 42 was also rerun. The model was recalibrated so that the estimated hydrographs for the two downstream stations of the Middle Fraser River, the FRASER RIVER AT BIG BAR CREEK (08MD013) and FRASER RIVER ABOVE TEXAS CREEK (08MF040), fitted best the observed provisional discharges. The estimated hydrograph for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) was obtained from the recalibration of the CLEVER Model in this step.

Figure 44 shows the estimated and observed provisional hydrographs for the two downstream stations in the Middle Fraser River. From this figure, it can be seen that the estimated hydrograph for the FRASER RIVER ABOVE TEXAS CREEK (08MF040) fits the observation better than it does in Figure 43 (e), even though the estimated hydrograph for the FRASER RIVER AT BIG BAR CREEK (08MD013) was overestimated slightly in the middle part of the hydrograph.




(a) FRASER RIVER AT BIG BAR CREEK (08MD013) (b) FRASER RIVER AB TEXAS CREEK (08MF040)

Figure 44. Estimated and observed hydrographs for FRASER RIVER AT BIG BAR CREEK (08MD013) and FRASER RIVER ABOVE TEXAS CREEK (08MF040)

## 5.3 Result of CLEVER Model estimated flooding hydrograph

Figure 45 shows the estimated flooding hydrograph for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) from July 1 to July 30, 2019. In the figure, this estimated hydrograph is plotted with the provisional discharge data for this station which was downloaded on December 7, 2019 and the return periods for comparison.

Figure 45 shows that the estimated peak is 713.5 $m^3/s$, which is a flow slightly greater than the 100-year return period flow (691.8 $m^3/s$), and which surpasses the historical maximum (699.8 $m^3/s$) recorded in 1991. Comparing with the observed provisional discharge downloaded from the WSC real-time hydrometric data site on December 7, 2019, the CLEVER Model estimated discharge during the flooding period (July 7 to 16, 2019) is about 100 $m^3/s$ higher than the observed provisional discharge. The estimated peak is 90 $m^3/s$ smaller than the observed provisional peak and comes about one day later.

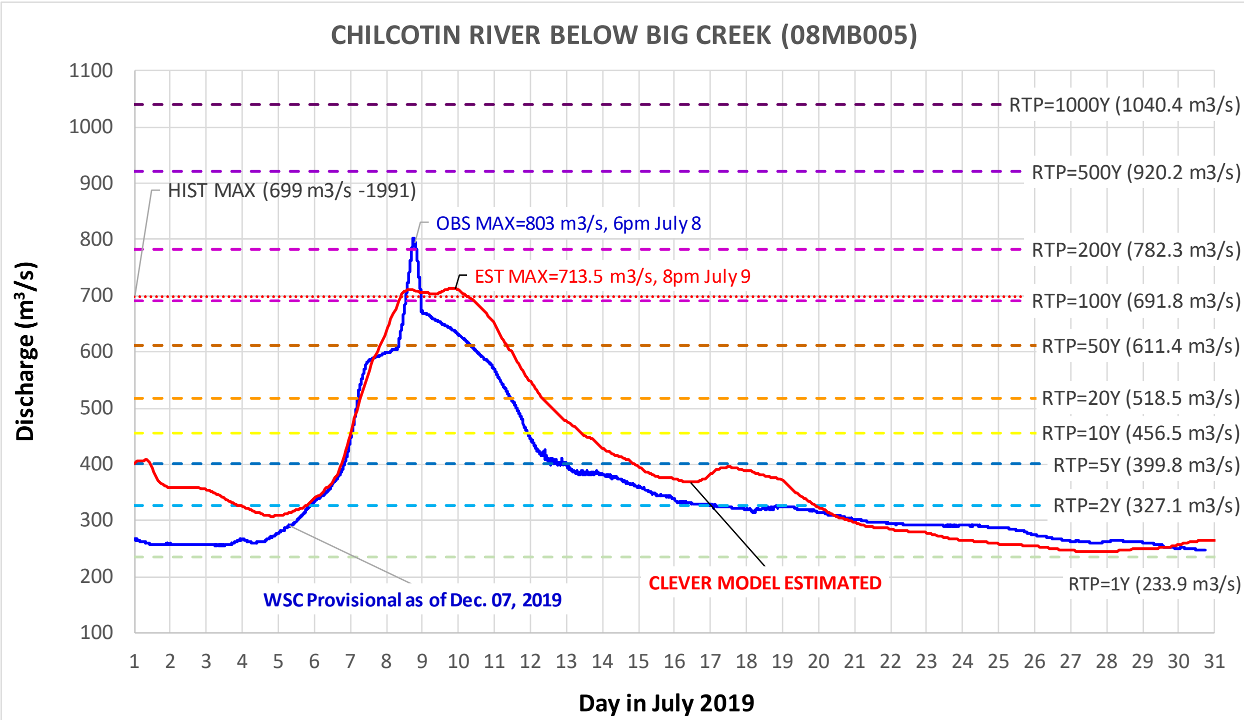



Figure 45. CLEVER Model estimated hydrograph (red line) for CHILCOTIN RIVER BELOW BIG CREEK (08MB005) from July 01 to July 30, 2019

# 6. Long-term model improvements

After the flooding event in the Chilcotin River in early July 2019, upgrading the CLEVER Model had been planned for the 2020 freshet. The current CLEVER Model was improved in two aspects: (1) massively increasing the number of modeled WSC hydrometric stations, and (2) allowing to export forecast for a single station or several related stations.

## 6.1 Massively increasing number of modeled WSC hydrometric stations

In order to avoid temporarily adding stations to the model when a severe flooding event is emerging or occurring, the number of WSC hydrometric stations included in the CLEVER Model has been massively increased, from 110 to 247 or by 134%, leaving no large gaps in most of the watersheds in the province. The new station list also includes four new stations for the Chilcotin River Watershed, CHILKO RIVER AT OUTLET OF CHILKO LAKE (08MA002), TASEKO RIVER AT OUTLET OF TASEKO LAKES (08MA003), BIG CREEK BELOW GRAVEYARD CREEK (08MB007) and CHILCOTIN RIVER NEAR HANCEVILLE (08MB012), which is a newly installed station to replace the CHILCOTIN RIVER BELOW BIG CREEK (08MB005).

Figure 46 shows a MapHub map with all the WSC hydrometric stations modeled in the CELVER Model for the 2020 freshet, which was updated on April 24, 2020.

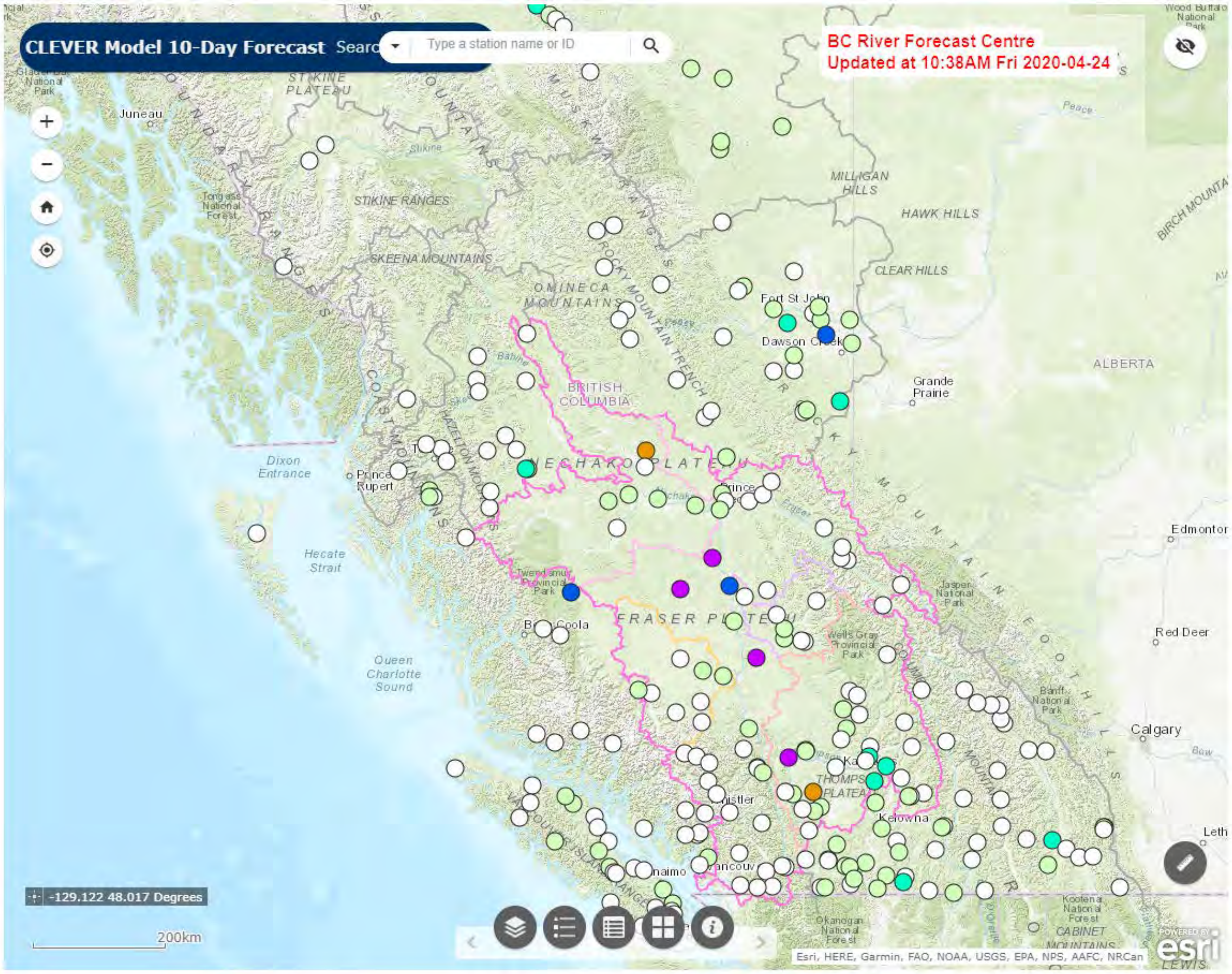



Figure 46. Map of CLEVER Model for 2020 freshet with all modeled WSC hydrometric stations updated on April 24, 2020

The WSC had decided to remove the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) and relocated it about 36 km upstream. The newly installed station was renamed as the CHILCOTIN RIVER NEAR HANCEVILLE (08MB012). However, the CLEVER Model for the 2020 freshet includes both the old and new stations for better model calibrations. The return periods for the new station were estimated from the those for the old station. And the “observed discharge” for the inactive old station is estimated by using the discharge data from the upstream new station CHILCOTIN RIVER NEAR HANCEVILLE (08MB012) and the other upstream station BIG CREEK ABOVE GROUNDHOG CREEK (08MB006).

## 6.2 Allowing to export forecast for a single station or several related stations

The old version of the CLEVER Model allowed users to recalibrate a single station but did not allow users to export the forecast for a single station due to the complication of the post-processing procedure. The upgraded CLEVER Model allows users to export the forecast for a single station or together with several other stations that are related to each other, such as stations within the same sub-basin, all the downstream stations of a specific station, or stations in the same group, before or after the forecast for all stations has been exported.

This is extremely useful when a specific watershed is under critical (flooding) conditions and a much urgent forecast is anticipated. Without going through all the other watersheds, the users may calibrate this watershed only and export and post the forecast for this watershed in a much shorter time. This is also useful when the users find that one or some of the watersheds require further calibrations after the forecast for all stations has been exported. The users can recalibrate these watersheds and re-export the latest forecast for these limited number of stations in a much shorter time.

# 7. Summary

Starting from the analysis of the precipitation and the hydrologic natures of the flooding event, this study attempted to review this complex flooding event occurred in the Chilcotin River watershed in early July 2019 from the perspective of hydrologic modeling efforts in the River Forecast Centre.

## 7.1 Complexity of the flooding event

The flooding event occurred in the Chilcotin River watershed in early July 2019 was very complex because of the following reasons:

(1) The maximum 24-hour rainfall recorded during the flooding event was 38 mm, which was a moderate rainfall only.

(2) There was no rainfall IDF analysis available for the climate stations located in the Chilcotin River watershed, thus it was difficult to determine the relative intensity of the rainfall amounts.

(3) The CHILCOTIN RIVER BELOW BIG CREEK (08MB005), which was the only WSC hydrometric station located in the Chilcotin River watershed that was modeled by the CLEVER Model, did not report discharge data correctly, and onsite measurements were difficult during the flooding event.

(4) The provisional discharge data for the CHILCOTIN RIVER BELOW BIG CREEK (08MB005) was significantly artificially adjusted (lifted and lowered) during the flooding event.

## 7.2 Precipitation natures of the flooding event

From the GIS isohyet maps of spatial distribution of rainfall depths, it is clear that the heaviest rainfall occurred in the southeast of the Chilcotin River watershed. Comparing the single-day (24-hour) and the 4-day total rainfall amounts with the long-duration (1- to 4-day) IDF analysis results, it can be determined that the maximum 24-hour rainfall (38 mm) recorded at the Fire Weather station NMI –

NEMIAH (216) is at the 10-year return period level only and is not the maximum historical record. The the maximum 4-day total rainfall (94.6 mm) recorded at the same Fire Weather station is at the 50-year return period level and is the maximum historical record. This 4-day total rainfall amount reflects climate change impacts and the severity of this flooding event.

## 7.3 Hydrometric natures of the flooding event

Comparing the provisional discharge data with the flood frequency analysis results, it is also clear that no flood was recorded at the three upstream stations located in the west of the Chilcotin River watershed, the TASEKO RIVER AT OUTLET OF TASEKO LAKES (08MA003), CHILKO RIVER AT OUTLET OF CHILKO LAKE (08MA002) and LINGFIELD CREEK NEAR THE MOUTH (08MA006). Out of the three stations, only the TASEKO RIVER AT OUTLET OF TASEKO LAKES (08MA003) recorded a flat peak at about the 2-year return period level. However, the downstream station of these three stations, the CHILKO RIVER NEAR REDSTONE (08MA001), recorded a flood between the 20- to 50-year return periods. The Big Creek located in the east of the Chilcotin River watershed also experienced severe flooding. The BIG CREEK BELOW GRAVEYARD CREEK (08MB007) recorded a peak at about the 10-year return period level, and the BIG CREEK ABOVE GROUNDHOG CREEK (08MB006) recorded a flood between the 50- and 100-year return periods. The CHILCOTIN RIVER BELOW BIG CREEK (08MB005) was not functioning properly during the flooding event. However, the latest WSC provisional discharge data (as of December 7, 2019) included a peak of 803 $m^3/s$, which is a flood between the 200- and 500-year return periods.

## 7.4 Immediate modeling efforts during the flooding event

The CHILCOTIN RIVER BELOW BIG CREEK (08MB005) was the only WSC hydrometric station that was modeled by the CLEVER Model during the flooding event. The station was not functioning properly during the flooding event, and the observed provisional discharge data recorded at this station was modified and artificially lifted and then lowered significantly. This artificial treatment to the observed provisional discharge data posed incredible uncertainties and difficulties for the real-time operational flood forecasting.

Faced with these incredible uncertainties and difficulties, the River Forecast Centre staff had used their best professional judgements to try their best to produce timely and reasonable flood forecasts for the public. They had made tremendous efforts to calibrate the model, change the model calibration strategy when necessary and improve the model immediately. From Sunday July 7 to July 16, 2019, the daily flood forecast and Flood Warnings/Watches and/or High streamflow Advisories were issued/ updated by 10:40 am each day and as early as 10 am some days.

## 7.5 Modeling efforts and long-term improvements after the flooding event

In order to have a better image of the early July 2019 Chilcotin River flood, the CLEVER Model, which has a physically based sub-model for open channel routing, was used to reconstruct a most-close-real estimation of hydrograph for the flooding event. The estimated peak of the flooding event is 713.5 $m^3/s$, which is a flow slightly over the 100-year return period flow (691.8 $m^3/s$), and which surpasses the historical maximum (699.8 $m^3/s$) recorded in 1991.

The CLEVER Model has been upgraded for the 2020 freshet. In the upgraded model, the number of modeled WSC hydrometric stations has been massively increased, from 110 to 247 or by 134%, leaving no large gaps in most of the watersheds in the province. The new station list also includes four new stations for the Chilcotin River watershed. A new tool has also been built in the upgraded model to allow users to export the forecast for a single station or several related stations.

# References

Luo, C., 2015. Technical Reference for The CLEVER Model – A Real-time Flood Forecasting Model for British Columbia, Technical Report, BC River Forecast Centre.

Stedinger, J.R., Vogel, R.M., Foufoula-Georgiou, E., 1992. Chapter 18 Frequency Analysis of Extreme Events, in: Maidment, D.R. (Ed.), Handbook of Hydrology, McGraw-Hill Inc., pp. 18.1-18.66.

# Appendix A: Long-duration (1- to 4-day) IDF analysis for climate stations located in and close to Chilcotin River watershed

(In the separate PDF file “ChilcotinFlood2019July_AppA_IDF.pdf”)

# Appendix B: Flood Frequency analysis for WSC hydrometric stations located in Chilcotin River watershed

(In the separate PDF file “ChilcotinFlood2019July_AppB_RTP.pdf”)