Clearwater River Watershed Flood Frequency Analysis

Technical Memorandum ENV-2021-048

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Clearwater River Watershed Flood Frequency Analysis

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I. Introduction

This document is prepared at the request of the Sedimentation and River Hydraulics Group and summarizes the Flood Frequency Analysis (FFA) along Clearwater River in Washington at fifteen locations of interest (Figure 1). Specifically, the key deliverables are 1) peak discharge annual exceedance probabilities (AEPs) ranging from 1/2 to 1/50 (2-yr to 50-yr) for each of the fifteen locations and 2) monthly summary statistics for the USGS gage 12040000 (Clearwater River near Clearwater, Washington).

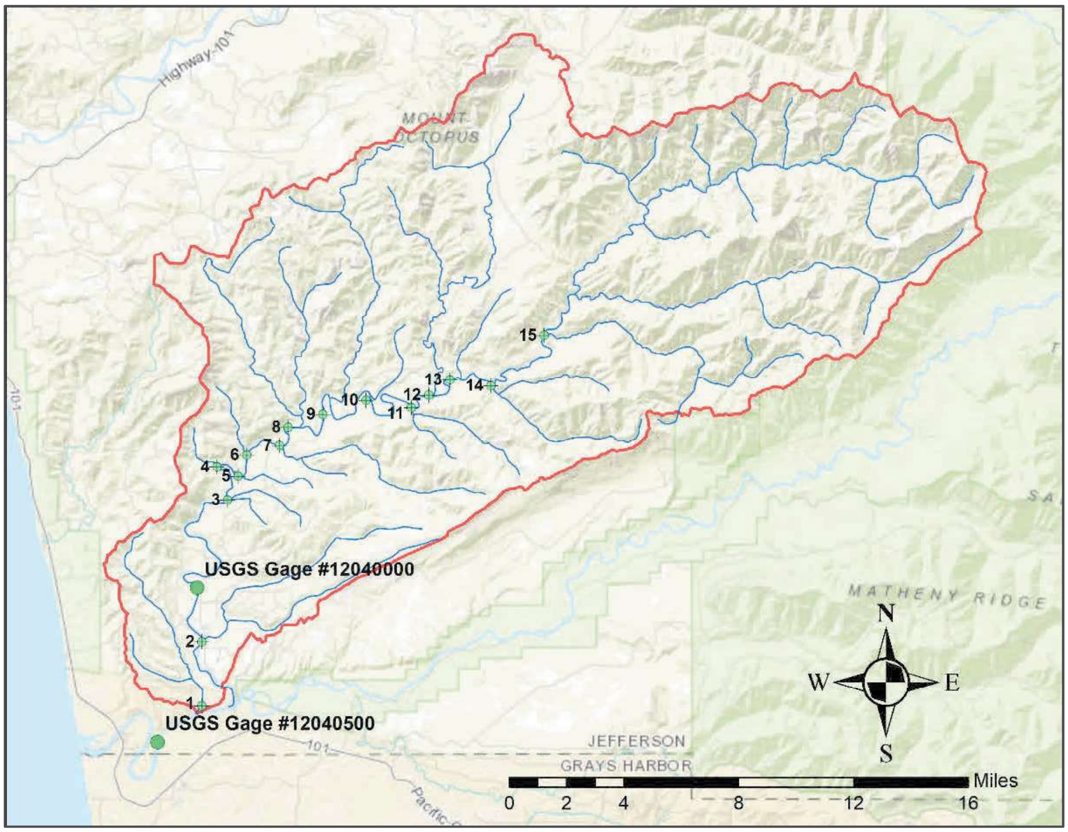

Figure 1 – Clearwater River watershed, Washington showing the location of the USGS gage 12040000 and the fifteen locations of interest.

The basis of the FFA is derived from annual peak discharge records from USGS gages 12040000 (Clearwater River near Clearwater, Washington – referred herein as the Clearwater River gage) and 12040500 (Queets River near Clearwater, Washington – referred herein as the Queets River gage). Peak discharge AEPs at the Clearwater River gage are calculated using methods outlined in USGS Bulletin 17C (England, et al., 2018). Peak discharge AEPs at the fifteen locations of interest are calculated using regional regression equations, unique for Washington, provided by USGS Scientific Investigation Report 2016-5118 (Mastin et al., 2016, referred herein as USGS SIR 2016-5118). The AEP peak discharge quantiles are further refined by weighting the Bulletin 17C AEP quantiles at Clearwater River gage and the AEP quantiles estimated using USGS SIR 2016-5118.

II. Watershed Characteristics

The Clearwater watershed, in the Olympic Peninsula of Washington State, has a drainage area of 156 mi^2 measured from its confluence at Queets River. Elevations in this watershed range from 26 feet at the confluence of Queets River to 3,800 feet in the mountains along the eastern boundary. Rainfall in the watershed tends to increase eastward approaching the windward faces of the Olympic mountains. The watershed receives an expected 133 inches of precipitation annually (Figure 2, PRISM Climate Group, 2012).

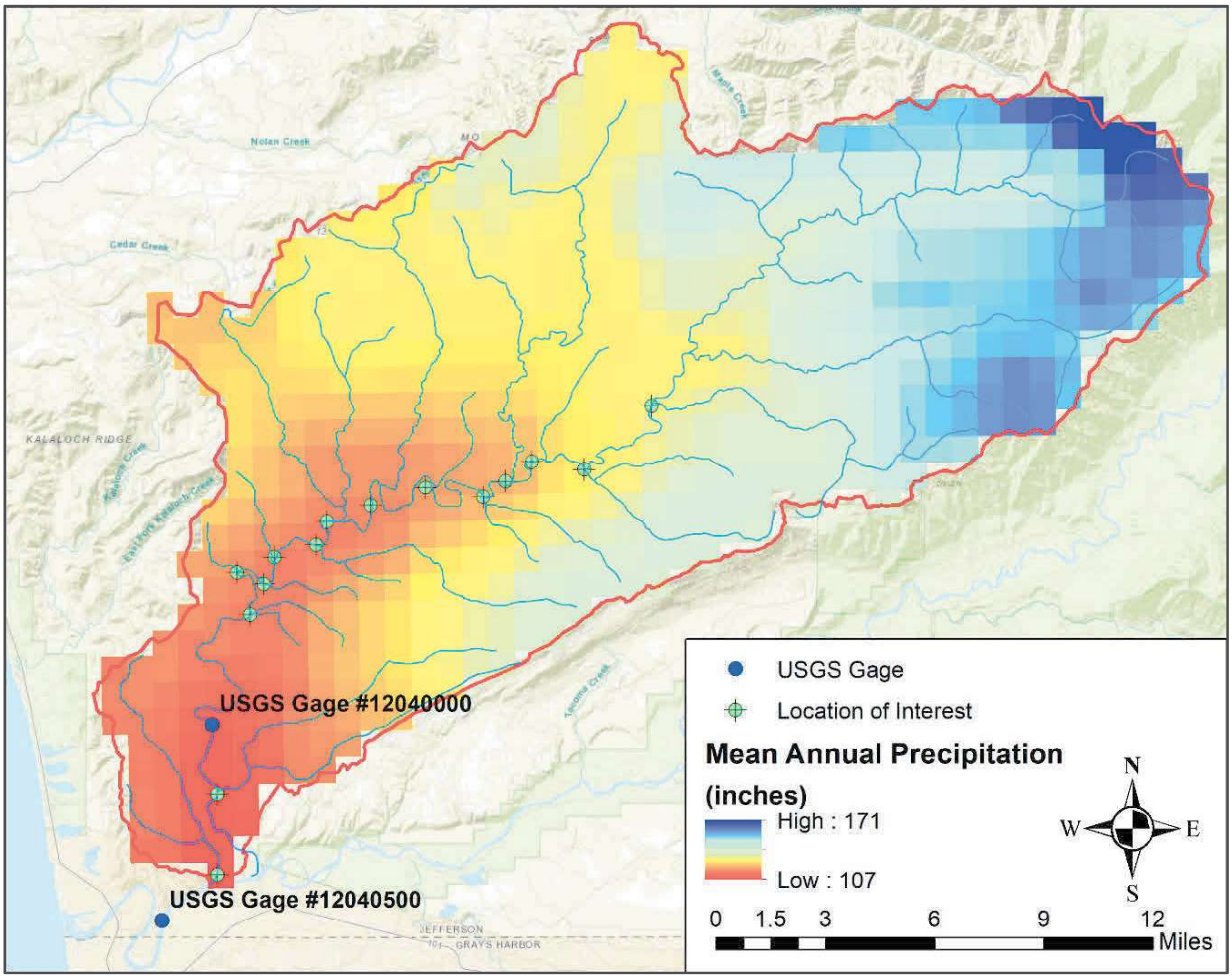

Figure 2 – Map showing mean annual precipitation estimates for Clearwater River Watershed.

Most annual peak flows in the Clearwater River watershed occur during winter months between November and January as a result of runoff from rainfall and rainfall-induced snowmelt (Mastin, et al., 2016). Figure 3 presents a monthly distribution of peak floods recorded at both Clearwater River and Queets River gages.

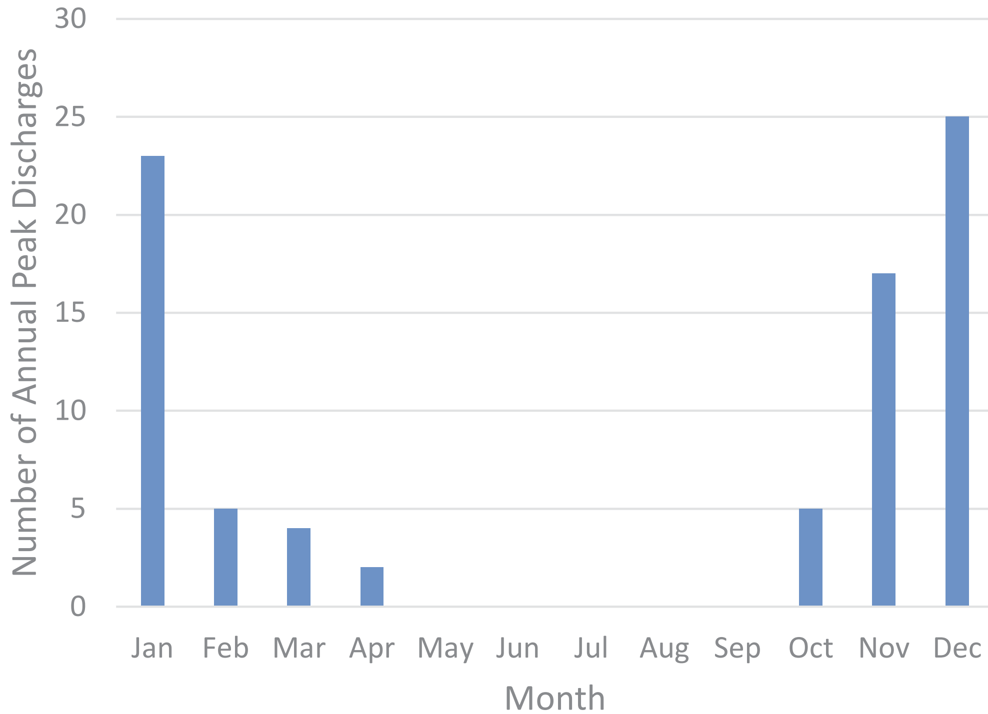

Figure 3 – Monthly distribution of historic peak floods recorded the Clearwater River and Queets River gages.

The contributing area for each location of interest (Figure 4) was delineated using ArcGIS with USGS 30 meter DEM data. These delineations were used to compute mean annual precipitation using PRISM data (PRISM Climate Group, 2012). Table 1 presents mean annual precipitation data for each location of interest.

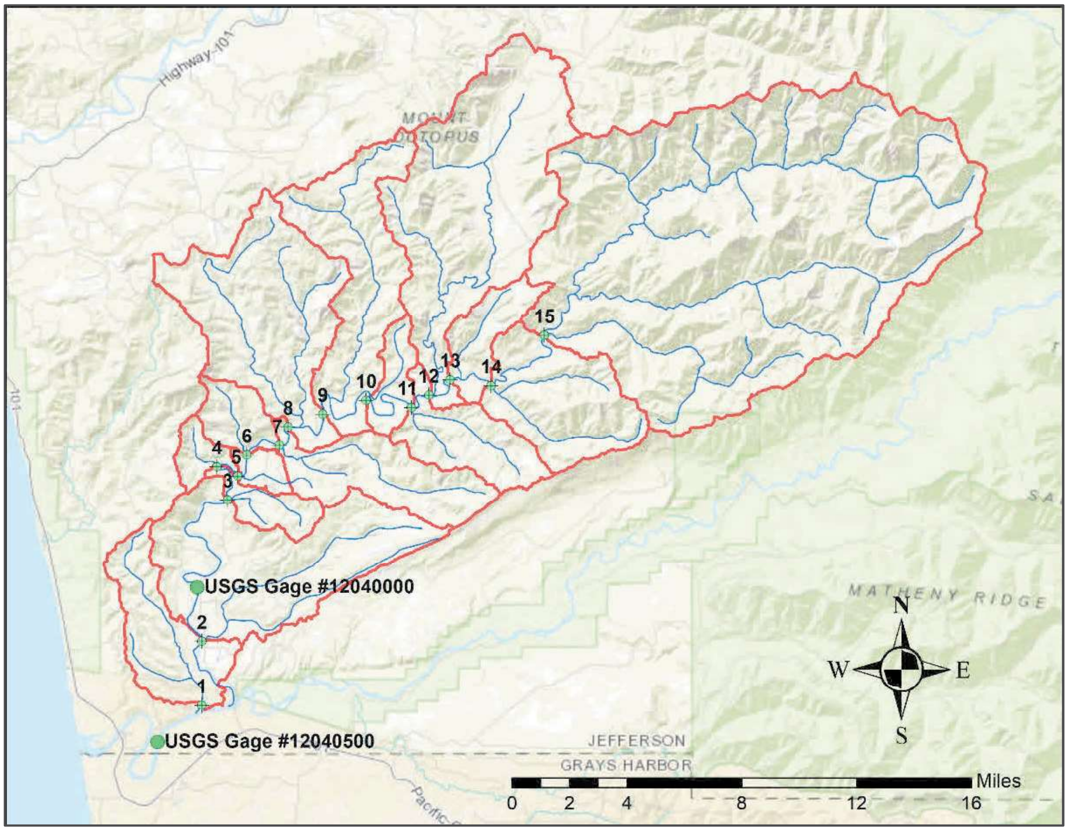

Figure 4 – Map showing contributing areas for each location of interest along the Clearwater River.

Table 1 – Contributing area and mean annual precipitation for locations of interest including the Clearwater River gage

Location of Interest	Area (mi^2)	Mean Annual Precipitation (inches)
1	157	133.4
2	151	134.3
3	136	136.0
4	134	136.2
5	133	136.4
6	132	136.6
7	129	136.9
8	123	137.4
9	109	139.2
10	98	140.8
11	96	141.1
12	91	141.7
13	71	145.0
14	67	145.9
15	59	147.3
Clearwater River Gage	140	135.2

III. Analysis

A. Data Sources

The systematic record at the Clearwater River gage contains 31 years of annual peak discharges between 1932 and 1966. The contributing area at this gage location is 140 mi^2. In addition to annual peak discharge records, the Clearwater River gage also recorded average daily flow from 1931 to 1949. The nearby Queets River gage has a contributing area of 445 mi^2 and 82 years of annual peak discharges recorded between 1931 and 2019. Although the Queets River gage recorded average daily flow as well, this analysis only considered annual peak discharges to be independent random variables suitable for augmenting data collected on Clearwater River. Of the 82 years recorded at the Queets River gage, 31 annual records overlap with the Clearwater River gage.

The Washington Division of Natural Resources (WDNR) maintains five streamflow monitoring gages in the Clearwater River watershed: #790, #724, #694, and #737. These gages recorded instantaneous streamflow from 2013 through 2018 on tributaries along the Clearwater River.

The streamflow observations, however, could not be used in this analysis because 1) the period of record observed at these locations was too short and 2) the observations were not on the main stem of Clearwater River.

B. Clearwater River Record Extension

In order to improve confidence in the FFA for the Clearwater River, the 31 years of annual peak discharge records from the Clearwater River gage were augmented with an additional 51 years of record from the Queets River gage. This was accomplished using the Maintenance of Variance Extension (MOVE.3) method described in USGS Bulletin 17C (England, et al., 2018, Vogel, et al., 1985). The MOVE.3 method uses the following equation to adjust the annual peak discharges recorded at the Queets River gage for substituting missing records at the Clearwater River gage:

$$Q_C = bQ_q^k \qquad (1)$$

Where Q_C is annual peak discharge at the Clearwater River gage and Q_q is the annual peak discharge at the Queets River gage; and b and k are linearly regressed coefficients. Using the overlapping years of record between the two gages, the constants b and k are calculated to be -0.70 and 1.04, respectively, with a strong, positive correlation of 0.93. The MOVE.3 method results in an augmented record at the Clearwater Gage having a total of 82 years of annual peak discharge records between 1931 and 2019. These records are presented in Figure 5.

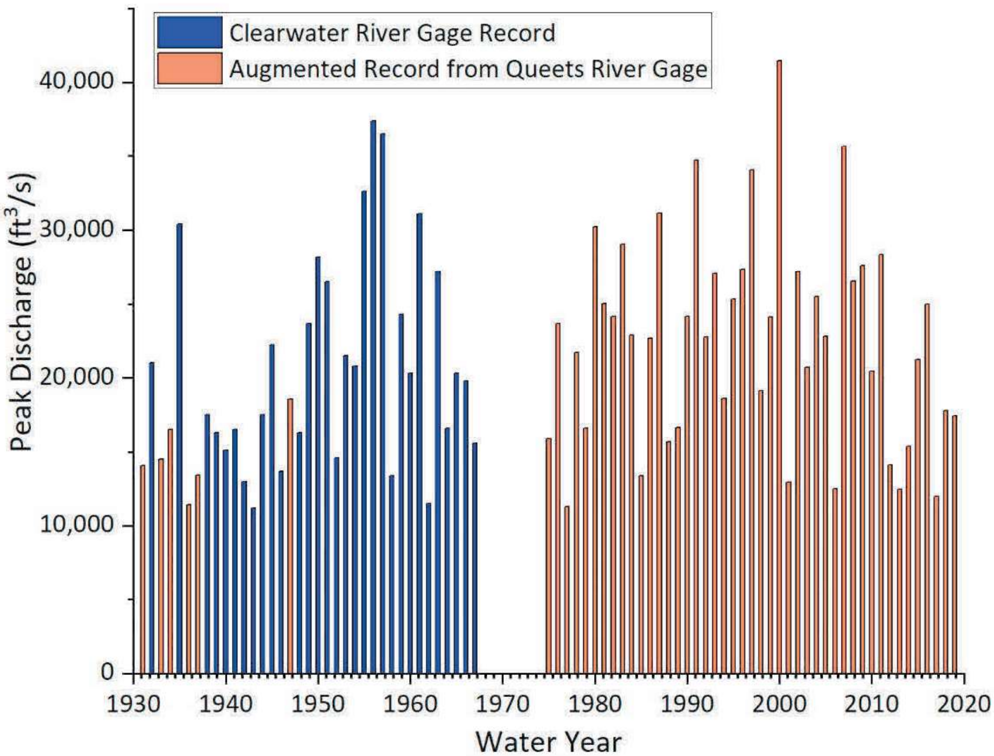

Figure 5 – Annual peak discharge records at the Clearwater River gage augmented with annual peak discharge records from the Queets River gage.

C. Bulletin 17C Peak Discharge Frequency Analysis (EMA)

AEP quantiles for the Clearwater River gage location were calculated using methods outlined in USGS Bulletin 17C (England, et al., 2018). Both the original gage record and the augmented gage record, described in section III.B, were analyzed. Bulletin 17C applies the Expected Moments Algorithm (EMA) (Cohn et al. 1997) to compute the first three expected moments using systematic records and non-exceedance thresholds. EMA assumes a Log-Pearson Type III (LP3) distribution describes the annual peak discharges and uses the calculated three moments, mean, standard deviation, and skew coefficient, to calculate the LP3 distribution parameters. The computer program PeakfqSA (Cohn, 2012) was used to apply methods outlined in Bulletin 17C for computing AEP quantiles for the augmented record at the Clearwater River gage. A non-exceedance "perception" threshold of 20,700 ft^3/s, the median value of the augmented record at the Clearwater River gage, was assumed. This "perception" threshold represents an annual peak discharge that would have needed to be exceeded to be included in the systematic record for missing years. The third moment, skew coefficient, was weighted using a regional skew of -0.07 and its mean square error (MSE) of 0.18, as recommended by USGS SIR 2016-5118 (Mastin et al., 2016). The resulting moments computed using PeakfqSA are a log-mean of 4.2986, a log-standard deviation of 0.1428, and a skew coefficient of 0.0445. Peak discharge AEP quantiles computed using PeakfqSA are presented in Table 2.

Table 2 – Peak discharge AEP quantile estimates with 90% confidence intervals for the augmented record at Clearwater River Gage. Median estimates using original (not augmented) gage record provided for comparison

Return Period (year)	Peak Discharge (augmented record) (ft^3/s)			Peak Discharge (original gage record) (ft^3/s)	Median Difference (ft^3/s)
	Median	Lower 90%	Upper 90%	Median	
2	19,800	18,700	21,100	19,900	-100
5	26,200	24,600	28,200	26,400	-200
10	30,400	28,200	33,200	30,600	-200
25	35,500	32,500	40,200	35,900	-400
50	39,400	35,500	45,900	39,800	-400

As a comparison, peak discharge AEP median quantiles, computed using only the recorded annual peak discharges at the Clearwater River gage and the regional skew coefficient of -0.07 with a MSE of 0.18, are presented in Table 3. When compared to the peak discharge AEP quantiles calculated for the Clearwater River gage without augmented records from Queets River gage, the difference in discharges is 1% and less. To simplify this analysis, peak discharge AEP quantile estimates from the not augmented gage analysis will be used for weighting with estimates from the regional regression equations discussed in Section D.

D. Peak Discharge Frequency Analysis using Regional Regression Equations

For locations without gage record, AEP quantiles can be estimated using regional regression equations presented in USGS SIR 2016-5118. This report specifies the following equation, for locations in Region 4 (defined in figure 20 of USGS SIR 2016-5118) can be used to estimate peak discharge AEP quantiles for the fifteen locations of interest (LOI) along the Clearwater River:

$$Q = aA^b 10^{cP} \qquad (2)$$

Where ***Q*** is the peak discharge AEP quantile for a specified LOI, ***A*** is the LOI drainage area (in mi^2), ***P*** is the mean annual precipitation (in inches), ***a*** is a constant, ***b***, and ***c*** are coefficients. The constant ***a*** and coefficients ***b*** and ***c*** are unique for a specified AEP and are presented in Table 3.

Table 3 – Constant and coefficient values used to calculate AEP peak discharges for locations of interest along the Clearwater River (adapted from USGS SIR 2016-5118)

Return Period (year)	*a*	*B*	*c*
2	15.346	0.911	0.0073
5	29.785	0.913	0.0060
10	42.073	0.915	0.0054
25	60.117	0.918	0.0047
50	75.162	0.920	0.0043

The values presented in Table 3, when applied to the values presented in Table 1, result in estimated peak discharge AEPs presented in Table 4 and Table 5.

Table 4 – Peak discharge AEP quantile estimates at each location of interest along Clearwater River estimated using equations from USGS SIR 2016-5118

Location of Interest	Median Peak Discharge (ft^3/s)				
	2-yr	5-yr	10-yr	25-yr	50-yr
1	14,500	19,000	22,600	26,400	29,500
2	14,200	18,600	22,000	25,700	28,700
3	13,300	17,300	20,500	23,800	26,500
4	13,100	17,100	20,200	23,600	26,200
5	13,100	17,000	20,100	23,400	26,000
6	13,000	16,900	20,000	23,300	25,900
7	12,900	16,700	19,700	22,900	25,500
8	12,400	16,000	18,900	22,000	24,500
9	11,400	14,700	17,300	20,100	22,300
10	10,700	13,700	16,100	18,600	20,600
11	10,500	13,500	15,800	18,300	20,200
12	10,100	13,000	15,200	17,500	19,400
13	8,500	10,800	12,500	14,400	15,900
14	8,300	10,400	12,200	13,900	15,300
15	7,500	9,500	11,000	12,500	13,800

Table 5 – Peak discharge AEP quantile estimates for the Clearwater River gage using regional regression equations from USGS SIR 2016-5118

Location of Interest	Peak Discharge (ft^3/s)				
	2-yr	5-yr	10-yr	25-yr	50-yr
Clearwater River gage	13,400	17,600	20,800	24,200	27,000

A 90% prediction interval (PI) is estimated for the regional regression equations using the following equation:

$$\frac{Q}{T} < Q < QT \qquad (3)$$

Where

$$T = 10^{\left[t_{\left(\frac{\alpha}{2}, n-p\right)} S_i\right]} \qquad (4)$$

The value $\boldsymbol{t}_{\left(\frac{\alpha}{2}, \boldsymbol{n-p}\right)}$ is from a Student's t-distribution with α = 0.10 for 90% prediction intervals with $\boldsymbol{n}$ - $\boldsymbol{p}$ degrees of freedom, and $\boldsymbol{S_i}$ is the standard error of prediction. The standard error is computed using the following equation:

$$S_i = \left[\sigma_\delta^2 + X_i(X^T \Lambda^T X)^{-1} X_i^T\right]^{0.5} \qquad (5)$$

Where $\boldsymbol{\sigma_\delta^2}$ is the model error variance (table 7, USGS SIR 2016-5118), $\boldsymbol{X_i}$ is the row vector starting with the number 1 and followed by the values of the basin characteristics for each location of interest (area and mean annual precipitation), $(\mathbf{X^T \Lambda^T X})^{-1}$ is to covariance matrix for the regional regression equation (table 7, USGS SIR 2016-5118), and $\boldsymbol{X_i^T}$ is the transpose of $\boldsymbol{X_i}$. TAB and TAB present the upper and lower 90% prediction interval peak discharge quantiles for each of the locations of interest.

Table 6 – Lower 90% prediction interval for peak discharge AEP quantile estimates for the Clearwater River gage using regional regression equations from USGS SIR 2016-5118

Location of Interest	Lower 90% PI Peak Discharge (ft³/s)				
	2-yr	5-yr	10-yr	25-yr	50-yr
1	900	1,200	1,300	1,400	1,400
2	800	1,100	1,300	1,300	1,300
3	800	1,000	1,100	1,200	1,200
4	700	1,000	1,100	1,100	1,100
5	700	1,000	1,100	1,100	1,100
6	700	1,000	1,100	1,100	1,100
7	700	1,000	1,100	1,100	1,100
8	700	900	1,000	1,000	1,000
9	600	800	900	900	900
10	600	700	800	800	800
11	500	700	800	800	800
12	500	700	700	800	700
13	400	500	600	600	600
14	400	500	500	500	500
15	300	400	500	500	500

Table 7 - Upper 90% prediction interval for peak discharge AEP quantile estimates for the Clearwater River gage using regional regression equations from USGS SIR 2016-5118

Location of Interest	Upper 90% PI Peak Discharge (ft^3/s)				
	2-yr	5-yr	10-yr	25-yr	50-yr
1	241,400	307,500	384,800	511,100	636,500
2	240,800	306,700	381,800	507,600	632,300
3	233,700	295,500	367,100	488,200	607,200
4	231,100	293,300	365,000	484,200	603,100
5	232,100	292,800	364,700	484,300	603,600
6	231,300	294,000	364,500	484,400	604,100
7	229,200	290,600	361,300	479,300	596,600
8	224,300	283,100	352,200	465,600	579,900
9	214,100	270,200	335,100	442,800	550,300
10	207,800	258,500	320,800	424,700	527,600
11	205,200	256,400	316,800	420,700	521,000
12	199,900	250,000	308,700	407,700	507,400
13	180,900	222,400	274,600	363,700	449,000
14	177,600	218,200	268,800	353,200	441,200
15	166,600	203,700	251,800	330,100	411,200

E. Estimating Peak Discharges at Locations of Interest

The accuracy of the estimated AEP peak discharge quantiles can be increased by weighting the regional regression equation estimates with AEP peak discharge estimates calculated using with EMA using systematic gage records (Mastin et al., 2016). Peak discharge AEP quantile estimates for un-gaged locations, calculated using the regional regression equations from USGS SIR 2016-5118, can be weighted using peak discharge AEP quantile estimates calculated using the gage record and methods outlined in Bulletin 17C. This is achieved using the following equation:

$$Q_{(u)wtd} = \frac{2\Delta A}{A_g} Q_{(u)reg} + \left[1 - \frac{2\Delta A}{A_g}\right] Q_{(u)g} \qquad (6)$$

Where ΔA is the absolute value of the difference between the drainage areas of the gage and the un-gaged location of interest, and $Q_{(u)reg}$ is the peak discharge AEP quantile estimate from the regional regression equation. The streamgage-based estimate for the un-gaged location of interest, $Q_{(u)g}$, can be calculated using the following equation:

$$Q_{(u)g} = \left[\frac{A_u}{A_g}\right]^b Q_{(g)wtd} \qquad (7)$$

Where A_u is the drainage area of the location of interest, A_g is the drainage area of the gage (Clearwater River gage for this analysis), and **b** is the exponent for the regional regression equation listed in Table 3. This equation is only valid if the ratio of A_g/A_u is between 0.5 and 1.5. Locations of interest #14 and #15 both have A_g/A_u ratios of 0.48 and 0.42, respectively and cannot be weighted using equation 6 because the term $\left[1 - \frac{2\Delta A}{A_g}\right]$ becomes a negative value. The weighted estimate of the flood quantile, $Q_{(u)wtd}$, is provided in Table 8 of the USGS SIR 2016-5118 report. Values for the weighted peak discharge AEP quantile estimates for Clearwater River, based on values presented in Table 5, are presented in Table 8.

Table 8 – Weighted peak discharge AEP estimates with 90% confidence interval provided by USGS SIR 2016-5118 for the Clearwater River gage

Return Period (year)	Weighted Peak Discharge (ft^3/s)		
	Median	Lower	Upper
2	19,900	17,600	22,400
5	26,300	22,900	30,200
10	30,500	26,000	35,900
25	35,800	29,400	43,700
50	39,800	31,500	50,100

The streamgage-based estimate for peak discharges for the locations of interest are presented in Table 9. These estimates use the weighted peak discharge estimates from Table 8 and the drainage areas presented in Table 1.

Table 9 – Streamgage-base peak discharge estimates for locations of interest along Clearwater River

Location of Interest	Median Peak Discharge (ft^3/s)				
	2-yr	5-yr	10-yr	25-yr	50-yr
1	22,100	29,200	33,900	39,800	44,200
2	21,300	28,100	32,600	38,300	42,600
3	19,400	25,600	29,700	34,900	38,800
4	19,100	25,300	29,300	34,400	38,200
5	19,000	25,000	29,000	34,100	37,900
6	18,800	24,900	28,800	33,800	37,600
7	18,500	24,500	28,400	33,300	37,000
8	17,600	23,300	27,000	31,700	35,200
9	15,800	20,900	24,200	28,400	31,600
10	14,400	19,000	22,000	25,800	28,600
11	14,100	18,600	21,600	25,300	28,100
12	13,400	17,700	20,600	24,100	26,800
13	10,700	14,100	16,300	19,100	21,200
14	10,200	13,500	15,600	18,300	20,300
15	9,100	12,000	13,900	16,200	18,000

Applying Equation 6 to the values presented in Table 4 and Table 9, weighted peak discharge quantile estimates can be calculated and are presented in Table 10. Similarly, the upper and lower 90% predication intervals of the regional regression equation were weighted with the 90% confidence intervals from the skew-weighted EMA analysis (Table 8). Upper and lower interval values are presented in Table 11 and Table 12.

Table 10 – Weighted median peak discharge quantile estimates for locations of interest along Clearwater River

Location of Interest	Median Peak Discharge (ft^3/s)				
	2-yr	5-yr	10-yr	25-yr	50-yr
1	20,200	26,700	31,100	36,500	40,600
2	20,200	26,700	31,000	36,400	40,500
3	19,100	25,200	29,200	34,300	38,100
4	18,600	24,600	28,500	33,500	37,200
5	18,300	24,200	28,100	33,000	36,700
6	18,100	23,900	27,800	32,600	36,200
7	17,600	23,300	27,000	31,700	35,200
8	16,300	21,500	25,000	29,300	32,600
9	13,900	18,100	21,100	24,700	27,400
10	12,100	15,800	18,400	21,400	23,800
11	11,800	15,400	17,900	20,900	23,100
12	11,100	14,400	16,800	19,500	21,600
13	8,500	10,800	12,600	14,400	15,900
14	N/A	N/A	N/A	N/A	N/A
15	N/A	N/A	N/A	N/A	N/A

Table 11 – Weighted lower 90% interval peak discharge quantile estimates for locations of interest along Clearwater River

Location of Interest	Lower 90% Peak Discharge (ft^3/s)				
	2-yr	5-yr	10-yr	25-yr	50-yr
1	15,000	19,600	22,200	25,100	26,900
2	16,100	20,900	23,700	26,800	28,700
3	16,200	21,100	24,000	27,100	29,100
4	15,500	20,200	23,000	26,000	27,800
5	15,100	19,600	22,300	25,200	27,000
6	14,700	19,200	21,800	24,600	26,300
7	14,000	18,200	20,600	23,300	25,000
8	11,900	15,500	17,600	19,800	21,200
9	8,000	10,400	11,800	13,300	14,200
10	5,400	7,000	8,000	8,900	9,500
11	4,900	6,400	7,300	8,200	8,700
12	3,900	5,100	5,800	6,400	6,900
13	500	600	700	700	700
14	N/A	N/A	N/A	N/A	N/A
15	N/A	N/A	N/A	N/A	N/A

Table 12 – Weighted upper 90% interval peak discharge quantile estimates for locations of interest along Clearwater River

Location of Interest	Upper 90% PI Peak Discharge (ft^3/s)				
	2-yr	5-yr	10-yr	25-yr	50-yr
1	77,200	99,800	123,300	160,500	196,200
2	57,400	74,600	91,300	117,800	142,800
3	33,600	44,200	53,400	67,300	79,800
4	39,300	51,400	62,500	79,500	95,200
5	43,300	56,300	68,600	87,700	105,600
6	46,300	60,200	73,400	94,200	113,800
7	52,800	68,300	83,600	107,900	130,900
8	70,500	90,300	111,200	144,500	177,100
9	105,400	133,800	165,300	216,700	267,500
10	131,400	164,100	203,200	267,900	331,600
11	135,200	169,500	209,100	276,500	341,400
12	144,600	181,300	223,600	294,500	365,700
13	179,500	220,800	272,600	361,000	445,700
14	N/A	N/A	N/A	N/A	N/A
15	N/A	N/A	N/A	N/A	N/A

F. Monthly Statistics

The Clearwater River Gage recorded 13 years of average daily flows from 1931 through 1949. These data were used to summarize daily flow statistic by month. Figure 6 and Table 13 presents the monthly summary statistics of these data at the Clearwater River gage.

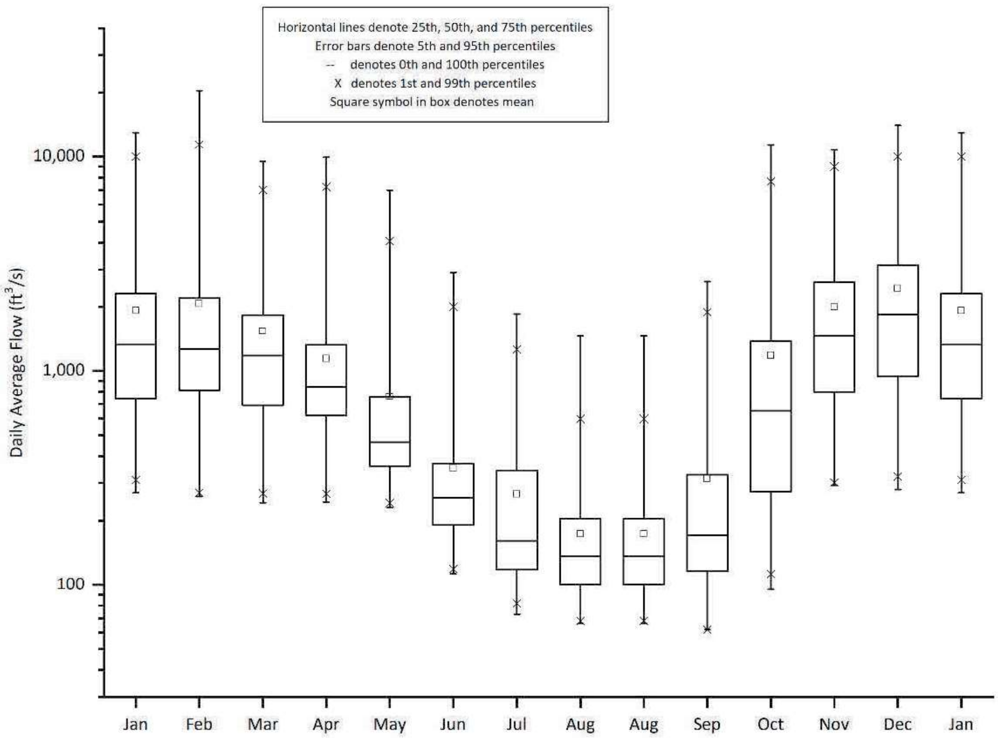

Figure 6 – Monthly boxplot summary statistics for Clearwater River gage.

Table 13 – Summary statistics of daily flow data recorded at Clearwater River gage (USGS gage 12040000)

Month	Summary of Daily Flows (ft^3/s)					
	Maximum	Minimum	Mean	Median	25th Percentile	75th Percentile
January	13,000	270	1,920	1,330	740	2,300
February	20,400	260	2,060	1,270	820	2,190
March	9,500	240	1,530	1,180	700	1,830
April	9,960	250	1,140	840	620	1,320
May	7,000	230	760	470	360	750
June	2,890	110	350	260	190	370
July	1,850	70	270	160	120	340
August	1,450	70	170	140	100	200
September	2,620	60	310	170	120	330
October	11,400	100	1,180	650	270	1,370
November	10,800	290	2,000	1,460	800	2,600
December	14,100	280	2,440	1,840	940	3,130

A 7-day, 10-year low flow estimate of 112 ft^3/s at the Clearwater gage location (USGS gage 12040000) was calculated using the online StreamStats program (www.streamstats.usgs.gov/ss).

IV. Conclusions and Recommendations

This study used a combination of methods to analyze frequency floods at the Clearwater River gage and 15 selected locations along the Clearwater River. A Bulletin 17C analysis was completed for the Clearwater River gage location using both the at-site measured peaks as well as an augmented record leveraging annual peak flows from the Queets River gage. Results from the two analyses were within approximately 1%; therefore, the original record was used in order to simplify the calculations. Figure 7 compares the peak discharge AEP quantiles calculated using methods outlined in USGS SIR 2016-5118. The EMA calculated quantiles are approximately 150% higher. The quantiles presented in Table 10 through Table 12 are heavily weighted towards the EMA quantiles.

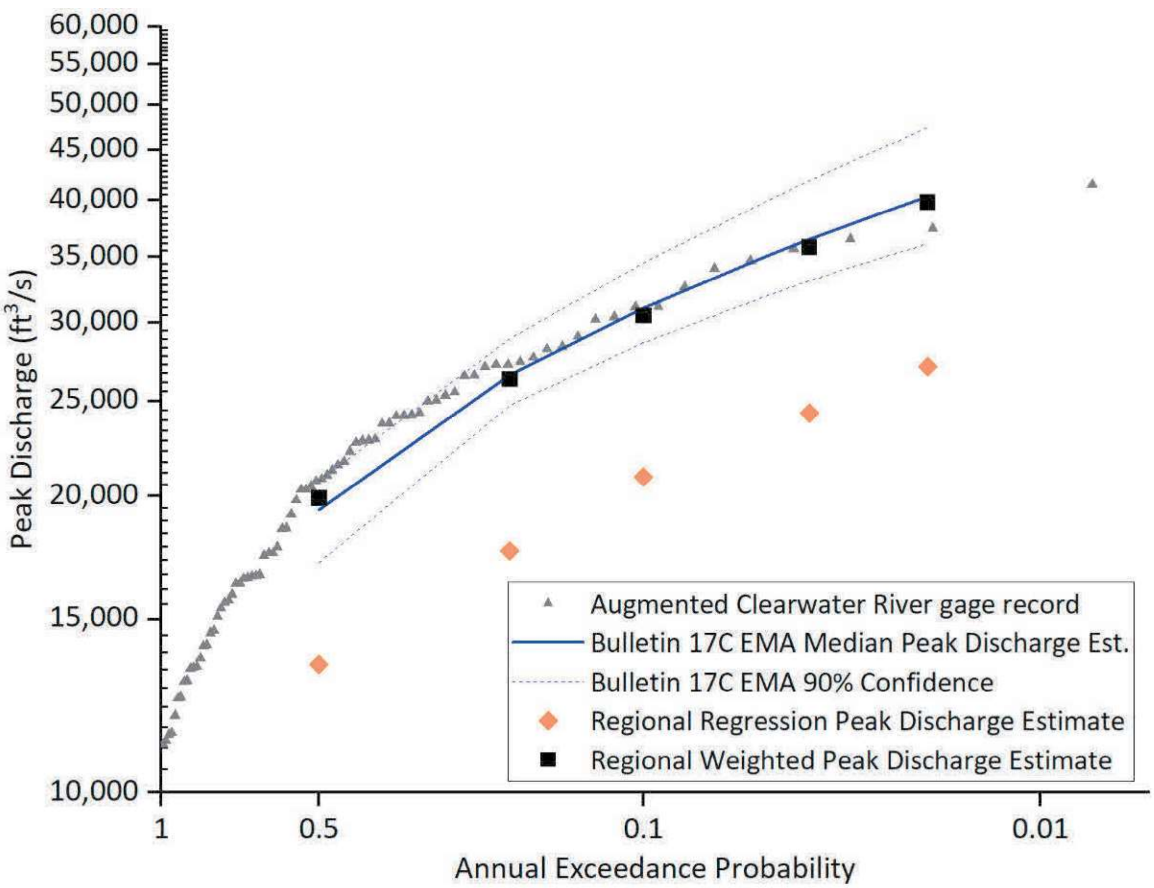

Figure 7– Comparison of peak discharge AEP quantiles estimated using different methods outlined in this analysis.

The values presented in Table 10 through Table 12 are suitable for analysis involving peak discharge AEP quantiles for locations of interest along Clearwater River. For sites #14 and #15, the streamgage-based peak discharge values presented in Table 9 are suitable for analysis involving peak discharge AEP quantiles.

V. Acknowledgements

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