Lower Columbia River Flood Stage-Frequency Study

Ryan Cahill, Hydraulic Engineer, U.S. Army Corps of Engineers, Portland, OR,
ryan.cahill@usace.army.mil
Chris Bahner, Senior Hydraulic Engineer, WEST Consultants, Salem, OR,
cbahner@westconsultants.com

Abstract

The Corps of Engineers recently completed a study (USACE 2022) with updated flood profiles and peak stage-frequency curves on the Lower Columbia River. These products show the chance of river levels rising above an elevation of interest in any given year. The study area extends from Bonneville Dam to Astoria, Oregon, over 130 river miles on the Columbia River. The last time a comprehensive study like this was performed was 1991. The study included both natural conditions with no reservoirs present (unregulated), as well as the condition with all current reservoirs present (regulated). This study used current USACE risk-based approaches to update peak stage-frequency curves with estimates of uncertainty. This study analyzed three flooding modes separately: spring snowmelt, winter atmospheric river, and winter coastal. These flooding modes were then combined to produce results on an annual basis. This study included the effect of likely levee breaches throughout the system in the adopted stage-frequency curves. The study reflects current river hydraulics and climate conditions. Flood risk is not a constant through time—it changes as a result of both natural and human-induced causes. While flood risk has changed in the past and will likely continue to change in the future, this report represents a best estimate of current-day conditions. This study included a sea level change assessment to show how far sea level change would propagate upstream during floods.

Key findings from this report are listed below:

- Upstream reservoir construction and operation has significantly reduced the risk of spring snowmelt flooding.
- Winter atmospheric river flooding currently poses the dominant risk for most of the Lower Columbia River.
- The uncertainty in the stage-frequency estimates is dominated by the limited period of record.
- River hydraulics appear to have changed through time.

Introduction

Purpose

The last major study to establish probabilities of flooding in the Lower Columbia River (LCR) is over 25 years old. Developed by the US Army Corps of Engineers (USACE) over the past three years, the present study uses current USACE risk-based approaches to create updated peak stage-frequency curves and flood profiles for the Columbia River below Bonneville Dam, the Willamette River below Willamette Falls, and the Multnomah Channel. The results of this study will primarily be used to facilitate flood risk assessments.

Study Area

This study focuses on the mainstem rivers within the LCR basin. The LCR basin is defined as the combined drainage below Bonneville Dam and Willamette Falls near Oregon City. The downstream boundary of the study is the long-term gage at Tongue Point near Astoria, Oregon. The mainstem rivers within the LCR that are the focus of this study include 1) the Columbia River from Bonneville Dam to Tongue Point, 2) the Willamette River from the Willamette River Falls to the confluence with the Columbia River, and 3) the Multnomah Channel. Figure 1 shows a map of the study area including the key gages used as locations to describe results throughout this report. The historic floodplain within the LCR is subject to flooding conditions on these major rivers. Major cities including Portland, OR, Vancouver, WA, and Longview, WA occupy considerable area along these rivers and have substantial infrastructure within the historic floodplain, and there are hundreds of miles of levees.

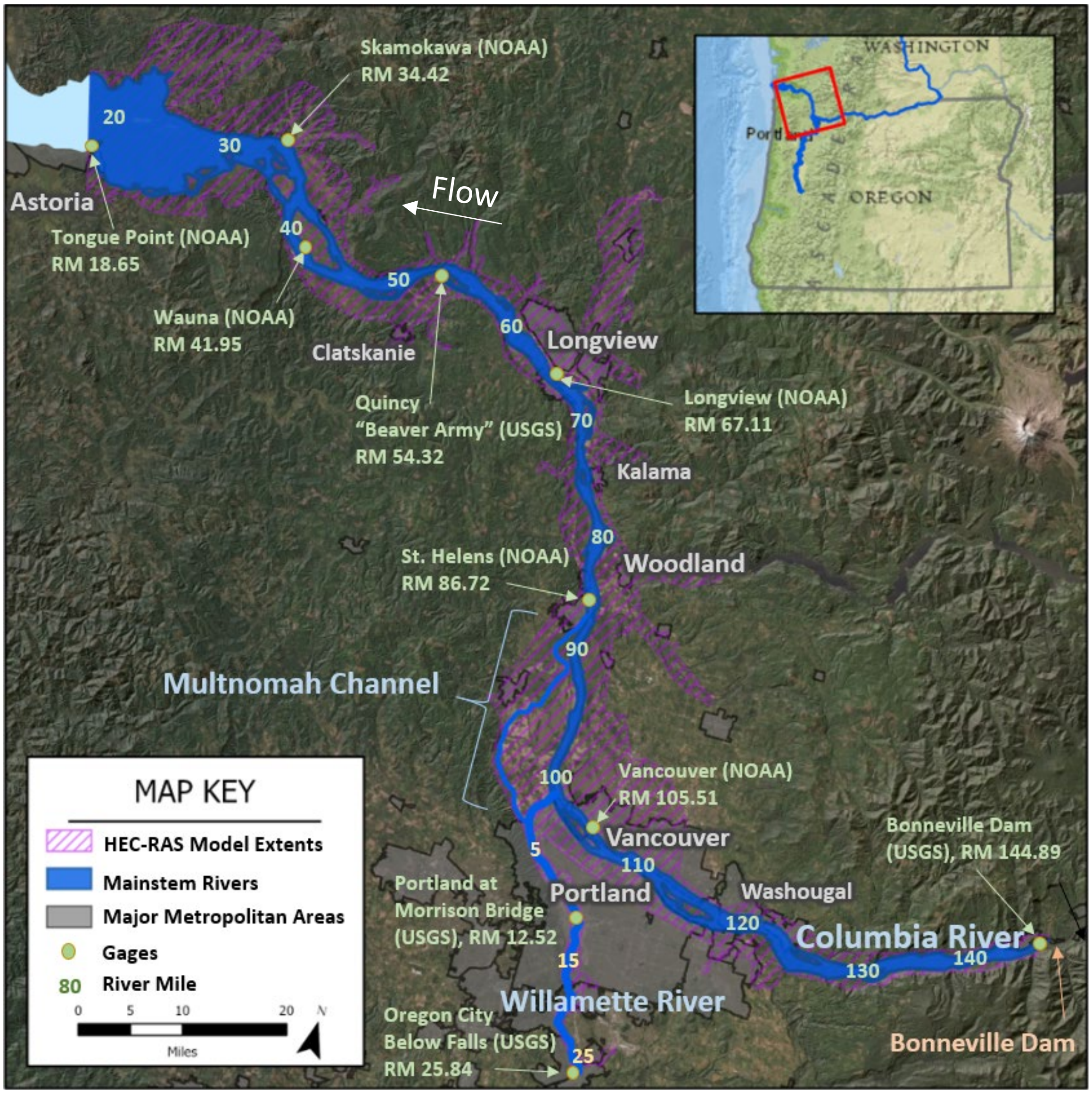

Figure 1. Lower Columbia River study area

Scope of Analysis

The main components of the project scope are listed below.

- **Frequency Range**: 50% annual exceedance probability (AEP) (2-year) to 0.1% AEP (1000-year). Evaluation of more extreme events would require site-specific investigations of extreme meteorology and hydrology. This study does not include a probable maximum flood (PMF) or dam failure scenarios, nor does it evaluate frequency of typical and low flow conditions.
- **Spatial extent**: Columbia and Willamette River downstream of Bonneville and Willamette Falls to Astoria at Tongue Point, including Multnomah Channel. Results for tributaries, side channels, sloughs, and within leveed areas are not included.
- **Flooding modes**: Stage-frequency curves are provided for three major flooding modes: spring snowmelt, winter atmospheric river, and winter coastal. Annual curves are calculated from combining the results from individual flooding modes.
- **Uncertainty**: Uncertainty is explicitly defined for the 5% and 95% confidence limits (90% confidence interval), using different methods for each flooding mode.
- **Duration**: Instantaneous peak stage only.
- **Upstream Reservoir Regulation**: Analysis includes natural conditions with no reservoirs present (unregulated), as well as the condition with all current reservoirs present (regulated).
- **Current Conditions**: The study reflects current-day conditions in all aspects, including river channel conditions, extreme storm meteorology and hydrology, levee development, and upstream reservoir regulation with associated agreements related to flood risk. These items may change in the future, but they are not included in the estimates of uncertainty.
- **Inundation Maps**: While a mapped floodplain could be created from the AEP profiles established in this study, this is beyond the scope of the present study. Developing maps according to FEMA regulations would require additional work.

Flood Hydrology

The seasonal water level patterns of the LCR system are a complex interaction of Columbia River inflows at Bonneville Dam, Willamette River inflows, tributary and local inflows, and tidal dynamics at the mouth. Historical high flows have come from spring snowmelt from the upper Columbia River Basin. The 1894 event, the largest known flood in recorded history, is estimated to have had an unregulated peak discharge of around 1.2 million cubic feet per second (cfs) at Bonneville Dam. Typical peak runoff hydrographs coming from the upper Columbia River Basin since completion of upstream dams in 1975 average around 300,000 cfs.

High river levels in the Lower Columbia and Lower Willamette Rivers can be generated from different flooding modes. The three general mechanisms are:

- Spring snowmelt
- Winter atmospheric river
- Winter coastal

Spring snowmelt (freshet) floods typically produce the highest flows on the Columbia River above Bonneville Dam, even with all upstream regulation effects accounted for. Spring snowmelt floods last for many days or weeks, as they are generated when a large snowpack melts rapidly. The most severe spring floods occur when significant rainfall occurs during a warm weather pattern, accelerating the melting of high elevation snowpack. The spring snowmelt flood of record is the June 1894 event.

While spring snowmelt often produces the highest flows on the Columbia River at Bonneville Dam, the highest stages in the LCR downstream of Bonneville do not always occur during the spring. High stages also occur during winter storm events when there are coincident high flows from the Willamette and other tributaries. Large winter rainfall events in the Pacific Northwest are caused by atmospheric rivers, which are enhanced water vapor plumes transporting large volumes of tropical moisture to extratropical locations. These storms normally occur during the period November through March and typically last only a few days, but they deliver a large amount of rain augmented by low elevation snowmelt over their relatively short duration. The winter atmospheric river flood of record is the February 1996 event.

The third flooding mode is termed winter coastal since it is driven by a combination of high tide and high storm surge from the ocean. This flooding mode can generate the annual peak stages in the lower 70 miles of the Columbia River. The annual maximum water surface elevation from this flooding mode typically occurs when a winter storm arrives at a time of relatively high tide. These storms may bring large amounts of rain, but typically, the maximum surge from the storm occurs well before the precipitation runs off and reaches the mouth of the Columbia River. In addition, many of the largest surge events do not have large rainfall, but instead are low pressure systems with high winds. While the winter coastal and winter atmospheric river flooding modes both occur during the same months (November-March), these flooding modes are distinct because of the different physical forcing mechanisms. The winter coastal flood of record is the January 1983 event.

Reservoir Regulation Effects on Flood Peaks

The Columbia River is heavily influenced by reservoir regulation, with most significant storage projects well upstream of Bonneville Dam. The completion of Canadian storage reservoirs in 1974 with flood risk management purposes, combined with U.S. reservoirs, greatly reduced the frequency and severity of spring freshet flood events (Nelson and Rockwood 1971). The Columbia basin storage upstream of Bonneville includes operations for both spring snowmelt and winter atmospheric flood events, but it is most effective for spring flooding. For spring freshet flooding, the storage reservoirs on the Columbia are operated in a seasonal pattern where water is released in the winter to make space that will be used to capture spring events. For winter atmospheric river floods, most runoff occurs downstream of storage dams. Reservoirs far upstream are also less effective at reducing winter atmospheric river peak flows due to the shorter forecast window of the winter storms.

The thirteen Willamette Valley dams that comprise the USACE Willamette Valley Project (WVP) were completed in 1969. In the Willamette basin, reservoirs are designed for winter atmospheric river flooding, but they control relatively less drainage area than the Columbia River reservoirs and have much less flood storage space. The WVP has minimal influence on spring snowmelt flooding from the Columbia River basin, since the reservoirs are already near full pool.

River Hydraulics

From the outflow at Bonneville Dam, the Columbia River flows 150 miles to the ocean downstream of Astoria, OR. The tidal influence from the ocean can affect water levels as far upstream as Bonneville Dam and several miles up the major tributaries including the Willamette, Lewis, and Cowlitz Rivers. From Bonneville Dam, the river flows through a reach without levees through the west end of the Columbia River Gorge into the highly leveed and urban area in the vicinity of Portland, OR and Vancouver, WA. For the next 60 miles, the river widens slightly through a broad but still mostly leveed floodplain, past St Helens, OR and Longview, WA. There are numerous islands, side channels, and large floodplain lakes. Below river mile (RM) 35 near Skamokawa, WA, the river widens and flattens into the tidal estuary.

The Columbia and Willamette Rivers have seen significant modifications to floodplain geometry through time as levees were constructed. A boom in levee construction occurred in the early 1900s, and the existing system of levees was generally in-place by the 1930s (USACE 1989). There have been various improvements and reconstruction of levees after flood events, but most of the levee systems in the LCR have existed for about a hundred years. While decreasing risk of flooding in the leveed areas, the levees increase channelization and increase flood stages relative to a non-leveed system. Disconnection from a large portion of the floodplain has resulted in modified fluvial dynamics and changes to ecosystem processes. The Columbia and Willamette Rivers have also seen major changes to the channel geometry due to creation of and changes to the Federal Navigation Channel (FNC) (USACE 2019b; USACE 2020b).

Supporting Studies

Developing updated stage-frequency information for the mainstem reaches of the LCR was a massive effort requiring an understanding of a multitude of complex, interrelated, driving factors related to hydrology and hydraulics. For this study, several efforts and studies were performed in a modular fashion, each with specific objectives formulated to fit into the larger framework of this stage-frequency effort. A list of the standalone supporting studies is below:

1. Lower Columbia Reservoir Operations (USACE 2018c)
2. Unsteady Flow Hydraulic Model of the Lower Columbia River System, Bonneville Dam to Astoria (USACE 2019b)
3. Lower Columbia and Willamette Rivers Elevation Datum Summary (USACE 2021a)
4. Historical streamflow and stage data compilation for the Lower Columbia River, Pacific Northwest (USGS 2021)
5. Astoria Gauge at Tongue Point, Stage Frequency Analysis (USACE 2020e)
6. Technical Memorandum for Lower Columbia River Stage-Frequency Study – Lower Willamette Routing (USACE 2018b)
7. Willamette River at Salem and Willamette Falls Flood Volume Frequency Curves, Winter Season (USACE 2020f)
8. Lower Columbia Stage-Frequency Curve Study: The Dalles Unregulated and Regulated Flood Flow Frequency Curves (USACE 2020g)
9. Lower Columbia River Stage-Frequency Study: Lower Columbia Tributary Flow-Frequency Curves (USACE 2019c, USACE 2020d)
10. Lower Columbia River Stage-Frequency Study-Critical Duration Analysis (USACE 2019d)

11. Lower Columbia River Flow and Stage Correlation Analysis (USACE 2019e, USACE 2020c)

Methods

The primary product of this analysis is stage-frequency curves with uncertainty for the mainstem LCR. In addition to annual curves, separate curves for the three distinct flooding modes (spring snowmelt, winter atmospheric river, and winter coastal floods) were developed. A summary of the methods is provided in more detail in the full report (USACE 2022).

This study analyzed each distinct mode of flooding in the LCR Basin separately and combined the results to produce an annual stage-frequency curve. Since the forcing hydrologic mechanisms in these three flooding modes are fundamentally different, a mixed population analysis was appropriate. In some past studies (USACE 1991), there was no distinction between the winter atmospheric river and winter coastal flooding modes. Instead, only a winter season was analyzed that included both flooding mechanisms. In the current study, analyzing all three mechanisms separately allows for greater understanding of each individual flooding mode, though the connections between the mechanisms are somewhat obscured. If new information in the coming years suggests that this study be updated, it is much more expedient to update individual flooding modes rather than requiring the large overhead of modeling all modes simultaneously.

Table 1 provides a summary of the methods used for each flooding mode. Simpler deterministic approaches were used when they provided reasonable results, and Monte Carlo approaches were used for more complex situations. Correlation and coincidence were considered for each flooding mode, although only the regulated winter atmospheric river flooding mode used a full correlation analysis in the Monte Carlo framework. Where deterministic runs were used in an analysis, the following nine AEP events and their corresponding 5% and 95% confidence limits were considered: 50%, 20%, 10%, 5%, 2%, 1%, 0.5%, 0.2%, and 0.1% events. Table 1 provides the methods used for frequency analysis of a regulated condition with all reservoirs present. The unregulated condition without any reservoir effects was also analyzed, but not for the winter coastal since reservoirs have negligible effect. Since the unregulated analyses were only for context, simplified deterministic methods were used (refer to USACE 2022 for more details).

Table 1. Summary of modeling approach for each flooding mode

Flooding Mode	Simulation type	Downstream Boundary condition	Tributary Inflows	Columbia River Flow	Hydrograph Shape
Spring Snowmelt	Deterministic	Median plus non-tidal residual effect	Median	Scaled to AEP	Balanced to 1-day and 7-day volume
Winter Atmospheric River	Monte Carlo	Tide and surge sampled separately	Randomly Sampled	Randomly Sampled	Scaled 5 historic events
Winter Coastal	Deterministic	Scaled to AEP elevations from stage-frequency analysis	Median	Median	Constant

After each flooding mode was analyzed, annual curves were generated by combining the stage-frequency curves for each individual flooding mode. Curve combination was performed at each cross-section from the hydraulic model separately. If the three flooding modes were perfectly correlated, then the maximum of the three inputs for each AEP would comprise the annual maximum. For instance, perfect correlation implies that the 0.1% AEP event for all three flooding modes occurs in the same water year. The other bookend for curve combination is if the flooding modes were perfectly independent and had no relation to each other. In this case, a simple mixed population analysis could be applied using total probability theorem concepts. However, the correlation analysis shows that there is moderate correlation between the flooding modes (USACE 2019e). For instance, a large winter atmospheric river that causes flooding tends to bring large amounts of snow to higher elevations, which can increase the chance of spring snowmelt flooding (USACE 2019e). Similarly, surge from winter coastal storms is moderately correlated with winter atmospheric river flooding. Independence cannot be assumed and a more sophisticated approach that considers correlation was required.

To combine the three flooding modes into an annual curve, a Monte Carlo simulation was performed separately for each cross-section. Refer to Figure 2 for a schematic of the process. The curve combination process used a nested-loop simulation, with knowledge uncertainty incorporated in an outer loop, and natural variability incorporated in an inner loop. Each iteration of the outer loop is known as a "realization," and each iteration of the inner loop is known as an event. To avoid introducing computational error, the Monte Carlo simulation included 500 realizations with 100,000 events each, which was sufficiently large to capture uncertainty of the 0.1% AEP (1,000-year) event. Stage-frequency curves for each flooding mode were sampled once per realization.

Knowledge uncertainty between the three flooding modes is assumed independent when sampling the stage-frequency curves, but natural variability includes the correlations between the flooding modes. The correlations calculated between the flooding modes apply within a given water year. In other words, the fact that spring snowmelt events are moderately correlated with winter atmospheric river events means that relatively large spring snowmelt events tend to happen more often in years with large winter atmospheric river events. In contrast, knowledge uncertainty reflects the confidence in the stage-frequency curves, and it is mostly governed by the limited period of record of floods available. As an example, if an additional 100 years of data were available, it is possible that the stage-frequency curves for each flooding mode would shift up or down based on the new data. However, there is no reason to believe the shifts in the stage-frequency curves of the different flooding modes would be related to each other. Therefore, the knowledge uncertainty between the three flooding modes was assumed independent.

After sampling the three frequency curves independently for a realization, individual events were simulated to account for natural variability. Sample events (water years within the realization) were created via a correlated random sample of peak stages for all three flooding modes. The simulation for each event (water year) was trivial; the annual maximum value is simply the maximum of the peak stages from each flooding mode. The resulting annual curves were provided for the median condition and estimated 5% and 95% confidence limits.

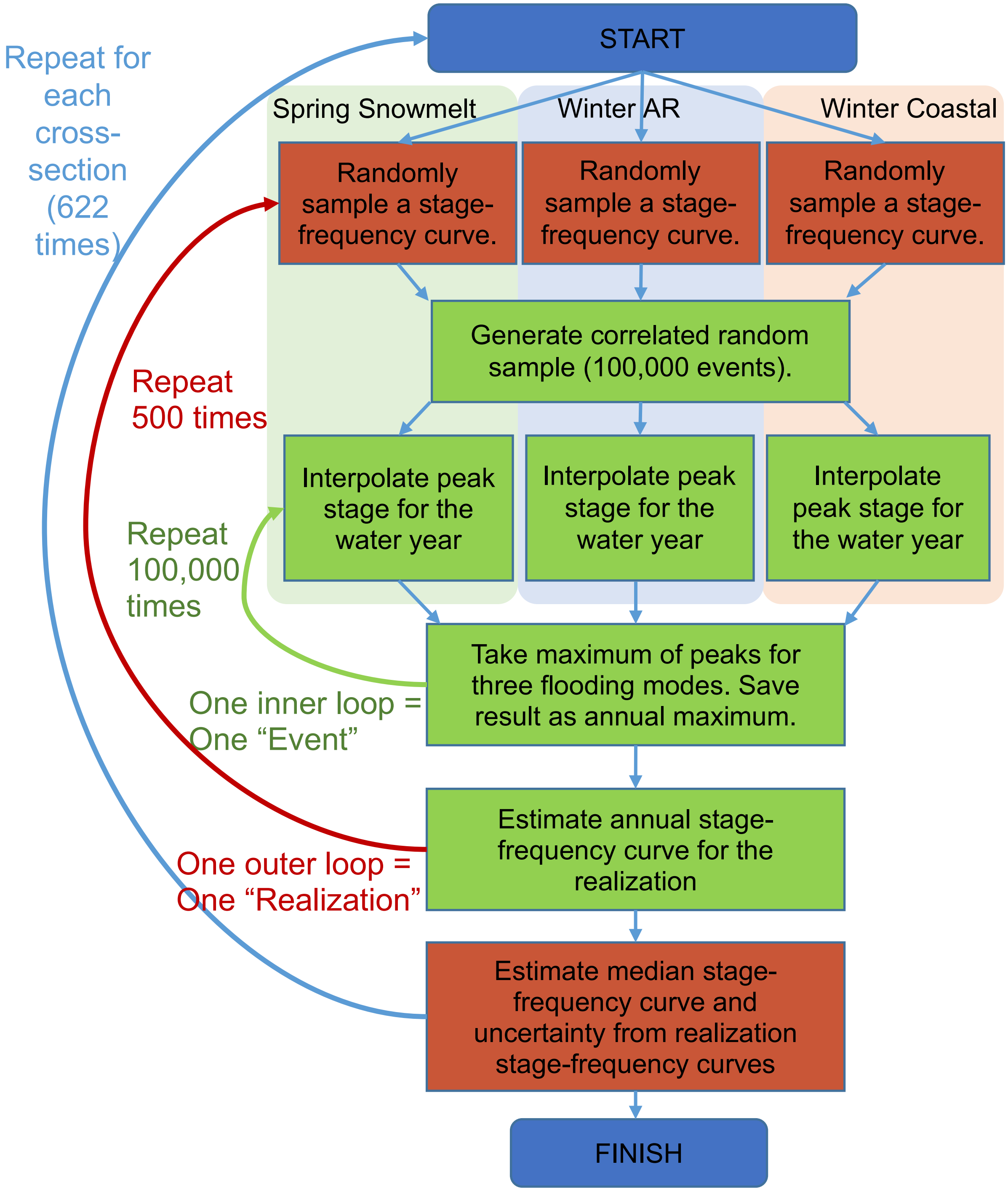

Figure 2. Schematic of Monte Carlo approach for annual maximum stage-frequency

Results and Discussion

An example of the computed stage-frequency curves at one location is shown in Figure 3. Full results are included in USACE 2022. The figure includes unregulated and regulated curves by flooding mode as well as the combined annual curves. “Winter Rainflood” is an alternate name for the winter atmospheric river flood mode.

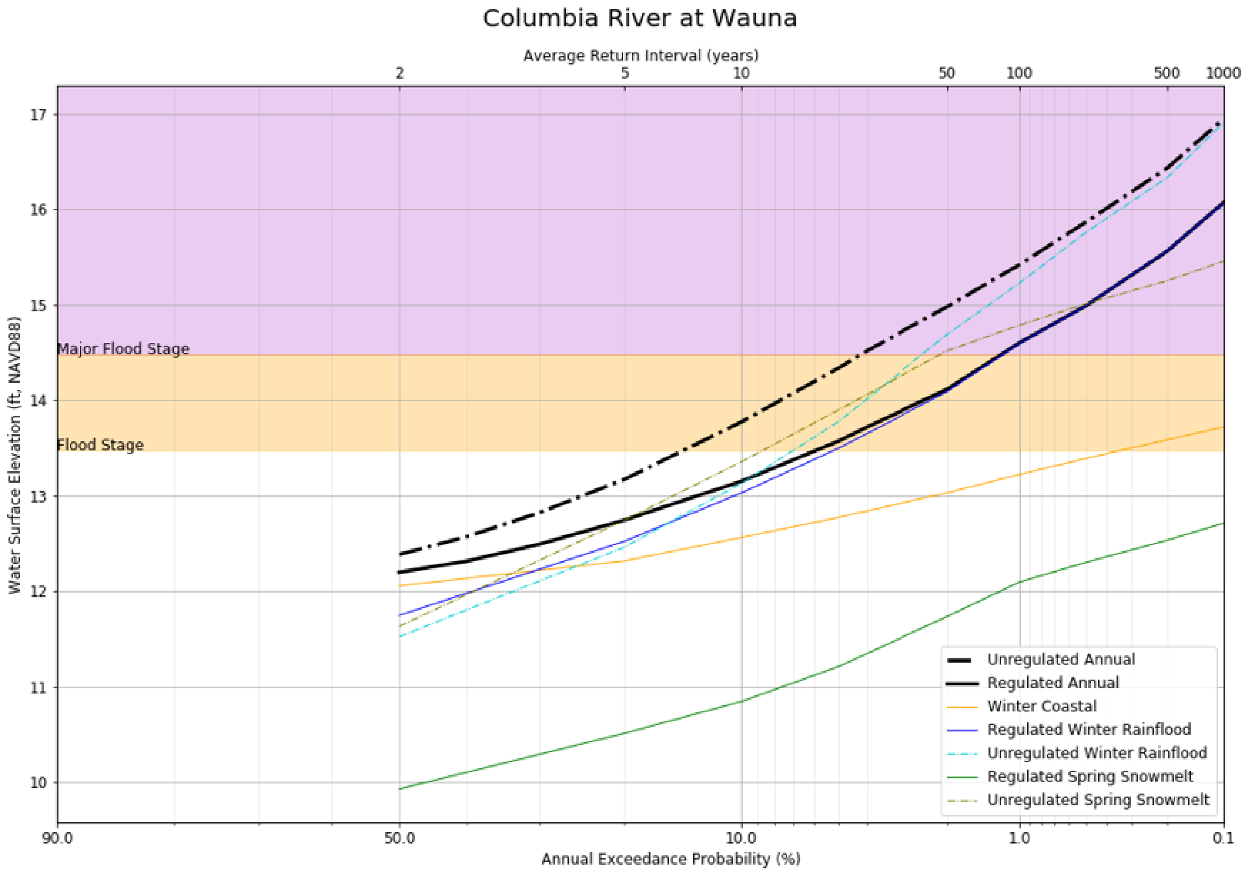

Figure 3. Stage-frequency curves for Columbia River at Wauna, RM 42

Figure 4 shows the adopted regulated flood profiles for the LCR for the 1% AEP condition with uncertainty. Many components of uncertainty were used to generate the final bounds, including hydrologic uncertainty from a limited period of record, model representation of reservoir operations, forecast uncertainty, levee breaches, hydraulic model uncertainty, and natural variability in channel roughness. The results show that the 5% and 95% confidence limits are well above 5 feet for most locations, and they can exceed 10 feet in some locations. At the downstream end, uncertainty is lower because the winter coastal condition governs, and the uncertainty associated with storm surge is much lower than the streamflow terms. Throughout the LCR, for both regulated and unregulated conditions, the hydrologic term was consistently the largest single component of uncertainty. While much effort went into this study, there are irreducible uncertainties that result from only having slightly over 100 years of record.

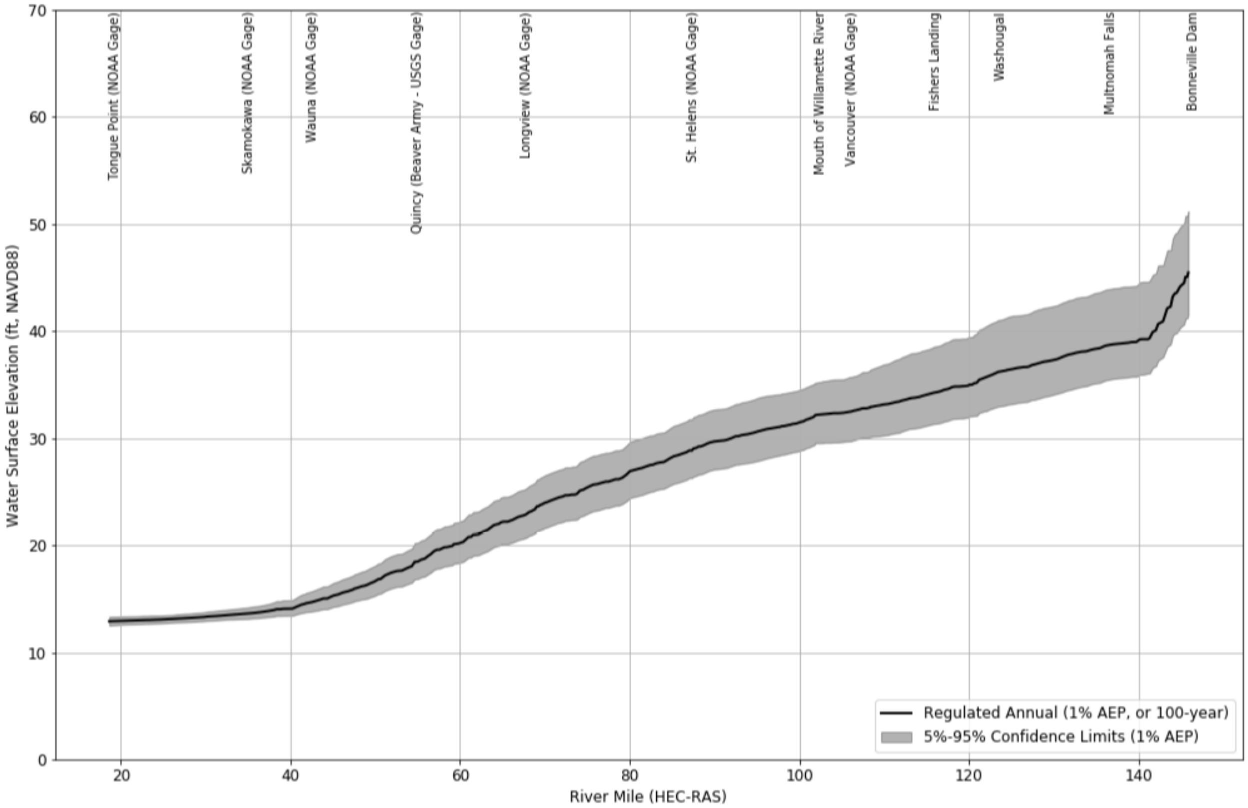

Figure 4. Uncertainty in the 1% AEP regulated annual flood profile for LCR

While the annual stage-frequency results will be used most commonly, it is useful to understand what the seasonal drivers are to the annual peak results. The study shows where the three different flooding modes (spring snowmelt, winter atmospheric river, and winter coastal) are most influential on the annual maximum flood profile. The term “dominant” describes which flood mode dominates the annual probability of flooding for a specific location. It does not mean that other flood modes are not possible at that location. Figure 5 visualizes the areas where different flooding modes are most dominant for the unregulated and regulated 1% AEP event, respectively. The most notable difference between the unregulated and regulated condition is the relative contribution of the spring snowmelt flood. In the unregulated condition, the spring snowmelt flood is highly influential on the Columbia down to about Longview (RM 67). In contrast, in the regulated condition, the spring snowmelt flood only contributes to the 1% AEP profile at the upstream end of the LCR (above RM 120). Before Columbia River Basin reservoirs were constructed, spring snowmelt floods usually generated the highest water of the season for most of the LCR. However, after construction of upstream reservoirs, the spring snowmelt floods have been greatly ameliorated, even at extreme events like the 0.1% AEP event. While upstream reservoir regulation has also reduced river levels during winter atmospheric river floods, the effect is more modest. With all reservoir regulation in place, winter atmospheric river events are a greater flooding threat to most of the LCR.

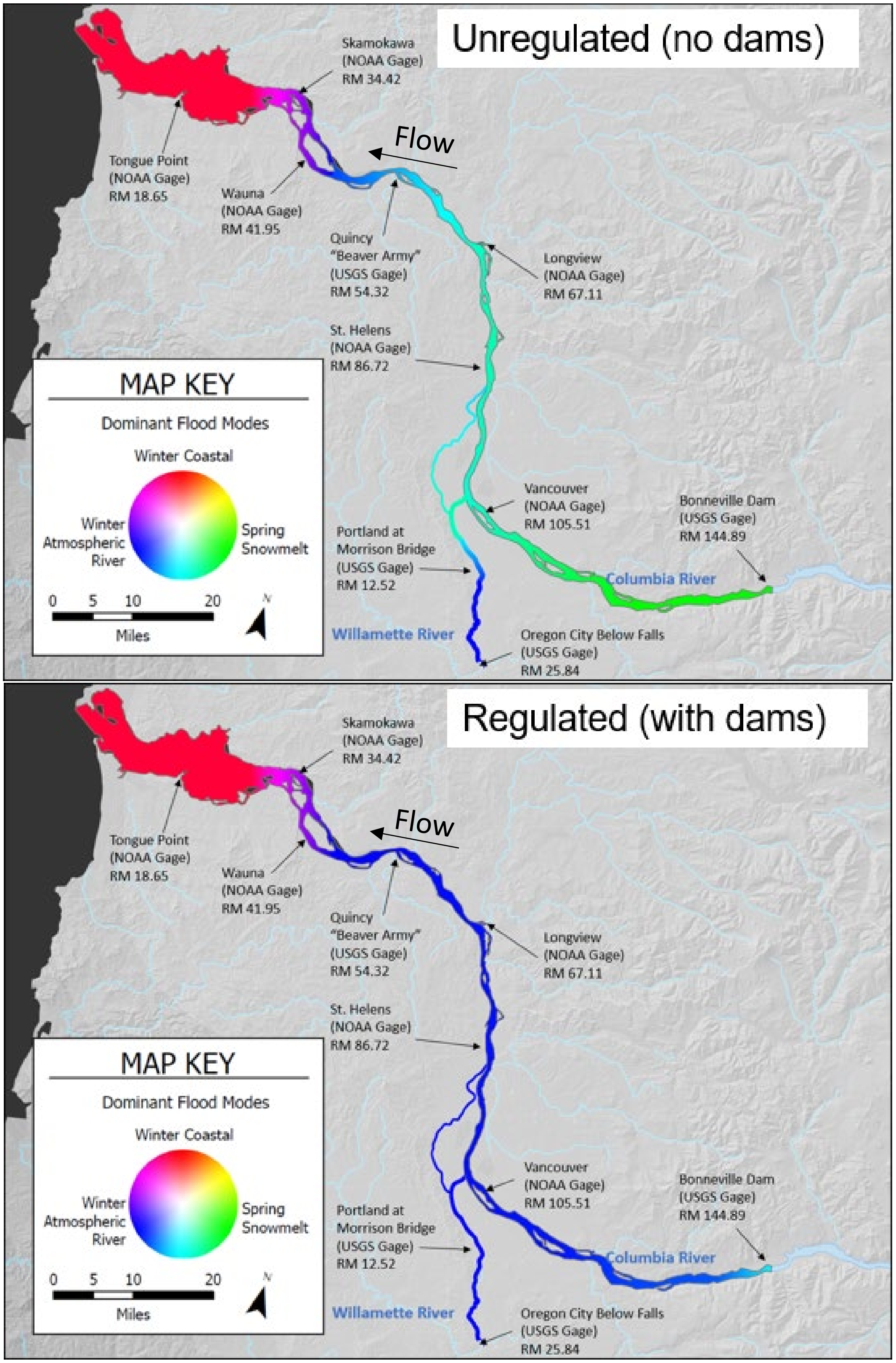

Figure 5. Dominant flood modes for LCR (1% AEP)

Climate Change Effects

A quantitative climate change analysis was not performed for this study, but a qualitative assessment of climate change effects to flooding in the LCR can be found in recent reports from the River Management Joint Operating Committee (RMJOC-II 2020). An overview of the findings and implications for this study are included here. The effect unregulated condition is covered in Part 1 (RMJOC-II 2018), and the regulated condition is covered in Part 2 (RMJOC-II 2020). Key conclusions from these studies related to flood risk in the LCR include:

- Future precipitation trends are uncertain, but a general upward trend is likely for the rest of the 21st century, particularly in the winter months.
- Average winter snowpacks are very likely to decline over time as more winter precipitation falls as rain instead of snow, especially in the US side of the Columbia Basin.
- By the 2030s, higher average fall and winter flows, earlier peak spring runoff, and longer periods of low summer flows are very likely.
- In the Willamette Basin, fall and winter flows are likely to increase.
- The spring snowmelt runoff is projected to peak at The Dalles about two weeks earlier for the 2030s and about a month earlier for the 2070s. Winter precipitation is very likely to increase and, due to warming temperatures, to result in increased rainfall runoff and less snow accumulation. The future projections indicate a potential overall increase in flood risk in the Columbia River Basin for both spring (April to May) and winter (November to March) flood events under current operating criteria.
- Identified shifts in runoff volume timing and variability in the spring could stress the reservoir system. Regulated spring high-flow events for the LCR are projected to be similar to the historical baseline in the 2030s and increase modestly in the 2070s.
- The greatest identified change in future flood risk is from increased winter flood volumes throughout the Columbia Basin. The effect is most notable in the LCR. Projected increases in winter flood risk are primarily linked to increasing flows from the Columbia main stem. Projected increases in inflow from the Willamette River during winter events further exacerbate this increase in flooding.
- The current system operations for flood risk management are not designed for the projected future hydroclimate of the basin. However, while changes to reservoir operating policies via adaptive management may partially ameliorate the climate effects, changes to operations are not anticipated to fully offset potential increases in flood risk.

Many of the conclusions of the RMJOC-II have a direct connection to the flood frequency curves in the current study. Winter atmospheric river flooding already dominates the large majority of geographic area of the LCR, even without considering climate change. Increases in winter atmospheric river intensity from climate change would translate to higher stage-frequency curves. This is expected for the entire range of probability, from frequent events like the 50% AEP (2-year) to larger events, like the 0.2% AEP (500-year).

The RMJOC-II reports include detailed discussion on climate effects on inland hydrology, but sea level change was not directly included. The present study included an assessment of sea level change (SLC), based on the Astoria Tongue Point gage. The online USACE Sea Level Curve Calculator was used to determine the low, intermediate, and high sea level change scenarios at Astoria, OR (USACE 2017b). The relative SLC projection curves estimated a SLC of 1.33 feet for the intermediate scenario and 5.94 feet for the high scenario by 2120. The low scenario was slightly lower than the current conditions. Since the low, intermediate, and high SLC scenarios may change through time, the assessment was generalized for various increments of SLC to make it more flexible. The SLC analysis evaluated increases in elevation ranging from 1 foot to 5.94 feet. These SLC increments were run through the HEC-RAS model for the regulated spring, regulated winter, and winter coastal conditions.

Figure 6 shows the increase in the peak WSE for the 1% AEP winter atmospheric river flooding mode due to the effects of SLC along the Columbia River. The effects of SLC diminish moving upstream in the system. At lower frequencies with higher riverine flows, the effects from SLC also decrease. At lower flows, the water is more confined by the channel and levees in the system making the effects from SLC more substantial. As flows increase, the water moves into the overbanks and begins to overtop lateral structures and levees, utilizing the volume available in those areas, reducing effects from SLC.

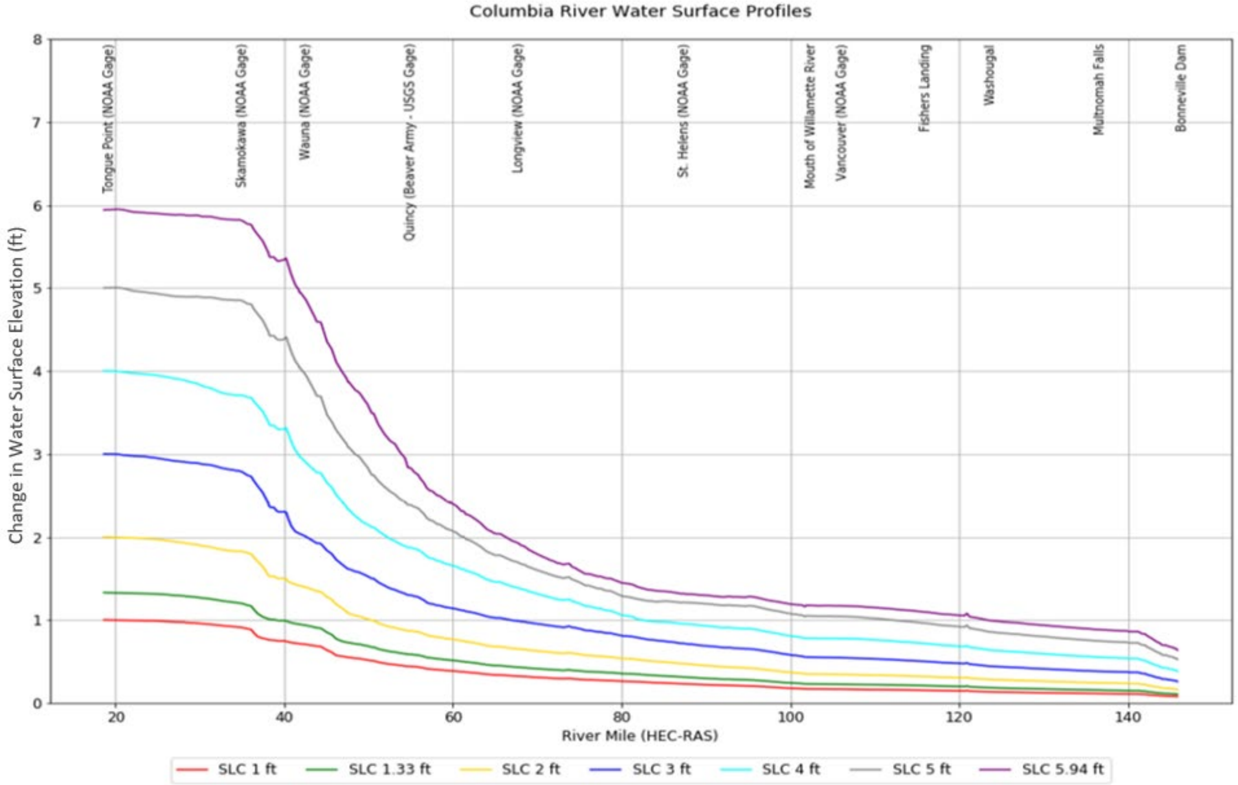

Figure 6. Columbia River SLC Difference from No Change Scenario 1% AEP, Winter Atmospheric River

Conclusions

The study results can be used for a variety of applications, including inundation mapping, levee assessments, and floodplain management purposes. Some general conclusions from the study are summarized below:

- **Reservoir regulation has significantly reduced the risk of spring snowmelt flooding**. This is not a new finding, but this study revisited the quantitative analysis. It confirmed that the upstream system of reservoirs has been effective in reducing even very large spring snowmelt floods. For example, at the 0.1% AEP (1000-year) event, the upstream reservoir system is expected to reduce regulated stage by about 10 feet at Bonneville, 7 feet at Vancouver, and 5 feet at Longview.

- **Winter atmospheric river flooding currently poses the dominant risk for most of the LCR**. While upstream regulation has reduced the severity of spring snowmelt floods, the effect on winter atmospheric river floods is more modest. For example, at the 0.1% AEP (1,000-year) event, the upstream reservoir system is expected to reduce regulated stage by about 2 feet at Vancouver, and 1 foot at Longview. As a result, the winter atmospheric river flooding mode is much more likely to produce the most extreme peak stages. There is less ability to address winter atmospheric river flooding with the existing system storage and operational design.
- **The uncertainty in the stage-frequency estimates is dominated by the limited period of record of flood events**. While many different sources of uncertainty informed the results, hydrologic uncertainty from a limited period of record was the largest single component at all locations. Since observed data is available only for around 150 years, there is relatively low confidence in estimates of extreme floods. For example, the 90% confidence interval of the 0.2% AEP (500-year) event at Portland spans about 7 feet.
- **River hydraulics appear to have changed through time**. This conclusion comes from the hydraulic model report (USACE 2019b). An illustrative example of this is the 1948 spring snowmelt flood, which had a peak flow of around 1 million cfs at The Dalles and a peak stage of about 36 feet NAVD88 at Vancouver. If the same flow of 1 million cfs were observed today, it is expected that the peak stage would be over 2 feet lower than observed in 1948. It is unknown how channel conditions will change in the future.
- **The regulated flood profiles from this study generally trend higher than previous studies**. While the spring snowmelt results are slightly lower than previous studies, this is outweighed by the increase in winter atmospheric river events. This study placed a larger focus on winter atmospheric river events than previous studies. Furthermore, there have been numerous winter atmospheric river events since the previous study (USACE 1991), including the February 1996 flood of record.

References

Nelson, M. & Rockwood, D. 1971. Flood Regulation by Columbia Treaty Projects. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, Vol 7798, pp 143-161.

River Management Joint Operating Committee (RMJOC) 2018. “Second Edition: Climate and Hydrology Datasets for RMJOC Long-Term Planning Studies (RMJOC-II); Part I: Hydroclimate Projections and Analyses.” June 2018.

RMJOC 2020. “Second Edition: Climate and Hydrology Datasets for RMJOC Long-Term Planning Studies (RMJOC-II); Part II: Columbia River Reservoir Regulation and Operations—Modeling and Analysis.” August 2020.

USACE 1989. “Lower Columbia River Flood Control Study, River Mile 0 to 145 Summary Report. Volume 2. Columbia River and Tributaries Study, CRT-69.” Prepared by North Pacific Division. January 1989.

USACE 1991. “Review of Flood Control, Columbia River Basin. Columbia River and Tributaries Study, CRT-63.” Prepared by North Pacific Division. June 1991.

USACE 2017b. “Sea Level Change Curve Calculator (2017.55) User Manual.” USACE Responses to Climate Change Program. July 2017.

USACE 2018a. “Lower Columbia River Hydrology Update. Technical Memorandum for Lower Columbia River Stage-Frequency Update Project.” Portland District. 25 July 2018.
USACE 2018b. “Technical Memorandum for Lower Columbia River Stage-Frequency Study – Lower Willamette Routing.” Prepared by WEST Consultants for Portland District. November 2018.
USACE 2018c. “Lower Columbia Reservoir Operations” Technical Memorandum. From Corinne Horner and Kevin Fagot, to Ryan Cahill. 05 November 2018. Final. Prepared by WEST Consultants for Portland District.
USACE 2019b. “Unsteady Flow Hydraulic Model of the Lower Columbia River System, Bonneville Dam to Astoria.” Prepared by Portland District. June 2019.
USACE 2019c. “Lower Columbia River Stage-Frequency Study: Lower Columbia Tributary Flow-Frequency Curves.” Technical Memorandum, from Chris Bahner. 11 April 2019. Prepared by WEST Consultants for Portland District.
USACE 2019d. “Lower Columbia River Stage-Frequency Study-Critical Duration Analysis.” Technical Memorandum. From Luciana Cunha and Lori Jones. 28 January 2019. Prepared by WEST Consultants for Portland District.
USACE 2019e. “Lower Columbia River Flow and Stage Correlation Analysis.” 14 June 2019. Prepared by WEST Consultants for Portland District.
USACE 2020b. “Lower Columbia River Sedimentation Report.” Final. Portland District. February 2020.
USACE 2020c. “Correlation of The Dalles to tributaries of the Lower Columbia for winter events.” Technical Memorandum for Lower Columbia River Stage-Frequency Study. Portland District. May 2020.
USACE 2020d. “Technical Memorandum for Lower Columbia River Stage-Frequency Study - Cowlitz River Regulated Volume Duration Frequency Curves for Monte Carlo Input.” Portland District. July 2020.
USACE 2020e. “Astoria Gauge at Tongue Point, Stage Frequency Analysis.” Portland District. August 2020.
USACE 2020f. “Willamette River at Salem and Willamette Falls Flood Volume Frequency Curves, Winter Season.” Portland District. August 2020.
USACE 2020g. “Lower Columbia Stage-Frequency Curve Study: The Dalles Unregulated and Regulated Flood Flow Frequency Curves.” Portland District. August 2020.
USACE 2021a. “Lower Columbia and Willamette Rivers Elevation Datum Summary.” Revision 2. Prepared by Cliff Bondurant, Survey Section, Portland District. February 22, 2021.
USACE 2022. “Lower Columbia River Basin Peak Stage-Frequency Report”. March 2022. Prepared by Portland District.
USGS 2021. “Historical streamflow and stage data compilation for the Lower Columbia River, Pacific Northwest.” By Carrie Boudreau, Mark Stewart, and Adam Stonewall. Open-File Report 2020–1138, 50 p.