

Dear Reader,

The study you are about to read examines various strategies for systemic flood risk reduction for the Puyallup River Watershed.

Glacial rivers like the Puyallup, Carbon and White Rivers are geologically young, volatile systems. Western Washington is home to several glacial systems that flow from the Cascade Mountain Range through highly urbanized areas to the Puget Sound (Salish Sea). When the floodplains of glacial rivers are highly developed, the existence of flood risk is inevitable. Further, climate change increases the likelihood of major flood events.

The intention of this study is to better understand the flood risk reduction potential of setback levees and tributary restoration in reducing peak flows in the lower Puyallup River. The analysis also looks at the sediment storage potential of these two strategies. In both cases, this analysis could help Floodplains for the Future (FFtF) partners better select and sequence actions to maximize the benefits of their investments.

The study is a launching point for more complex strategic discussions about managing for flood risk, achieving other community needs such as salmon recovery and agricultural viability, and continued learning about how to engage with and manage an incredibly complex and dynamic glacial river system.

FFtF partners recognize levee setbacks and floodplain reconnection projects have significant benefits beyond reduction in flood risk, including reduced maintenance costs, and habitat improvements for salmon.

Here are a few conclusions by the FFtF partnership about the report's findings:

- Climate Change is going to result in more and bigger floods in the Puyallup Watershed.
- Tributary restoration is a potential strategy to help reduce flood risk and retain sediment upstream.
- Continued conversations are needed on how to synchronize tributary projects with levee setback projects.
- Levee setbacks provide more than flood storage benefits, ex: sediment storage, habitat, localized lowering of Base Flood Elevation (BFE).
- Slowing flood waters lengthens high water events. This can impact downstream infrastructure by increasing wear and tear.
- Flood risk in the Puyallup Watershed is extreme.
- A suite of solutions is required to reduce flood risk.

We hope you find this study informative and applicable to the work you are doing! We'd love to hear your thoughts and conclusions.

Floodplains for the Future Partnership



Puyallup River Watershed Flood Storage Assessment



**FLOODPLAINS
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1 EXECUTIVE SUMMARY

This study was conducted to evaluate flood storage strategies and support stakeholder decisions within the Puyallup River Watershed in Washington State. The potential amount of flood water that can be stored within a valley (termed flood storage volume) was estimated for 32 levee setback project areas and potential restoration within 26,600 acres of major tributary valleys during the 100-year flood (Q100). Analyses provide approximations of flood storage to use in relative comparisons and for conceptual consideration of how flood storage volume estimates relate to flood peak reduction, which is more related to flood damage reduction than flood storage by itself. Flood storage estimates for the levee setback projects were originally developed and reported by Geoengineers (2008) and represent the maximum amount of potential instantaneous flood storage – the results were further contextualized as part of this study. Tributary restoration flood storage volume estimates were made by classifying the watershed into areas conducive for flood storage using a GIS based analysis and estimating increases in floodplain inundation using at-a-station hydraulic calculations. Tributary restoration flood storage volume estimates were contextualized using the volume of the 1996 flood that exceeded the National Weather Service’s flood threshold (4 days). Additionally, analyses were conducted to estimate how each flood reduction strategy relates to sediment deposition within the basin.

The primary results and conclusions of the study are as follows:

- ▶ The 32 levee setback projects were estimated to store 5,400 acre-feet of water during the existing condition Q100 flood which accounts for 3.3% of the total volume of water over the 4-day duration encompassing the flood’s volume.
- ▶ Tributary restoration within 26,600 acres of major tributary valleys was estimated to store between 11,800-31,600 acre-ft of water during the existing condition Q100 flood which accounts for between 7%-19% of the same 4-day duration flood volume.
- ▶ From a climate change perspective, tributary restoration was estimated to store 27,100 acre-ft during the projected 2080s Q100 flood which accounts for 7% of the future flood volume
- ▶ Levee setback projects encompass 5 times the flood storage volume per unit area, which is likely due to their lower slopes compared to the tributary restoration areas.
- ▶ Flood storage within levee setback projects may reduce downstream flood peaks by attenuating the flood wave (reducing the peak magnitude and increasing its duration) due to the low valley slope of the project areas.
- ▶ Flood storage within restored tributary valleys may reduce downstream flood peaks by de-synchronizing the peaks among tributaries.
- ▶ Focused restoration treatment of individual sub-watersheds such as South Prairie Creek may be more likely to show measurable decreases in downstream flood peaks than dispersed restoration within numerous tributaries, because of the potential to desynchronize flood peaks.
- ▶ Additional hydrologic and hydraulic modeling would be needed to quantify the magnitude of flood peak reduction from any actions. The flood storage volumes estimated here provide a rough approximation of the total potential flood storage, they cannot be used to estimate the implications for flood peaks.
- ▶ Long-term sedimentation of levee setback projects is unlikely as long as the river is able to migrate into newly formed floodplain areas.

- ▶ Tributary restoration is likely to store sediment and reduce downstream sediment loads and the magnitude of effect depends on the magnitude of tributary restoration. For example, values could range from ~3,000 cubic yards for a small pilot project reach to ~2,350,000-5,270,000 cubic yards for restoration of the full 26,000 acres of valley bottom included in our study area.
- ▶ Both strategies to increase flood storage capacity also bring additional benefits such as enhancing aquatic habitat and improving climate resiliency.

2 INTRODUCTION

Floodplains by Design, Floodplains for the Future (FFtF), the University of Washington Climate Impacts Group (CIG) and other stakeholders are working together in the Puyallup River watershed to restore aquatic habitat and reduce flood risk through levee setbacks, land acquisitions, restoration, and other actions. However, the potential amount of flood water (termed “flood storage volume” hereafter) that can be stored by this diverse range of actions is not sufficiently quantified to allow for direct comparison. In order to fill this data gap and support stakeholder decisions about how to prioritize actions within the Puyallup River Watershed, this report presents estimates of flood storage volumes for both proposed main stem levee setback projects and hypothetical restoration scenarios within the major tributaries of the watershed. The report also conceptually relates flood storage volumes to potential decreases in flood peaks, termed flood peak reduction, as well as estimates of how both flood reduction strategies influence sediment transport within the basin. A full hydraulic analysis of flood peak reduction and sediment transport is beyond the scope of this planning-level effort.

The analysis presented within this report is guided by the following study questions:

1. How do flood storage volumes compare:
 - a. Between levee setbacks and tributary restoration?
 - b. Between flood storage volumes achieved by each strategy and current and future flood volumes?
2. How do flood storage volumes relate to flood peak reduction?
3. How does sediment deposition relate to levee setbacks and tributary restoration?

2.1 Study Area

The study was conducted within the entire Puyallup River watershed which encompasses 985 mi² and is located in both Pierce and King Counties in Washington State (Figure 1) (USGS, 2022). The watershed has a total relief of 14,400 feet which ranges between Mt. Rainier and the Puget Sound and has an average mean annual precipitation of 69 inches. Major tributaries to the Puyallup River include the White River, the Carbon River, the Mowich River, and South Prairie Creek. The upper portion of the watershed is primarily forested, with much of the area protected within Mt. Rainier National Park and the remainder managed by either the U.S. Forest Service (USFS) or private timberlands, including over 90,000 acres owned by the Muckleshoot Tribe. The middle portions of the watershed are mixed between agricultural lands and private development and the lower portions of the watershed contain the cities of Tacoma, Puyallup, Sumner, Pacific, Auburn, and Orting. The Muckleshoot Indian Reservation is located within the lower portions of the White River watershed and the Puyallup Indian Reservation is located within the lower portions of the Puyallup River watershed. Mud Mountain Dam, a flood control facility operated by the U.S. Army Corps of Engineers (USACE) is located on the White River.

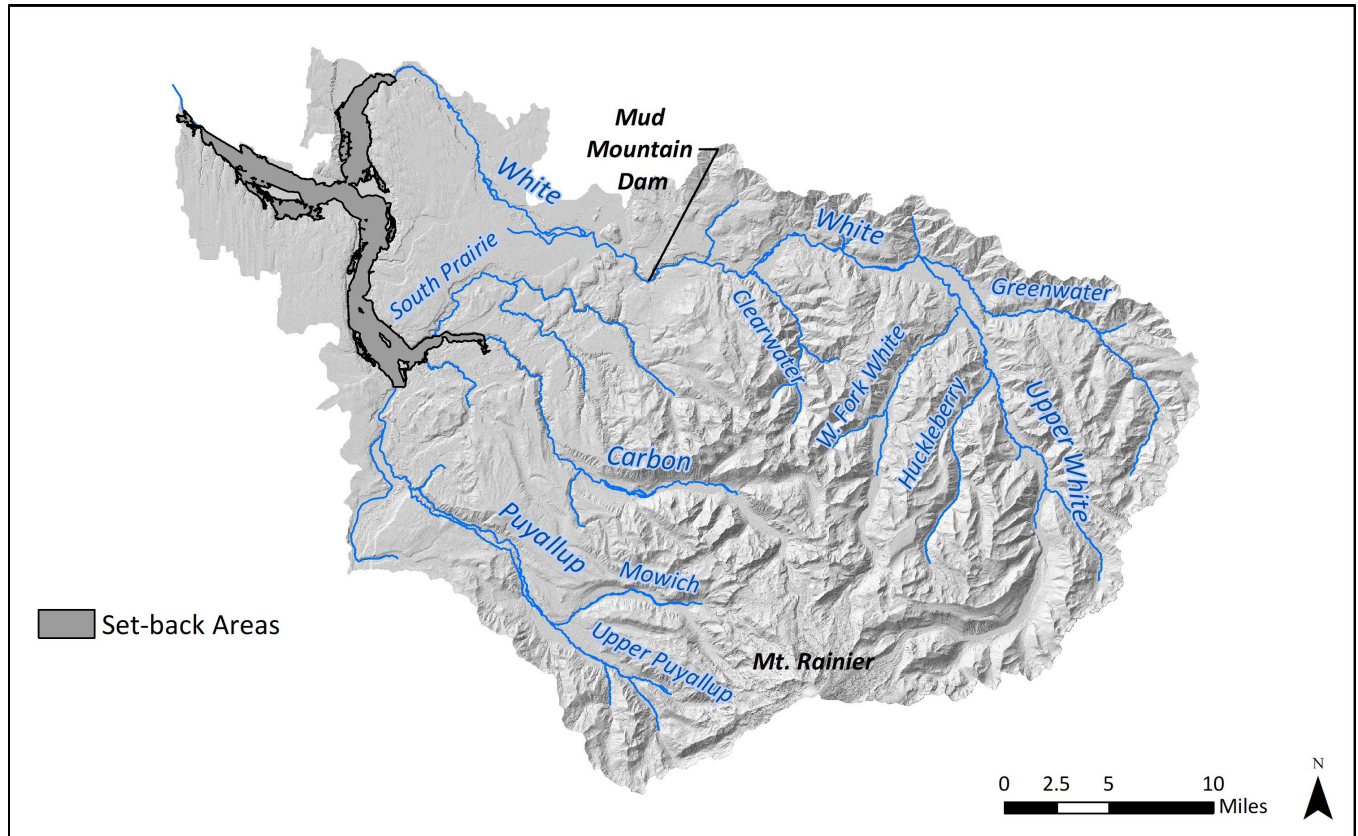


Figure 1. Overview map of the Puyallup River Watershed.

3 FLOOD STORAGE VOLUMES

Flood reduction actions such as setting back levees along major rivers (main stem levee setbacks) or restoring natural processes within tributaries (tributary restoration strategy) may reduce overall flood peaks by increasing the volume of water that inundates a valley (and thus decreasing the volume within the channel) during a flood. Levee setbacks achieve increased valley inundation through increases in the available floodplain area within a given reach while tributary restoration increases water within the valley through increases in roughness which slow velocities and raise water surface elevations, spreading out water across the valley to areas not currently inundated. Termed “Flood Storage Volume,” this volume of water can be calculated for different flood reduction scenarios in order for one aspect of their effectiveness to be compared. The flood storage volume can also be compared to the total volume of a particular flood in order to further contextualize each strategy and provide a common baseline for comparison.

The following section describes methods and results of our analysis to estimate flood storage volumes for the main stem levee setback and tributary restoration flood reduction scenarios within the Puyallup River watershed. The section is organized into the following sub-sections:

- ▶ Flood Hydrology and Volumes
- ▶ Flood Storage Volumes from Main Stem Levee Setback Projects
- ▶ Flood Storage Volumes from Tributary Restoration

3.1 Flood Hydrology and Volumes

A hydrologic evaluation of the flow record and observed flood volumes was conducted in order to contextualize the flood storage volumes estimated for main stem levee setbacks and tributary restoration. The most downstream USGS gage within the watershed (Puyallup at Puyallup, WA – USGS 12101500) was selected as the location of analysis. The gage is below all proposed actions besides one levee setback project and integrates the flow from the Puyallup River and all of its tributaries and thus represents the total outflow flood volume within the system. Flood recurrence intervals were calculated for the entire period of record from the gage using the USGS software program PeakFQ which utilizes the Log Pearson Type III analysis (USGS, 2006). The magnitude of peak flows were estimated for the 100-year (Q100), 50-year (Q50), and 25-year (Q25) recurrence intervals.

The discharges associated with the flood recurrence intervals were then used to scale the hydrograph from the February 1996 flood in order to calculate flood volumes for each recurrence interval (Figure 2, Table 1). The February 1996 flood was selected as the storm event for analysis because it is the largest volume storm for which continuous discharge data is available (since 1989) and because it is the basis of the synthetic hydrograph used to evaluate the main stem levee setbacks with a 1-dimensional HEC-RAS model in the 2008 levee setback report (Geoengineers, 2008). The February 1996 hydrograph from the Puyallup at Puyallup gage was scaled by taking the ratio of the flood's peak discharge (46,700 cfs) and the estimated peak discharge at each recurrence interval (e.g.: $Q100 = 59,750$ cfs; $Q100/\text{February 1996} = 1.28$) and multiplying it by the instantaneous discharge measured during the February 1996 flood at each time-step to generate a synthetic hydrograph for each recurrence interval upon which to calculate volumes (Figure 2). Note that this method provides an approximation of the flood hydrograph at each recurrence interval and a basis for comparison of flood volumes between different frequency events rather than mimicking observed values for individual storms. The effect of climate change on future flood volumes was accounted for in the analysis by scaling the estimated Q100 discharge by an additional 37%, which is the estimated increase in peak discharge for the basin (Mauger et al., 2015; calculations based on Hamlet et al., 2013). Volumes for each synthetic hydrograph were then calculated using a trapezoidal integration approach.

In order to account for the portion of each flood that is likely to cause major flooding within the basin, flood volumes for each recurrence interval were calculated for the duration during which each hydrograph exceeded the Flood Stage published by the National Weather Service (NWS). For the Puyallup at Puyallup gage, the NWS flood stage is 26.2 feet which is estimated to represent a discharge of 35,496 cfs using the most recently published rating curve (USGS, 2021). We selected the Flood stage instead of the Moderate or Major Flood stage in order to conservatively represent typical flooding conditions within the basin. The resulting flood volumes were then used to contextualize the flood storage volumes of main stem levee setback projects and tributary restoration (Figure 2, Table 1).

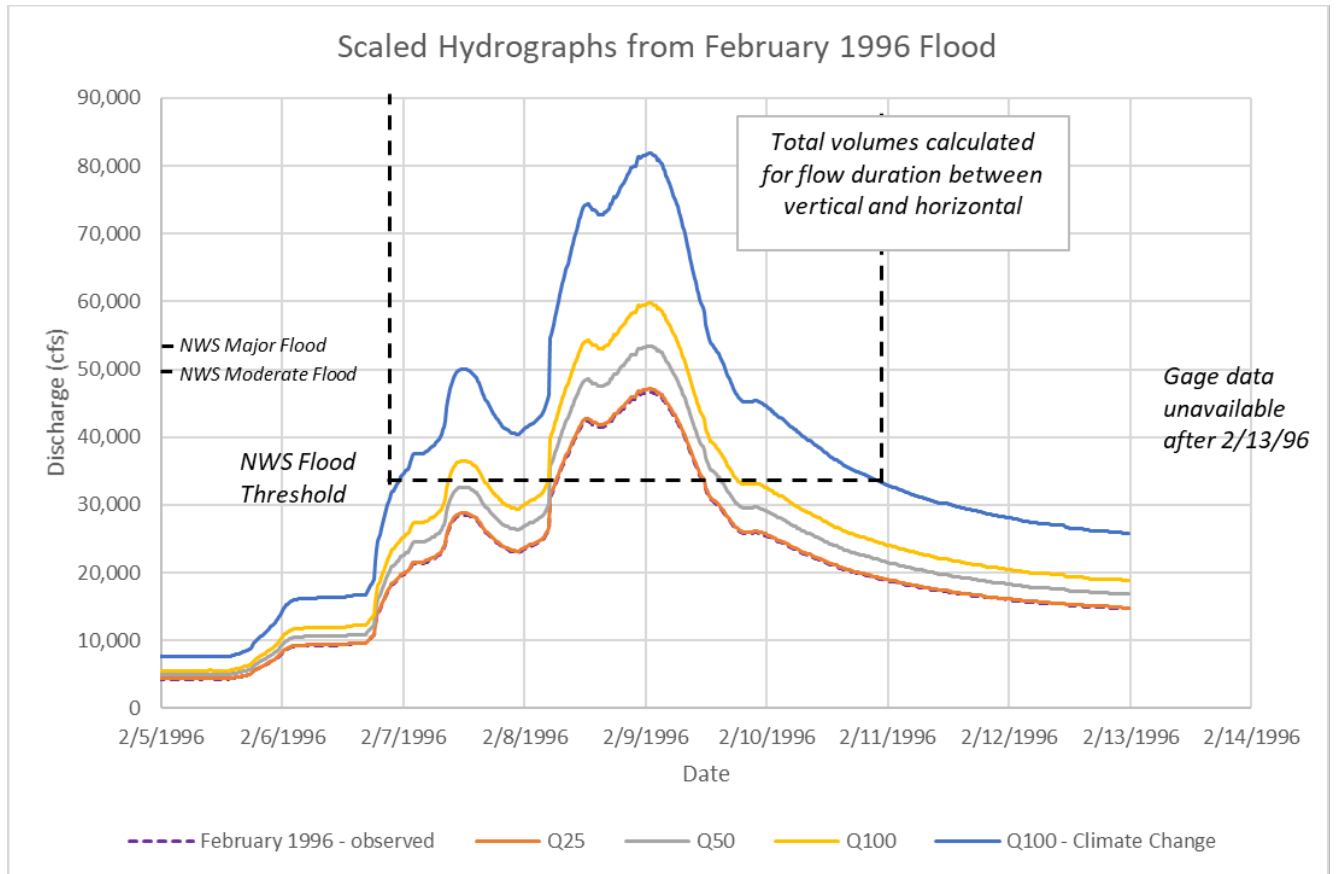


Figure 2. Scaled hydrographs of the February 1996 flood from the USGS Puyallup River at Puyallup, WA gage (USGS 12101500). The observed February 1996 flood, which was estimated to have a 25-year recurrence interval, (dashed purple line) was scaled using flood frequency statistics calculated using PeakFQ. Volumes of each flood were calculated for the duration of the flood that exceeded the National Weather Service’s Flood Stage of 26.2 ft which is estimated to represent a discharge of 35,496 cfs using the most recently published rating curve.

Table 1. Instantaneous flood peak discharges and four-day flood volumes used to contextualize flood storage estimates. The peak discharges were calculated using PeakFQ on gage data from the USGS Puyallup River at Puyallup, WA gage (USGS 12101500).

Flood	Peak Discharge (instantaneous,cfs)	Estimated Volume above flood threshold (4-days, acre-ft)
February 1996	46,700	94,000
Q25	47,090	95,000
Q50	53,440	123,000
Q100	59,750	163,000
Q100 - Climate Change	81,858	386,000

3.2 Flood Storage Volumes from Main Stem Levee Setback Projects

Levee setback projects within the large rivers of the Puyallup River watershed have been discussed for several decades, and several of the projects have already been built (e.g., the Countyline Setback Project along the White River) or are in development. In 2008, a levee setback feasibility analysis was conducted by the Pierce County Public Works and Utilities department and Geoengineers. The report proposed 32 levee setback projects within the basin and evaluated their feasibility and effectiveness which included estimating flood storage volumes within each project area (Geoengineers, 2008). For the purposes of this study, the project locations and flood storage volume results from each levee setback project presented in the 2008 are used directly.

3.2.1 Methods

Flood storage volumes for the 32 main stem levee setback projects were calculated directly from data presented in the 2008 report (Figure 3; Geoengineers, 2008). Flood storage volumes were estimated in the 2008 study using a 1-D HEC-RAS model where flow through the proposed levee setback projects was simulated by removing the existing levees from the modeling surface and calculating the volume within each project area using the modeling program. Results are presented in the 2008 report as the change in maximum storage (MFS) and the change in total storage (TFS) with all values in acre-ft. We utilized the MFS values because they are more representative of the influence of each levee setback project on flood peak reduction as they represent the maximum instantaneous flood storage volume instead of integrating all of the water that passes through each project area during the duration of a flood.. The MFS values from the 2008 study were summed across all proposed setback levees for each recurrence interval: Q25, Q50, and Q100. The total volumes were then compared to the calculated flood volumes described above.

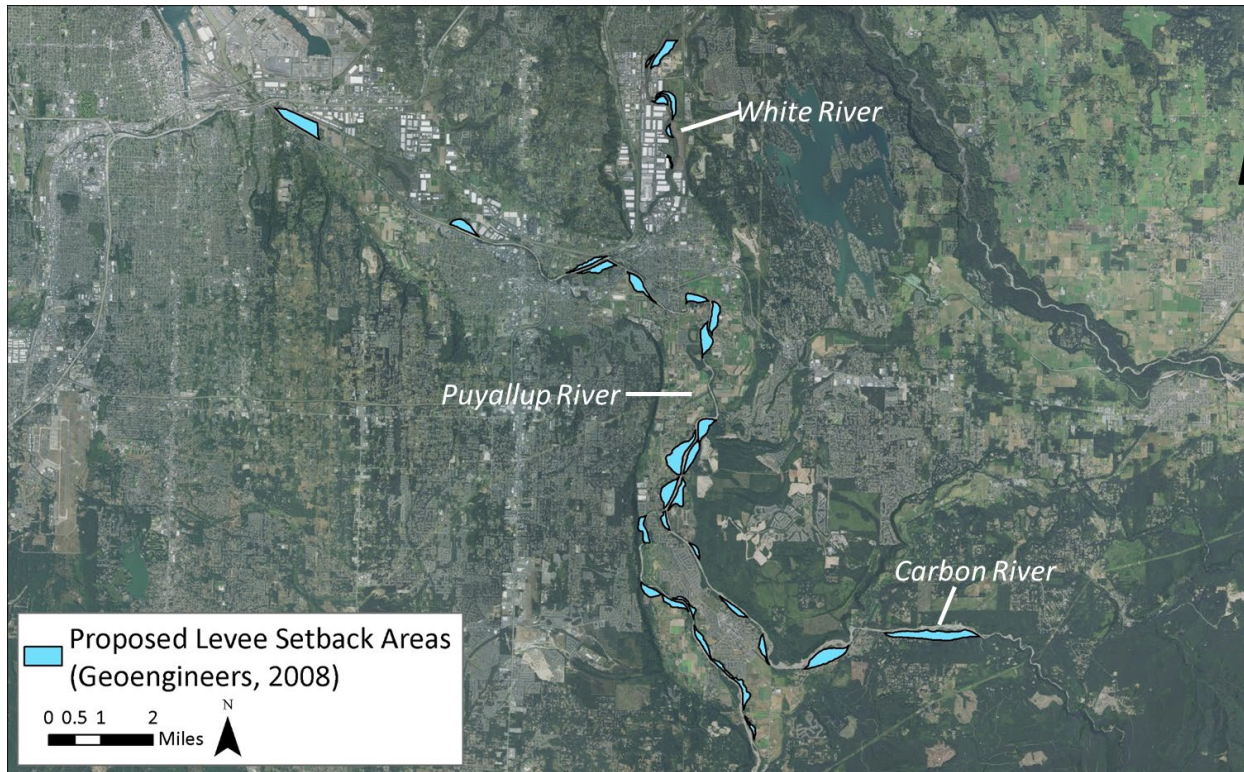


Figure 3. Locations of the proposed levee setback areas used in this analysis. The levee setback areas were first presented in Geoengineers, 2008.

3.2.2 Results

There is large variability in the flood storage volume estimates for the individual main stem levee setback projects (Table 2). Some projects such as the Carbon Confluence site are predicted to store very little flood volumes (0.4 acre-ft at the Q100) while others, such as the Union Pacific Setback (674.2 acre-ft at the Q100) are predicted to store greater volumes. The differences are likely due to the size and relative elevation of the project area, slope of the surrounding valley, and complexities in flood hydraulics which dictate how much water will inundate a particular levee setback area.

We compared the results to the total volume of the Q100 flood to provide context and as a means by which to compare main stem levee setbacks to tributary restoration. When contextualized to the flood volumes, the cumulative, instantaneous flood storage of all of the individual projects is less than 3.3% of the total flood at the Q100, which occurs over 4 days. The small percentage is partially due to the relatively small size of the project areas in comparison to the total volume of flood waters for the watershed, but also due to the different time-scales of the compared values. The flood storage volumes for the main stem levee setbacks represent the volumetric storage potential at a moment in time, whereas the total Q100 flood volume is integrated over the duration of the flood. Thus, the values provide some relative context, but are not an indication of flood peak reduction, as discussed below.

Table 2. Flood storage volume estimates for the main stem levee setback projects. Estimates of the Maximum Flood Storage (MFS) were calculated in Geoengineers, 2008 and compared against flood volumes presented in Table 1 as part of this study.

Site Name	Site Number	River System	Bank	System Rivermile	ΔMFS, c=25 (acre-feet)	% of Q25 flood	ΔMFS, c=50 (acre-feet)	% of Q50 flood	ΔMFS, c=100 (acre-feet)	% of Q100 flood
Union Pacific Setback	01	Puyallup	right	2.6	94.6	0.10%	501.2	0.41%	674.2	0.41%
Freeman Oxbow Wetland	02	Puyallup	right	6.7	109.0	0.12%	158.2	0.13%	223.1	0.14%
White & Puyallup Confluence	03	Puyallup	right	9.4	73.1	0.08%	161.7	0.13%	198.5	0.12%
Golf Course Oxbow Setback	04	Puyallup	left	9.6	35.7	0.04%	53.5	0.04%	82.5	0.05%
Sumner Setback	05	Puyallup	left	10.7	13.8	0.01%	74.1	0.06%	113.8	0.07%
Riverside Dr	06	Puyallup	right	12.2	-4.3	0.00%	41.4	0.03%	74.1	0.05%
Riverside Park	07	Puyallup	right	12.8	12.9	0.01%	24.4	0.02%	39.1	0.02%
Sportsman Reconnection	08	Puyallup	left	13.2	13.5	0.01%	79.0	0.06%	112.0	0.07%
Fennel Creek	09	Puyallup	right	15.2	19.8	0.02%	76.7	0.06%	123.3	0.08%
116th Reconnection	10	Puyallup	left	15.7	306.9	0.32%	549.8	0.45%	911.4	0.56%
Canyon Falls Creek	11	Puyallup	right	15.9	64.1	0.07%	142.1	0.12%	186.7	0.11%
McCutcheon Rd & 128th	12	Puyallup	right	16.7	30.1	0.03%	98.7	0.08%	121.7	0.07%
Upper Puyallup Confluence	13	Puyallup	left	16.8	4.8	0.01%	66.4	0.05%	93.0	0.06%
South Fork	14	Puyallup	left	17.7	47.2	0.05%	43.6	0.04%	34.8	0.02%
Horse Haven	15	Puyallup	left	19.2	-4.2	0.00%	1.0	0.00%	11.0	0.01%
150th Street	16	Puyallup	left	19.6	6.7	0.01%	3.8	0.00%	3.7	0.00%
Gratzer Ave NE HCOT	17	Puyallup	right	19.8	14.8	0.02%	18.2	0.01%	21.7	0.01%
Calistoga	18	Puyallup	right	20.6	38.4	0.04%	35.6	0.03%	31.3	0.02%
190th Ave downstream	19	Puyallup	right	21.3	122.4	0.13%	104.4	0.08%	94.2	0.06%
190th Ave upstream	20	Puyallup	right	22.6	8.0	0.01%	8.9	0.01%	10.3	0.01%
Carbon Confluence	21	Carbon	left	0	-2.4	0.00%	-1.1	0.00%	0.4	0.00%
Right Bank Carbon	22	Carbon	right	0.8	0.2	0.00%	0.7	0.00%	2.7	0.00%
High School	23	Carbon	left	2	56.4	0.06%	59.6	0.05%	63.4	0.04%
Bridge Street	24	Carbon	left	3.1	84.3	0.09%	87.5	0.07%	92.1	0.06%
West Setback	25	Carbon	left	4.3	128.9	0.14%	145.6	0.12%	187.5	0.11%
Alward Road	26	Carbon	left	6.4	1514.1	1.60%	1,513.7	1.23%	1,499.8	0.92%
Interurban-White Site	27	White	right	2.6	3.4	0.00%	4.8	0.00%	7.1	0.00%
24th St E Pointbar	28	White	left	3.2	12.3	0.01%	17.9	0.01%	21.9	0.01%
8th St E Setback (B)	29	White	left	3.9	0.0	0.00%	-1.5	0.00%	8.5	0.01%
Pacific Pointbar	30	White	right	4	4.2	0.00%	5.3	0.00%	4.8	0.00%
Pacific Park	31	White	right	5.1	7.8	0.01%	9.5	0.01%	10.6	0.01%
Countyline site	32	White	left	5.1	270.3	0.29%	288.7	0.23%	343.1	0.21%

In total, the main stem levee setback projects are predicted to store 3.3% of the Q25 flood volume (3,087 acre-ft), 3.6% of the Q50 flood volume (4,374 acre-ft) and 3.3% of the Q100 flood volume (5,402 acre-ft) (Table 3). The majority of the flood storage is predicted to occur within the 916 acres of projects along the Puyallup River for the Q50 and Q100 floods, where total flood storage volumes range from 1,007 acre-ft (1.1%) at the Q25 to 3,160 acre-ft (1.9%) at the Q100. Despite being about one-third of the total area of the Puyallup projects, the levee setbacks along the Carbon River are predicted to store more volume during the Q25 flood (1,782 acre-ft; 1.9%) and similar volumes under the Q50 (1,806 acre-ft; 1.5%) and Q100 (1,846 acre-ft; 1.1%) floods. This may be due to the relatively large predicted flood storage volumes of the Alward Rd. project, which accounts for over a quarter of the total flood storage volume under the Q100 flood. Further analysis is needed to confirm the results for the Alward Rd. project because the predicted volumes are larger than we would expect given that the project accounts for only 10% of the total setback area. Projects along the White River are predicted to store the least amount of flood storage volumes of the three basins included in the study area.

Table 3. Flood storage volume estimates for the main stem levee setback projects.

River System	Area (acres)	Q25		Q50		Q100	
		Flood Storage at Peak (acre-feet) [ΔMFS]	% of flood	Flood Storage at Peak (acre-feet) [ΔMFS]	% of flood	Flood Storage at Peak (acre-feet) [ΔMFS]	% of flood
Puyallup	916	1,007	1.1%	2,243	1.8%	3,160	1.9%
Carbon	326	1,782	1.9%	1,806	1.5%	1,846	1.1%
White	120	298	0.3%	325	0.3%	396	0.2%
Total	1,363	3,087	3.3%	4,374	3.6%	5,402	3.3%

3.3 Flood Storage Potential from Tributary Restoration

We estimated the potential additional flood storage volume from extensive tributary restoration in the Puyallup River watershed by estimating the increase in overbank flow due to instream restoration treatments in 12 pilot reaches and using results at these reaches to extrapolate to the entire tributary network. This analysis assumes restoration throughout all tributaries without regard to land ownership or floodplain infrastructure and assumes aggressive placement of instream structures, such as engineered log jams, that increase hydraulic roughness and raise water surface elevation (Figure 4). The workflow, described in more detail below, included the following steps:

1. Classify areas of the watershed, based on valley width and gradient, that are likely to provide flood storage capacity based on the findings of previous research and professional experience;
2. Estimate the flood storage potential from tributary restoration within pilot reaches of each stream class using at-a-station hydraulic calculations;
3. Extrapolate the results from each pilot reach to the entire stream class using the average depth increase following restoration and the valley bottom area of the full stream class; and
4. Total the flood storage potential from all stream classes and contextualize using calculated flood volumes.



Figure 4. Example of potential restoration treatment considered for the tributary restoration scenario. This treatment includes the placement of engineered log jams (ELJs) throughout the active channel and floodplain in order to increase hydraulic roughness throughout a reach which will slow velocities and increase floodplain connectivity. Photo from a restoration project on South Prairie Creek, WA.

3.3.1 Methods

Stream Network Classification

Determine Physical Characteristics

The flood storage volume assessment started with a geospatial analysis of a composite lidar digital elevation model (DEM) to map the natural drainage network across the subject watersheds. Steps of this analysis include flow correction to account for flow paths that are not present in the DEM (i.e., culverts), mapping of the drainage network and stream reaches, measure of surface-derived geomorphic characteristics, estimation of bankfull discharge and depth, and mapping of approximate valley bottom extent. Outputs of the geospatial analysis were then used for the numeric and geometric analysis to estimate flood volume and sediment storage potential.

Inputs to the model included Pierce and King County lidar DEMs from 2003 to 2016 with a mean annual precipitation overlay (PRISM Climate Group, 2012). The lidar DEM was down-sampled to a 9-foot cell resolution from the native 3-foot cell. The down-sampling uses the mean elevation of the underlying 3-foot cells and aids the analysis by removing noise from the data and speeding processing. Analysis was conducted in ArcMap 10.8 using the Spatial Analysis toolset.

Flow Correction

Recognizing that not all flow paths are represented in a DEM, flow correction measures were applied to the surface to account for culverts or other flow paths which may not be present in the DEM. The methods used for

this processing were based on selective drainage methods for continuous surface flow for lidar-derived surfaces published by USGS (Poppenga et al., 2010).

The flow correction processing identifies isolated depressions on the surface in excess of a threshold size and depth. For our analysis, depressions had to be at least 1 foot deep and 5,000 square feet to be included in flow correction steps. These depressions were evaluated and the lowest elevation point for each was isolated. The DEM was then analyzed within a 400-foot distance of the low point to identify the nearest point on the DEM with a lower elevation value to serve as an outlet. Each low point and outlet pair is then connected on the DEM with a one-cell wide, smooth gradient pathway between the two elevation points. Thus, outflow paths are ‘burned’ into the DEM out of select depressions, correcting most of the limitations to developing a continuously draining surface. Any depressions remaining on the DEM (those below the selected threshold values and those with no outlet found) are then filled to develop the flow-corrected DEM.

Drainage Analysis

The flow-corrected DEM was used to develop a surface-conforming, continuous drainage network within the study area. Mapping flow paths based directly on digital surface data allows for the direct query of elevations, gradient, and connected floodplain features. Flow paths with a minimum drainage area of 0.1 square miles were mapped, initially, as part of the drainage network. This threshold on drainage area conformed roughly with upper reaches of the headwater and intermittent streams of the National Hydrography Dataset (NHD) (USGS, 2019). The drainage network is split into stream reach units, with reach breaks occurring at flow line confluences and at boundaries of waterbodies mapped within the NHD, with a maximum length of 2500 feet.

For each stream reach, data was recorded for drainage area, minimum and maximum elevations, length, gradient, and stream order. The catchment area of each stream reach was also analyzed to determine the spatial average for annual precipitation.

Using the drainage area and average annual precipitation calculated for each stream reach, the Q2 and Q100 flow discharge was estimated using USGS Region 3 regression equations (Mastin et al., 2017). The Q2 discharge values were used as an approximated bankfull flow when calculating an estimated bankfull depth for each reach. Estimates of bankfull depth used the regional hydraulic geometry equations for Pacific Maritime Mountain Streams (Castro & Jackson, 2001).

Valley Bottom Mapping

In order to assess the geomorphic conditions of the valley at each stream reach, we returned to the DEM for further analysis. The DEM was analyzed to determine the relative position of each elevation point in relation to the stream to which it drains by creating a relative elevation model (REM). REMs are commonly used tools in geomorphology and are derived by subtracting a smoothed plane of the water surface elevation along a valley from the elevations of the full topography, essentially removing the slope of the valley from the topography.

This comprehensive mapping of relative geomorphic position (through the creation of a REM) above each stream reach was used to delineate the extent of the alluvial valley bottom for each stream reach. As the scale of each stream or river reach varies widely across the watershed, no single relative elevation value was appropriate for all stream reaches. Rather, a 5x multiple of the estimated bankfull depth was used as a relative elevation value for mapping valley extent in each stream reach. This method of valley bottom mapping is informed by the U.S. Forest Service’s Valley Confinement Algorithm (Nagel et al., 2014), which found a bankfull depth derived flood factor to be a valid tool in determining valley confinement.

Select stream classes that are conducive to flood storage

The Puyallup River watershed was classified using the physical characteristics of slope and valley bottom area in order to select areas conducive to flood storage. Previous research indicates that the slope of a reach is one of the primary factors that determines how much flood water can be stored through restoration because it dictates the increase in water depth that can be achieved through restoration (i.e., increased roughness) as well as the underlying properties of the flood wave that determines how the water will respond to restoration actions and influence flow downstream (Abbe et al., 2019). The general conclusions of previous studies demonstrate that in general, areas with a lower slope show a greater flood storage response than areas with higher slopes. Based on the results of the previous research, we classified the delineated stream-network based on slope and only included areas with a slope less than 3% (0.03 ft/ft) for inclusion in this analysis.

The area of the valley bottom defines the potential area in which flood volumes can be stored, and thus the larger the valley bottom, the greater potential flood storage. Valley bottoms within the Puyallup River watershed have been formed by both fluvial (i.e., river derived) and glacial processes and thus vary significantly in width depending on how they were formed. In general, glacially formed valleys (e.g., the Carbon River valley) are wider than fluvially formed ones (e.g., the Voight Creek valley). To incorporate valley bottom area into the watershed classification process, polygons of the delineated valley bottoms were overlaid onto the lidar hillshade and visually categorized based on their geomorphic characteristics and size.

The watershed was classified for flood storage potential by overlaying the stream network symbolized by slope onto the valley bottom polygon and visually categorizing areas with similar characteristics (e.g., low slope and wide valley). Care was taken to incorporate the geomorphic setting of the area (e.g., glacially influenced, watershed setting) into the classification procedure so that areas within a particular class have similar characteristics. The characterization was performed by a geomorphologist and verified by a licensed professional geologist. The area of the watershed where main stem levee setback projects are proposed was excluded from the screening analysis.

Estimate Flood Storage Volumes

Pilot Reach Selection

Three pilot reaches were selected within each stream class in order to estimate the potential flood storage volume. Pilot reaches were visually selected by evaluating the entire stream class within ArcGIS. Reaches were delineated within areas with generally straight valley geometry in order to maintain accurate estimates through the at-a-station approach and that were indicative of the typical channel and valley morphology of the stream class. Pilot reaches were between 0.5 and 1.5 miles long.

Hydraulic Analysis

An at-a-station hydraulic analysis was performed within each pilot reach for the Q100 flow to estimate the flood storage potential from tributary restoration using Manning's Equation, which quantifies the relationship between flow characteristics, including velocity and water surface elevation, and channel characteristics, including gradient, channel shape, and hydraulic roughness. Four or five cross-sections were drawn for each reach and interpolated using the composite lidar DEM (described above) in order to generate ground elevations. Each cross-section was then evaluated using the Manning's Equation, using the underlying lidar topography, the bed slope, an existing or restored roughness value, and the estimated Q100 discharge for each reach to determine the water surface elevation that solves the equation using an algorithmic iteration procedure. An existing condition roughness value (i.e., Manning's n) of 0.05 was used for the entire watershed, which is typical for the coarse gravel/cobble bedded rivers found throughout the project area. A single roughness value was used to reduce the number of variables in order to better understand the factors influencing flood storage

potential such as slope and valley geometry even though the single value is likely an overestimate for some reaches and an underestimate for others.

To simulate the effect of restoration within each pilot reach the roughness was increased above the existing condition which accounted for the expected restoration approach of installing engineered log jam (ELJ) structures. To account for the variability of potential treatments, a range of roughness increases (EC to Restored) was evaluated:

- ▶ Low restoration: 0.05 to 0.075
- ▶ Moderate restoration: 0.05 to 0.1
- ▶ High restoration: 0.05 to 0.125

The restored roughness values are much higher than those calculated for gravel bedded streams and are representative of dense placements of large wood throughout the active channel corridor of each pilot reach.

Once the water surface elevation was estimated for each cross-section under the existing and restored scenarios, values from 4-5 cross-sections were interpolated across the reach to simulate the water surface that would occur during the Q100 flood and create a 2-dimensional surface. The depth for each condition (Existing and restored) was then calculated by differencing the interpolated water surface elevation from the composite bare-earth DEM. The change in depth between existing and restored conditions was then calculated by differencing the two different depth rasters. The mean depth difference (i.e., how much more water is predicted to be in the valley under restored conditions) was calculated using the geospatial statistic tools in ArcGIS and is used as one of the primary metrics for each pilot reach. The area of inundation under the restored condition was then calculated using ArcGIS and compared to the area of the full valley bottom within the pilot reach in order to calculate the percent of the valley that is inundated under restored conditions. This value was also used as a primary metric in the extrapolation procedure described below.

Flood storage potential of stream classes

The results from the hydraulic analysis within each pilot reach were then extrapolated across each stream class to generate estimates of flood storage potential across the entire study area. To create metrics for each stream class the results from each of the 3 pilot reaches for the *average depth difference* and *percent of valley inundated* were averaged. The average results for each stream class were then extrapolated to the entire stream class using the following equation which calculates how much extra volume could be stored within each stream class if the depth increased similarly to the pilot reaches between existing and restored conditions and the valley throughout each stream class was inundated at a similar percentage:

$$\text{Average depth increase (ft)} \times \text{Total valley bottom area (acres)} \times \% \text{ valley inundated} \\ = \text{Flood storage volume (acre - ft)}$$

Equation 1. Flood storage volume calculations for the tributary restoration strategy

Flood storage volumes were then calculated for each stream class using the same procedure.

3.3.2 Results

Stream Network Classification

Physical Characteristics of Stream Network

The stream network within the Puyallup River Watershed was classified into four classes based on their physical characteristics of slope and valley bottom area and how they relate to flood storage potential (Figure 5, Figure 6, Figure 7, and Table 4). Class A represents reaches that have a low gradient (<1%) and wide valley and consist of large, glacially influenced, main stem rivers such as the White River (below the forks) and the middle Puyallup River below the Electron Canyon. Class A also includes the lower portion of South Prairie Creek, which has an over-widened valley relative to its current size because it was formerly the flow path for the White River (Andersen and Jaeger, 2019). Class B represents reaches with a moderate gradient (1-3%) and wide valley bottom and consists of mid-sized, glacially influenced rivers that are higher in the watershed than the class A streams. Glacial influence was inferred based on the U-shaped valley geometry and large width relative to the stream size. Class B includes reaches of the Carbon River, the main stem Puyallup River below the Mowich River confluence, the Mowich River, the Upper White River, the West Fork White River, and Huckleberry Creek. Class C represents reaches with a moderate gradient (1-3%) and a moderately sized valley and includes larger, non-glacial rivers, and smaller glacially influenced rivers. Class C includes reaches of the Upper Puyallup River, the Greenwater River, and the Clearwater River. Class D represents smaller rivers and creeks with a narrow valley and a low-moderate gradient (<1%-3%). Class D consists of non-glacially influenced systems where fluvial processes have primarily defined the valley bottom and includes Voight Creek, Wilkeson Creek, and the upper portions of South Prairie Creek above the Wilkeson Creek confluence.

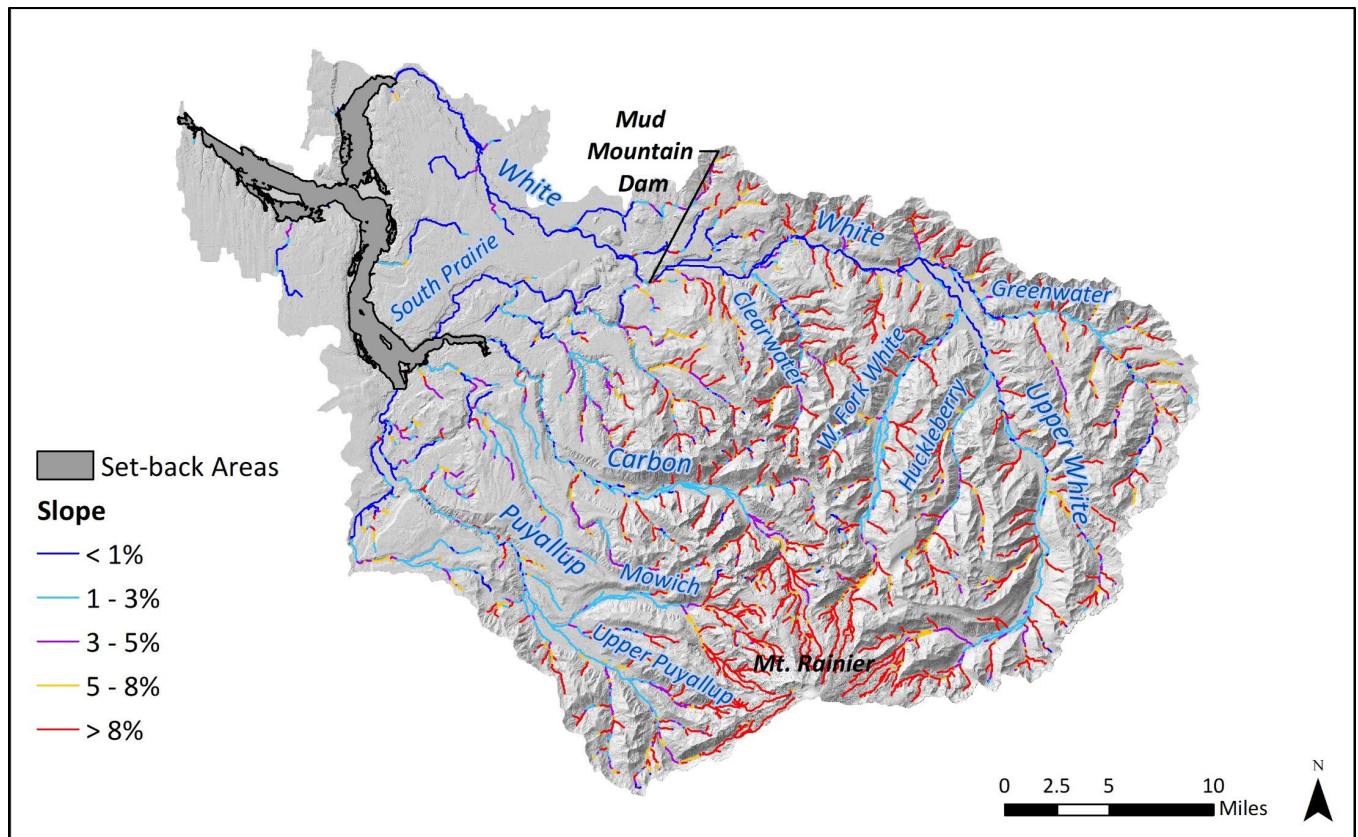


Figure 5. Slope map of streams within the Puyallup Watershed. Slopes were derived using a composite lidar digital elevation model using a geospatial algorithm in ArcGIS described Stream Network Classification methods section.

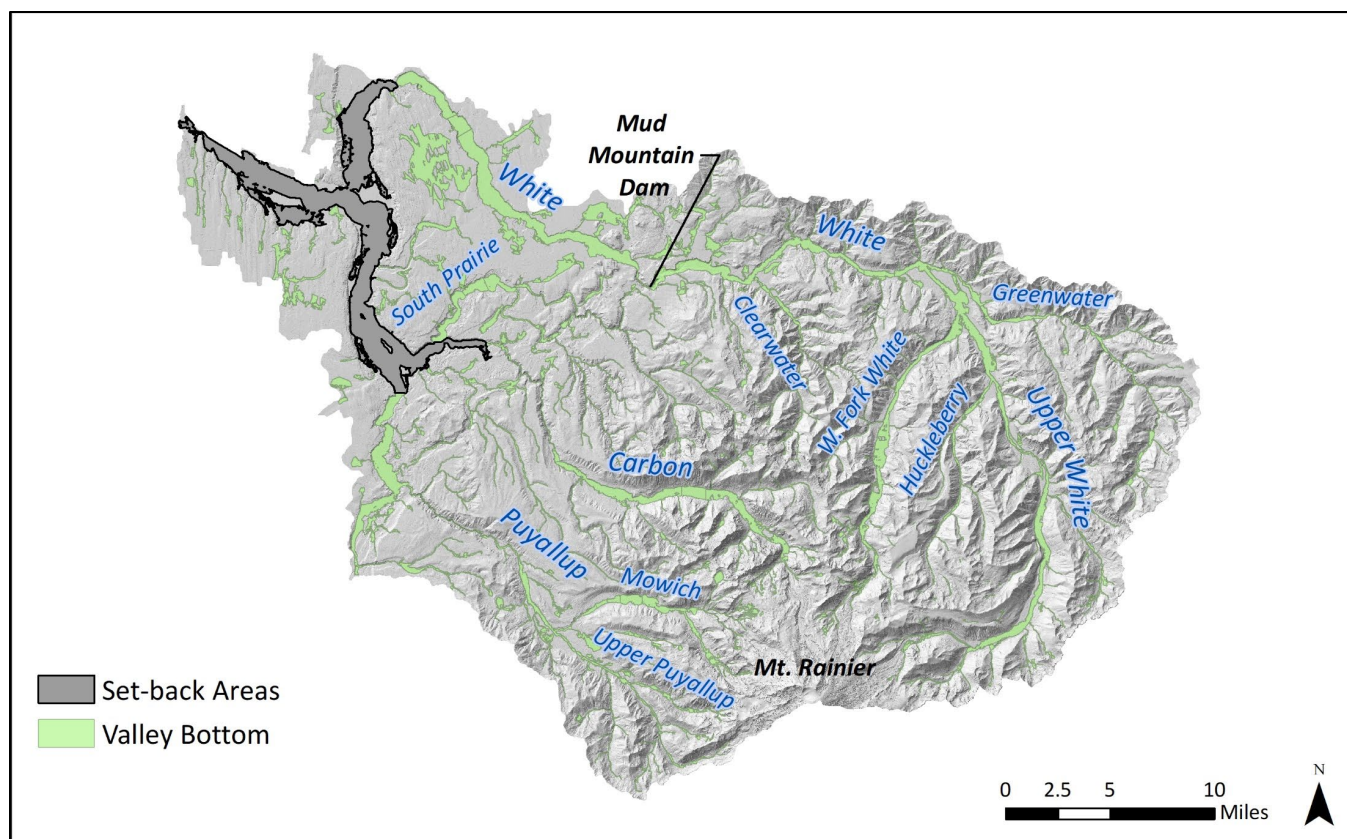


Figure 6. Map of valley bottoms within the Puyallup Watershed. Valley bottoms were delineated using a composite lidar digital elevation model and a geospatial algorithm in ArcGIS described in the Stream Network Classification section above.

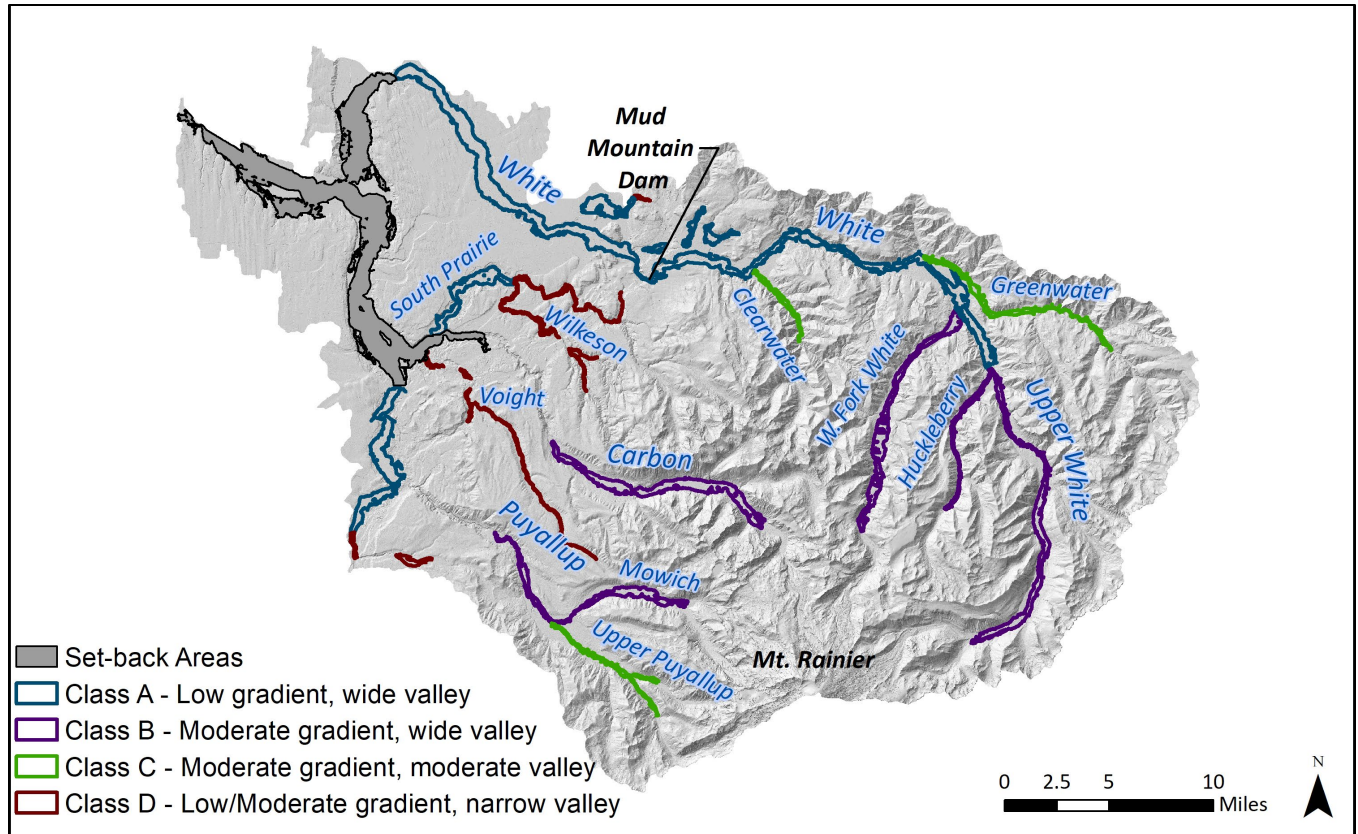


Figure 7. Stream network classification used to define tributary restoration areas within the Puyallup Watershed. Stream reaches were classified by the stream slope and valley bottom area and grouped based on their geomorphic characteristics.

Table 4. Description of Tributary Restoration stream classes.

Class	Description	Valley Bottom Area (acres)	Stream Length (miles)	Major Rivers and Creeks
Class A	Low gradient, wide valley	14,700	102	White River, Puyallup River, South Prairie Creek (lower)
Class B	Moderate gradient, wide valley	9,900	107	Middle Puyallup River, Mowich River, Carbon River, West Fork White River, Upper White River, Huckleberry Creek
Class C	Moderate gradient, moderate valley	800	39	Upper Puyallup River, Clearwater River, Greenwater River
Class D	Low/Moderate gradient, narrow valley	1,200	54	Voight Creek, Wilkeson Creek, South Prairie Creek (upper)

Pilot Reach Selection

Three pilot reaches were selected within each of the four stream classes in order to conduct the hydraulic analysis. The reaches were all located within relatively straight portions of the valley and have channel and valley morphologies representative of each stream class. Table 5 lists the stream name and physical characteristics for each pilot reach and the location of each pilot reach is shown in Figure 8.

Table 5. Pilot reaches and characteristics used to conduct the hydraulic analysis and estimate flood storage volumes for the tributary restoration strategy.

Reach Name	Stream Name	Class	Length (ft)	Slope (ft/ft)	Q100 (cfs)	Valley Area (acres)
Middle White	White River	A	5,000	0.004	40,000	400
Upper Middle White	White River	A	7,700	0.007	27,800	224
South Prairie Downstream	South Prairie Creek	A	6,000	0.0055	7,500	325
Mowich Wide	Mowich River	B	5,600	0.017	6,500	280
Mowich Moderate	Mowich River	B	3,000	0.015	6,600	65
Carbon Wide	Carbon River	B	6,000	0.015	8,900	375
Upper Puyallup	Puyallup River	C	4,000	0.02	7,400	40
Clearwater	Clearwater River	C	4,200	0.011	5,550	67
Greenwater	Greenwater River	C	3,000	0.009	5,700	64
Voight	Voight Creek	D	2,000	0.022	2,000	15
South Prairie Upstream	South Prairie Creek	D	2,400	0.008	4,900	21
Wilkeson	Wilkeson Creek	D	1,600	0.012	2,600	12

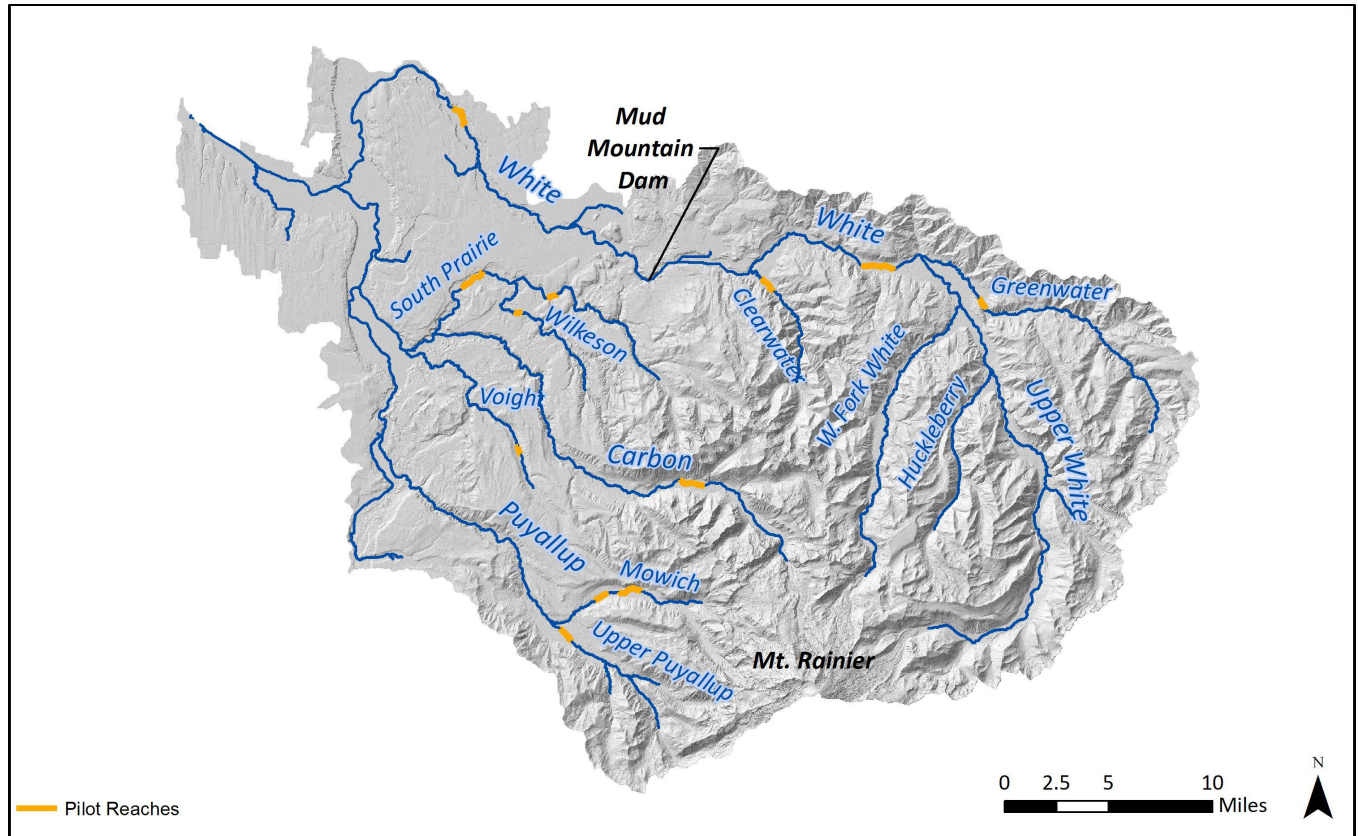


Figure 8. Locations of pilot reaches used to conduct the hydraulic analysis and estimate flood storage volumes for the tributary restoration strategy.

Hydraulic Analysis

At-a-station hydraulic calculations

At-a-station hydraulic calculations were performed on each pilot reach to simulate the potential flood storage increase from tributary restoration under the Q100 flood (Figure 9, Table 6). The average depth increase values ranged from 0.5 ft (Low scenario in the Voight Creek reach) to 3.8 ft (High scenario for the Upper Middle White reach) and varied depending on the roughness scenario and the relation between valley width, Q100 discharge, and slope. As expected, average depth increases were lowest for the low roughness scenario and highest for the high roughness scenario. In terms of physical characteristics, reaches with low slopes and higher discharges relative to their valley width showed greater depth increases and reaches with higher slopes and wider valleys relative to their discharge showed lower depth increases. Reaches such as the Mowich Wide reach have a large, glacially carved valley with a lower overall discharge and thus showed less of a depth increase under restored conditions. Voight Creek had the lowest average depth increase due to its high slope and low discharge. Even though there was variability amongst the stream classes, overall, the average depth increase metric was remarkably similar across the pilot reaches for each roughness scenario (i.e., the average depth increase varied from 0.9-2.7 feet for the moderate scenario), indicating that while physical characteristics do drive some variation in flood storage potential, the restoration approach (and amount of roughness increase) has a greater influence.

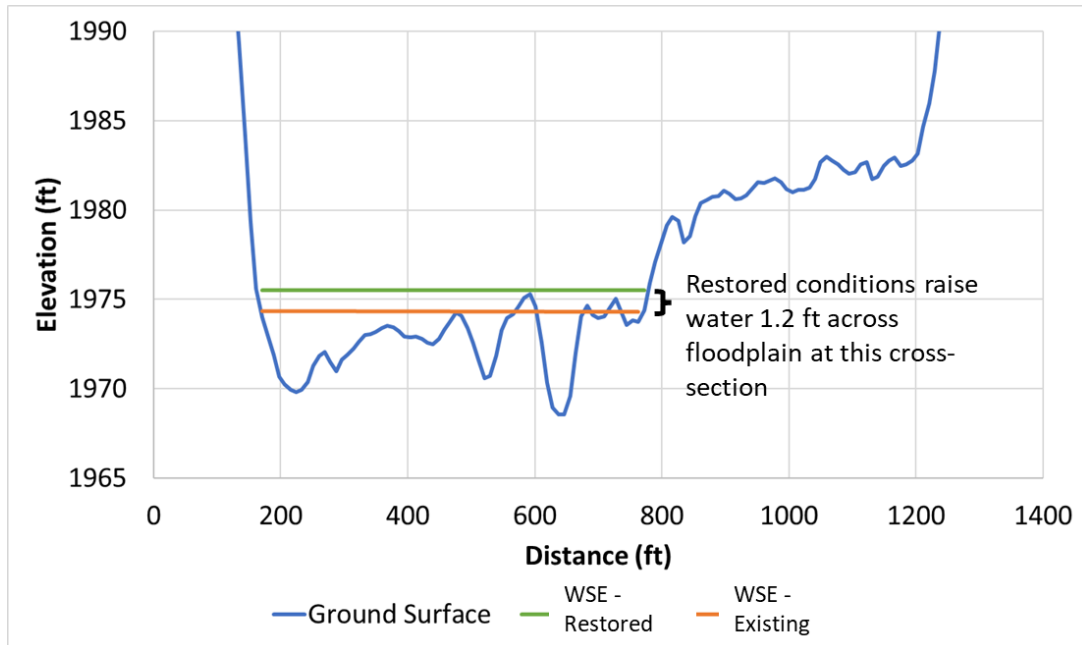


Figure 9. Example of at-a-station hydraulic calculations for one cross-section in the Mowich Wide pilot reach for the moderate roughness scenario. For this cross-section, increases in roughness in the restored condition raised water surface elevations by ~1.2 feet across the valley compared to existing conditions.

Table 6. At-a-station hydraulic results for the pilot reaches for the 100-year flood (Q100). Results for the Average Depth Increase and % Valley Inundated are presented for the moderate roughness scenario, with values for the Low and High roughness scenarios in parentheses). The range of results among pilot reaches is almost as big as the range between high/low scenarios.

Reach	Class	Avg Depth Increase (ft)	% Valley inundated
Middle White	A	1.9 (1.0 - 2.6)	76% (75% - 76%)
Upper Middle White	A	2.7 (1.5 - 3.8)	55% (54% - 55%)
South Prairie Project	A	1.2 (0.7 - 1.8)	36% (34% - 38%)
Mowich Wide	B	1.0 (0.6 - 1.3)	34% (30% - 37%)
Mowich Moderate	B	1.1 (0.7 - 1.5)	59% (56% - 62%)
Carbon Wide	B	1.0 (0.6 - 1.3)	39% (33% - 44%)
Upper Puyallup	C	1.9 (1.0 - 2.3)	55% (50% - 59%)
Clearwater	C	1.3 (0.7 - 1.7)	58% (55% - 62%)
Greenwater	C	1.6 (1.0 - 1.7)	49% (45% - 51%)
Voight Creek	D	0.9 (0.5 - 1.1)	51% (44% - 54%)
South Prairie Upstream	D	1.6 (0.9 - 2.2)	80% (78% - 82%)
Wilkeson Creek	D	1.2 (0.6 - 1.6)	64% (60% - 67%)

The percent valley inundated metric varied from 30% for the low scenario in the Mowich Wide Reach and 82% for the high scenario in the South Prairie upstream reach. The influence of physical characteristics (slope, discharge, valley bottom area) was similar to the average depth increase results. In contrast, the roughness scenarios had much less of an influence with the greatest variation of 9% in the area inundated for the Upper Puyallup Reach. The lack of influence of roughness indicates that the floodplain within the pilot reaches has likely equilibrated (i.e., adjusted its geometry) to convey existing flood discharges and that increases in depth associated with increased roughness are generally contained within the equilibrated floodplain area. There is a greater variation in the percent valley inundated metric across pilot reaches compared to the average depth increase metric, indicating that physical characteristics such as slope and valley width have a greater influence on the results.

At-a-station hydraulic calculations were also performed on the pilot reaches for the 2080s projected Q100 discharge using the moderate restoration roughness scenario (Table 7). The average depth increase ranged from 1.0 ft in the Voight Creek reach to 3.2 ft in the Upper Middle White reach and the percent valley inundated metric ranged from 38% in the South Prairie Project reach to 83% in the South Prairie Upstream reach. The results were greater than the existing conditions Q100 results shown above which demonstrates that the tributary restoration approach is still viable under a changing climate.

Table 7. At-a-station hydraulic results for the pilot reaches using the moderate roughness range and 2080 predicted 100-year flood discharges.

Reach	Class	Avg Depth Increase (ft)	% Valley inundated
Middle White	A	2.2	76%
Upper Middle White	A	3.2	56%
South Prairie Project	A	1.6	38%
Mowich Wide	B	1.1	39%
Mowich Moderate	B	1.3	62%
Carbon Wide	B	1.1	46%
Upper Puyallup	C	1.8	60%
Clearwater	C	1.5	63%
Greenwater	C	1.7	55%
Voight Creek	D	1.0	57%
South Prairie Upstream	D	1.9	83%
Wilkeson Creek	D	1.4	69%

Flood Storage Potential of Stream Classes

The flood storage potential of tributary restoration was estimated by extrapolating the results of the pilot reach hydraulic analysis across each stream class and contextualized with the scaled flood volumes (Table 8). For the full restoration area the results ranged from 11,800 acre-ft (7% of the Q100 flood) for the low restoration scenario to 31,600 acre-ft (19% of the Q100 flood) for the high restoration scenario, with 22,000 acre-ft (14% of the Q100 flood) estimated for the moderate restoration scenario. The results for each stream class had a wide

variation, ranging from 400 acre-ft (0.2% of the flood) for the low restoration scenario in Class C to 22,900 acre-ft (14%) for the high restoration scenario in class A. The variability between the stream classes can primarily be explained by the large difference in valley bottom area, which ranged from 800 acres in Class C to 14,700 acres in Class A. Class A also had the highest average depth increase and second highest average percent of valley inundated metrics across the four classes, primarily due to the high discharge, low slope, and wide valleys of the rivers included.

Table 8. Flood storage volume estimates for the tributary restoration strategy during the existing conditions 100-year flood. Results are presented for the moderate roughness scenario with values for the Low and High roughness scenarios in parentheses.

Class	Average Depth Increase (ft)	Average % valley inundated	Valley bottom area (acres)	Flood storage volume (acre-ft)	% of 100-year flood stored
Class A	1.9 (1.1 - 2.8)	56% (54% - 57%)	14,700	15,800 (8,500 - 22,900)	10% (5% - 14%)
Class B	1.0 (0.6 - 1.4)	44% (40% - 47%)	9,900	4,500 (2,400 - 6,400)	3% (2% - 4%)
Class C	1.6 (0.9 - 1.9)	54% (50% - 57%)	800	700 (400 - 900)	0.4% (0.2% - 0.6%)
Class D	1.2 (0.7 - 1.6)	65% (61% - 68%)	1,200	1,000 (500 - 1,400)	0.6% (0.3% - 0.9%)
		Total	26,600	22,000 (11,800 - 31,600)	14% (7% - 19%)

Table 9. Flood storage volume estimates for the tributary restoration strategy during the 2080s projected 100-year flood. Results are presented for the moderate roughness scenario only.

Class	Average Depth Increase	Average % valley inundated	Valley bottom area (acres)	Flood storage volume (acre-ft)	% of flood
Class A	2.3	57%	14,700	19,500	5%
Class B	1.2	49%	9,900	5,600	2%
Class C	1.7	59%	800	800	0.2%
Class D	1.4	69%	1,200	1,200	0.3%
		Total	26,600	27,100	7%

Flood storage estimates were also calculated for the projected 2080s 100-year flood using the moderate restoration scenario (Table 9). The total flood storage volume across stream classes was estimated to be 27,100 acre-ft, which is greater than the estimates for the existing Q100 flood. However, the total % of the flood (7%) was less than the existing conditions scenario because of the much larger overall flood volume (359,000 acre-ft for the 2080s 100-year flood versus 262,000 acre-ft for the existing conditions 100-year flood). Greater average depth increases were estimated for the climate change flood and ranged from 1.2-2.3 ft. A greater percent of valley inundation is also predicted to occur compared to the existing flood with values ranging from 49%-69%. The variation in results between stream classes were similar to the existing conditions flood estimates with the

difference between flood storage volumes being primarily driven by the differences in valley bottom area. These results indicate that the tributary restoration flood storage strategy would perform similarly under predicted climate change conditions as they will under existing hydrologic conditions.

The flood storage estimates were also summarized by their position relative to Mud Mountain Dam on the White River, which is one of the primary flood reduction strategies currently deployed within watershed (Table 10). A majority of the flood storage volume estimated by this study is on the White River and therefore influenced by Mud Mountain Dam, with 36% above the dam and 34% below it. This is because much of the classified stream network used in this study is within the White River sub-watershed which is the larger than the other sub-watersheds and has a comparatively larger valley bottom and lower slope. The remainder of the watershed not influenced by the dam accounts for 30% of the estimated flood storage volume.

Table 10. Flood storage volume estimates for the tributary restoration strategy during the existing conditions 100-year flood in relation to their position to Mud Mountain Dam. Results are presented for the moderate roughness scenario with values for the Low and High roughness scenarios in parentheses.

Relation to Mud Mountain Dam	Valley Bottom Area (acres)	Flood storage Volume (acre-ft)	% of total
Above	11000	8,000 (4,300 - 11,500)	36% (36% - 36%)
Below	7000	7,400 (4,000 - 10,700)	34% (34% - 34%)
N/A	8000	6,600 (3,500 - 9,400)	30% (30% - 30%)

Storing and slowing flood waters above and below Mud Mountain Dam could be a strategy to increase the resiliency of dam operations. Mud Mountain Dam has a limited reservoir volume and historically low flow release targets due to sediment aggradation downstream. As flood magnitudes increase with climate change, the reservoir volume may become insufficient to accommodate increased flow while maintaining the release targets. Increasing flood storage through restoration upstream of the dam could slow and reduce the volume of water entering the reservoir during a flood which would reduce pressure on the reservoir and dam operations. Additionally, slowing and storing water downstream of the dam could augment operations by decreasing downstream flooding even if elevated releases are needed to maintain capacity within the reservoir. Taken together, restoration strategies above and below the dam could work in tandem with dam operations to increase flood storage capacity while also enhancing aquatic habitat.

As with the levee setback projects, we compared the results to the total volume of the Q100 flood to provide context and as a means for comparison between flood reduction strategies. When contextualized to the flood volumes, the cumulative, instantaneous flood storage of the tributary restoration strategy is 7-19% of the total flood at the Q100 which occurs over 4 days. While higher than the levee setback projects, these percentages are still relative to the duration of time of the Q100 flood used for comparison. The flood storage volumes of the tributary restoration scenario represent the volumetric storage potential at a moment in time, whereas the total Q100 flood volume is integrated over the duration of the flood. Therefore, the flood storage estimates provide some relative context, but are not an indication of flood peak reduction which is discussed below.

3.4 Flood Storage Potential – Comparison of Levee setbacks and tributary restoration

The flood storage potential of tributary restoration projects is ~4 times larger than that of the levee setback projects identified in the 2008 report (Table 11, Figure 10). This is due to the much larger treatment area of the tributary restoration areas compared to the levee setback projects with the tributaries comprising 26,000 acres compared to 1,362 acres for the levee setbacks. Because of this, there is significantly more area upon which to store flood waters. However, despite the smaller area, the levee setback projects are almost 5 times as effective per treated area at storing flood water than the tributary restoration strategy. This is likely caused by the lower valley slope in the levee setback projects, which has been shown to influence the ability of a particular reach to store flood waters in previous work and will be discussed further in the following section (Abbe et al., 2019). Taken together, the results demonstrate that both strategies can increase flood storage volumes and could be employed together as a part of a suite of flood reduction strategies within the basin.

Table 11. Flood storage volume estimates for the tributary restoration and levee setback strategies during the existing conditions 100-year flood. For the tributary restoration strategy, results are presented for each roughness scenario as *Moderate (Low-High)*.

Action	Area (acres)	Flood Storage Volume (acre-ft)	% of Q100 flood	Volume per Area (acre-ft/acre)
Tributary Restoration	26,000	22,000 (11,800 - 31,600)	14% (7% - 19%)	0.8 (0.5 – 1.2)
Levee Setbacks (2008 Report)	1,362	5,402	3.3%	4.0

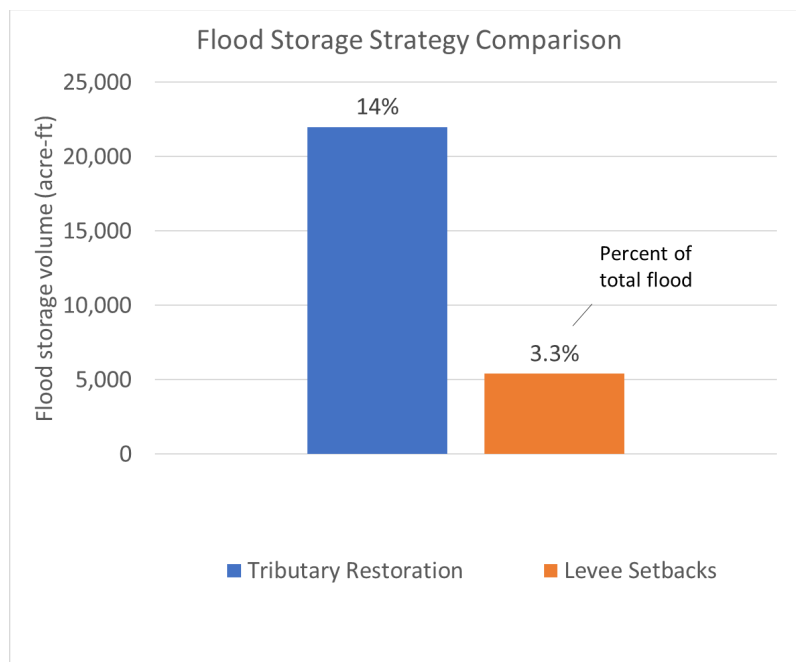


Figure 10. Flood storage volume estimates for the tributary restoration and levee setback strategies during the existing conditions 100-year flood. For the tributary restoration strategy, results are presented for the moderate roughness scenario only.

4 FLOOD PEAK REDUCTION

One of the overall goals of flood damage reduction strategies is to reduce the peak discharge of a flood so that less developed areas are inundated, flood depths decrease, and less overall damage occurs. While the flood storage estimates developed in this study are related to flood peak reduction, the relationship is not direct. Flood storage estimates characterize a snapshot in time and do not account for the overall flux of water transported by a flood. Flood peak reduction can be accomplished by several physical mechanisms, some of which may occur in some cases due to increasing flood storage via levee setbacks and tributary restoration (Figure 11). We review the physical mechanisms below and discuss the applicability to the levee setbacks and tributary restoration considered in this study.

There are three general mechanisms by which flood peaks can be reduced (Figure 11). The flood wave can be physically altered by modifying the flow (depth and velocity) so that the flood occurs over a longer period of time and the peak discharge is reduced. This process is called flood wave attenuation (A) and can be accomplished by increasing flood depths and/or decreasing velocities and is driven by the slope of the valley and amount of hydraulic roughness on the floodplain. Another mechanism is to physically remove water from the flood (B) by storing it in depressions on the floodplain or infiltrating it into groundwater, effectively decreasing the overall volume of the flood and decreasing the peak discharge. A third mechanism to reduce flood peaks is to de-synchronize the flood peaks of sub-watersheds (C) so they no longer compound to generate a large flood peak downstream. This could be accomplished by slowing velocities within one sub-watershed to delay the peak of the flood. While each flood storage strategy considered above is related to each of these mechanisms, the applicability of each of these mechanisms to increased flood storage depends on the physical characteristics and flood hydraulics of each of the areas in which the flood storage strategies are employed. The following section describes each of these mechanisms in greater detail, particularly as they relate to levee setback projects and tributary restoration.

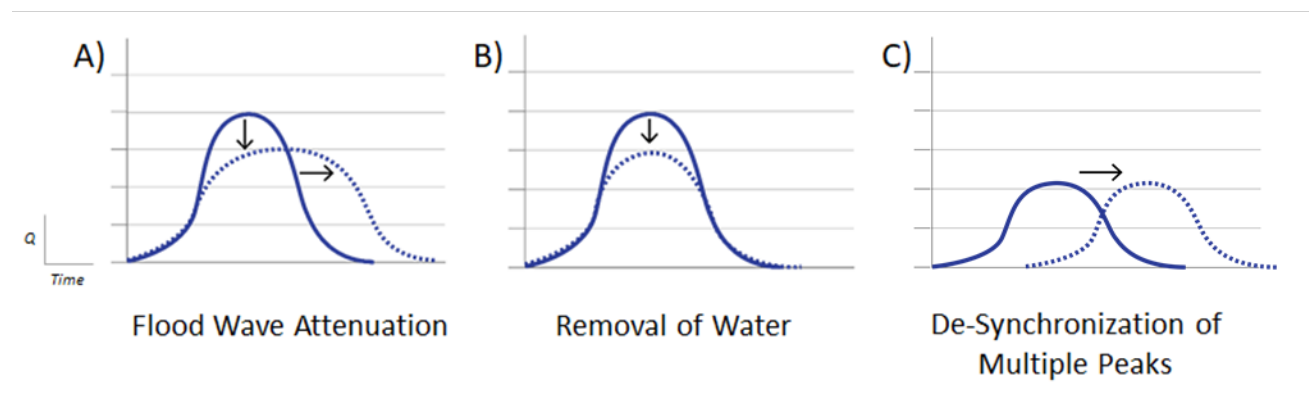


Figure 11. Conceptual diagram of mechanisms that can reduce the peak magnitude of floods.

4.1 Flood Wave Attenuation

Flood wave attenuation occurs when changes in the hydraulics of a flood cause the peak discharge to be reduced and the flood duration to increase (Ponce, 1997; Sturm, 2010; Abbe et al., 2019). For example, increases in depth caused by increased roughness through tributary restoration or decreases in velocity due to increased floodplain inundation within a levee setback project may alter the hydraulics of a particular flood enough to cause wave attenuation. However, the tendency for particular changes in hydraulics to cause the flood wave to attenuate is dependent on the driving mechanisms by which the momentum of the water is translated downstream.

Momentum transfer in flood waves can be approximated by three forces – Inertial, pressure, and gravitational forces. Inertial and pressure forces are related to the flow velocity and depth, respectively, and can be altered through restoration and engineering actions. Gravitational forces however, are related to the slope of the valley (where lower slopes have less gravitational influence than higher slopes) and cannot be altered within the timescale of a flood. Waves in which the three forces are relatively equal are termed either dynamic or diffusion waves. For these types of waves, changes to the inertial and pressure forces can influence the overall dynamics of the wave and cause wave attenuation. Waves in which the gravitational force is much greater than both the inertial and pressure forces are termed kinematic waves. For these types of waves, no amount of change to the flow hydraulics will cause attenuation. Because of this, the ability for a flood storage strategy to cause wave attenuation within a particular reach is primarily determined by the slope of the underlying valley.

To investigate the likelihood that the tributary restoration strategy could cause wave attenuation we determined the expected wave type within each pilot reach using methods presented in Ponce et al., 1989 and Equation 2 (Table 12). The same approach could not be used for the levee setback projects because estimates of average velocity and depth were not available.

Wave is Kinematic if $T_r V_o S_o / y_o > 85$ (Ponce, 1989)

Equation 2. Wave type equation

Where T_r is the time of rise of the inflow hydrograph (assumed to be 1 day based on available USGS gage data), V_o is the average velocity (from at-a-station hydraulic calculations), S_o is the bed slope (from lidar), and y_o is the average flow depth (from at-a-station hydraulic calculations).

Table 12. Expected wave type within the pilot reaches during the existing conditions 100-year flood. Waves that are categorized as kinematic are likely not able to be attenuated through increases in roughness. Waves categorized as dynamic or diffusion waves may be able to be attenuated through increases in roughness. These results are expected to be similar to those for smaller magnitude, higher frequency.

Reach	Class	Slope (ft/ft)	Avg Depth - EC (ft)	Avg Velocity - EC (ft/s)	Flood Routing Parameter (Kinematic if >85)	Wave Type
Middle White	A	0.004	3.95	4.5	392	Kinematic
Upper Middle White	A	0.007	5.4	7.6	848	Kinematic
South Prairie Project	A	0.0055	2.4	4.4	876	Kinematic
Mowich Wide	B	0.017	2	6.2	4,530	Kinematic
Mowich Moderate	B	0.015	2.2	6.1	3,616	Kinematic
Carbon Wide	B	0.015	2.2	6.0	3,533	Kinematic
Upper Puyallup	C	0.02	3.7	9.9	4,611	Kinematic
Clearwater	C	0.011	2.8	6.1	2,068	Kinematic
Greenwater	C	0.009	3.1	6.0	1,499	Kinematic
Voight Creek	D	0.022	1.6	6.4	7,553	Kinematic
South Prairie Upstream	D	0.008	3.2	5.6	1,218	Kinematic
Wilkeson Creek	D	0.012	2.5	5.8	2,425	Kinematic

Based on the results of Equation 2, all of the pilot reaches were predicted to exhibit kinematic flood waves and therefore wave attenuation is not expected to occur through changes to flood hydraulics (Table 12). This is due to the relatively high slopes of the tributary restoration area which cause the gravitational forces to dominate momentum transfer during floods. These results are consistent to previous work where a slope threshold under which wave attenuation can occur of 0.001 ft/ft was determined by Abbe et al. (2019) using an idealized two-dimensional hydraulic model.

To further investigate the wave attenuation potential of the flood storage strategies of this study the slopes of both the levee setback areas and tributary restoration areas were plotted against the 0.001 ft/ft slope threshold (Figure 12 and Figure 13).

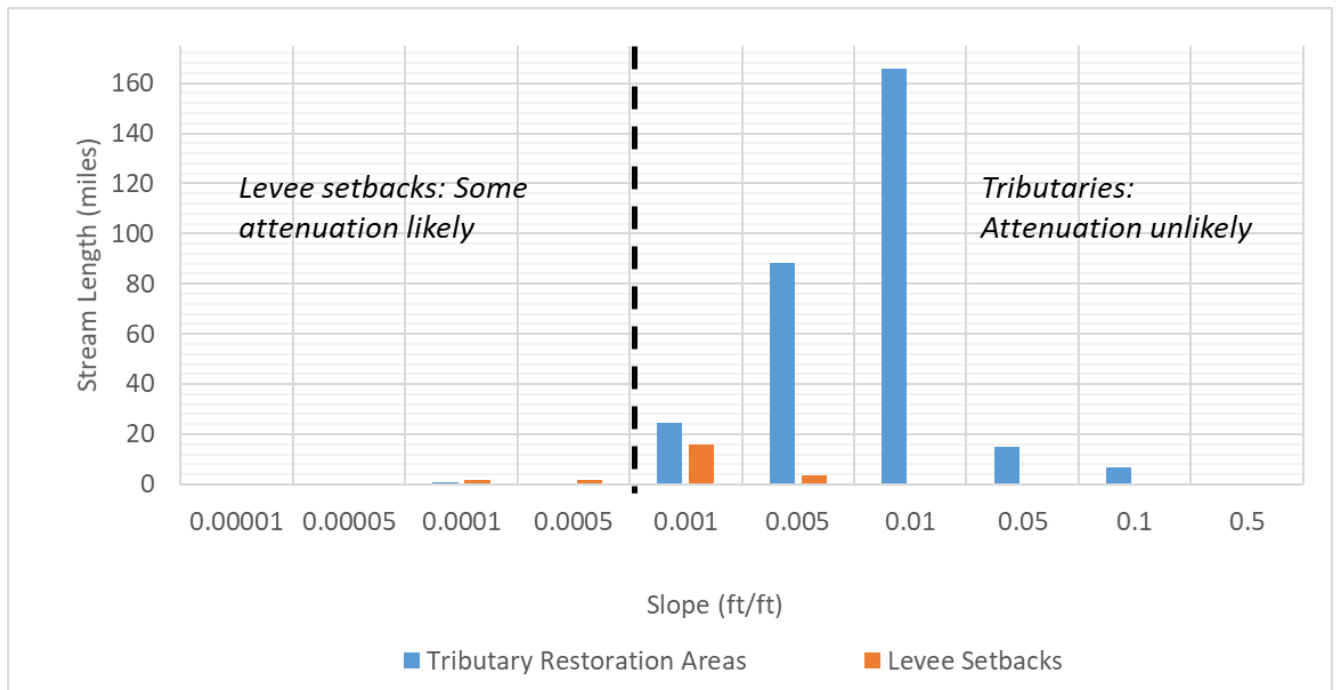


Figure 12. Distribution of stream slopes within the tributary restoration and levee setback project areas. Wave attenuation is likely in reaches where stream slopes are less than 0.001 ft/ft but is not expected when slopes are steeper than 0.001 ft/ft. Each number on the X-axis represents the upper bound for the stated bin of data. For example, the reaches with slopes that are less than 0.001 and greater than 0.0005 are plotted in the 0.001 bin.

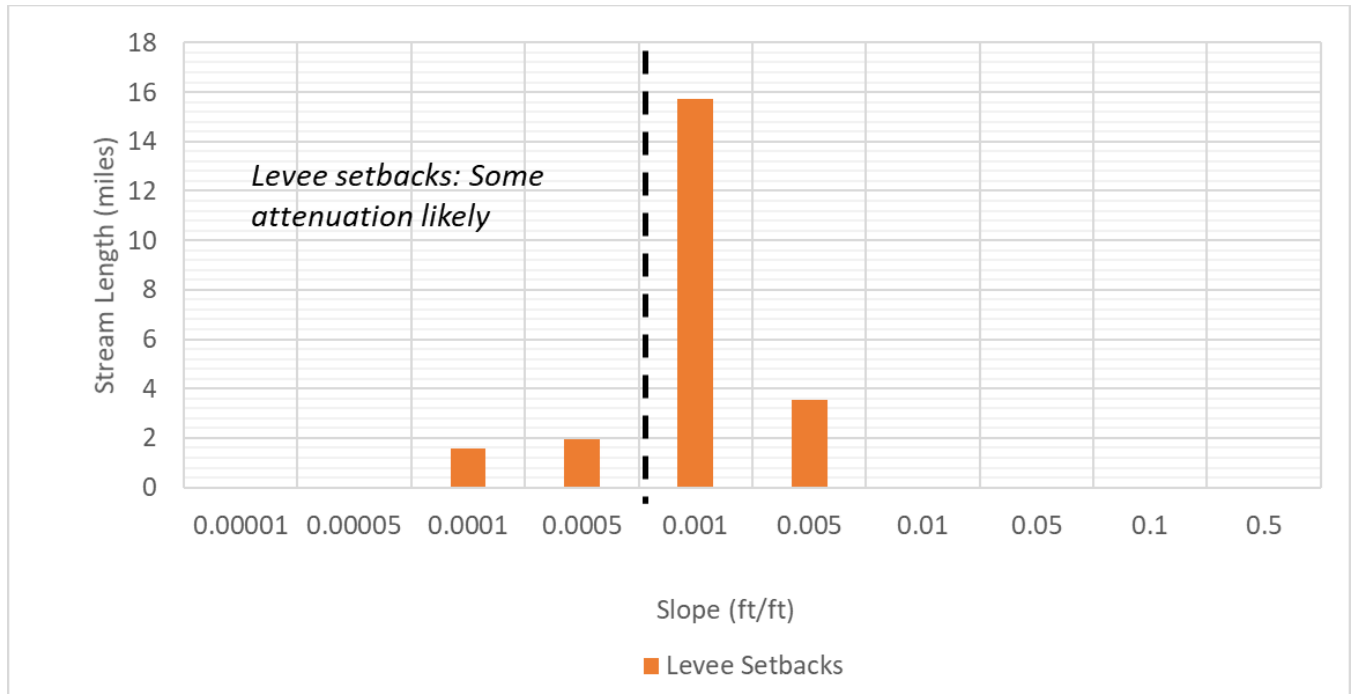


Figure 13. Distribution of stream slopes within the levee setback project areas. Wave attenuation is likely in reaches where stream slopes are less than 0.001 ft/ft but is not expected when slopes are steeper than 0.001 ft/ft. Each number on the X-axis represents the upper bound for the stated bin of data. For example, the reaches with slopes that are less than 0.001 and greater than 0.0005 are plotted in the 0.001 bin.

Based on the slope threshold of 0.001 ft/ft, most of the tributary restoration area is too steep for wave attenuation to occur. However, some of the levee setback project areas are below the threshold and therefore changes to flood hydraulics caused by those projects are likely to attenuate the flood wave. This likely explains the higher flood storage volume/area ratio of the levee setback projects versus the tributary restoration areas because the lower slope of some of the levee setback areas allows for the flood wave to be attenuated.

Because of the complex interaction between flow hydraulics and valley geometry, further study is needed to refine this analysis and estimate the specific wave attenuation properties of each flood storage strategy and project area. This could be performed using a 2-dimensional hydraulic model which specifically accounts for the different momentum mechanisms of flood waves and how they change with changes to flow hydraulics.

4.2 Physical Removal of Water from Flood

Physically removing water from a flood is another mechanism at which the peak of a flood can be reduced. From a mass-balance perspective, removing water from the flood reduces the amount of water that is transported downstream, thus reducing the overall peak of the flood. One way that this occurs is when flood waters inundate depressions on the floodplain that are disconnected from the river channel and therefore from return flow. Another way that water can be physically removed from a flood is when water inundates a floodplain and infiltrates into an alluvial groundwater aquifer. Because water in both situations cannot return back into the flood wave during the timescale of the event, it is effectively removed from the flood hydrograph and should therefore reduce downstream flood peaks if the volume is large enough to have a significant impact. The following section presents results from two separate analyses that were conducted to estimate the volume of water that could be physically removed from the flood with both mechanisms under the tributary restoration scenario.

4.2.1 Water stored in floodplain depressions

Methods

Estimates of water that can be stored in floodplain depressions were made using geospatial tools in ArcGIS on each of the 12 pilot reaches. First, the fill tool was used to fill any sinks (i.e., floodplain depressions) within the bare earth DEM. The subsequent raster was then differenced from the bare-earth DEM in order to calculate the volume of each floodplain depression. The volume raster was then clipped to account for only areas in which floodplain inundation was expected to increase under restored conditions (i.e., which depressions would only be filled under restored conditions and not existing conditions). The total depression storage volume was then calculated for each pilot reach and extrapolated to each stream class by the percent inundation of the valley bottom. The floodplain depression storage estimates were made using only the moderate roughness scenario.

Results

Water stored in floodplain depressions is expected to negligibly influence downstream flood peaks under the tributary restoration scenario (Table 13). For the entire treatment area, only 29 additional acre-ft of water is estimated to be stored within floodplain depressions under restored conditions compared to existing conditions which represents 0.02% of the total flood volume. The lack of additional storage in floodplain depressions is likely because most of the fluvial valley is already inundated under existing conditions during the Q100 flood - filling most of the floodplain depressions. These results indicate that physically removing water into floodplain depressions through tributary restoration is likely not a primary mechanism for reducing downstream flood peaks in the Puyallup watershed.

Table 13. Volume estimates for water that is likely to be stored within floodplain depressions within the tributary restoration project area under restored conditions. These results represent the change in floodplain depression storage between restored and existing conditions.

Class	Average increase in storage (ft ³ /acre)	Valley Bottom Area (acre)	Flood storage (acre-ft)	% of total flood
A	41	14,700	14	0.01%
B	47	9,900	11	0.01%
C	92	800	2	0.00%
D	119	1,200	3	0.00%
		Total	29	0.02%

4.2.2 Water infiltrated into groundwater

Methods

Estimates of groundwater infiltration volumes were made using an empirical approach presented in Doble et al. (2012) which incorporates hydraulic and geologic characteristics to calculate the expected volume of the pressure driven flux of flood waters into alluvial aquifers. Calculations were performed for both existing and restored conditions on each of the 12 pilot reaches and differenced in order to estimate the change in groundwater infiltration. The estimates were then extrapolated to the entire treatment area using the approach described above for the flood storage volume estimates. The hydraulic characteristics were derived from the

flood storage volume estimates described above and the geologic characteristics were selected using a range of site appropriate values for nearby watersheds (Abbe et al., 2019). Groundwater infiltration estimates were made for a range of parameter values (low, medium, high) in order to represent the variability of the hydraulic properties of the floodplain sediments and antecedent conditions within the watershed. Table 14 below shows the values used in the calculations:

Table 14. Input parameters used to estimate the volume of water that is likely to be infiltrated into groundwater aquifers during the 100-year flood. Groundwater infiltration estimates were conducted using a range of input parameters (low, medium, high) in order to express potential variability in the calculations.

Input Parameter	Low	Medium	High
Lateral extent of flooding	Based on hydraulic calculations Varies per pilot reach		
Depth in Floodplain	Based on hydraulic calculations Varies per pilot reach		
Saturated Hydraulic Conductivity of the Aquifer (ft/second)	4.50E-05	9.40E-05	1.40E-04
Aquifer Thickness (feet)	25	25	25
Duration of flood wave (Days)	2	3	4
Depth to groundwater (feet)	3	4	5
Specific yield (ratio)	0.2	0.3	0.4
Hydraulic Conductivity of clogging layer (ft/second)	3.99E-06	7.11E-06	2.36E-05
Thickness of clogging layer (feet)	2	1.25	0.5

Results

Groundwater infiltration is expected to remove between 1,030-3,390 acre-ft from the Q100 flood which accounts for between 0.6-2.1% of the total flood volume (Table 15). While the volumes are in the same order of magnitude to the flood storage volume estimates of the levee setback projects, they require treating a significantly larger area. These estimates are lower than nearby basins such as the Newaukum River, which is likely because the tributary restoration area in the Puyallup Watershed is less incised and thus the depth to groundwater, which dictates the total storage capacity, is less than in an incised system (Abbe et al., 2019). Taken in conjunction with the flood storage volume estimates, groundwater infiltration should provide an additional mechanism to reduce downstream flood peaks, although the magnitude will likely be small in comparison to the footprint of restoration (0.04-0.1 acre-ft/acre) due to the small relative volume and large treatment area (26,000 acres).

Table 15. Volume estimates for water that is likely to infiltrated into groundwater within the tributary restoration project area under restored conditions. These results represent the change in floodplain depression storage between restored and existing conditions.

	Increase in GW Infiltration (acre-ft)		
Class	Low	Medium	High
A	310	610	1,020
B	620	1,230	2,030
C	50	110	170
D	50	130	170
Total	1,030	2,080	3,390
% of flood	0.6%	1.3%	2.1%

4.3 De-synchronization of flood peaks

Flood peak desynchronization is another method by which peak flow in the Puyallup may be reduced. This is the principle behind Mud Mountain Dam, which delays the peak of the flood from the White River by retaining most of the flow during a large storm event and then releasing the water at a steady rate after the peaks from other sources in the watershed have passed. This pattern is visible in Figure 14, which plots the hydrographs from several USGS gages in the Puyallup watershed during the January 2009 flood. During the January 2009 flood, the hydrographs from the Carbon River, South Prairie Creek, and the tributaries upstream of the Carbon River all reach their peaks at roughly the same time, while discharge from the White River is artificially lowered for the duration of the storm peak and then raised to around 10,000 cfs after the overall peak has passed. Even with the Lower White peak effectively removed from the equation, the peaks from the remaining tributaries are synchronous (i.e., coincide temporally), and therefore combine to create a much higher peak discharge in the Puyallup than in any of its individual tributaries.

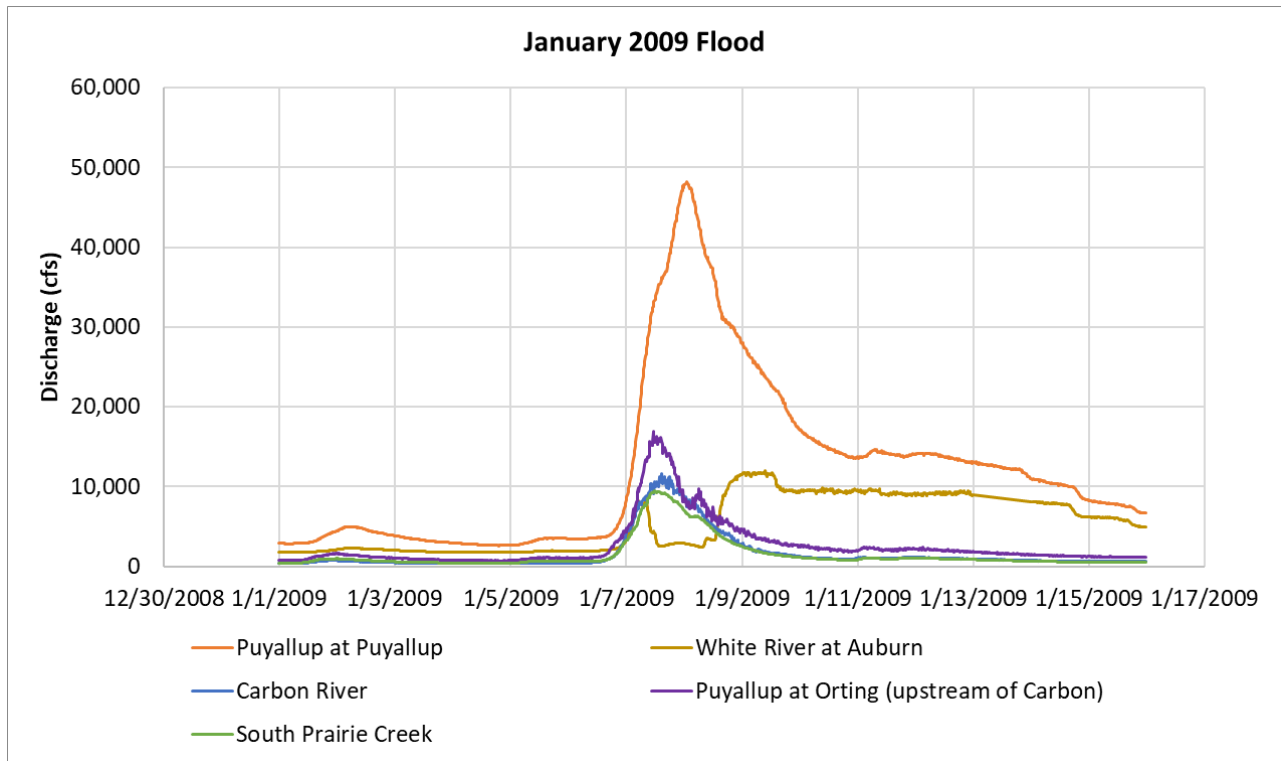


Figure 14. Hydrographs from the January 2009 flood for USGS stream gages in the Puyallup River Watershed.

Dams are often used to achieve flood peak desynchronization; the question here is whether the same end can be achieved using restoration. If the tributary flood waves can be parsed apart by slowing water at different rates across the watershed or by focusing restoration actions in one subwatershed to slow its flood wave, then fewer peaks will be stacked on top of one another and therefore the peak discharge in the Puyallup River will be reduced. Dixon et al (2016) looked into this question using a numerical model of the Lymington River watershed (98 km²) and found that restoration actions focused in subwatersheds desynchronized the flood peaks enough to cause a reduction in peak of 20-40% in the Lymington River, which is comparable to the projected 2080s peak flow estimates. To investigate whether this effect could be achieved in the Puyallup watershed, we conducted a proof-of-concept simulation using ArcGIS data and the coding platform R (R Core Team, 2017).

4.3.1 Methods

Using methods described above, a shapefile representing the network of streams in the Puyallup watershed was developed containing data regarding the length of each stream segment and estimates of the 100-year peak discharge at each stream segment. Stream segments were classified into the four stream classes used in the flood storage volume extrapolation procedure, and using the at-a-station methodology described above, an estimate of average velocity under existing and restoration conditions was obtained for each group and assigned to the segments contained therein (Table 16). Segments in the flow network that were not classified were assigned existing and restoration velocities equal to the average of the velocities in all classes.

Table 16. Velocity estimates for each stream class used in the De-synchronization of sub-watersheds proof-of-concept simulation. Velocity estimates were developed for each pilot reach using the hydraulic analysis calculations described above and were averaged for each stream class.

Class	Average Existing Velocity (ft/second)	Average Restored Velocity (ft/second)	Change (ft/second)
Class A	5.5	3.5	2.0
Class B	6.1	3.6	2.5
Class C	7.3	4.2	3.1
Class D	5.9	3.7	2.2
Unclassified	6.2	3.5	2.7

Upon this network of data, a simple code was written to track flow through the watershed. Travel time under existing and restoration conditions for each stream segment was calculated based on the length of the segment and the assigned velocities. Segments were assigned levels based on their position in the network, with level one segments being those which have no segments upstream of them, and the level number increasing the further downstream in the watershed the segment is. A synthetic Q100 hydrograph (see example in Figure 15) was created for each level 1 stream segment starting at time 0 and lasting 20 hours, with a 4-hour peak. The hydrograph was then translated forward in time according to the travel time associated with the segment in question, and then the hydrograph was transferred to the stream segment immediately downstream, and so on. In cases where a stream segment has multiple tributaries, the tributary hydrographs are added together and then the summed hydrograph is translated according to travel time. In this way, a hydrograph is calculated for every stream segment in the flow network based on velocity, segment length, and estimated Q100 in the highest tributaries. This set-up allows the potential effects of restoration, represented in this simulation as a slowing of velocity in specified areas, to be tested on a large scale.

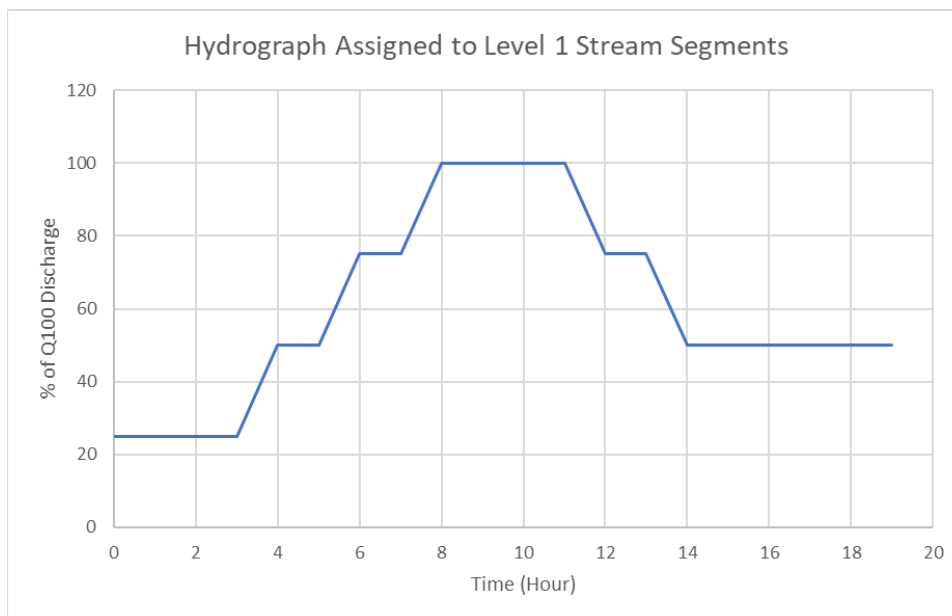


Figure 15. Example synthetic hydrograph used as inflow quantities for level 1 streams in the De-synchronization of sub-watersheds proof-of-concept simulation.

To test the hypothesis that restoration could lower peak flows in the Puyallup River by desynchronizing subwatershed flood peaks, this simulation was run for 7 scenarios. The first scenario represented existing conditions and had the estimated existing velocity assigned to all stream segments. The second scenario imagined a fully restored state in which all stream segments in the watershed had undergone restoration and therefore all stream segments were assigned the slower, “restored” velocity. The remaining scenarios tested the impact of restoring one subwatershed while leaving the others under existing conditions – restoration rotated between the watersheds of South Prairie Creek, Lower White River (downstream of the dam), Carbon River, Upper Puyallup River, and Puyallup River upstream of the confluence with the Upper Puyallup.

This analysis is based on several assumptions that should ultimately be refined before the results are considered as anything more than a proof of concept. First, the simulation assumes that the flood-generating storm event hits every point in the watershed simultaneously. A more realistic simulation would take into account the movement of the storm over time. Second, the simulation uses the simple USGS regional regression equations to estimate the Q100 discharge at each of the level 1 tributaries (Mastin et al., 2017). Based on the results of this analysis, this approach appears to overestimate flows in these high tributaries, and that overestimation ripples throughout the watershed. Third, the existing and restored velocities assigned to each stream segment are roughly estimated based on the stream segment’s classification; the velocity does not vary within a stream class regardless of the stream segments’ slope or other attributes. While this is sufficient for a concept-level analysis since the classifications were intended to separate stream segments into like categories, a more definitive answer would require a more fine-grained approach to velocity estimation.

4.3.2 Results and Discussion

After each scenario was run in the model, the resulting hydrograph was pulled from the downstream-most stream segment in the Puyallup River, and the maximum discharge was extracted to represent the peak (Figure 16). Table 17 shows the impact that all restoration scenarios had on the peak relative to existing conditions which resulted in a 43% reduction in the overall peak due to the slower velocities in the restored reaches and subsequent de-synchronization of the sub-watershed hydrographs which is similar in magnitude to the projected 2080s increase in peak flows. It should be noted again however, that the simulated results are from a highly simplified model that does not reflect observed conditions. Therefore, these results should be considered a proof-of-concept and not reflective of observed conditions.

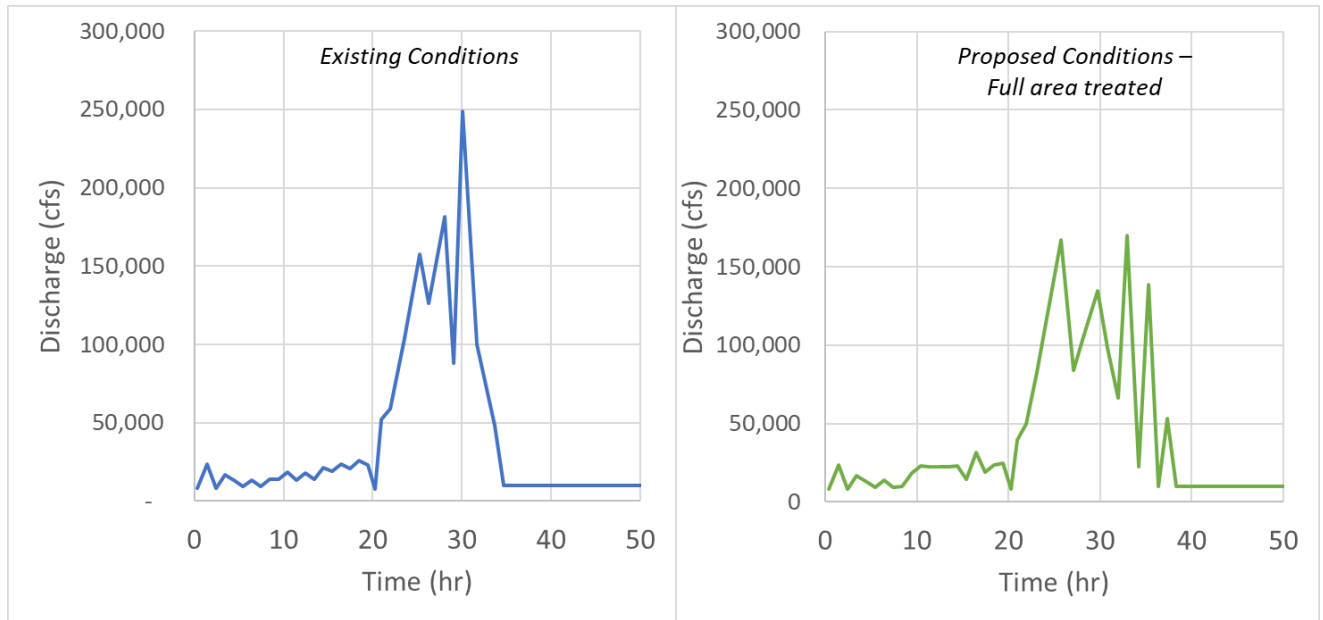


Figure 16. Outflow hydrographs for existing and restored (full area treated) conditions from the De-synchronization of sub-watersheds proof-of-concept simulation. These hydrographs underscore the conceptual nature of the simulation because they are not reflective of observed gage data at the downstream end of the watershed.

Table 17. Peak reduction results for the treatment scenarios run using the De-synchronization of sub-watersheds proof-of-concept simulation. Each row presents results for scenarios where the particular sub-watershed shown in the left most column was treated. The last row presents results for the scenario where the full tributary restoration project area was treated.

Sub-watershed Treated	Percent of Watershed Treated	Percent Reduction in Peak at Outlet
South Prairie	2%	13%
Lower White	6%	11%
Carbon	8%	6%
Upper Puyallup	8%	2%
Puyallup	12%	35%
All Classified Areas Treated	59%	43%

The results are more variable for the sub-watershed scenarios, in which restoration was focused in only one sub-watershed. For instance, restoring the South Prairie Creek watershed resulted in a 13% decrease in peak discharge despite only 2% of the watershed being treated. In this case, the South Prairie Creek flow peak was aligned with the other peaks in the existing conditions scenario, and so slowing it down de-synchronized the South Prairie wave from the other sub-watersheds and had a large impact on the downstream peak. In contrast however, treating only the Upper Puyallup sub-watershed resulted in only a 2% reduction in the downstream peak despite treating an area 4 times greater than South Prairie Creek. This is likely because the Upper Puyallup sub-watershed was not synchronized to the other peaks and thus treating that area had a negligible impact on the outlet hydrograph.

Regardless of the uncertainties, this analysis suggests that restoration may reduce the downstream flow peak via flood peak desynchronization. Three different sub-watershed scenarios resulted in downstream peak reductions greater than 10%. Comparing the size of each sub-watershed to the percent reduction in peak associated with its restoration may also provide guidance for planners in terms of where to focus future analysis and, ultimately, restoration dollars, to achieve the most effect.

Because of the inherent uncertainty in this proof-of-concept simulation, a more refined approach and accurate model is needed to test these results and focus in on where restoration could be most effective in reducing the downstream flood peak through peak desynchronization. A hydrologic model of the Puyallup watershed would be able to overcome many of the simplifying assumptions regarding the magnitude and spatial distribution of inflows. A paired hydraulic model would be able to better evaluate site specific changes to flood hydraulics caused by tributary restoration.

5 SEDIMENT ANALYSIS

An analysis of the sediment storage potential within the main stem levee setback projects and tributary restoration treatment areas was also conducted in order to better understand how these flood peak reduction actions would influence sediment transport dynamics (and vice-versa) within the basin. The Puyallup River watershed has a large sediment load because of the underlying geology and glacial and volcanic activity in the watershed (Anderson and Jaeger, 2019). Because of this, sediment is currently believed to be partially contributing to flooding in the lower watershed because of increases in bed elevations due to aggradation. Therefore, it is important to understand how the levee setback and tributary restoration flood reduction strategies may influence (and be influenced by) sediment transport dynamics. For the levee setback projects, the primary study question was related to whether flood storage potential may be lost within the project areas due to sedimentation. For the tributary restoration treatment area, the study question is associated with quantifying how much sediment the projects may store and thus reduce sediment loads downstream. The following section describes the methods and results used to answer each of these questions.

5.1.1 Sedimentation Potential in Levee Setback Projects

Methods

The sedimentation potential of the proposed levee setback projects was evaluated by analyzing topographic changes within the Countyline Levee Setback project area because the project has already been built and several years of topographic data are available for analysis. Identified trends from the Countyline Project will be used to infer sedimentation potential for the other levee setback projects but sedimentation estimates for all projects were not calculated. The Countyline Levee Setback project was constructed on the White River near the King and Pierce County line and was completed in 2017. The project setback and existing left bank levee – constructing a new side channel and opening up ~100 acres of floodplain. Since the project's completion, King County has collected annual topobathymetric lidar to assess changes within the site. Changes within the first year following construction were reported by King County in a 1-2 Year Monitoring report in which they present an estimate of the volume of sediment aggradation within the site between 2017-2018 (Lincoln et al., 2020). For this study, we repeated their analysis using the more recent 2018, 2019, and 2020 topobathymetric lidar digital elevation models (DEMs) to estimate how the project has responded since their initial monitoring report.

To conduct the analysis, a DEM of difference (DoD) was created by differencing two consecutive years of lidar DEMs (i.e., 2019 minus 2018) in ArcGIS. Each pixel of the resulting raster was then multiplied by the raster cell size (3 ft x 3 ft) in order to calculate a volume of change within each pixel. All of the pixels were then summed in order to calculate the total volume of change within each time period. The analysis was repeated for all years of

available data (2018 to 2019 and 2019 to 2020). The results were used to evaluate the response within project area and consider how sediment dynamics will change within the other proposed levee setback projects.

Results

The results of the topographic change analysis within the Countyline project area indicate that the river and floodplain are adjusting to the new conditions while a “dynamic equilibrium” is being established and that as long as the river is able to migrate into the newly formed floodplain long term aggradation (and subsequent loss of flood storage volume) is not expected within the project area (Table 18). Immediately following construction there was a significant amount of aggradation (1.35 ft) which was likely due to a large decrease in sediment transport capacity because of the increase in floodplain inundation extent. However, aggradation decreased in the subsequent year (0.13 ft) and there was a net loss of sediment (-0.03 ft) 2 years after construction. These results suggest that the river is establishing a “dynamic equilibrium” with the newly occupied floodplain and that aggradation into the new floodplain area is being balanced by increases in erosion as new channels are formed and the river migrates across the valley bottom. While sedimentation rates may continue to fluctuate with upstream sediment pulses and the frequency of flood events, sediment deposition is likely to be balanced by erosion rates over the long-term and an overall loss of flood storage is not expected.

Table 18. Topographic change results for the Countyline Levee Setback project. Results were generated using lidar digital elevation models provided by King County.

Time period	2017 to 2018 (1-2 year monitoring report)	2018 to 2019 (topobathy lidar)	2019 to 2020 (topobathy lidar)	3 year average
Sediment volume (cu yd)	245,000	23,000	-5,000	87,667
Depth of aggradation/erosion (ft)	1.35	0.13	-0.03	0.48

The conclusion that long-term sedimentation within the Countyline project is unlikely can be extrapolated to the remainder of the levee setback projects as long as the river is not constrained from migrating across the valley bottom to form new floodplain areas in the vicinity of those project sites. However, because of spatio-temporal complexities in site specific hydraulics and sediment loads for each of the levee setback project areas, storage estimates (or lack thereof) cannot be extrapolated across the project areas. Furthermore, future monitoring work within the Countyline project is needed to confirm the 3 year trends identified by this study. Monitoring work should also be conducted in future levee setback projects as well.

5.1.2 Sediment Storage Potential of Tributary Restoration

Methods

The sediment storage potential of tributary restoration was estimated by evaluating potential sediment storage within each pilot reach and performing a similar extrapolation procedure to the flood storage estimates. For the sediment estimate it was assumed that there would be a high density of ELJ placements throughout the active channel and floodplain of each pilot reach. In order to maximize the flood storage potential, it was assumed that the backwater from each structure would extend to the downstream end of the next structure, effectively raising the entirety of the flood’s water surface profile. Because of the decreased velocities associated with each ELJ placement it was assumed that a wedge of sediment would aggrade upstream of each structure and extend to the next structure. The full structure height (see below) was used to account for aggradation potential within

the active channel, and a smaller structure height of 0.5 ft was used to account for lower aggradation rates within the floodplain due to the higher existing elevations compared to the current channel. The channel dimensions were measured for each reach and the floodplain dimensions were calculated using the hydraulic analysis described above.

The total volume of aggraded sediment within each reach was then calculated by quantifying the volume of the aggraded wedge within the channel and floodplain. The volume was then adjusted to account for differences in restoration approach and geomorphic adjustments of the morphology following restoration (i.e., new channels formed to maintain sediment transport continuity) by including obstruction percentage (how much of the valley width is obstructed by ELJs) and trapping efficiency (what proportion of the full sediment wedge is actually retained behind the structures) quantities to the calculation. A range of values were estimated by varying the structure height, obstruction percentage, and trapping efficiency as follows (Table 19):

Table 19. Input parameters for the tributary restoration sediment storage analysis.

Scenario	Structure Height (ft)	Obstruction Percentage	Trapping Efficiency (%)
Low	4	40%	40%
Moderate	5	50%	50%
High	6	60%	60%

An average depth of aggradation within each pilot reach was then calculated for each scenario by dividing the estimated aggradation volume by the valley bottom area. The results were then averaged across each stream class and extrapolated using the valley bottom area of the full stream class in a similar fashion to the flood storage estimates.

Results

The sediment storage potential was estimated to be between 2,350,000-5,270,000 cubic yards of sediment throughout the tributary restoration area (Table 20). Put into context, these volumes equate to between 130-300 years of the total estimated load of bedload sediment exported to Puget Sound¹ (Czuba et al., 2011; Czuba et al., 2012). These estimates represent an extreme high bound because not all restoration projects would occur at once nor would the entire sediment load of the system be stored because sediment transport continuity would be maintained through the restored channel network. However, these estimates demonstrate that tributary restoration within the watershed could store a significant quantity of sediment and are used to explain what is volumetrically possible. The sediment storage potential, like the flood storage potential, would scale with project size, and benefits could still be achieved from individual projects even though they would be small compared to the overall sediment load. These results indicate that storing sediment would be an additional benefit of the tributary restoration strategy.

¹ The estimated load of bedload sediment was calculated by multiplying the estimated total sediment load from the Puyallup Watershed of 980,000 tonnes/year from Czuba et al., 2011 by the estimate that bedload represents 4% of the total load. The 4% estimate was estimated using data presented in Czuba et al., 2012.

Table 20. Sediment storage volume estimates for the tributary restoration strategy.

Class	Area (acres)	Estimate of stored sediment volume (cubic yards)		
		Low	Moderate	High
Class A	14,700	1,310,000	2,040,000	2,940,000
Class B	9,900	920,000	1,430,000	2,060,000
Class C	800	40,000	70,000	100,000
Class D	1,200	80,000	120,000	170,000
Total (cubic yards)		2,350,000	3,660,000	5,270,000
Years of total bedload export to Puget Sound (USGS, 2011)		130	210	300

6 CONCLUSION

This study demonstrates that both main stem levee setback projects and tributary restoration show potential for increasing flood storage within the Puyallup River Watershed. While the estimated flood storage volumes from tributary restoration are much larger than for the main stem levee setback projects, they involve treating a much larger area. On a per unit area basis, the levee setback projects are almost 5 times as effective at increasing flood storage volume, likely due to their lower slope. Projects to increase flood storage volume through levee setbacks and restoration also bring additional benefits of increasing sediment storage (tributary restoration), improving aquatic habitat, and reducing development in the floodplain where the risk is the highest. Increasing flood storage capacity of the watershed also increases climate resiliency in preparation for projected increases in peak flows.

Peak flows may also be reduced by both strategies, but for different reasons. Because of the low slope of the levee setback project areas, that strategy may be able to attenuate the flood wave and decrease downstream peak magnitudes. On the other hand, restoring some or all of the major tributaries may cause the peaks of the individual flood waves to de-synchronize which could also decrease downstream flood peaks. Physically removing water from the flood by storing it in floodplain depressions or within alluvial aquifers is not likely to have a substantial effect on flood peaks. In all situations however, hydrologic and hydraulic modeling is needed to quantify the amount of flood peak reduction obtained by each strategy and to directly compare between them. The results of this study can be used to focus future modeling efforts. For example, these results suggest further effort should be focused on lower gradient levee setback project areas or the simulation of the effects of intensive restoration in one tributary.

Taken all together, both levee setbacks and tributary restoration represent potential strategies for reducing flooding within the Puyallup River Watershed while also bringing additional benefits for aquatic habitat, sediment storage, and land use planning.

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